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AAIA

Air Accident Investigation Authority

# Propulsion System Fire (SCF–PP–PSF)

## Investigation Report

## Serious Incident to

## Boeing 747-8F, N624UP

## Hong Kong International Airport

## 20 July 2021

08-2022

# AAIA Investigations

Pursuant to Annex 13 to the Convention on International Civil Aviation and the Hong Kong Civil Aviation (Investigation of Accidents) Regulations (Cap. 448B), the sole objective of the investigation and the Investigation Report is the prevention of accidents and incidents. It is not the purpose of the investigation to apportion blame or liability.

The Chief Inspector ordered an inspector's investigation into the serious incident in accordance with the provisions in Cap. 448B.

This serious incident final report contains information of an occurrence involving a Boeing 747-8 freighter, registration mark N624UP, operated by United Parcel Service Company, which occurred on 20 July 2021.

The National Transportation Safety Board (NTSB) of the United States of America, being the investigation authority representing the State of Registry, the State of the Operator, the State of Design and the State of Manufacture of the aircraft, the Federal Aviation Administration (FAA), Boeing, General Electric Company (GE), Woodward (the fuel metering unit manufacturer), and the aircraft operator, provided assistance to the investigation team.

Unless otherwise indicated, recommendations in this report are addressed to the regulatory authorities of the State or Administration having responsibility for the matters with which the recommendation is concerned. It is for those authorities to decide what action is taken.

This Investigation Report supersedes all previous Preliminary Report and Interim Statement concerning this serious incident investigation.

All times in this Investigation Report are in Hong Kong Local Times unless otherwise stated.

Hong Kong Local Time is Coordinated Universal Time (UTC) + 8 hours.

Chief Accident and Safety Investigator

Air Accident Investigation Authority

Transport and Logistics Bureau

Hong Kong

December 2022

# Synopsis

At 1216 hours on 20 July 2021, a United Parcel Service Company (UPS) Boeing 747-8 freighter, with registration mark N624UP, departed from Hong Kong International Airport (VHHH) for Dubai International Airport (OMDB) with flight number UPS3.

About four minutes after take-off, the flight crew shut down the left outboard (No. 1) engine due to excessive engine speed, and then elected to return the aircraft to Hong Kong. After landing on Runway 07L, the No. 1 engine caught fire during water application by the airport fire contingent (AFC). There was no other damage to the aircraft apart from the thermal damage to the engine. No one was injured.

After the post-event inspection of the No. 1 engine by the Air Accident Investigation Authority (AAIA) of Hong Kong, the engine was removed and sent to the engine manufacturer, GE, for further examination under the supervision of the NTSB of the United States of America.

The examination identified a fuel leak from the supply pressure (P1) bypass valve port fitting on the fuel metering unit. The subsequent inspection revealed that the fitting was finger loose with a gap between the fitting and the housing. The packing of the fitting was also found damaged.

The investigation found that this serious incident was caused by improper installation of the P1 bypass valve port fitting on the fuel metering unit, resulting in a fuel leak that rendered the engine fire.

The investigation team has made two safety recommendations.

# Contents

# 1. Factual Information

## 1.1. History of the Flight

(1) At 1216 hours on 20 July 2021, a UPS Boeing 747-8 freighter, registration mark N624UP, departed from Hong Kong International Airport (VHHH) to Dubai International Airport (OMDB) with flight number UPS3.

(2) During the transition from take-off to climb (approximately around 300 feet above ground), the left outboard (No. 1) engine experienced a fan speed (N1) exceedance. The Engine Indicating and Crew Alerting System (EICAS) displayed the caution message "ENG 1 LIM EXCEED" and N1 indications in red. The flight crew commanded the engine to idle.

(3) After the engine idle speed was commanded, the engine speed still oscillated around the take-off speed / overspeed limit, resulting in a loss of thrust control (LOTC).

(4) About four minutes after take-off, at 1220 hours, the flight crew shut down the No. 1 engine according to the operating procedures, and returned the aircraft to Hong Kong.

(5) About 12 seconds after shutdown, the EICAS displayed the warning message "FIRE ENG 1". The flight crew pulled the No. 1 engine fire handle and discharged two fire extinguisher bottles, but the fire warning continued. The fire warning ended shortly before landing. The total fire alarm time was approximately 9.5 minutes.

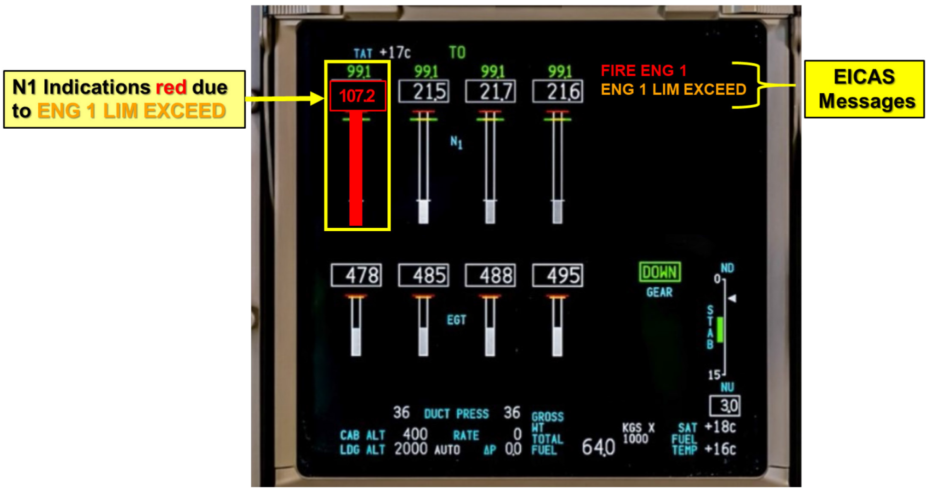



**Figure 1: Example of Displayed EICAS Indications and Messages**

(6) After the aircraft landed safely on the then Runway 07L at 1230 hours, the airport fire contingent (AFC) inspected the No. 1 engine and the brakes of the aircraft and found no fire.

(7) About 22 minutes after landing, at 1252 hours, the AFC noticed white smoke and then fire in the No. 1 engine when water was being applied to the engine surrounding to maintain cooling effect. Additional fire suppressants were applied to the engine and the fire was extinguished within 40 seconds.

(8) There was no other damage to the aircraft apart from the thermal damage to the engine. No one was injured.


**Figure 2: Flight Path with Key Events**

## 1.2. Injuries to Persons

The persons on board included three crew members including one captain, one first officer, and one relief first officer. There were no injuries to persons as a result of this occurrence.

<table>
<tr><td colspan="7">Injuries to Persons</td></tr>
<tr><td>Persons on board:</td><td>Crew</td><td>3</td><td>Passengers</td><td>0</td><td rowspan="2">Others</td><td rowspan="2">0</td></tr>
<tr><td>Injuries</td><td>Crew</td><td>0</td><td>Passengers</td><td>0</td></tr>
</table>

**Table 1: Injuries to Persons**

## 1.3. Damage – Aircraft

(1) The engineering inspection revealed thermal damage, sooting, and discolouration at the exterior core section of the No.1 engine. Details are in Section 1.16.1.: Powerplant Examination at GE Facility.

(2) The engine pylon, both thrust reversers, exhaust sleeve, and exhaust cone all suffered heat damage and were removed and replaced. All of these items were deemed beyond economical repair.

## 1.4. Other Damage

No other damage was caused.

## 1.5. Personnel Information

### 1.5.1. Flight Crew

(1) The flight crew consisted of one captain, one first officer, and one relief first officer. The captain was the pilot flying (PF) in the left seat. The first officer was the pilot monitoring (PM) in the right seat.

(2) The flight crew held valid licences and medical certificates. Crew licence information is located in Section 6.2: Pilot Information.

# 1.6. Aircraft Information

## 1.6.1. Aircraft

(1) The Boeing 747-8F is a wide-body four-engine aircraft developed and manufactured by The Boeing Company. The aircraft concerned is powered by four GE GEnx-2B67/P engines. The aircraft has been operated by UPS since November 2020.

(2) The aircraft had a valid Certificate of Registration and a valid Standard Airworthiness Certificate. Details are in Section 6.3: Aircraft Details.

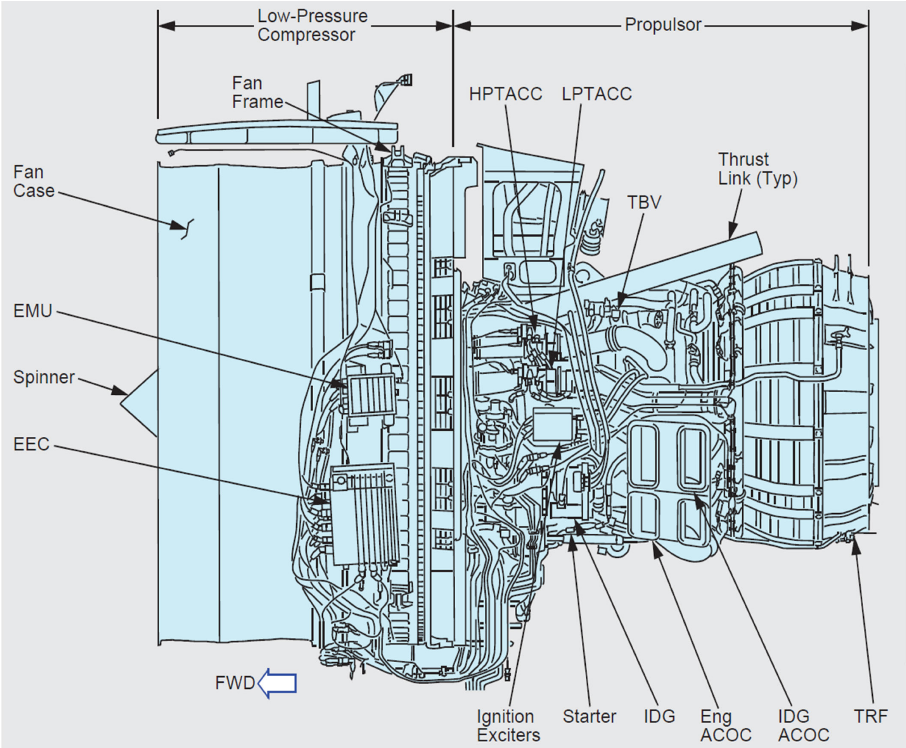
## 1.6.2. Engine

(1) The GEnx-2B67/P engine is a dual rotor, axial flow, high bypass ratio turbofan engine. The 10-stage high-pressure compressor (HPC) is driven clockwise aft looking forwards (ALF) by a 2-stage high-pressure turbine (HPT). The single-stage fan and 3-stage low-pressure compressor (LPC) are driven counter-clockwise ALF by a 6-stage low-pressure turbine (LPT).

(2) The engine control system includes a Full Authority Digital Engine Control (FADEC), which has an aircraft connection for digital communication. It gives information to the aircraft for flight deck indication, maintenance reports, and engine condition monitoring.

(3) The Electronic Engine Control (EEC) continuously monitors itself and the engine systems for normal operation, and sends engine status and fault data to EICAS for flight deck display.

(4) When the engine operates, the thrust lever angle resolver sends a Thrust Resolver Angle (TRA) signal to the EEC. The EEC sets the N1 thrust command using data from the Air Data Inertial Reference Units (ADIRUs) to calculate a Mach speed reference. Mach speed reference is a property of air density. The EEC electronically controls the fuel metering valve in the fuel metering unit (FMU).

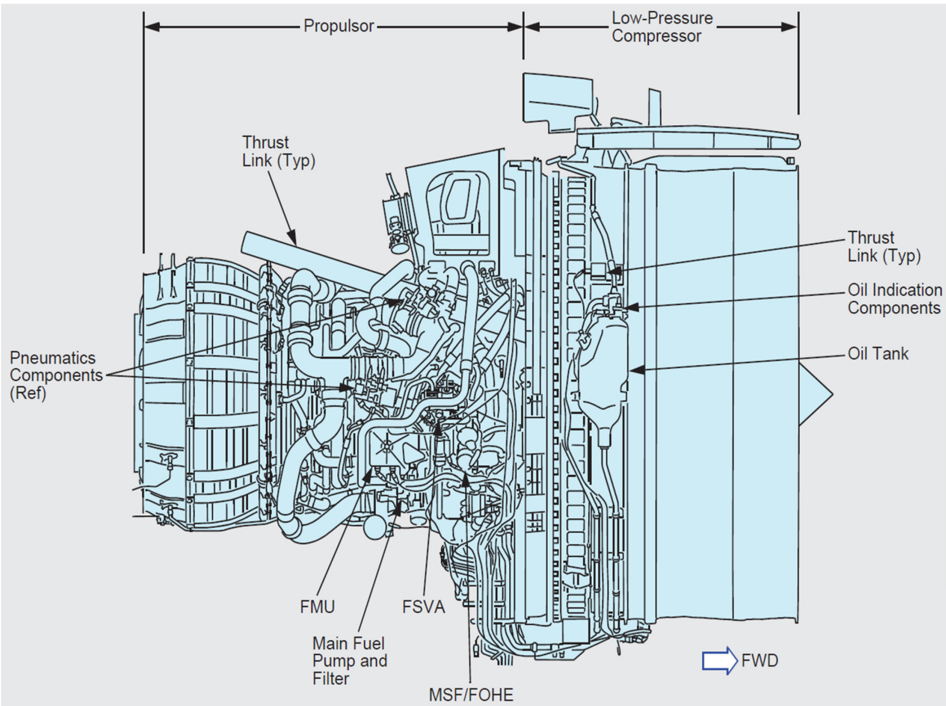



These components are on the engine left side:

- Engine Monitoring Unit (EMU)
- Electronic Engine Controller (EEC)
- Ignitors
- Starter
- Integrated Drive Generator (IDG)
- Engine Air Cooled Oil Cooler (ACOC)
- IDG ACOC
- Transient Bleed Valve (TBV)
- Low Pressure Turbine Active Clearance Control (LPTACC) valve
- High Pressure Turbine Active Clearance Control (HPTACC) valve.



**Figure 3: GEnx-2B Turbofan Engine – Left Side**




These components are on the engine right side:

- Fuel Metering Unit (FMU)
- Main fuel pump and filter
- Flow Split Valve Accumulator (FSVA)
- Main Fuel Oil Heat Exchanger (MFOHX)
- Oil tank
- Oil indication sensors.



**Figure 4: GEnx-2B Turbofan Engine – Right Side**

## 1.6.3. Engine Fuel System

(1) The fuel system supplies fuel to the engine for combustion and provides servo fuel to operate engine air system actuators and the fuel metering valve (FMV).

(2) The accessory gearbox drives a two-stage fuel pump, which supplies high-pressure fuel to the FMU through the fuel/oil heat exchangers.

(3) High-pressure fuel flows directly to the FMU. Servo fuel goes through the fuel/oil heat exchanger before it goes to the FMU servo fuel section. Fuel flow divides in the Fuel Split Valve (FSV).

(4) The EEC sends a signal to the FMU, which meters the fuel to the fuel nozzles. The internal FMV of the FMU controls the quantity of fuel flow to the Flow Splitter Valve (FSV).

(5) When the fuel control switch is set to RUN, the FMU opens the internal High Pressure Shutoff Valve (HPSOV) if there is sufficient fuel pressure, and metered fuel then flows to the combustor.

(6) The EEC uses the FSV to control the metered fuel to the fuel nozzles, depending on the engine power setting.

(7) The FSV controls the quantity of fuel going into the 22 fuel nozzles via the Pilot Secondary Fuel Manifold (PSEC), the Pilot Primary and Main Staged Fuel Manifold, and the Primary and Main Unstaged Fuel Manifold, which are connected to all the fuel nozzles, 18 fuel nozzles, and 4 fuel nozzles respectively.

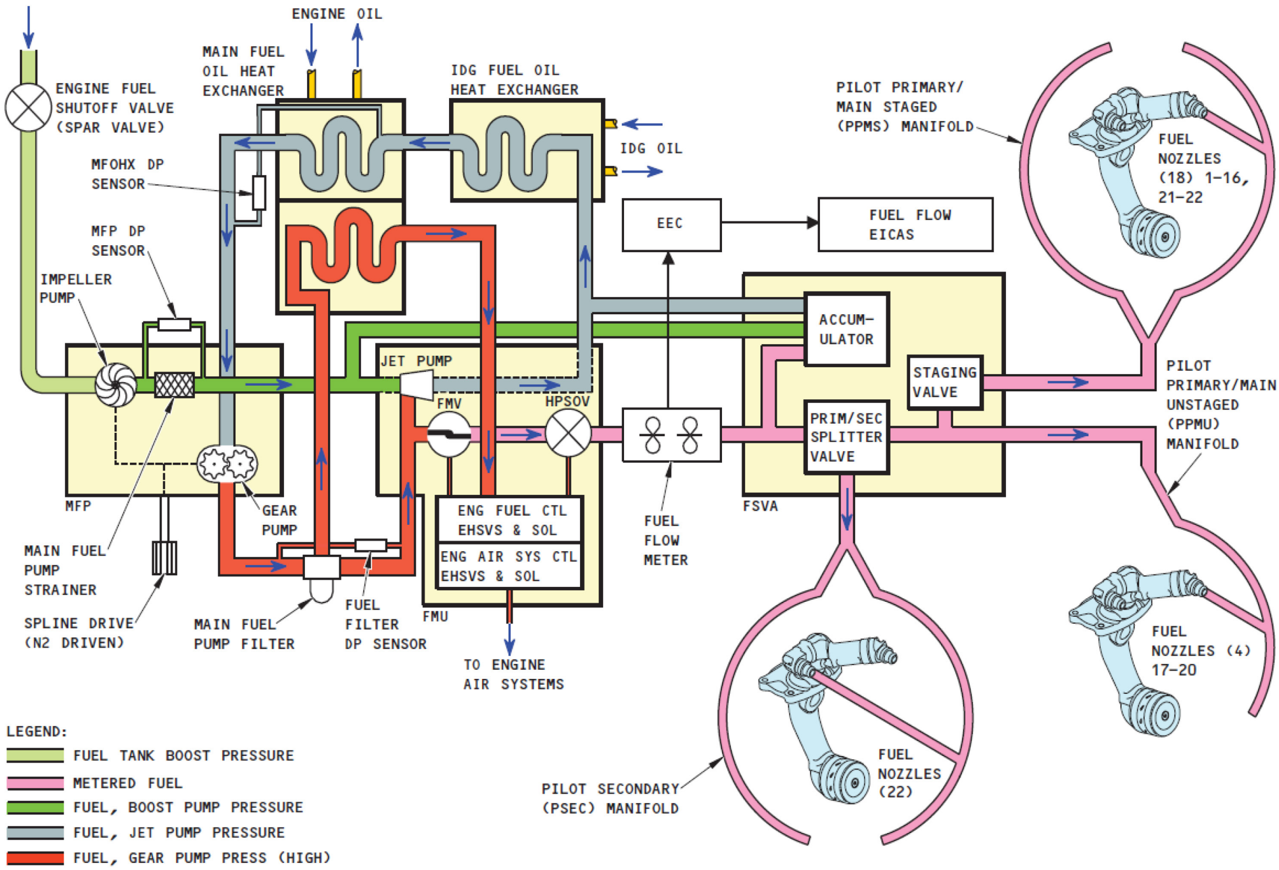





**Figure 5: Engine Fuel System Schematic**

## 1.6.4. Engine Fire Protection System

(1) Dual-loop (redundant) fire and overheat detectors are provided at each engine. The fire detection system provided means to alert the flight crew.

(2) Fire and overheat warning indications include descriptive EICAS messages, master caution and warning lights, aural warning for fire and overheat conditions, fire handle and fuel control switch lights for engine fire conditions to aid flight crew response.

(3) Two fire extinguisher bottles are installed on each wing. Either bottle can be discharged to either engine installed on that wing.

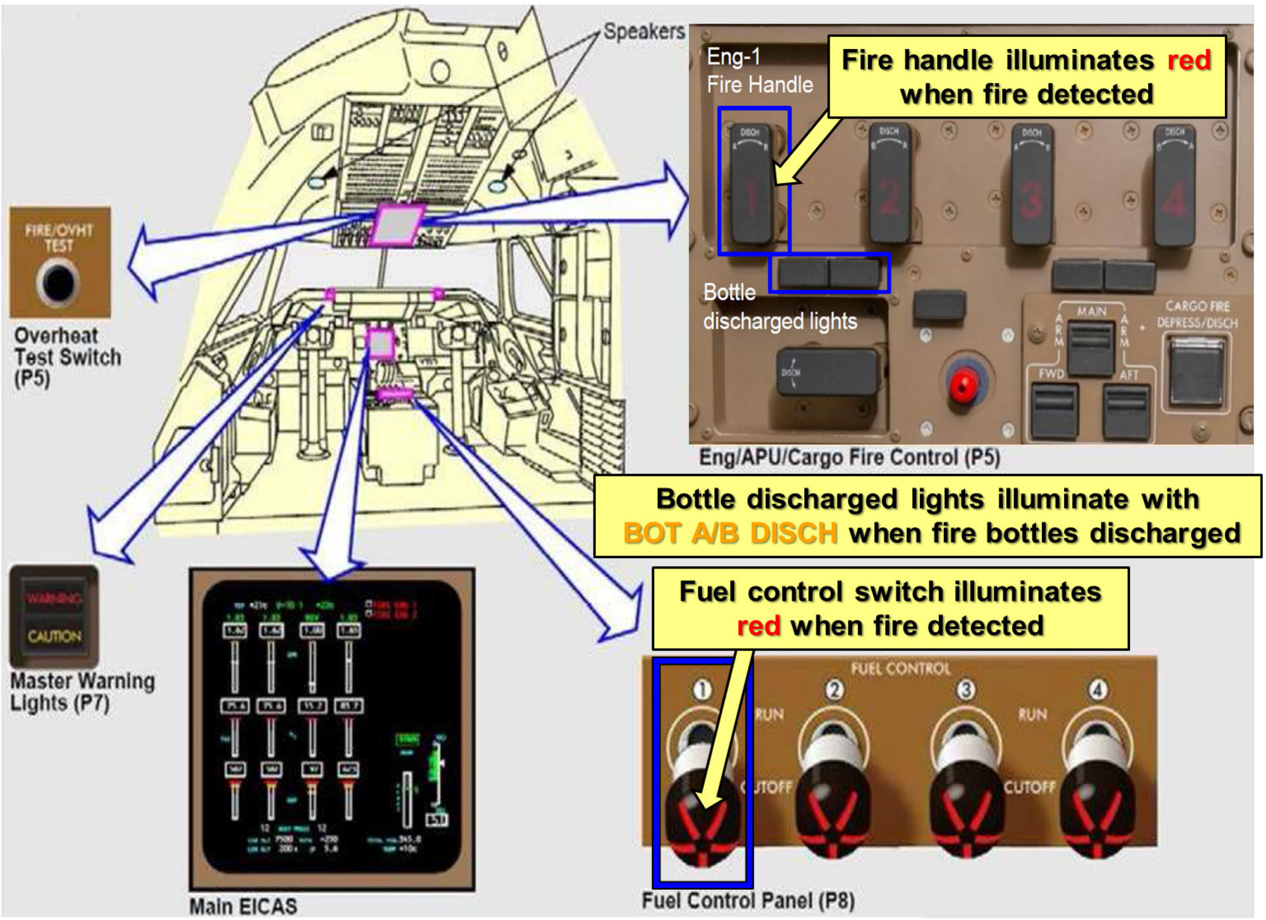





**Figure 6: Engine Fire Protection System**

## 1.6.5. Maintenance History

(1) According to the operator, the engine was installed as new. The only engine maintenance was the replacement of the fuel filter, main fuel pump strainer and lube flow screen on 7 July 2021 as the engine condition monitoring had alerted of a rising differential fuel pressure indication on the No. 1 engine.

(2) After the replacement, the pressure indication returned to normal and remained stable until the date of occurrence.

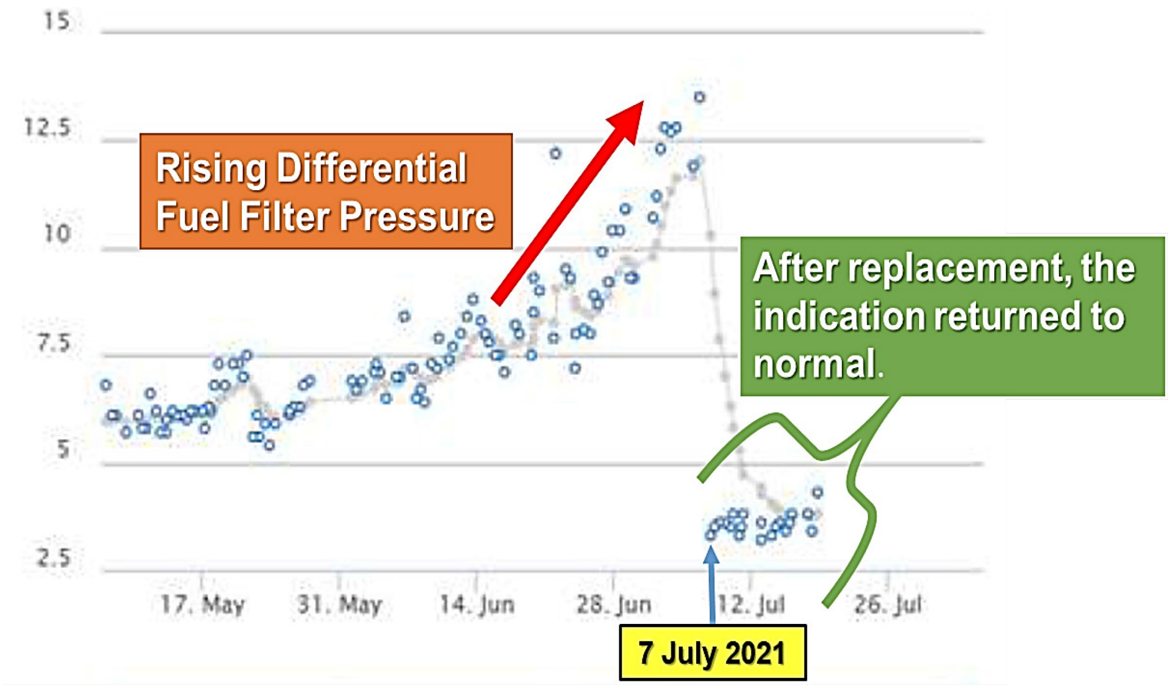



**Figure 7: Trend of Fuel Filter Delta Pressure**

## 1.7. Meteorological Factors

The Meteorological Aerodrome Weather Report (METAR) for Hong Kong International Airport (VHHH) at 1200 hours indicated that the wind speed was 8 knots. The surface wind direction was 080 degrees. The visibility was 10 kilometres or above. There were a few clouds at 500 feet above sea level. The air temperature was 26 degrees Celsius and the dew point was 24 degrees Celsius.

## 1.8. Navigation Aids

There were no reports of abnormal operation of any ground-based navigation aids or aerodrome visual ground aids at the time of the occurrence.

## 1.9. Communications

(1) The aircraft was equipped with three Very High Frequency (VHF) radio communication systems which were serviceable.

(2) All communications between Hong Kong ATC and the aircraft were recorded by ground-based automatic voice recording equipment. There was no interruption to such communications.

# 1.10. Aerodrome Information

Information on the Hong Kong International Airport is listed in Section 6.4 Aerodrome Information.

# 1.11. Flight Recorders

## 1.11.1. Flight Data Recorder

The aircraft was equipped with a 25-hour flight data recorder (FDR)[1] of P/N 2100-4045-22. The FDR was functional and recording data. The flight data captured all of the flight parameters required for the analysis of this occurrence.

## 1.11.2. Cockpit Voice Recorder

(1) The aircraft was equipped with a 120-minute cockpit voice recorder (CVR)[2] of P/N 2100-1925-22. The CVR was functional and recorded voice.

(2) Since the power supply of the CVR was not isolated immediately after the occurrence, the relevant CVR data was overwritten and not available for investigation.

# 1.12. Wreckage and Impact

(1) The aircraft was not damaged except thermal damage observed at the exterior core section of the No. 1 Engine.

(2) The soot shown at the openings of the thrust reverser (T/R)'s four pressure relief doors on the No. 1 engine.

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[1] FDR – a device used to record specific aircraft performance parameters. The purpose of an FDR is to collect and record data from a variety of aircraft sensors onto a medium designed to survive an accident.

[2] CVR - a device used to record the audio environment in the flight deck for accidents and incident investigation purposes. The CVR records and stores the audio signals of the microphones and earphones of the pilots’ headsets and of an area microphone installed in the cockpit.

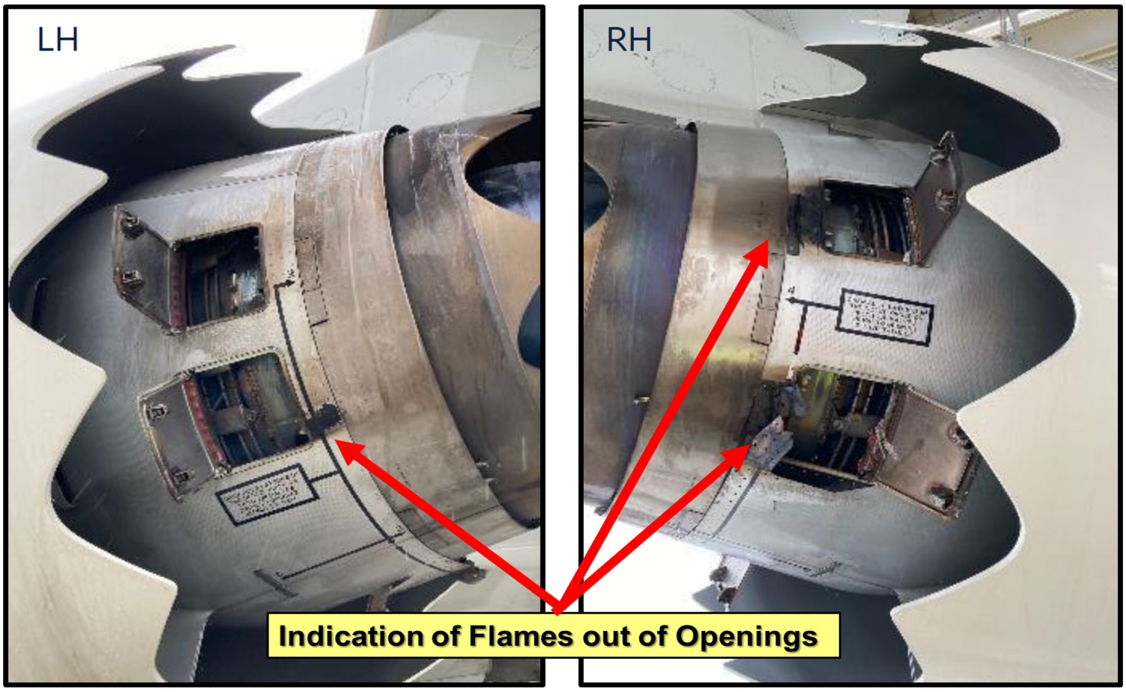



**Figure 8: Soot shown at the Openings of T/R Pressure Relief Doors**

(3) After opening the engine core cowling, thermal damage was observed on both sides of the exterior engine core. Details are in Section 1.16.1.: Powerplant Examination at GE Facility.

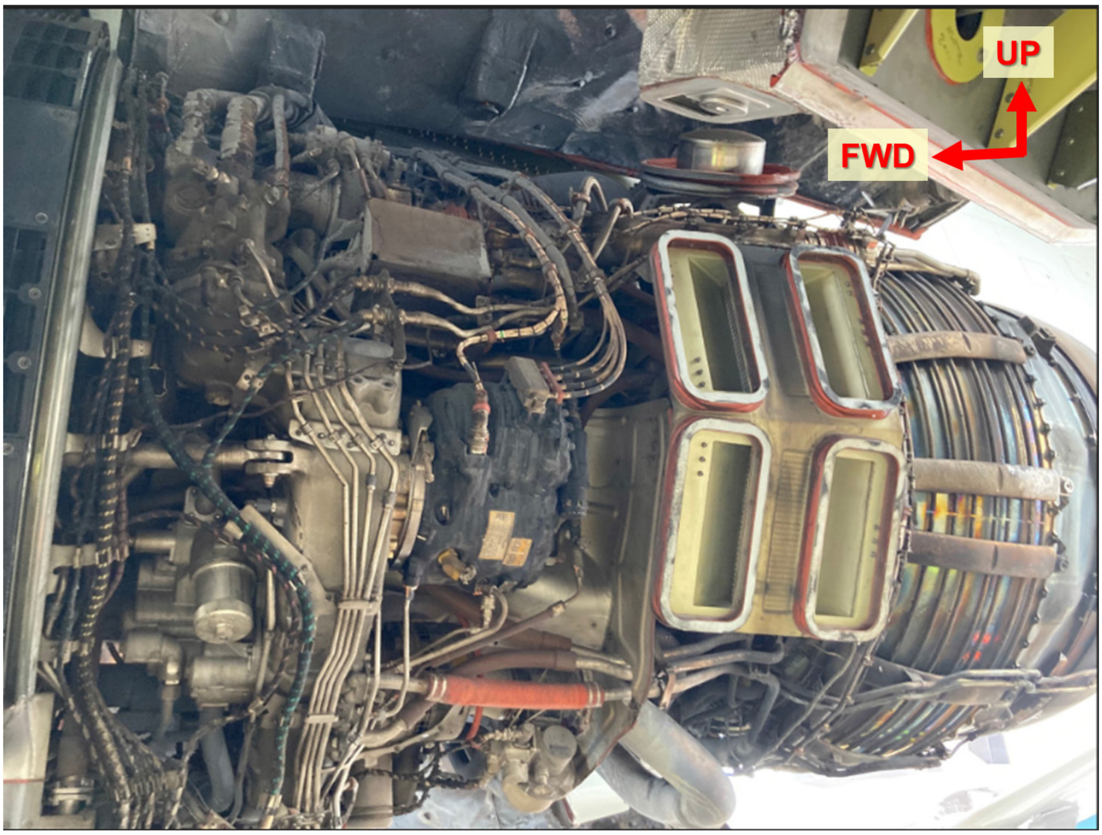



**Figure 9: Left-Hand Side of the Exterior Engine Core**

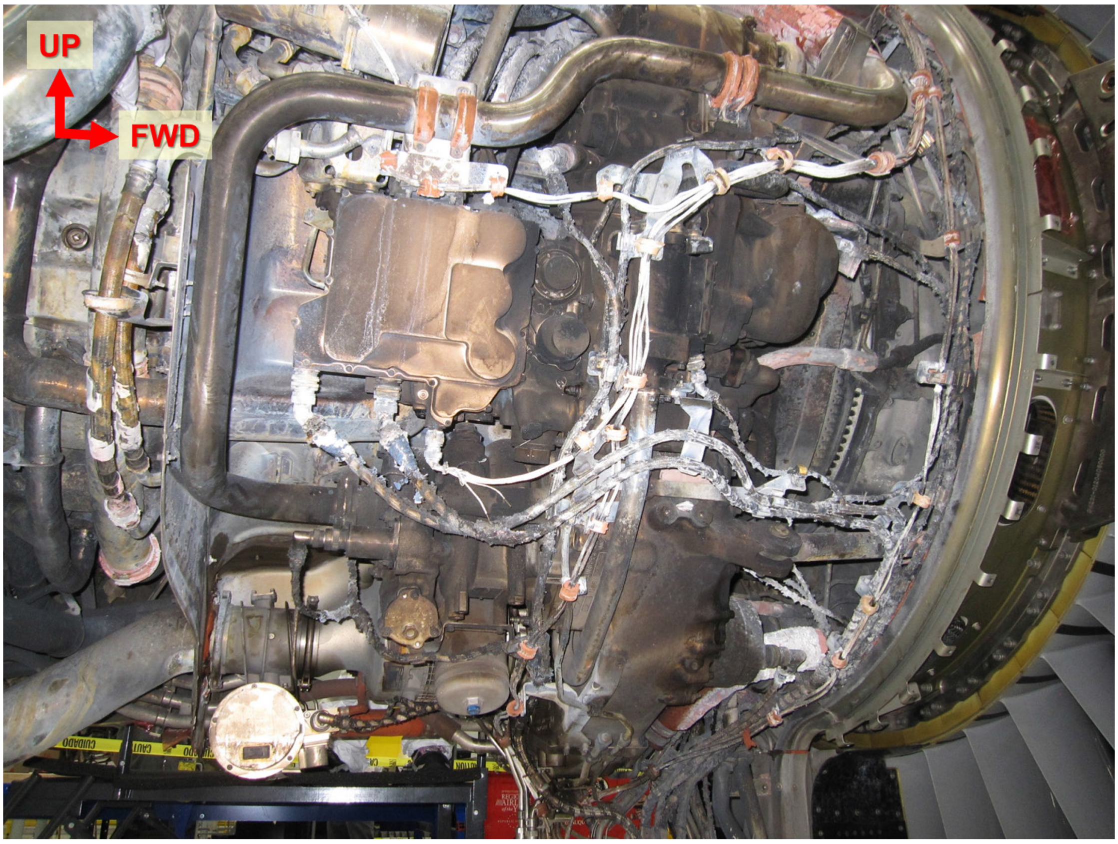



**Figure 10: Right-Hand Side of the Exterior Engine Core**

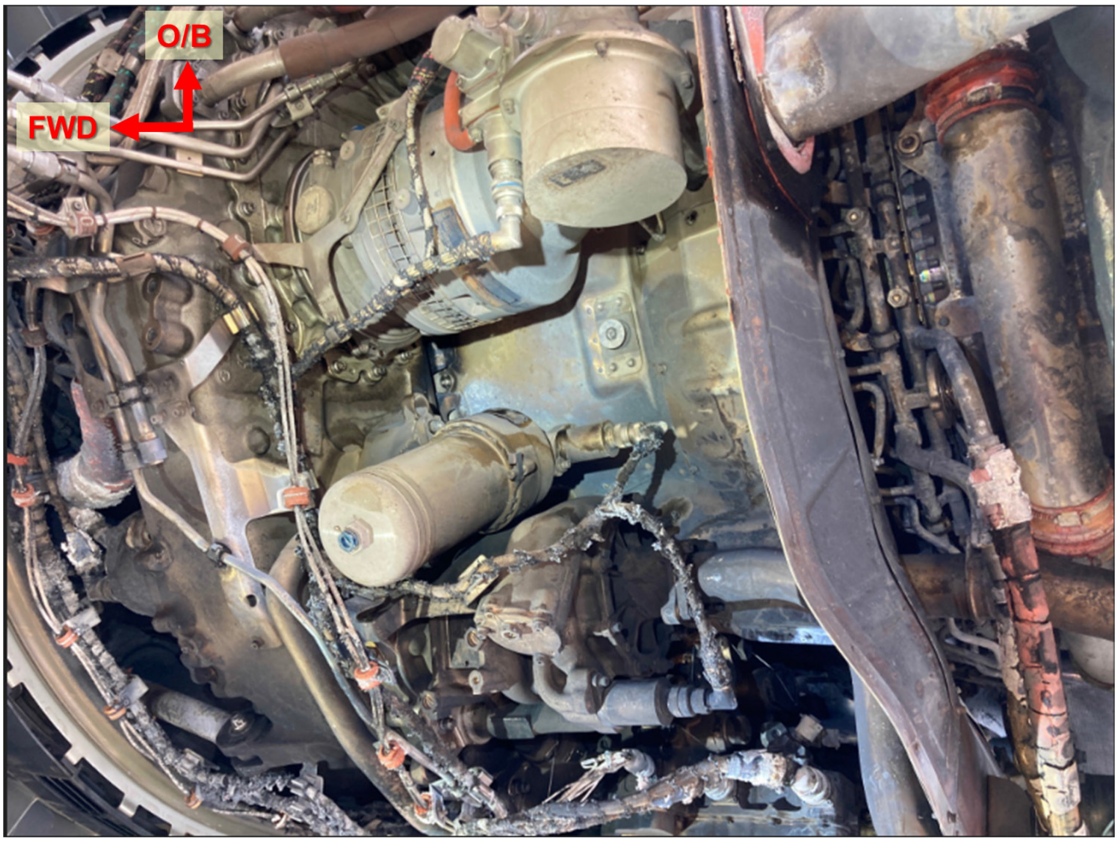



**Figure 11: Under Section of the Exterior Engine Core**

## 1.13. Medical/Pathological Information

No medical or pathological investigations were conducted as a result of this occurrence, nor were they required.

## 1.14. Smoke, Fire, and Fumes

(1) At 1220 hours, the "FIRE ENG 1" EICAS warning message appeared for 12 seconds after the No. 1 engine shutdown. The flight crew pulled the No. 1 engine fire handle and discharged two fire extinguisher bottles, but the fire warning continued.

(2) The fire warning ended shortly before landing. The total fire alarm time lasted for approximately 9.5 minutes. After the aircraft landed safely on Runway 07L, the AFC inspected the No. 1 engine and brakes and found no fire.

(3) About 22 minutes after landing, at 1252 hours, the AFC noticed white smoke and then fire in the No. 1 engine when water was being applied to the engine surrounding to maintain cooling effect. Additional fire suppressants were applied to the engine and the fire was extinguished within 40 seconds.

**Figure 12: No.1 Engine Ground Fire**

(4) Thermal damage, sooting, and discolouration were identified at the exterior core section of the No. 1 engine. The damage was examined in detail during the examination at the engine manufacturer's facilities as described in Section 1.16.1.

## 1.15. Survival Aspects

The AFC arrived at the scene shortly after the aircraft stopped on the runway and no injuries were reported, therefore no investigation into the survival aspects was required.

## 1.16. Tests and Research

After the post-event inspection of the engine by the AAIA, the engine was removed and sent to the engine manufacturer, GE, for fuel leak check and component removal in accordance with the work scope developed by GE and then approved by the AAIA. The NTSB provided oversight of the fuel system leak check, component removal, and follow-on component examinations on the request of the AAIA.

### 1.16.1. Powerplant Examination at GE Facility

A Powerplant Group comprised of members from the NTSB, the FAA, Boeing and UPS, convened at the GE Florence, Kentucky On-Wing Support (OWS) facility to perform the fuel leak check and to remove and retain those specific fuel system components thought to have contributed to the fuel leak that resulted in the under-cowl fire.

#### 1.16.1.1. External Examination

(1) Prior to the leak check, an external examination of the engine was performed to document the fire damage and a swab sample was taken of yellowish powder residue at about the one o'clock position on the environmental cooling manifold.

(2) From the aft fan case back to the LPT cooling air manifold on the LPT case, the thermal and fire damage was most pronounced from about the nine o'clock to six o'clock position (aft looking forward).

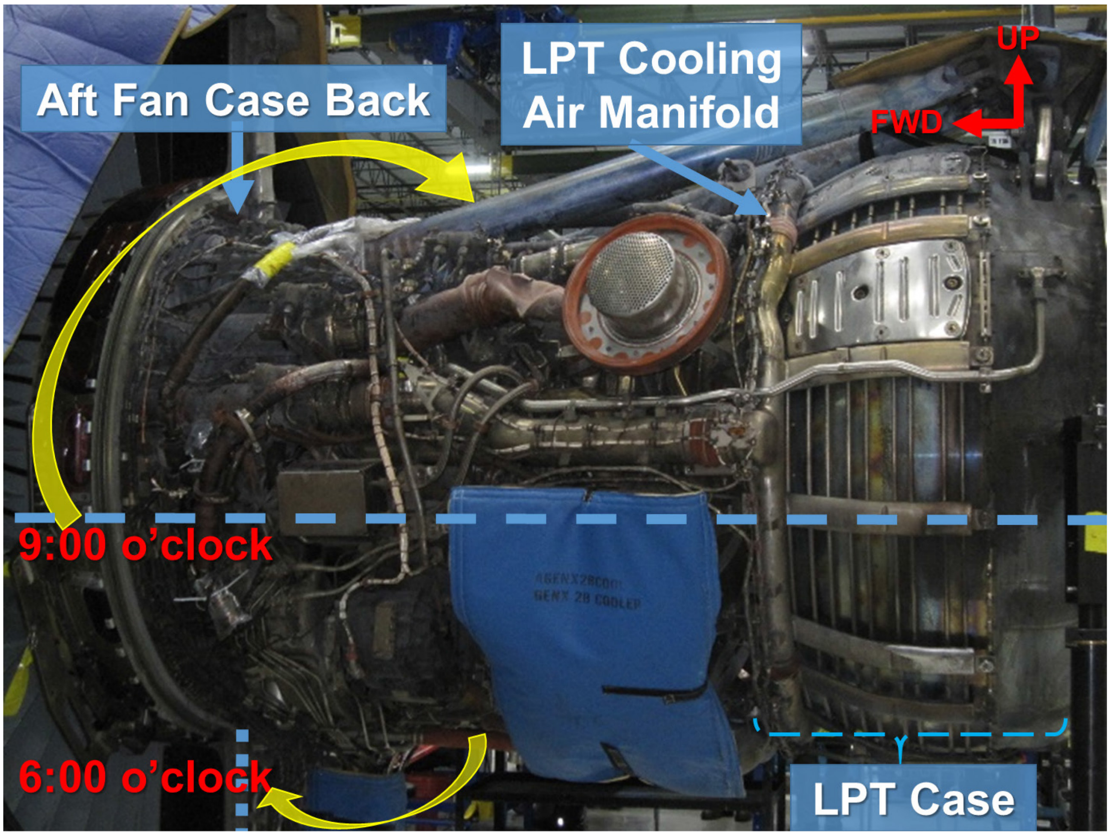



Figure 13: Left Side of Engine

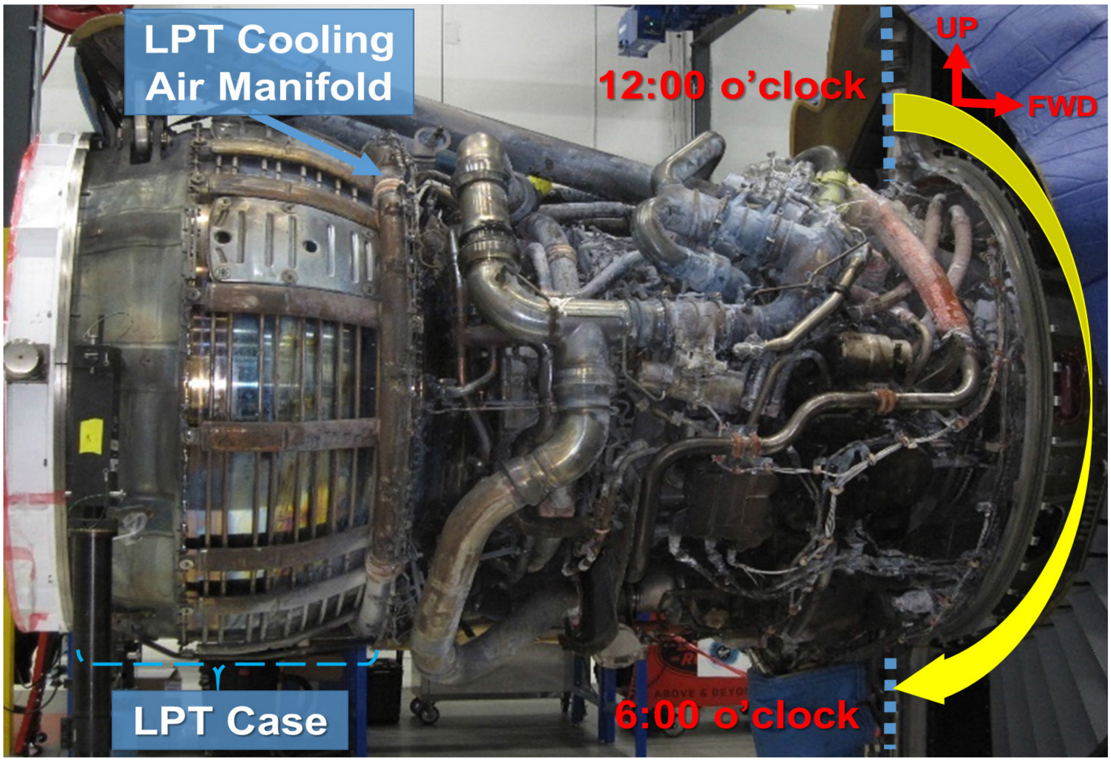



Figure 14: Right Side of Engine

(3) The thermal and fire damage consisted of sooting and melted or consumed c-clamp/p-clamps cushions, fire loop rubber isolators, electrical cable outer sheathing, and fire sleeves.

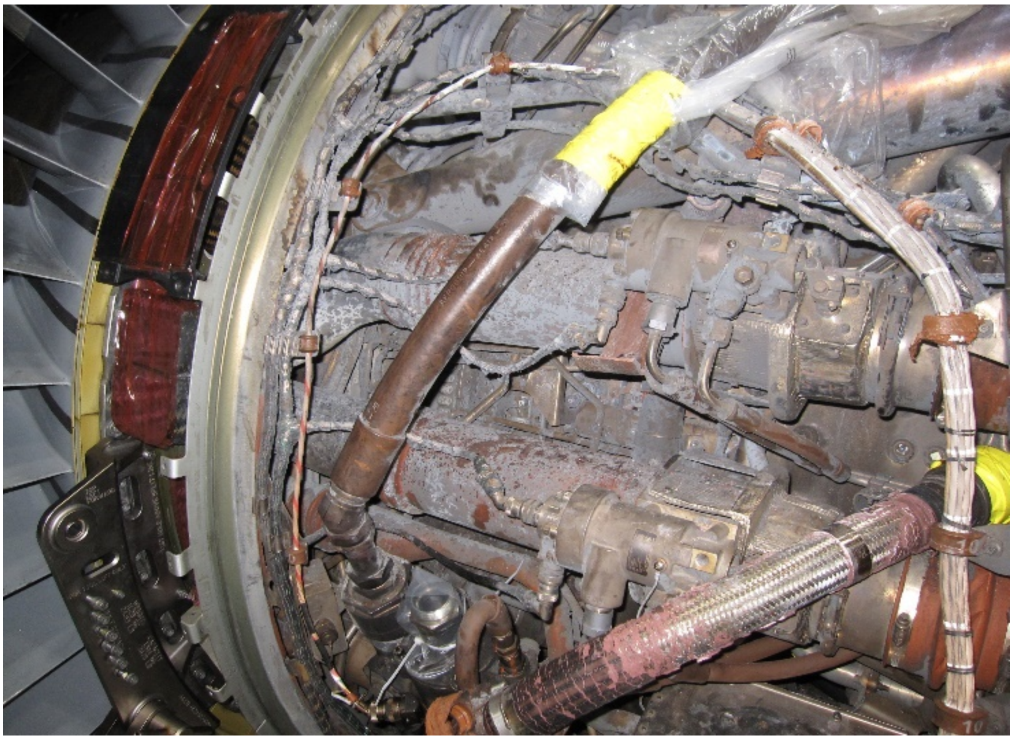


**Figure 15: Left Side Close-Up of Thermal and Fire Damage**

**Figure 16: Right Side Close-Up of Thermal and Fire Damage**

(4) All the fire loops, overheat detectors, and responders appear to be continuous and intact. Below the FMU at about the 5 o'clock position, the conductors of the electrical wires appeared to be exposed.

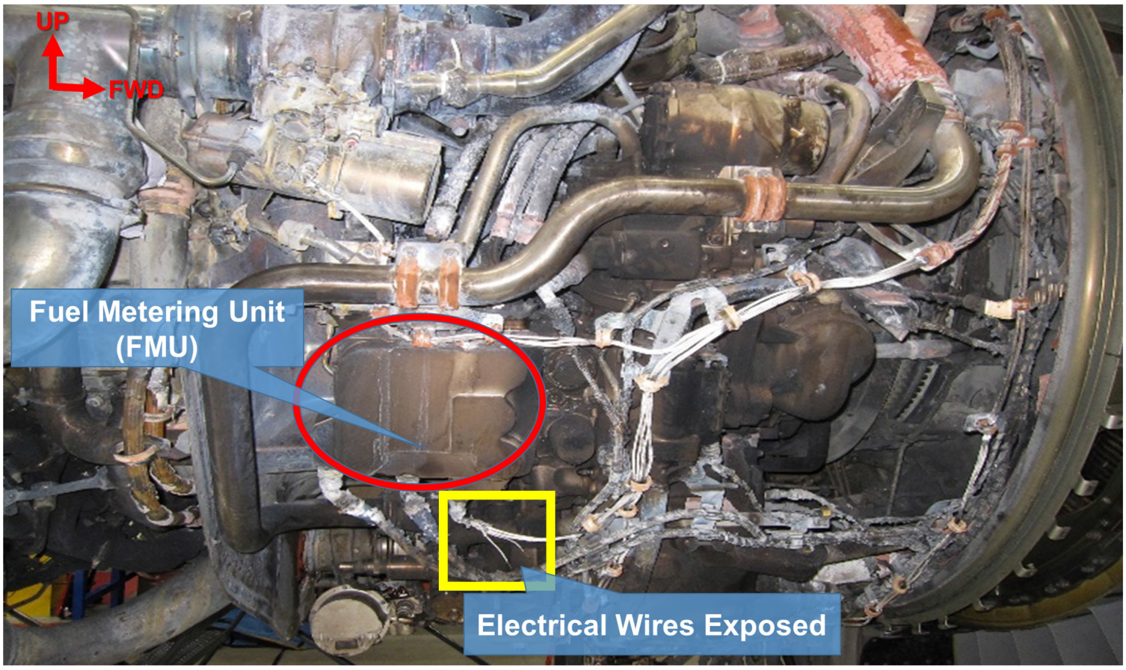



**Figure 17: Electrical Wires Exposed below FMU**

(5) A detailed inspection revealed that the electrical wires exposed were from the fuel shutoff valve electrical connector, which was still installed and connected to the FMU.

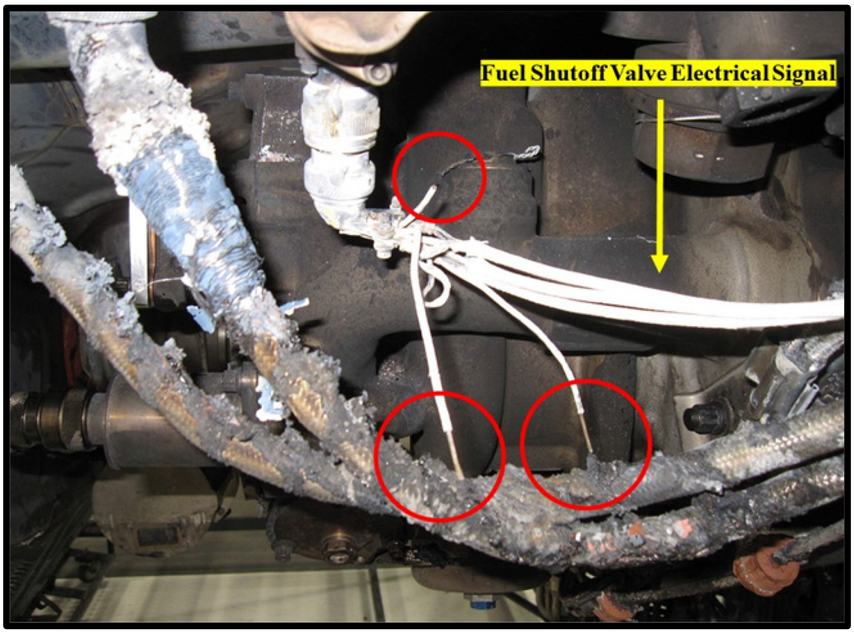



**Figure 18: Fuel Shutoff Valve Electrical Signal Wires Exposed**

(6) The Boeing performed a continuity check of the FMU and engine harness connectors. The results were normal.

(7) After checking with the wiring diagram, it was confirmed that the exposed electrical wires were unused wires with an end cap on the end, as shown in the graphic below.

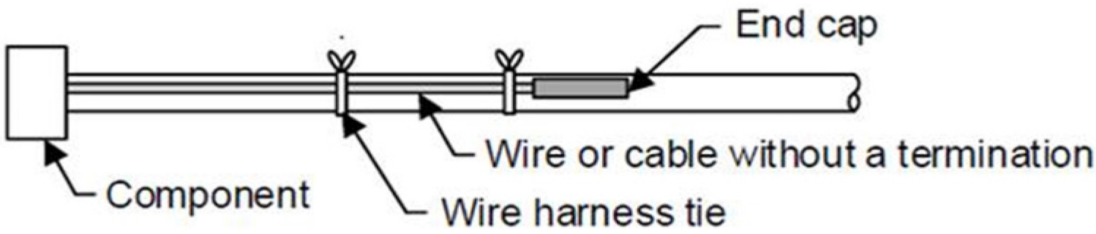



**Figure 19: Standard Practice for Capping the Unused Electrical Wires**

(8) The end caps of the electrical wires likely melted as a result of thermal damage. Thus, the electrical wires became exposed.

(9) The top of the engine, from about 9 o'clock to 3 o'clock position, was covered in a bluish powder residue, and yellowish powder residue at about the 1 o'clock position on the environmental cooling manifold.

**Figure 20: Yellowish Residue Near Top**

(10) A swab of the yellowish powder residue was taken for analysis. The results showed that the residue was consistent with the fluorescent penetrant inspection developer. The investigation was unable to determine when this developer was applied to this area.

### 1.16.1.2. Engine Fuel System Leak Check

(1) The GE performed a fit check of the specialized hardware and connections that were created to conduct the leak check without disturbing any of the engine components.

(2) The fuel supply line to the main fuel pump (MFP) was removed and the inlet port was capped with a special plate and sealing gasket.

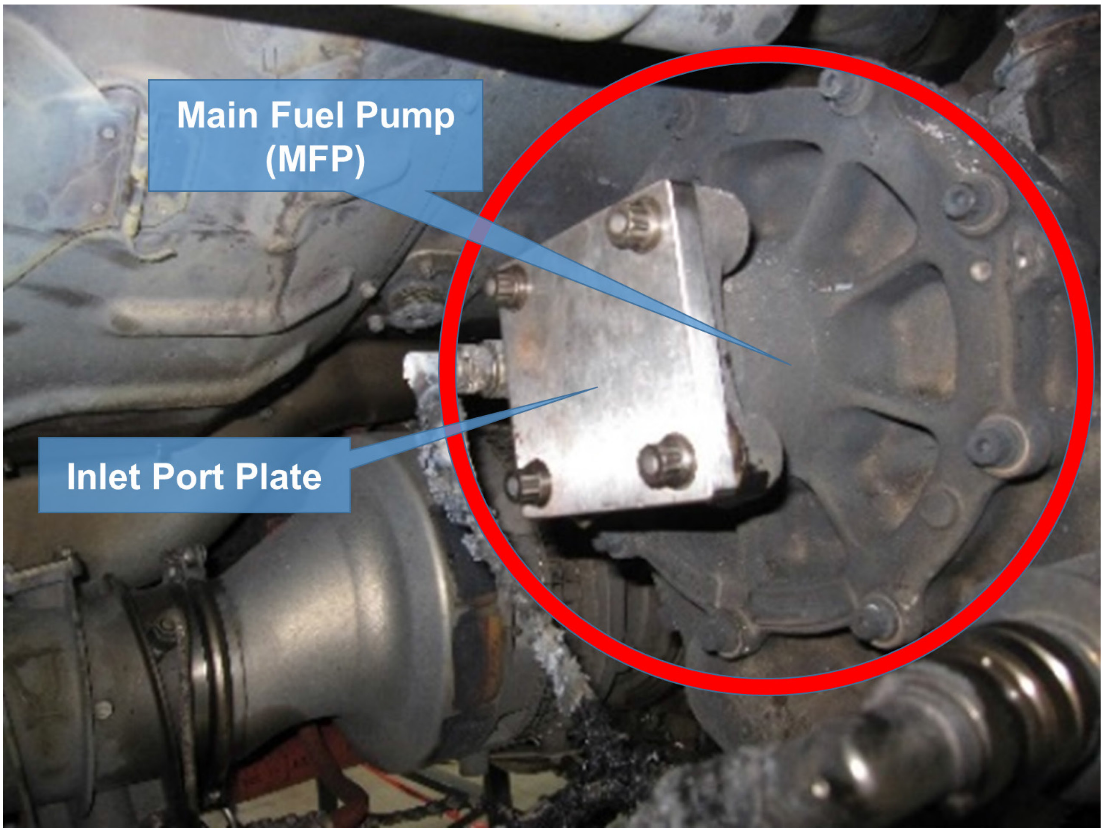



**Figure 21: Inlet Port Plate Installed in MFP**

(3) The drain plug on the MFP was removed and a fitting was connected while the other end of the fitting was connected to a nitrogen tank.

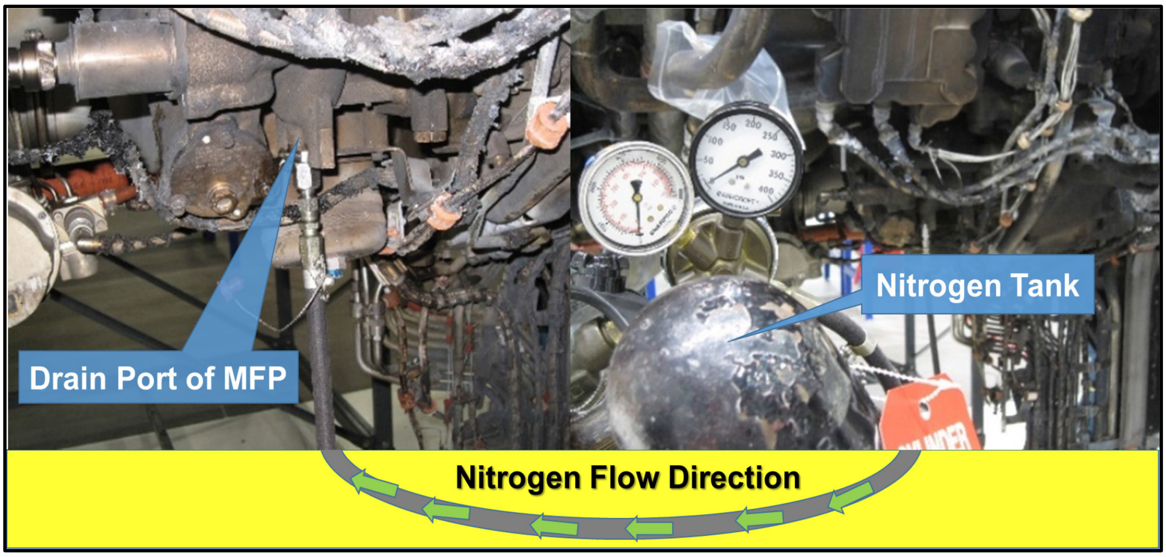



**Figure 22: Leak Check Set-Up**

(4) The initial leak test called for nitrogen to be initially introduced to the MFP drain plug up to 10 pounds per square inch (psi) and held for three minutes.

(5) Nitrogen was slowly introduced, and fuel/nitrogen was seen/heard leaking from multiple locations of the FMU before even reaching the 10 psi level.

**Figure 23: Fuel Leaking from Multiple Locations of FMU**

(6) The leaks were observed coming from:

a) the variable bleed valve (VBV) fuel manifold
b) the variable stator vane (VSV) fuel manifold
c) the core compartment cooling (CCC)-start bleed valve (SBV)-heated servo pressure (PHS) fuel manifold
d) two pressure taps on the back side of the FMU.

(7) Due to multiple fuel leaks from the FMU, it was decided to isolate the FMU by installing cover plates on the manifold ports labelled A, B, and C in the figure below.

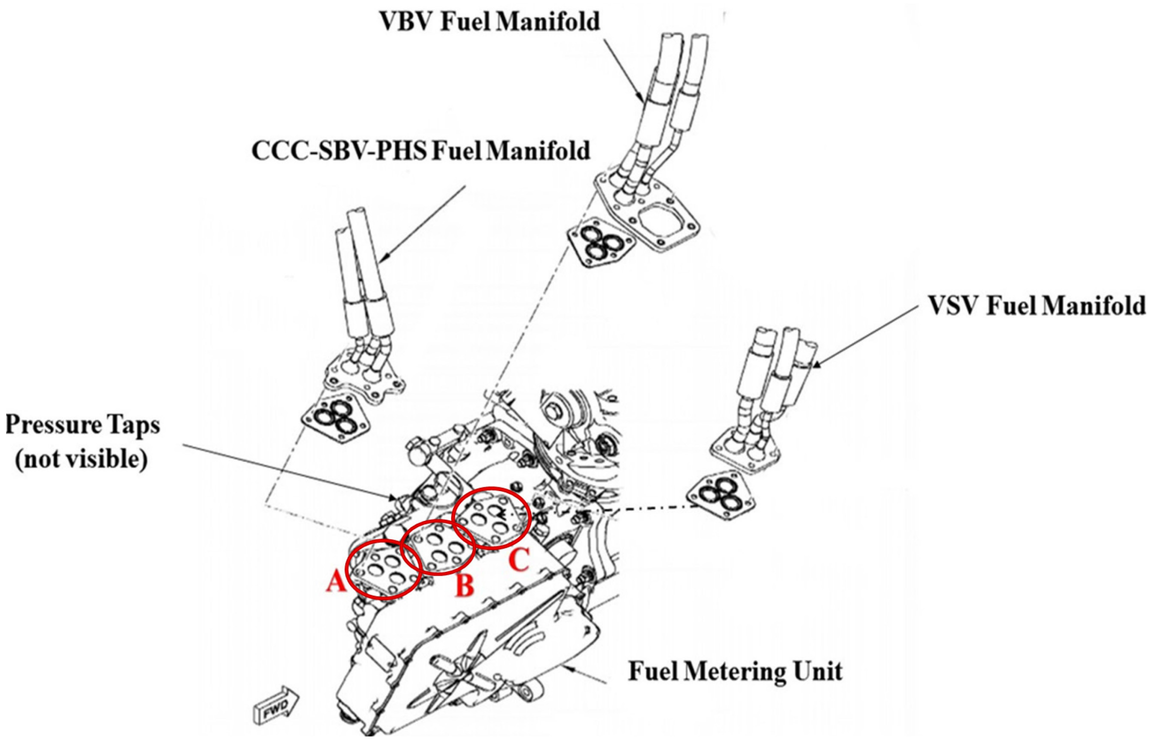



**Figure 24: Leak locations of Fuel Metering Unit**

(8) With the manifold port covers installed, nitrogen was slowly introduced again into the MFP drain port up to 40 psi and several additional leaks were noted when Leak-Tec fluid was applied to the pressure tap ports on the inboard side of the FMU.

(9) Examination of the main fuel filter (MFF), main fuel pump (MFP), the IDG fuel/oil cooler and main fuel oil heat exchanger (MFO HEx) exhibited no leaks.

(10) Fittings were then connected to each branch of the fuel split valve-to-fuel manifold secondary pilot fuel supply line and nitrogen was introduced at 10 psi.

**Figure 25: Fitting On Fuel Split Valve-To-Fuel Manifold Secondary Pilot Fuel Supply Line**

(11) Using Leak-Tek fluid, nitrogen was seen leaking from the top and bottom of the fuel flow transmitter (FFT). No other leaks were noted. The nitrogen pressure was increased in 10 psi increments up to 30 psi. No additional leaks were observed other than what was observed coming from the FFT.

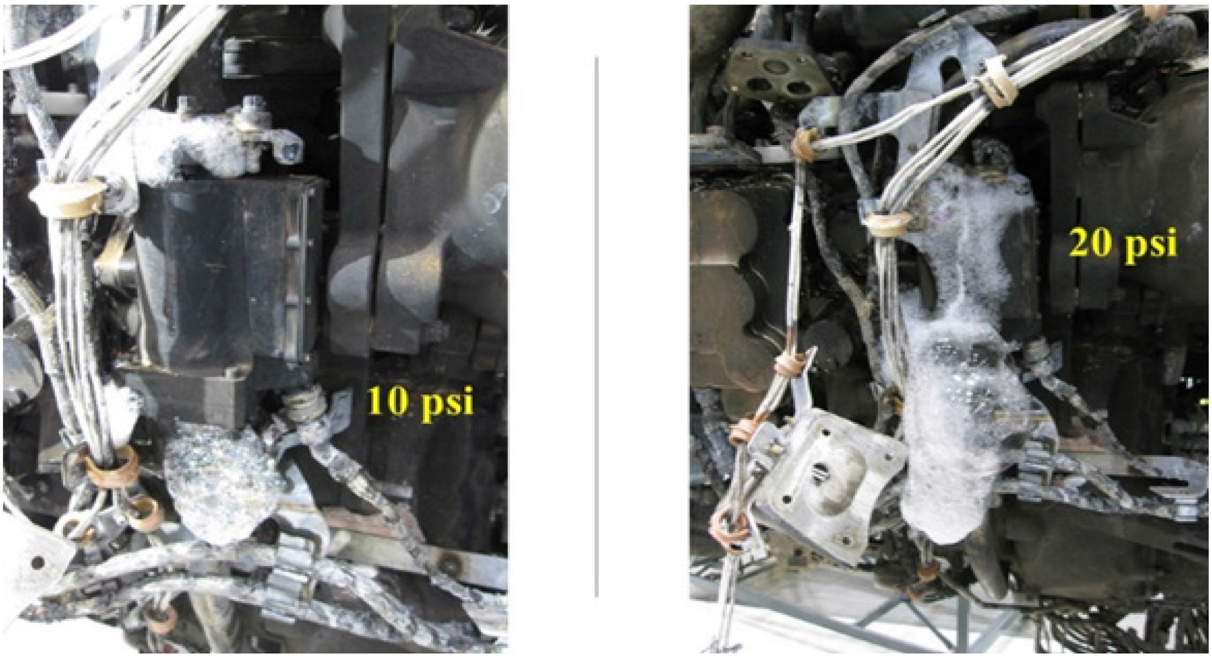



**Figure 26: Leaking from Top and Bottom of FFT**

(12) These flexible portions of the fuel lines have a plastic inner core that during the testing was found to have melted due to fire, so fuel leaked through the metal outer braid.

(13) The fire damage to the fuel lines did affect the integrity of the tube and would definitely leak during the leak check. These interface leaks were considered to be a result of the fire, not the cause.

(14) The results of the engine leak check are shown in the table below.

| ITEM | ENGINE LEAK CHECK RESULT |
|---|---|
| FMU | Leak from 4 locations. |
| MAIN FUEL PUMP | No leak |
| MAIN FUEL FILTER | No leak |
| IDG HEAT EXCHANGER | No leak |
| FUEL/OIL HEAT EXCHANGER | No leak |
| FUEL FLOW TRANSMITTER | Interface leaks due to fire damage. |
| FLOW SPLIT VALVE | No leak |

**Table 2: Results of the Engine Leak Check**

(15) According to the results, the FMU was removed from the engine and sent to the manufacturer for further examination.

## 1.16.2. FMU Examination at Woodward Facility

A Powerplant Group comprised of members from the NTSB, the FAA, Boeing, UPS, GE and Woodward, the fuel metering unit manufacturer, convened at the Woodard facility in Loves Park, Illinois to perform the FMU examination.

### 1.16.2.1. Visual Examination

(1) The FMU was of GE part number (PN) 2459M17P02, Woodward PN 8062-1177, serial number (SN) WYGN2972, which was manufactured in November 2019.

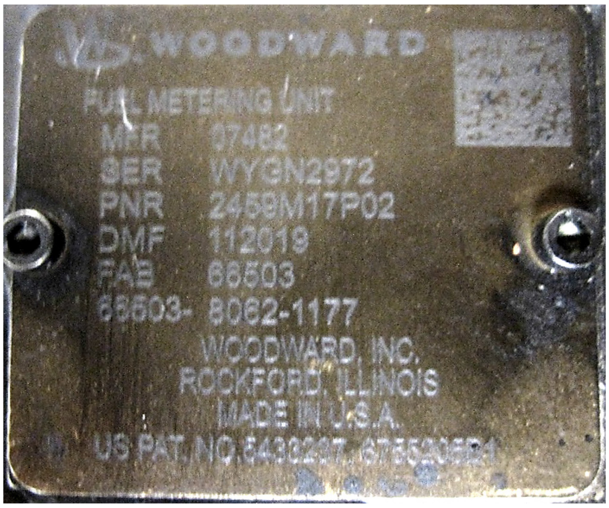



**Figure 27: Data Plate of FMU**

(2) The FMU was completely sooted, but there were no signs of thermal distress to the housing.

(3) Visual inspection of the FMU revealed that the safety wire from one of the drain plugs was found broken; it appeared to be a clean cut.

(4) According to GE Field Support, the FMU was drained in Hong Kong for engine shipment; thus, the safety wire was cut to drain the unit. This was confirmed and photographed at the engine.

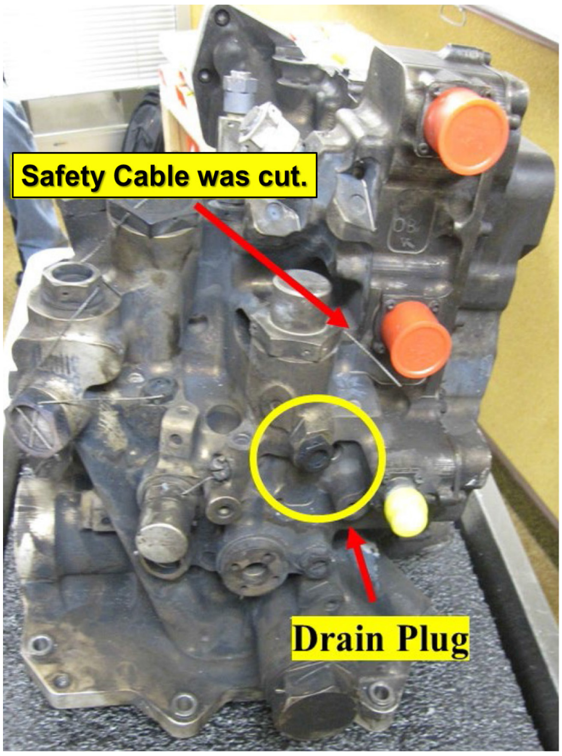
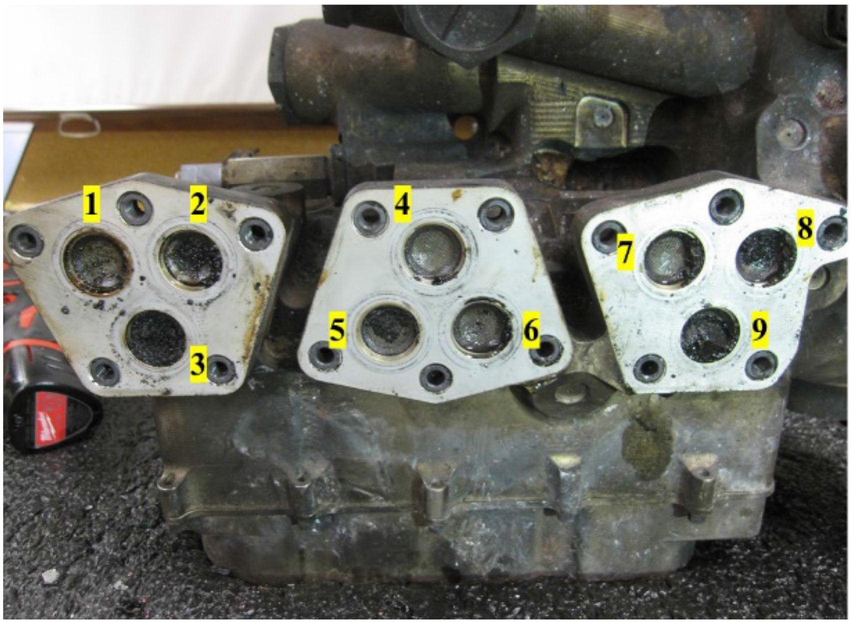



**Figure 28: Cut Drain Plug Safety Cable**

(5) The plastic protective covers of the manifolds were removed to inspect the packing condition of each numbered port.

**Figure 29: Manifolds with Covers Installed**




1. CCC
2. PHS (heated servo pressure)
3. TBV Head
4. VBV Rod
5. VBV Head
6. LPT ACC Head
7. VSV Rod
8. VSV Head
9. HPT ACC Head

**Figure 30: Covers Removed and Ports Exposed**

(6) Each fuel port has a primary black packing (O-ring) with a whitish flat backup split ring on either side of the primary packing. The O-rings and the backup split rings were all intact, in good condition, and did not exhibit thermal or heat distress.

**Figure 31: Condition of Packing & Back-up Split Rings**

(7) Visual examination of the electric connector plugs (Channel A, Channel B, and Airframe Shutoff (AFSO)) revealed that all the pins were present and intact, and no thermal distress was noted; the Channel A and AFSO green rubber grommet exhibited some minor thermal damage.

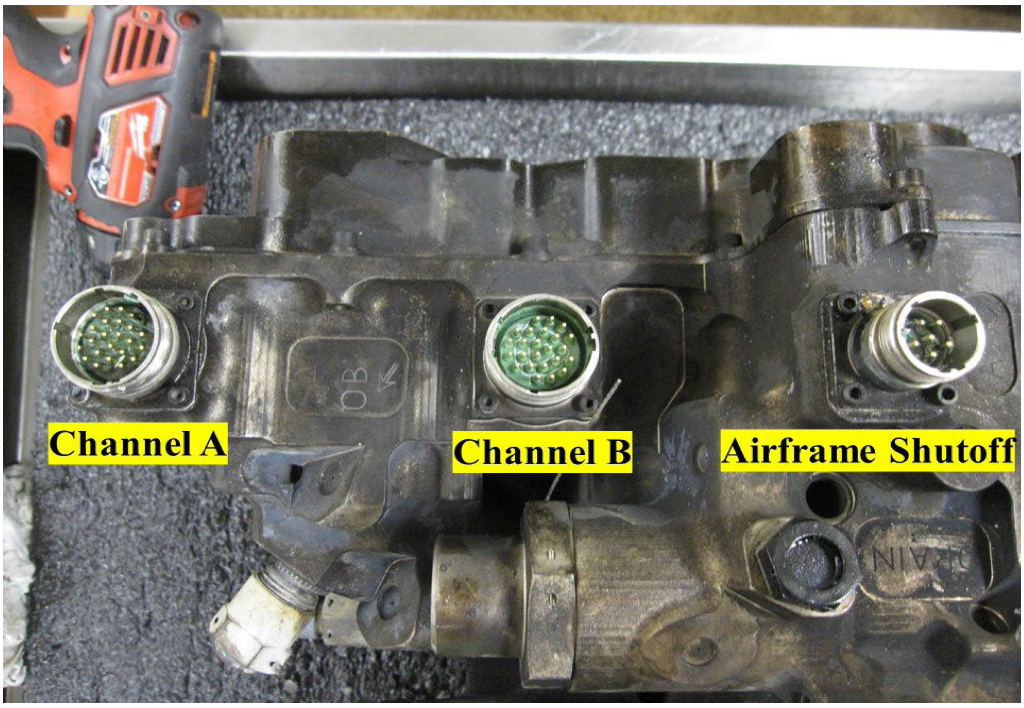



**Figure 32: FMU Electrical Connectors**

(8) A continuity check was performed on the pin connectors for each of the electrical connectors. The results were found normal.

### 1.16.2.2. Nitrogen Leak Test

(1) A nitrogen leak test was performed to confirm leak locations in the FMU. Cover plates were placed on the three manifold pads and a base plate was placed on the fuel port face.

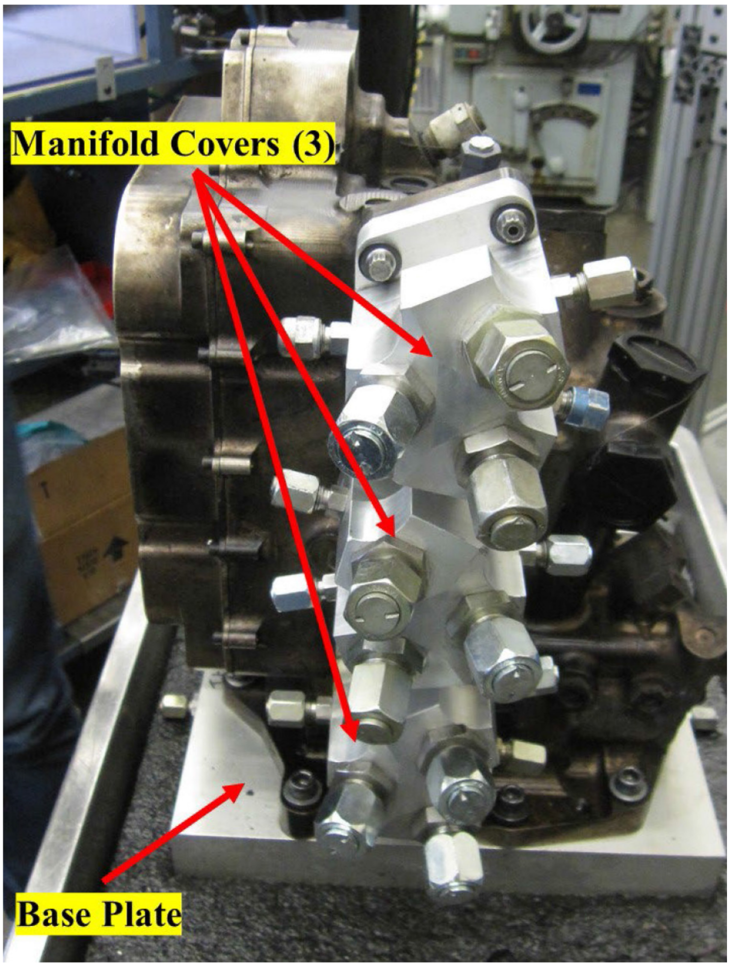



**Figure 33: Nitrogen Test Covers and Base Plates**

(2) The base plate is fitted with three fittings labelled “high”, “middle”, and “low” and are used to pressurize the FMU. The “high” fitting is for the supply pressure (PS or P1), the “middle” is for PB2 bypass supply, and the “low” is for PB bypass supply.

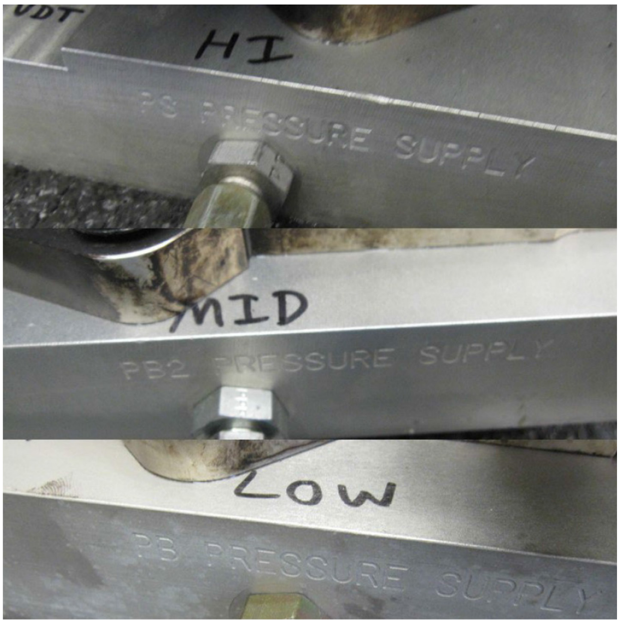



**Figure 34: Base Plate Fitting Labels**

(3) Nitrogen at 45 psi was introduced into a T-fitting to supply pressure to the “high”, “middle”, and “low” fittings on the base plate all at the same time, essentially pressurizing the entire FMU.


**Figure 35: Nitrogen Test Set-up**

(4) Leaks were observed coming from two PB2 bypass fittings[3] and the P1 bypass valve port fitting. At all three leak locations, the fittings were loose. No other leak locations were identified.

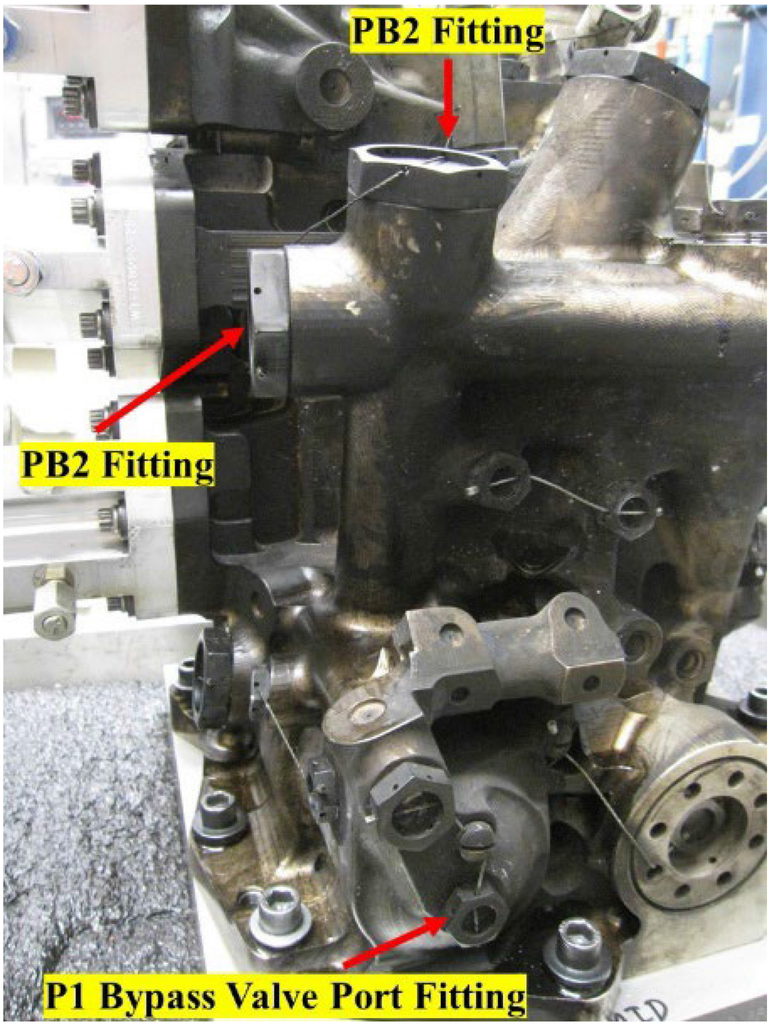



**Figure 36: Nitrogen Leak Locations**

## 1.16.2.3. Calibration Fluid Leak Test

(1) A calibration fluid leak test was performed to quantify the leak rates from the FMU with a representative fluid.

(2) The calibration fluid leak test set-up was essentially the same as the one for the nitrogen leak test; pressurized calibration fluid was applied to all three base fittings at the same time.

[3] The PB2 ports are used to facilitate machining of the FMU housing only.

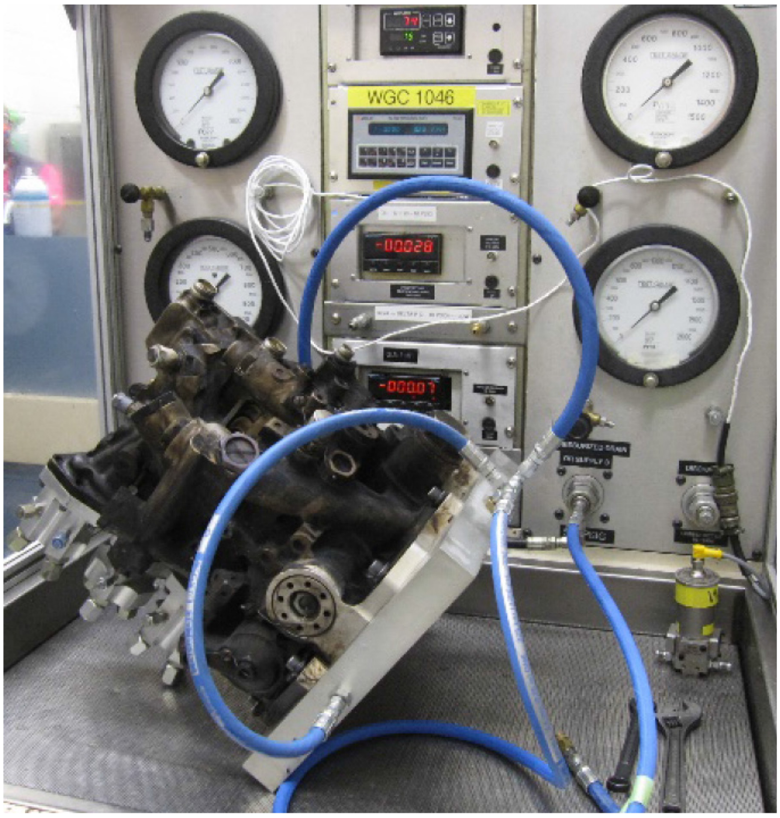



**Figure 37: Calibration Fluid Leak Set Up**

(3) Calibration fluid at about 12 psi was introduced and leaks were observed from the same two PB2 bypass fittings and the P1 bypass valve port fitting that was observed in during the nitrogen leak check. No new leaks were observed.

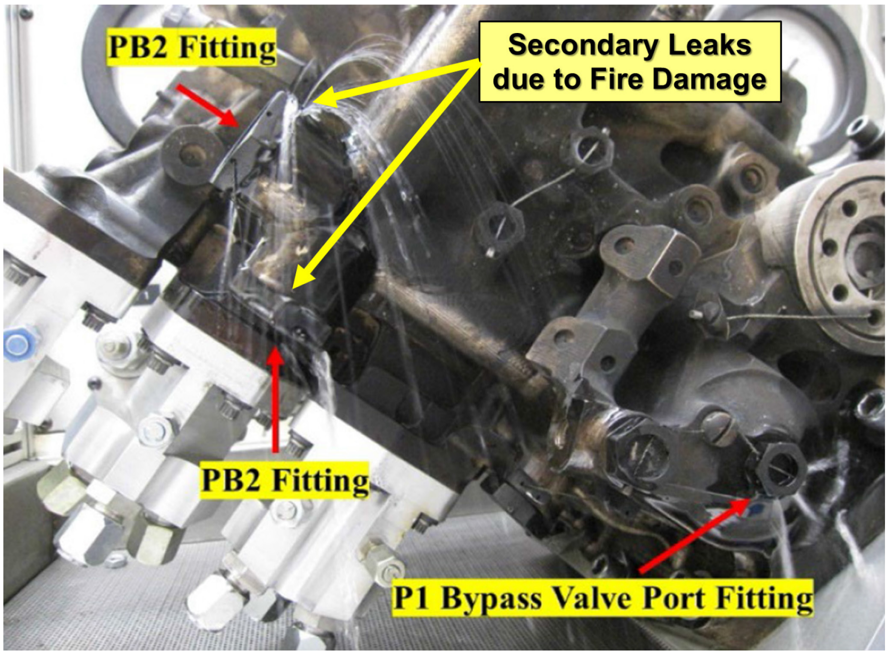



**Figure 38: Calibration Fluid Leak Locations**

(4) The FMU was tilted in such a manner so that the P1 bypass valve port fitting leak could be isolated from the other two leak locations. The objective was to capture the calibration fluid in order to determine the leak rate from the P1 bypass valve port fitting only.

(5) Again, at about 12 psi, calibration fluid was collected for 1 minute and 445 cubic centimetres (cc) of fuel (0.740 pounds) was collected. The leak observed from the P1 bypass valve port fitting was isolated to a single general location.

(6) The leak rate of 445 cc per minute at 12 psi corresponded to a 0.038” external leak orifice. This external leak size was compared to a later analysis investigating how this leak had caused N1 to reach the overspeed limit in Section 1.16.3.

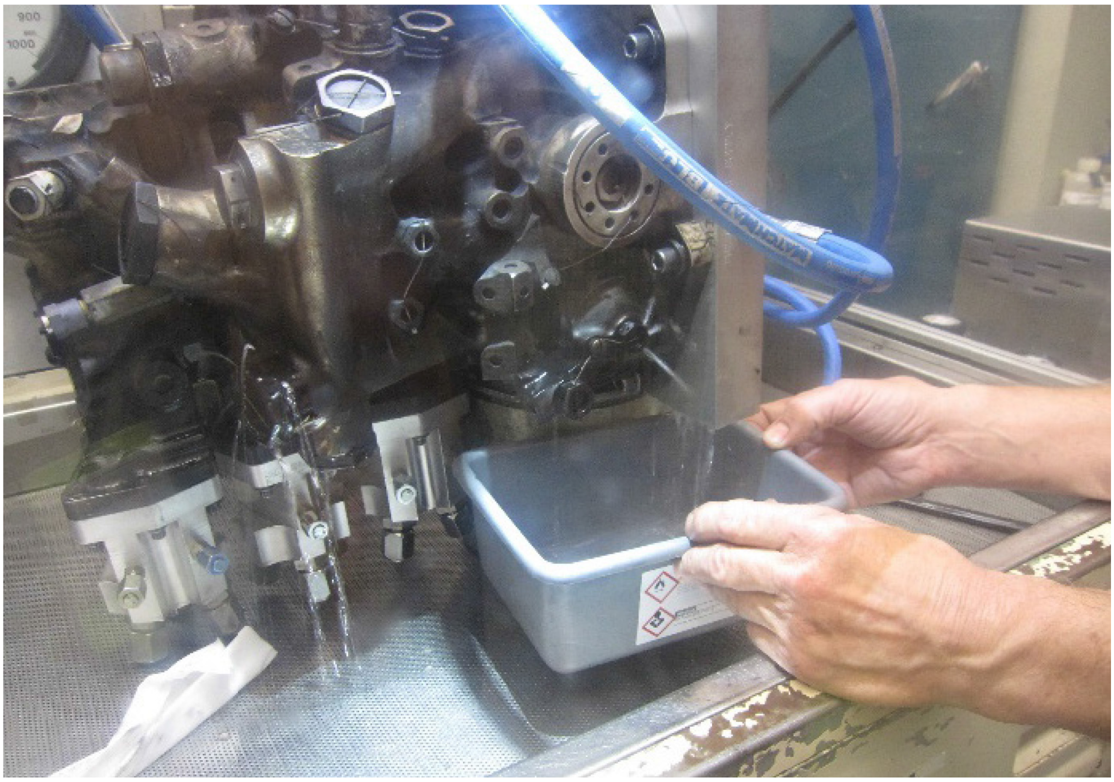


**Figure 39: Calibration Fluid Collected From P1 Bypass Valve Port Fitting**

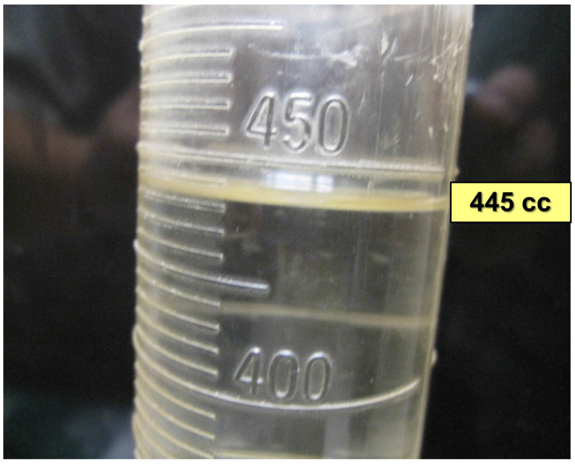



**Figure 40: Amount of Calibration Fluid Collected at ~12 Psi for 1 Minute**

### 1.16.2.4. Gap Check

(1) The gap between the P1 bypass valve port fitting and the housing was measured. To measure the gap between the housing and the P1 bypass valve port fitting, several different feeler gauge were placed between the bottom of the P1 bypass valve port fitting and the FMU housing.

(2) The largest (thickest) feeler gage that was able to be inserted into the gap between the bottom of the P1 bypass valve port fitting and the FMU housing was 0.018-inch (0.457 millimetres) thick.

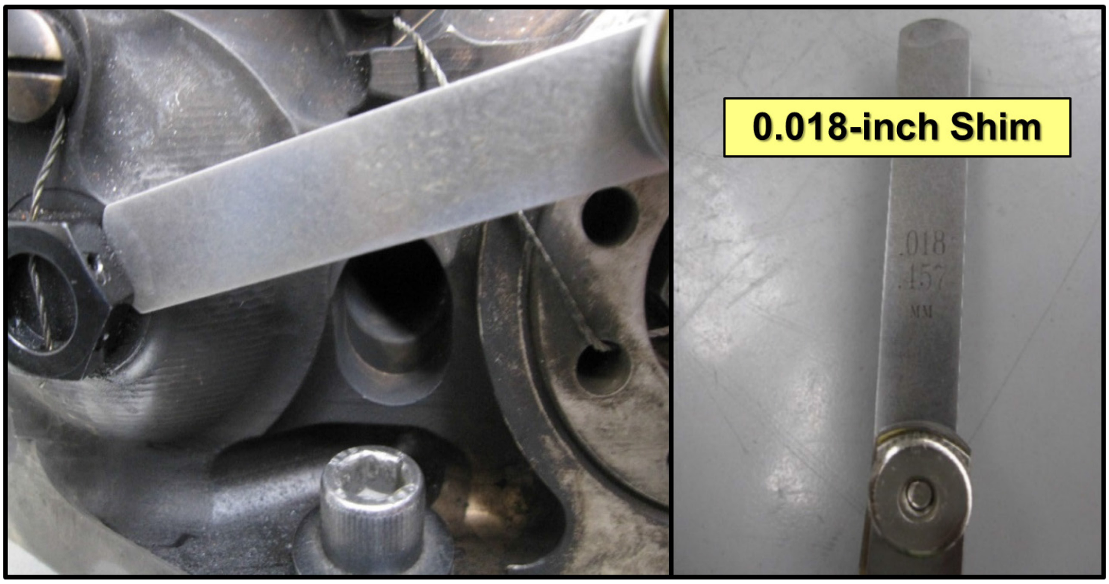



**Figure 41: Feeler Gage Between FMU and P1 Bypass Valve Port Fitting**

(3) For a normal installation, there should be no gap. Since the fitting thread is 0.4375-20, i.e. 0.050" per turn, the 0.018-inch gap would equal to 1/3 turn loosen. To torque the fitting to specification, an additional 1/3 turn is required.

(4) There was no noticeable gap between the PB2 bypass fittings and the FMU housing. Thus, no measurements were taken.

### 1.16.2.5. Packing Condition Check

(1) The PB2 bypass and two P1 bypass valve port fittings were removed to access the condition of the packings; these were the locations that leaked during the nitrogen and the calibration fluid leak tests.

(2) Before removing the fittings, all three were marked to document their "original" position prior to removal. i.e. how "tight" they could get with the as-installed lockwire.

(3) Due to fire damage, the packings were entirely consumed at both PB2 bypass fitting locations. All that remained was the residue of the packings were noted.

**Figure 42: PB2 Bypass Packings Consumed**

(4) The packing for the P1 bypass valve port fitting was present and still had a reasonably round cross-section. However, a section of the packing, less than 1/4, of the circumference, was missing. Signs consistent with nibbling and extrusion damage at the broken edges of the packing were noted.


**Figure 43: Damaged P1 Bypass Valve Port Fitting Packing**

(5) New packings were installed on the PB2 bypass and P1 bypass valve port fittings and the fittings were reinstalled to the specified torque.

(6) The alignment marks for the PB2 bypass fittings went past the original "tight" marks in the tightening direction; they appeared to be about a ¼ of a flat past the original "tight" mark.

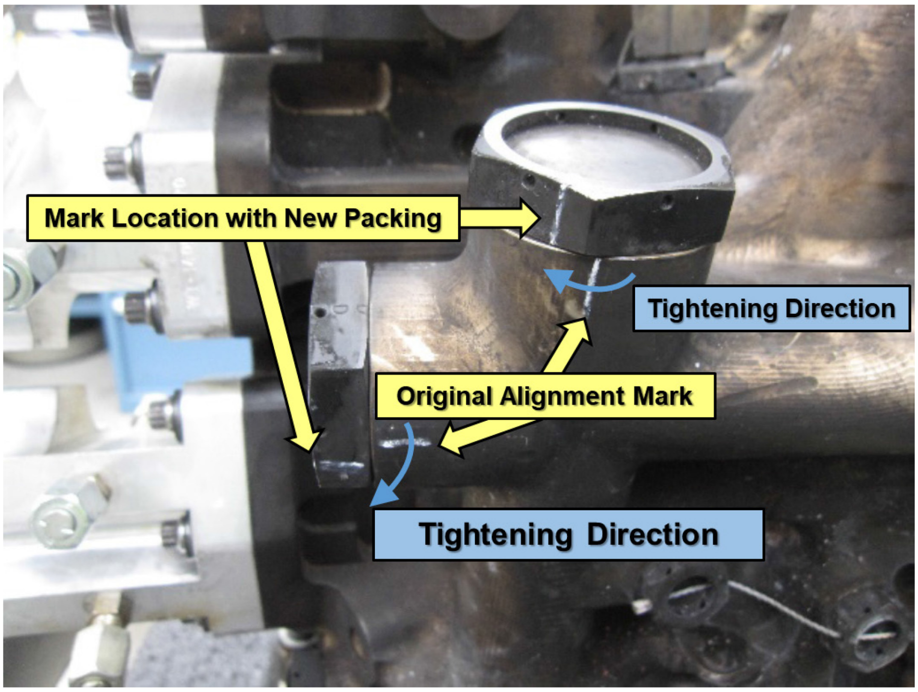



**Figure 44: PB2 Bypass Fitting Alignment Marks With New Packings Installed**

(7) With a new packing installed on the P1 bypass valve port fitting and the fitting reinstalled to the specified torque, the new position of the alignment mark on the fitting was about two flats from the original "tight" position in the tightening direction.

(8) Installing and torquing the fitting with new packing eliminated the 0.018-inch gap observed previously. Two flats of additional rotation corresponds to 0.018-inch gap based on the thread pitch, as noted in Section 1.16.2.4.

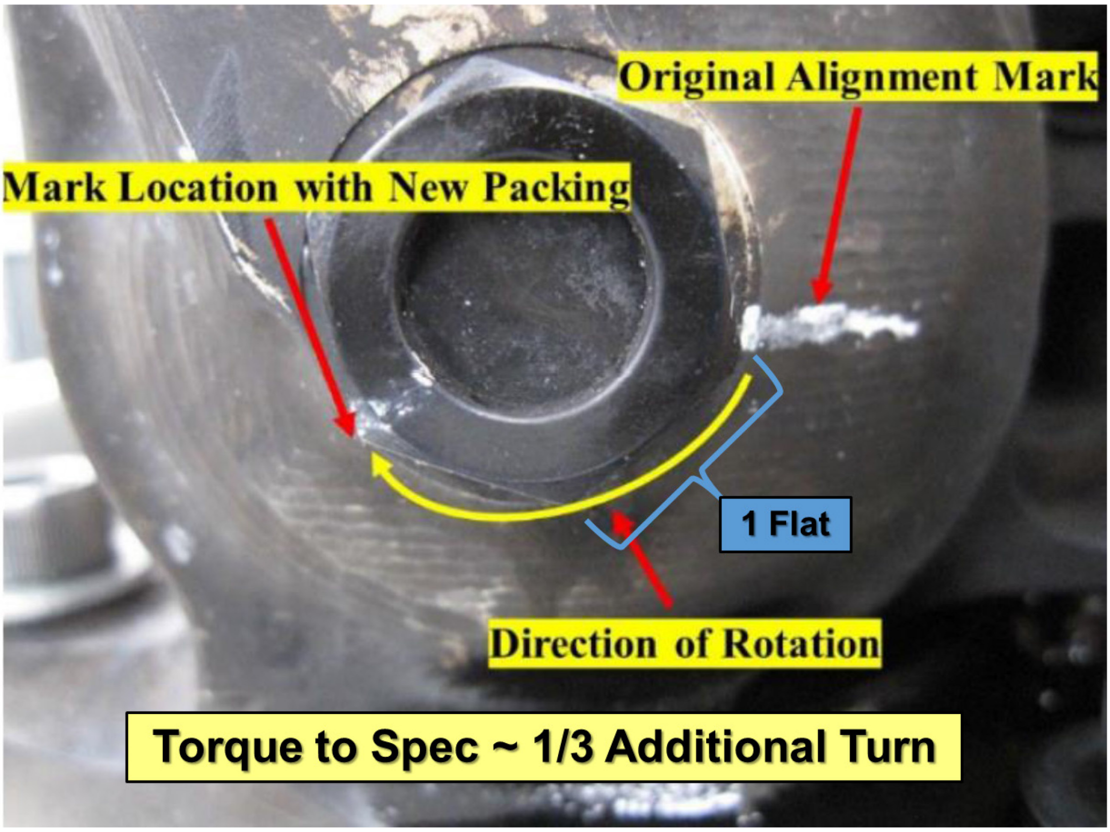



**Figure 45: P1 Bypass Valve Port Fitting Alignment Mark With New Packing Installed**

### 1.16.2.6. Simulation of the P1 Bypass Valve Port Fitting Leak

(1) An exemplar FMU was installed on a test stand with a needle valve attached to the P1 bypass valve port fitting to vary the amount of simulated leak (flow rate) from the P1 bypass valve port fitting.

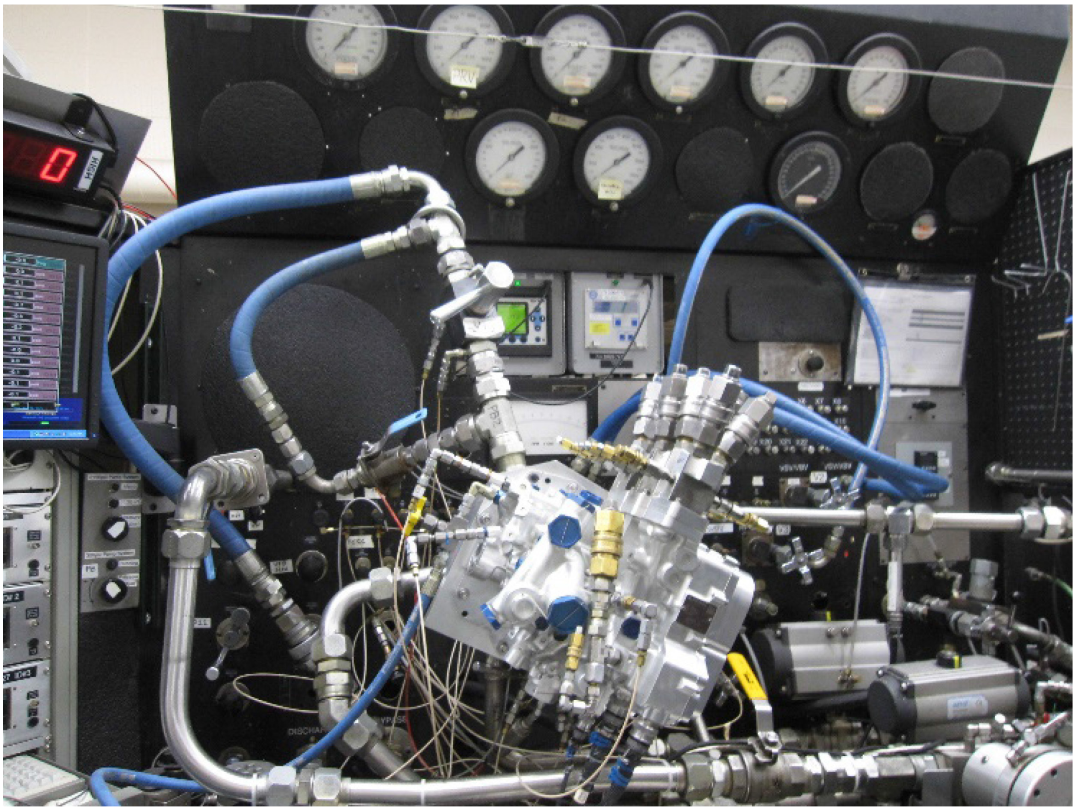


**Figure 46: Exemplar FMU on Test Stand to Simulate the Leak**

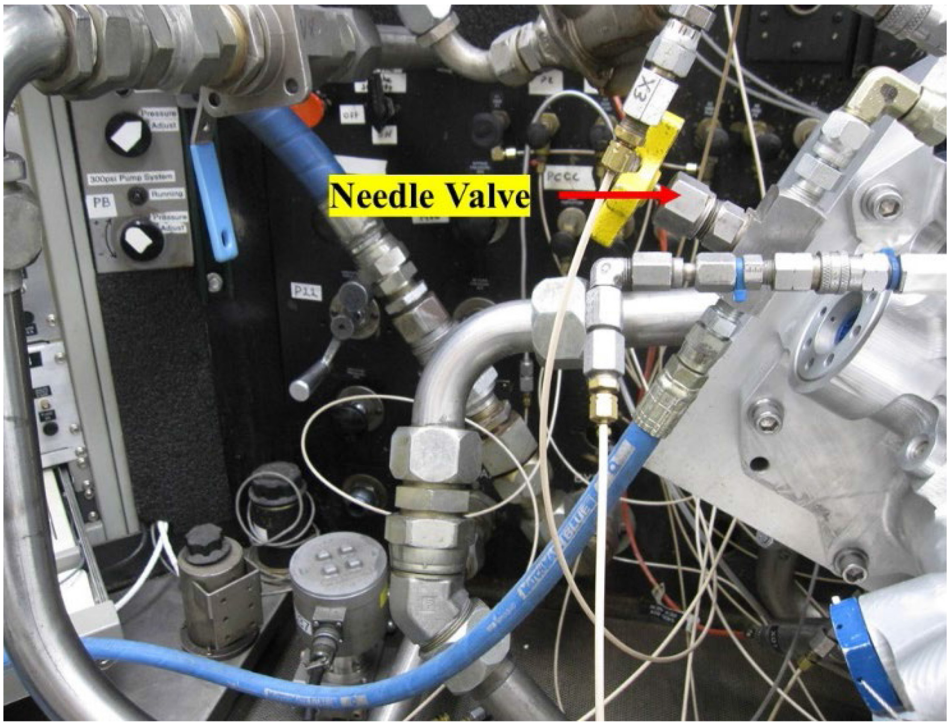



**Figure 47: Needle Valve Set Up**

(2) A flowmeter was attached downstream of the P1 bypass valve port fitting line to measure the flow rate that corresponded to the opening of the needle valve.

(3) This test was an attempt to simulate the conditions the FMU experienced at the time the fuel flow deviation was first noted on the FDR.

(4) The test parameters were set to ground idle, which according to the FDR data, was when the fuel flow deviation was first noted; essentially setting up the same engine conditions that the FMU could have experienced at the time of the fuel leak and prior to the initial engine fire.

(5) The initial conditions for the test were:

1) metered flow (Wf) 678.9 pounds per hour (PPH),
2) high bypass pressure (PB) flow 1407.8 PPH,
3) inlet flow (Wi) 26721.3 PPH,
4) ΔP = 51 pounds per square inch differential (psid), and
5) 0.1031 volt per volt FMU valve linear variable differential transformer (LVDT) position


**Figure 48: Test Parameters**


**Figure 49: Test Parameters**

(6) The needle valve was slowly opened to vary the pressure across the metering valve (ΔP = P1-P2) from its normal operating ΔP pressure of about 50 psi to the event ΔP pressure of about 95.5 psi. The 95.5 psi was a calculated value based on FDR data and not an actually recorded parameter.

(7) The opening of the needle valve allowed fuel to leak thus increasing the ΔP. The fuel flow rate (the simulated leak rate from the P1 bypass valve port fitting) was recorded as 155.8 PPH.

(8) The leak rate at approximately idle conditions corresponded to a 0.033" external leak orifice. This external leak size was compared to a later analysis investigating how this leak caused N1 to reach the overspeed limit in Section 1.16.3.


**Figure 50: Leak Rate from P1 Bypass Valve Port Fitting**

(9) The amount of flow from the discharge tube was recorded by the flowmeter.

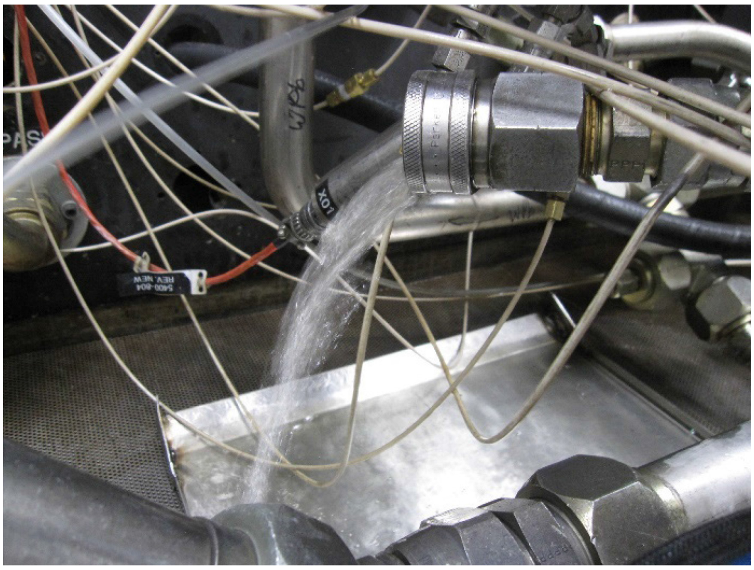


**Figure 51: Fluid Leak from P1 Bypass Valve Port Fitting**

(10) After the needle valve was opened to simulate the leak, the metered flow (Wf) value changed to 933.2 PPH.


**Figure 52: Meter Flow Rate With Leak**

### 1.16.2.7. Modified Acceptance Test of Event FMU

(1) Two test points were performed after replacing the o-rings on the three leaking plugs to verify the functionality of the FMU; one was at near sub-idle and the other was at about cruise.

(2) The Powerplant Group came to consensus that these two representative tests were sufficient to validate the operation of the FMU. No leaks were observed during any of the modified Acceptance Test Procedure (ATP) testing.

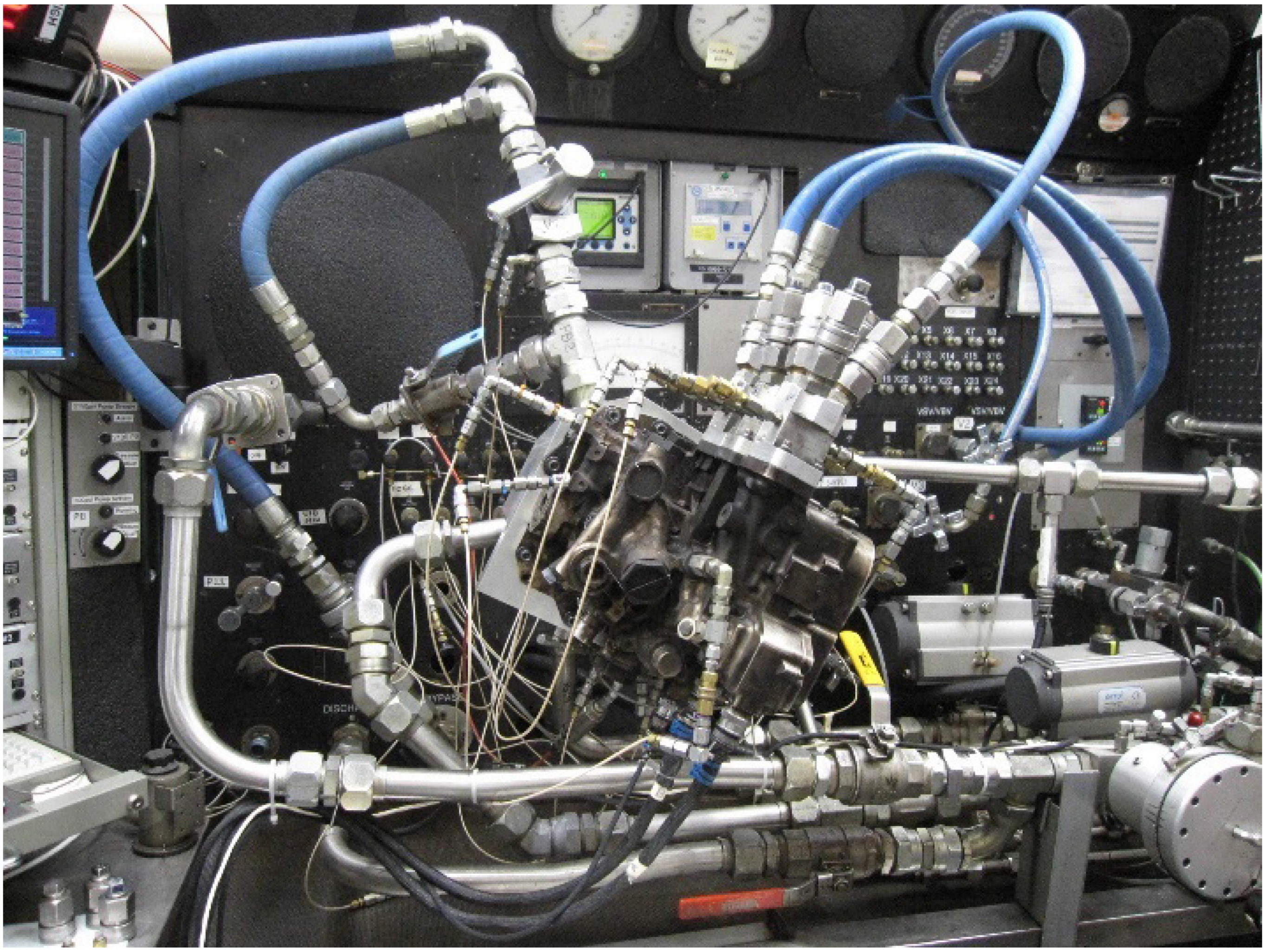


**Figure 53: Event FMU on the Test Stand**

(3) The first test was the one at the near sub-idle. The input pressures and flow rates were as follows:

1) Wi – Inlet flow - 2254-2346 PPH
2) WPB – Bypass flow - 250-350 PPH
3) PB – Bypass Pressure – 20-70 pounds per square inch gauge (psig)
4) P22-PB – Discharge Bypass Pressure – 50-70 psid
5) LVDT – +0.1897 volt/volt

(4) With these input values, the metered fuel flow rate from the FMU (WF) was recorded as 291 PPH (limit is 293-313 PPH) and the ΔP (P1-P2) was 50.2 psid (limit 40-60 psid).


**Figure 54: Near Sub-Idle Test**

(5) When Woodward shipped the event FMU, the as-shipped value for WF was 293 PPH and for ΔP was 50.5 psid. So for this test point, WF and ΔP valves correlated well with the as-shipped values. It was concluded that the event FMU worked normally near sub-idle conditions.

(6) The second test was representative of operating conditions at cruise. The input pressures and flow rates were as follows:

1) Wi – Inlet flow - 40180-41820 PPH
2) WPB – Bypass flow - 6790-7504 PPH
3) PB – Bypass Pressure – 225-235 psig
4) P22 – Discharge Bypass Pressure – 460-480 psid
5) LVDT – -0.1775 volt/volt

(7) With these input values, the metered fuel flow rate from the FMU (WF) was recorded as 7253 PPH (limit is 6968-7326 PPH).


**Figure 55: About Cruise Test**

(8) When Woodward shipped the event FMU, the as-shipped value for WF was 7207 PPH. So for this test point, WF correlated well with the as-shipped value. It was concluded that the event FMU worked normally about cruise conditions.

(9) Based on the results of the various leak checks and the modified ATP testing, it is concluded that the event FMU operated normally after replacing the packings and retightening the P1 bypass valve port fitting. No disassembly of the FMU was needed to further support the investigation.

### 1.16.2.8. Conclusion of the FMU examination

(1) In conclusion, the FMU examination identified the fuel leakage at the fuel supply pressure (P1) bypass valve port fitting on the FMU. The subsequent inspection revealed that the fitting was loose with a gap between the fitting and the housing, and the packing of the fitting was also found damaged. The P1 bypass valve port fitting leak rate was quantified, as well as the resulting effect on FMU performance.

## 1.16.3. Study of N1 Reaching Overspeed Limit

(1) After confirming the fuel leak at the P1 bypass valve port fitting, GE studied how this leak could cause N1 to reach the overspeed limit.

(2) The main engine fuel system components and the internal structure of the FMU are shown in the following figures:

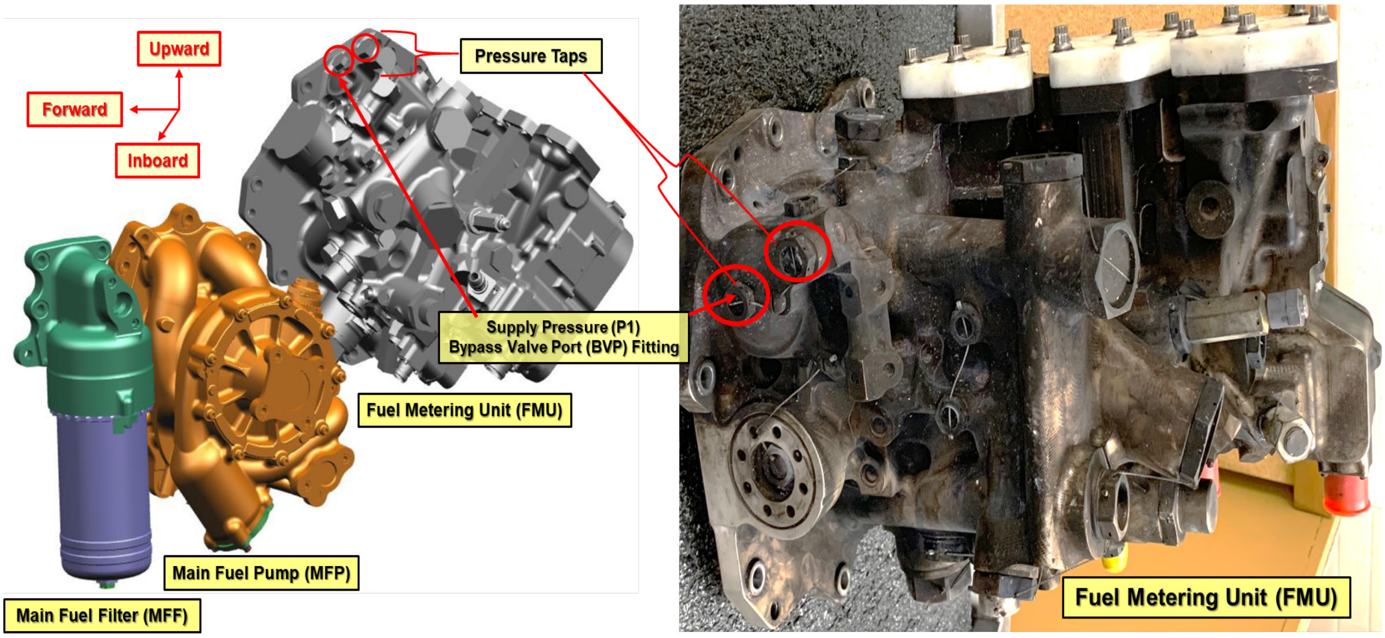



**Figure 56: Main Engine Fuel System Components**

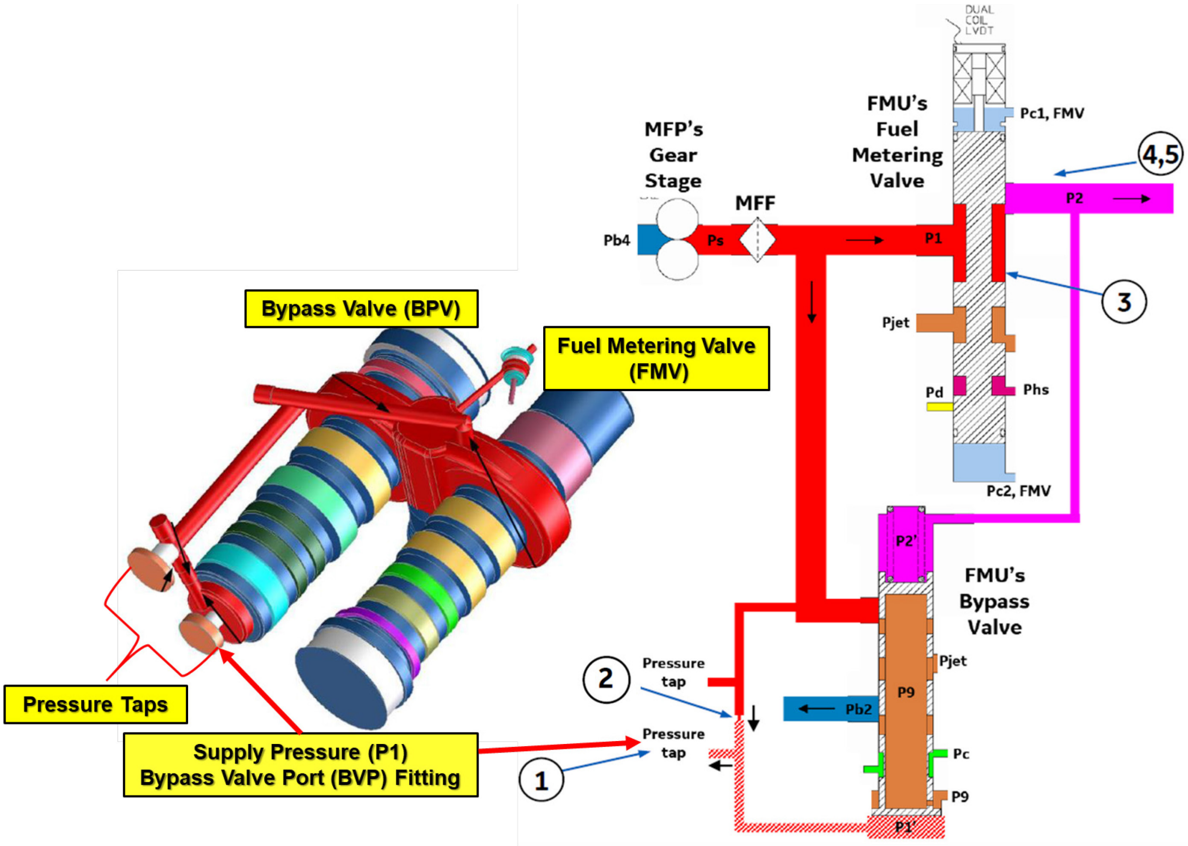



**Figure 57: Internal structure of the FMU**

(3) The external fuel leak occurred at the P1 BVP fitting, i.e. the P1 sense line of the bypass valve (BPV). See ① in the figure above.

(4) The leak caused the BPV to sense a different, lower pressure (P1') because flow across the damping orifice was metered. See ② in the figure above.

(5) The BPV moved to a more closed position, resulting in higher delta pressure across the FMV, and therefore more flow thru the FMV. See ③ in the figure above.

(6) FADEC commanded the FMV to a more closed position to maintain fan speed. See ④ in the figure above.

(7) FADEC calculated fuel flow based on FMV position. The actual flow was higher than calculated, due to the higher delta pressure across the FMV. See ⑤ in the figure above.

(8) When FADEC demanded additional fuel flow to protect against flame-out, additional fuel was sufficient to result in N1 reaching the FADEC overspeed limit.

(9) The FMU examination estimated an external leak effective diameter of 0.033-inch at Idle (Section 1.16.2.6) which increased to 0.038-inch at takeoff conditions (Section 1.16.2.3). By applying these effective leakage diameters to this N1 overspeed scenario, the resulting calculated engine fuel flows agree with the FDR recorded fuel flows at idle and takeoff, respectively.

## 1.16.4. Flight Test for Post-Shutdown Surface Temperatures

(1) To help understand the ground fire event, GE had previously conducted a flight test to collect post-shutdown surface temperatures data as shown below.

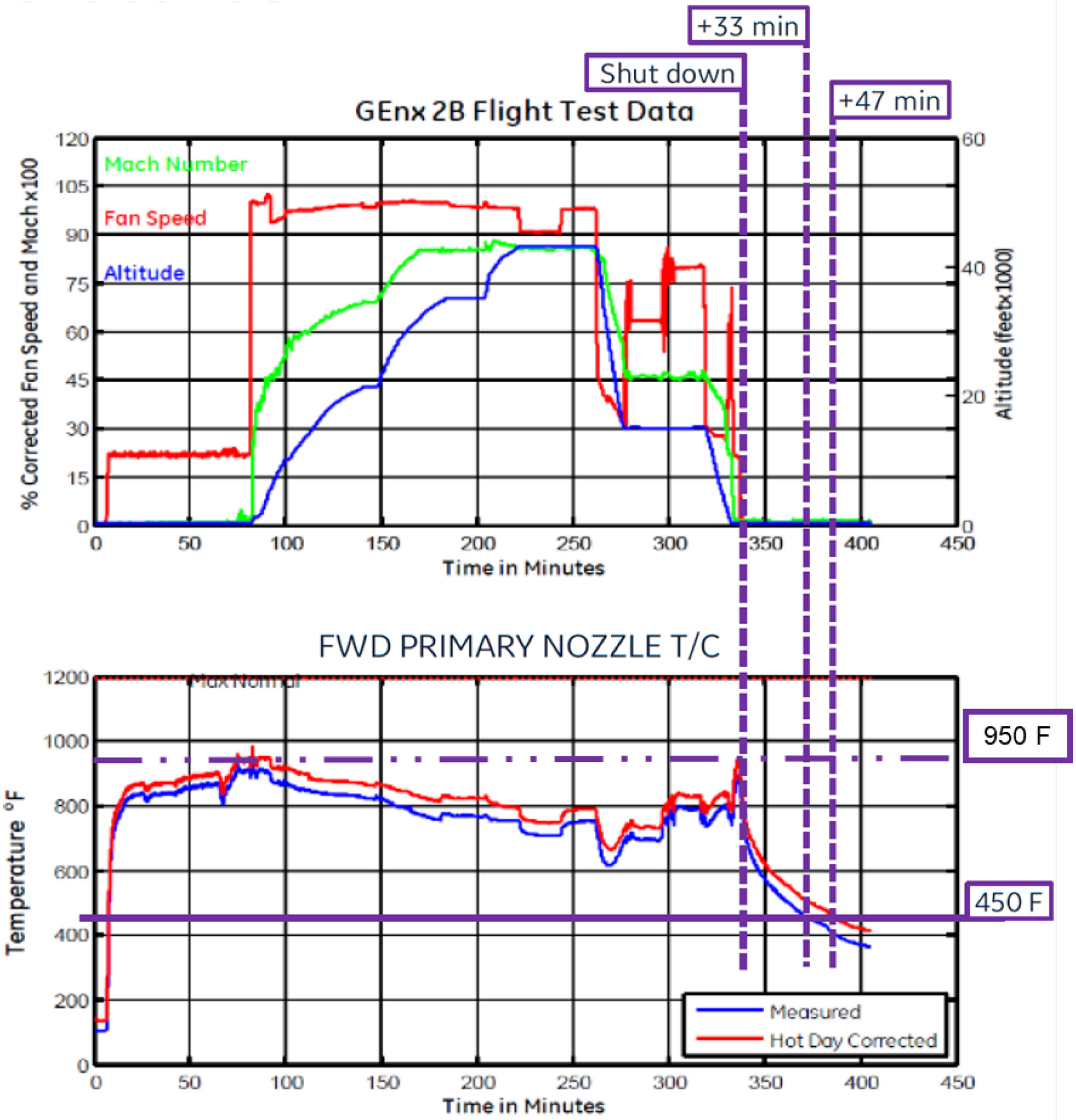



**Figure 58: Post-Shutdown Surface Temperatures of Genx-2B Engine**

(2) During normal operation, even at ground idle or after the engine shutdown, the surface temperature of multiple parts in the aft section of the core compartment exceed 450 degrees Fahrenheit (°F), which is the auto-ignition temperature of the fuel in still air.

(3) After the engine shutdown, forward primary nozzle temperatures was above 450 °F for at least 33 minutes as tested, and 47 minutes when corrected for hot day conditions.

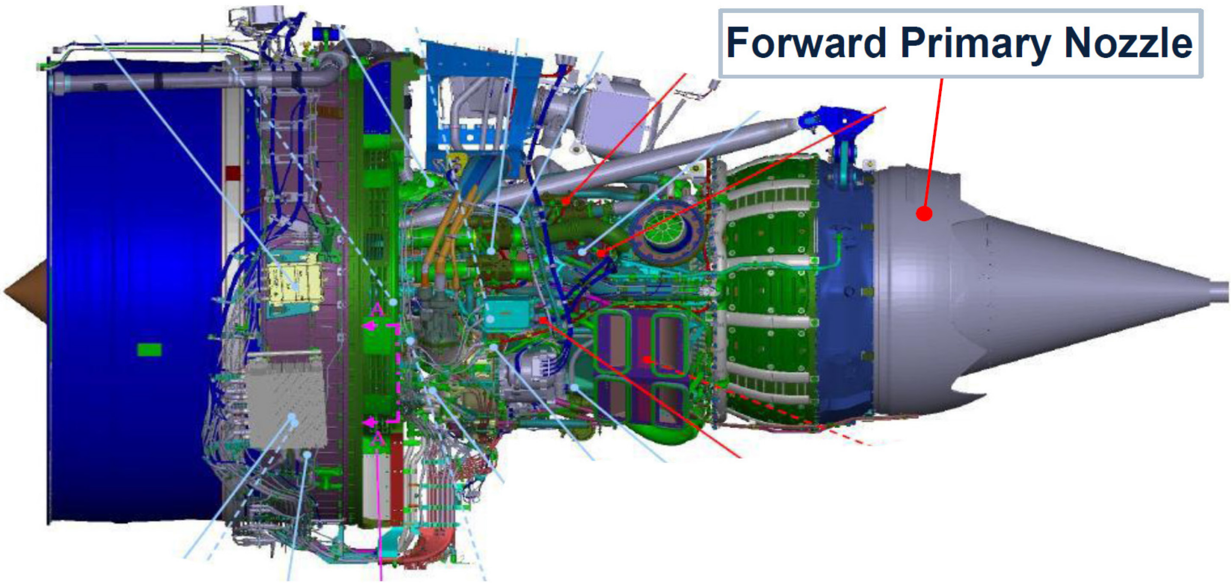



**Figure 59: The Location of Forward Primary Nozzle**

(4) On the event date of 20 July 2021, the ambient temperature in Hong Kong was 80 °F (27 degrees Celsius).

(5) For the incident flight, the fire was present during descent. The aircraft came to a complete stop only one minute after the fire warning disappeared.

(6) The temperature of the fire was estimated to reach about 1000 - 1200 °F, which is higher than the temperature at the forward primary nozzle during normal shutdown (about 950 °F). Under-cowl temperatures likely exceeded normal ambient conditions of the fire zone. Under-cowl area likely contained components above fuel auto-ignition temperature even after 22 minutes of shutdown.

(7) For both in-flight fire and ground fire, if there is sufficient fuel leakage, components above fuel auto-ignition temperature could ignite the fuel in the under-cowl area.

### 1.16.5. Study of Fuel System Leakage After Engine Shutdown

(1) To understand where the sufficient fuel to start the fire came from, GE sought to understand how the fuel system leaked after the engine shutdown.

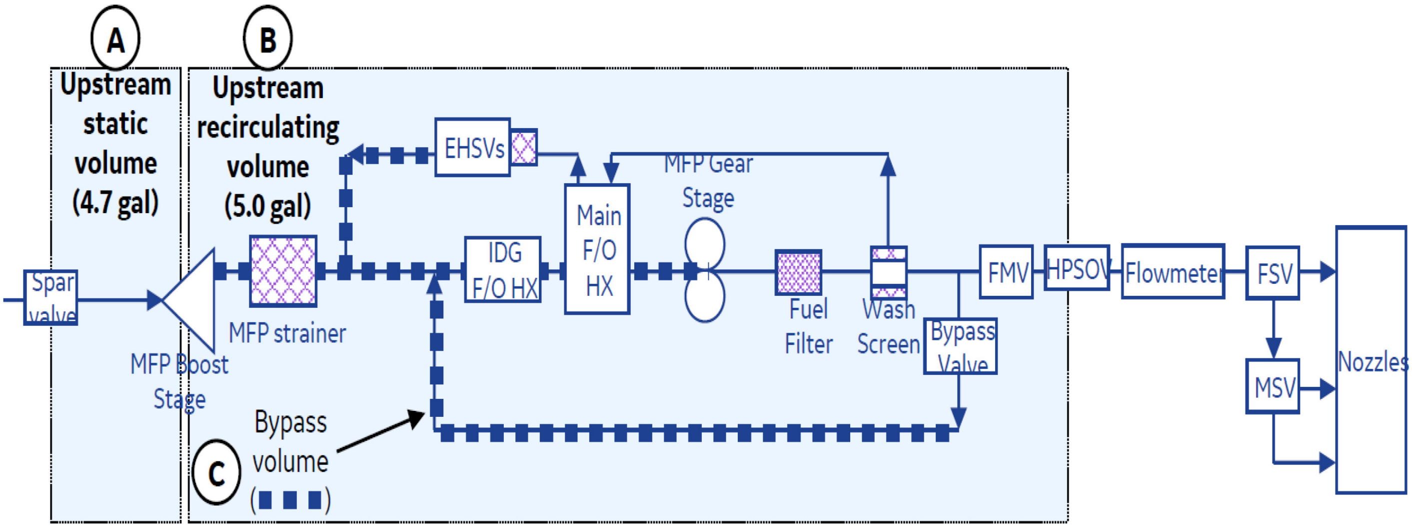



**Figure 60: Block Diagram of Engine Fuel System**

(2) By design, the upstream static fuel volume ("Ⓐ") was 4.7 gallons, the upstream recirculating fuel volume ("Ⓑ") was 5.0 gallons and the bypass volume ("Ⓒ") was approximately 1/3 of the total recirculating volume, i.e. approximately 1.7 gallons.

(3) When the fuel switch was off, the spar valve and HPSOV were moved to the close position.

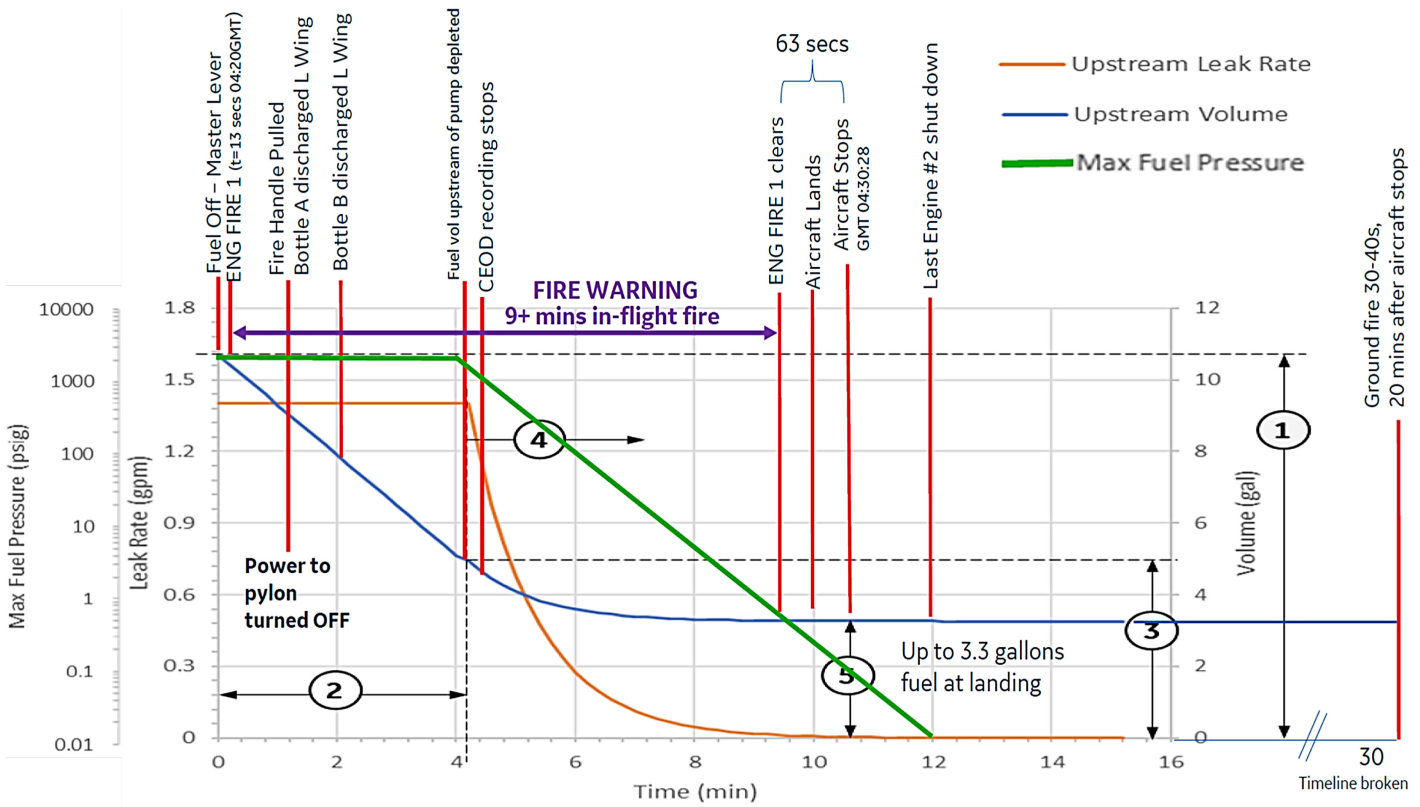



**Figure 61: Timeline of Upstream Fuel Volume / Leak Rate with Key Events**

(4) When fuel was shut off, 9.7 gallons of fuel (Ⓐ: 4.7 gallons + Ⓑ: 5 gallons) were trapped between the spar valve and HPSOV. This volume expanded to 10.7 gallons due to the thermal expansion of the fuel. The upstream leak was from the P1 bypass valve port fitting of the FMU. See ① in the figure above.

(5) The upstream static volume of fuel (Ⓐ) was being drained by the boost pump. Gear stage performance (and the FMU leak rate) was maintained. The FMU leakage continued at the rate of around 1.4 gallons per minute (gpm). See ② in the figure above.

(6) The upstream static volume of fuel (Ⓐ) was depleted around 4 minutes after shutdown until the trapped fuel from the spar valve to the inlet of the main fuel pump was exhausted. 5 gallons of fuel remained in the total upstream recirculating system (Ⓑ). See ③ in the figure above.

(7) Gear stage performance degraded as recirculating bypass volume (Ⓒ) was reduced. The pump performance (therefore FMU leak rate) was assumed to decay linearly with respect to the remaining bypass volume. See ④ in the figure above.

(8) Bypass volume ( Ⓒ ) was depleted. The remaining volume approaches 3.3 gallons in the total upstream system. FMU leak was no longer pressure driven but due to gravity/drip only that occurred about 10 minutes after engine shutdown, shortly before landing. See ⑤ in the figure above.

### 1.16.5.1. Duration of In-flight Fire

After the engine shutdown, the high-pressure fuel leak persisted at a rate of around 1.4 gpm for about 4 minutes. The pressure and leak rate decayed as the fuel recirculating downstream of the main fuel pump continued to leak for about another 6 minutes. Therefore, the fuel leak was the ignition source for about 10 minutes, which closely matched the 9.5-minute fire warning duration. The fire was likely an auto-ignition of fuel caused by hot engine components.

### 1.16.5.2. Duration of Ground Fire

The trapped fuel volume remaining at landing was calculated to be 3.3 gallons remaining. The 3.3 gallons of remaining fuel at landing was available for the 30-40 second ground fire.

## 1.16.6. Woodward Pressure Cycle Testing

(1) Woodward engineering testing of various gaps showed that a 0.018-inch gap would last between 34 and 139 cycles before the o-ring distress would progress to a leak at nominal take-off conditions. Thus, ATP testing during the production does not result in a leak for this condition.

(2) Initial cycling simulating engine take-off conditions (~1408 psig), 0.014-inch and lower gap survived the full 50,000 pressure cycles without leakage.

| Gap Size (in inches) | Pressure Cycles under Take-off Conditions | Result |
|---|---|---|
| 0.018” gap | 34 - 139 Cycles | Leak occurred. |
| 0.016” gap | 5320 Cycles | Leak occurred. |
| 0.014” gap | >50K Cycles | No leakage. |
| 0.012” gap | >50K Cycles | No leakage. |
| 0.010” gap | >50K Cycles | No leakage. |

**Table 3: Pressure Cycle Testing under Take-off Conditions**

(3) Woodward had planned to introduce a 0.005” shim check to verify the proper installation of the P1 bypass valve port fitting.

(4) Woodward had completed pressure cycle testing to validate the 0.005” shim check. No leak was found after 10,000 pressure cycles at engine maximum operating pressure.

| Gap Size (in inches) | Pressure Cycles under Maximum Working Pressure | Result |
|---|---|---|
| 0.007” gap | 8706 Cycles | Leak occurred. |
| 0.006” gap | >10K Cycles | No leakage. |
| 0.005” gap | >10K Cycles | No leakage. |
| 0.004” gap | >10K Cycles | No leakage. |
| 0.003” gap | >10K Cycles | No leakage. |

**Table 4: Pressure Cycle Testing under Maximum Working Pressure**

(5) To sum up, the fitting is expected to be properly torqued with no gap. If the fitting is just finger tightened, there would be about a 0.018” gap. Operator cannot achieve a 0.005” gap by finger tightening. 0.005” shim is the appropriate tool for go/no-go check.

(6) The 0.005” shim check was incorporated into the GE SB to inspect the population of FMUs to assure proper seating and torque of the P1 bypass valve pressure port fitting.

## 1.16.7. Study of FMU Assembly Process at Woodward

(1) The assembly process at the time of unit assembly was to install 7 similar fittings and then tighten them. There was no one-over-one torque verification in place at the time of this unit's manufacture date, 20 November 2019.

(2) Production Manufacturing Integration System (MIS) instructions for assembling the FMU were revised to include the torque audit on 30 December 2019. Torque audit is 100% torque verification. All threaded plugs are independently verified to proper torque value by an independent operator prior to safety cabling and final inspection.

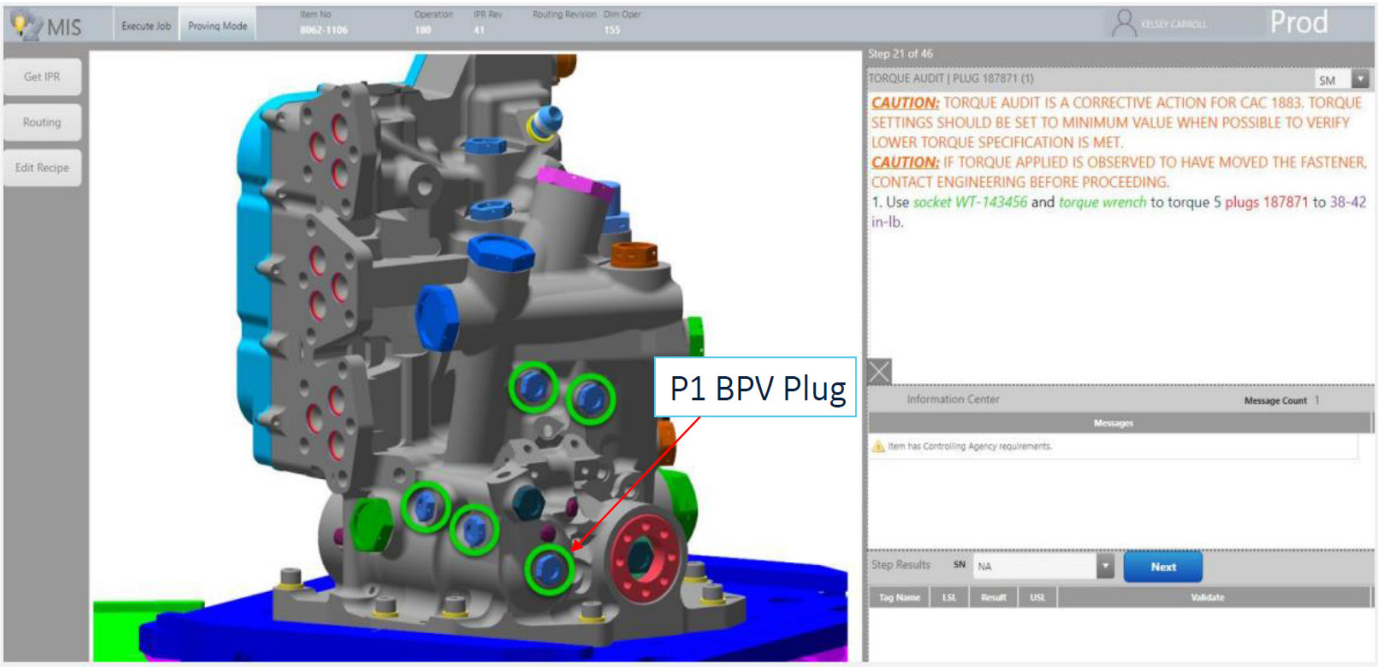



**Figure 62: Revised MIS Instructions to Include Torque Audit**

(3) After the occurrence, the repair and overhaul facilities also established the torque verification procedure of the P1 bypass valve port fitting on 4 October 2021. The fitting is independently verified to proper torque value by an independent operator prior to safety cabling and final inspection.

# 1.17. Organisation, Management, System Safety

## 1.17.1. Federal Aviation Administration (FAA)

The FAA is the regulatory authority responsible for the airworthiness and environmental certification of all aeronautical products, parts, and appliances designed, manufactured, maintained or used by persons under the regulatory oversight of the United States. It carries out the functions and tasks of the State of Design and State of Manufacture of Boeing 747-8F aircraft.

## 1.17.2. UPS

The UPS holds an Air Operator's Certificate (AOC) issued by the FAA. The operator has been using Louisville Muhammad Ali International Airport (KSDF) as the base for cargo operations since 1988. The existing fleet consists of Airbus A300-600F, Boeing 757-200F, 767-300F, MD-11F, 747-400F, and 747-8F aircraft types for cargo operations.

# 1.18. Additional Information

## 1.18.1. Boeing Quick Reference Handbook

(1) Boeing publishes an aircraft technical document named Quick Reference Handbook (QRH) that contains all the procedures applicable for abnormal and emergency conditions in an easy-to-use format.

(2) There are non-normal checklist procedures in the QRH for pilots to handle engine limit exceedance and engine fire situations as shown below.

7.2 747-8 Quick Reference Handbook

## [] ENG 1, 2, 3, 4 LIM EXCEED

Condition: An engine limit exceedance occurs.

1 Thrust lever
(affected engine) . . . . . . . . . .Confirm . . . . Retard until the ENG LIM EXCEED message blanks or the thrust lever is at idle

2 Choose one:

◆ENG LIM EXCEED message is **blank**:

►►**Go to step 3**

◆ENG LIM EXCEED message **shows**:

FUEL CONTROL switch
(affected engine) . . .Confirm . . . CUTOFF

Transponder mode selector . . . . . TA ONLY

**Note:** Select the ENG 1, 2, 3, 4 SHUTDOWN non-normal when requesting landing performance.

■ ■ ■ ■

Check that RPM and EGT follow thrust lever movement.

3 ⚠ Thrust lever
(affected engine) . . . . . . . . . . . Advance slowly

**Note:** Run the engine at a thrust setting that keeps the engine indications within limits. Do not use FMC performance predictions.

4 Transponder mode selector . . . . . . . . . . . .TA ONLY

■ ■ ■ ■



**Figure 63: Non-Normal Checklist for ENG LIM EXCEED Message**

8.2 747-8 Quick Reference Handbook

## [] FIRE ENG 1, 2, 3, 4

Condition: Fire is detected in an engine.

1 Thrust lever
(affected engine) . . . . . . . . . Confirm . . . . . . Idle

2 FUEL CONTROL switch
(affected engine) . . . . . . . . . Confirm . . . CUTOFF

3 Engine fire switch
(affected engine) . . . . . . . . . Confirm . . . . . . Pull

4 **If** the FIRE ENG message stays shown:

Engine fire switch
(affected engine). . . . . . . . . . Rotate to the stop and hold for 1 second

**If** after 30 seconds, the FIRE ENG message stays shown:

Engine fire switch
(affected engine) . . . . . . . . . Rotate to the other stop and hold for 1 second

5 Transponder mode selector . . . . . . . . . . . . TA ONLY

6 Choose one:

◆ FIRE ENG message **stays shown**:

Plan to land at the nearest suitable airport.

►► **Go to step 7**

◆ FIRE ENG message **blanks**:

►► **Go to step 7**

7 Do **not** accomplish the following checklist:

OVHT ENG NAC

**Note:** Select the ENG 1, 2, 3, 4 SHUTDOWN non-normal when requesting landing performance.

■ ■ ■ ■



**Figure 64: Non-Normal Checklist for FIRE ENG Message**

## 1.18.2. Issuance of Related Technical Publications

### 1.18.2.1. GE Service Bulletin (SB)

(1) GE issued SB 73-0092 R00, namely FMU Bypass Valve Plug Clearance Inspection, on 3 December 2021. The Service Bulletin is applicable to all GEnx-2B engines with specific FMU criteria.

(2) The SB provides inspection criteria and both on-wing and off-wing instructions of 0.005” shim check to verify that the P1 bypass valve port fitting on the FMU is properly installed.

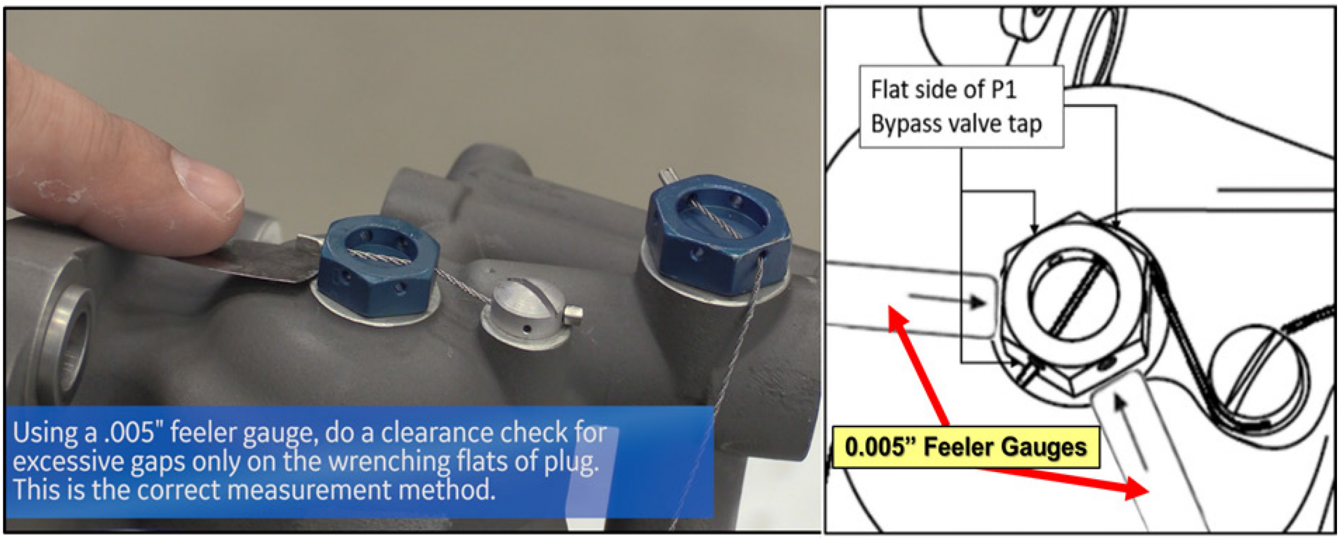



**Figure 65: 0.005” Shim Check**

(3) Also, the SB provides the instructions to correct any defect and defines all of the hardware required.

(4) Since the concerned FMU can also be installed on GEnx-1B model turbofan engines, a similar SB was issued for all GEnx-1B engines with specific FMU criteria, reference SB 73-0100 R00.

#### 1.18.2.2. FAA Airworthiness Directive (AD)

(1) The FAA, the primary certification authority of Boeing 747-8F aircraft, issued AD No. 2022-04-07 on 15 February 2022 to address the fuel system leakage from the FMU, which was caused by an improperly torqued FMU BPV fitting.

(2) The unsafe condition, if not addressed, could result in the loss of engine thrust control, in-flight shutdown (IFSD), and reduced control of the aircraft.

(3) As the unsafe condition was identified, mandatory measures in the form of an Airworthiness Directive had to be issued.

(4) This AD requires either an on-wing or off-wing shim check inspection using a 0.005-inch feeler gauge of the FMU P1 bypass valve port fitting within 150 flight cycles after the effective date of this AD, 9 March 2022.

(5) If the 0.005-inch feeler gauge can fit between the fitting and the FMU housing on the flat side, before further flight, the operator must remove the FMU and replace it with an FMU eligible for installation.

## 1.19. Useful or Effective Investigation Techniques

Not applicable.

# 2. Safety Analysis

*The Safety Analysis provides a detailed discussion of the safety factors identified during the investigation, providing the evidence required to support the findings, contributing factors and the safety recommendations.*

## 2.1. Flight Operations

### 2.1.1. Crew Qualifications

Referring to 1.5.1 and 6.2, the flight crew were properly licensed, medically certified in accordance with the licensing requirements of the United States of America, and adequately rested to operate the flight.

### 2.1.2. Operational Procedures

Based on the flight data analysis, the flight crew performed the non-normal checklist procedures adhering to the QRH shown in 1.18.1 to handle the situations of N1 exceedance and engine fire warning.

### 2.1.3. Weather

Referring to 1.7, the prevailing weather conditions were generally fine for the flight and were not a factor in the occurrence.

### 2.1.4. Navigation Aids

Referring to 1.8, there was no report of abnormal operation of any ground-based navigation aids or aerodrome visual ground aids.

### 2.1.5. Communications

Referring to 1.9, all communications between Hong Kong ATC and the aircraft recorded were clear and there was no report of a defective radio communication system in the cockpit.

## 2.2. Aircraft Maintenance

(1) Referring to 1.6.1, the aircraft held a valid FAA Standard Airworthiness Certificate.

(2) Referring to 1.6.5, the investigation team did not identify any maintenance-related issue, nor inherent aircraft defect that may lead to the serious incident. Aircraft maintenance was not a factor.

## 2.3. Analysis of Fuel Leakage

(1) Referring to 1.16.1.2, the fuel system leak checks at the GE facility identified multiple fuel leaks from the FMU. The FMU was removed from the engine and sent to the manufacturer for further examination.

(2) Referring to 1.16.2, the further examination of the FMU at the Woodward facility found that the fuel leaked from the P1 bypass valve port fitting. The fitting was hand tightened only and found to have a 0.018-inch gap observed between fitting and FMU housing. If the fitting was properly installed, there should be no gap between the fitting and the FMU housing.

(3) Since the safety issue on the FMU was identified, the AAIA immediately worked with the NTSB and the technical advisors to identify any safety actions in order to prevent future occurrences. On 24 September 2021, the AAIA issued Safety Recommendations 10-2021 and 11-2021 to the FAA. Details are in Section 4: Safety Recommendation Report.

## 2.4. Flight Data Analysis

(1) The AAIA conducted the analysis of the flight data in conjunction with NTSB, Boeing and GE.

(2) The main purpose of the analysis was to understand the following three key phases in order to establish the cause of the occurrence:

a) Phase 1: Engine Overspeed,
b) Phase 2: In-flight Fire, and
c) Phase 3: Ground Fire

(3) The analysis was performed taking into account the flight crew actions read from the flight data, as shown in the figure below:

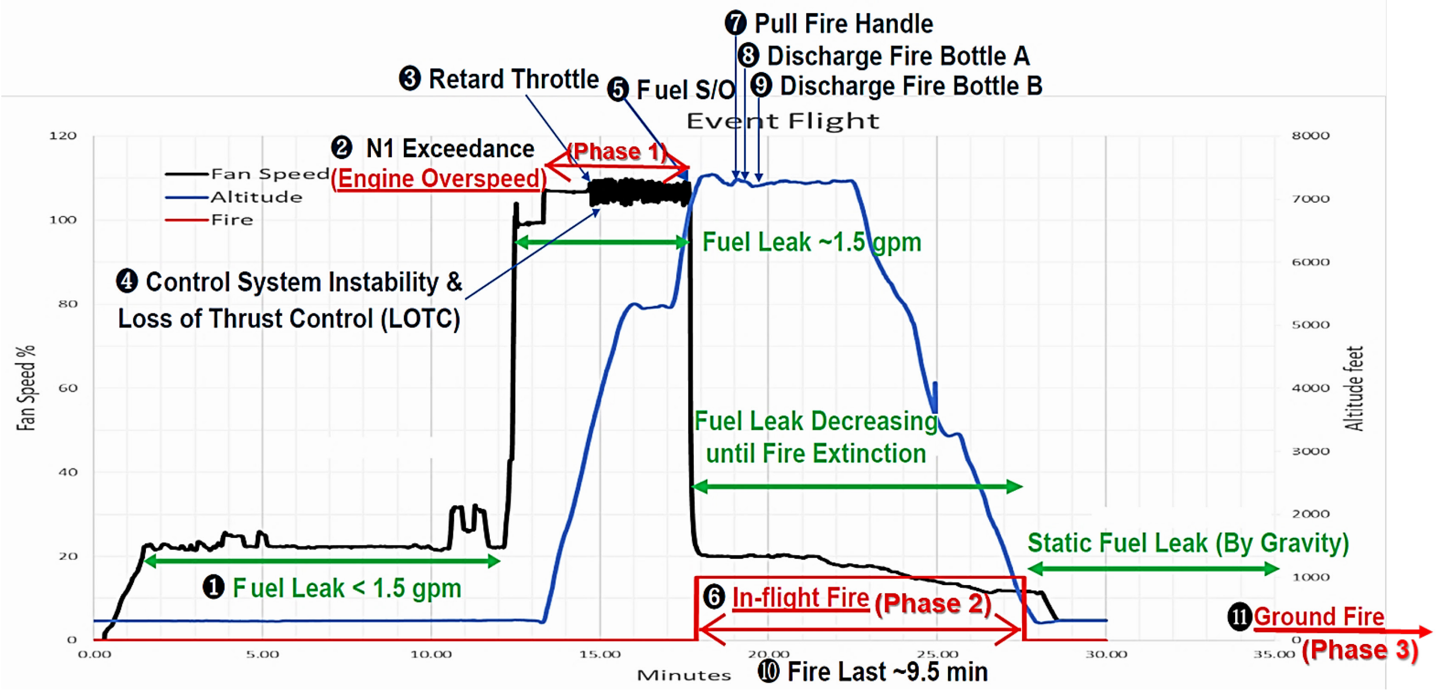



**Figure 66: Three Key Phases of the Event**

## 2.4.1. Flight Data Observations

(1) The FMU leak started at idle. See ❶ in the figure above.

(2) During the take-off roll, the N1 exceedance warning was annunciated. See ❷ in the figure above.

(3) The engine did not respond to throttle reduction. The engine control system became unstable and LOTC occurred. See ❸ and ❹ respectively in the figure above.

(4) Fuel was shut off and the fire started 12 seconds after engine shutdown due to a reduction in under-cowl airflow and ignition on the hot surfaces. See ❺ and ❻ respectively in the figure above.

(5) The flight crew pulled the fire handle to isolate the engine from the aircraft and discharged fire extinguisher bottle A. See ❼ and ❽ respectively in the figure above.

(6) The fire warning remained and the flight crew immediately discharged the fire extinguisher bottle B. See ❾ in the figure above.

(7) The fire lasted about 9.5 minutes. See ❿ in the figure above.

(8) The fire reignited on the ground approximately 22 minutes after the aircraft stopped and lasted about 40 seconds. ⓫ in the figure above.

## 2.4.2. Understanding the Phases of the Occurrence

### 2.4.2.1. Phase 1: Engine Overspeed

(1) Referring to the FMU examination in Section 1.16.2, it was found that the P1 bypass valve port fitting (a threaded fitting) on the FMU was finger tightened at production and safety cabled in place without final torque being applied. The O-ring between the fitting and the FMU housing was not properly supported, resulting in the failure of the O-ring and a fuel leak from this location on the event flight.

(2) Referring to the study of N1 reaching the overspeed limit in Section 1.16.3, as the throttle was commanded to take-off power, the fuel leak rate increased and the disagreement between calculated and actual fuel flow increased.

(3) The calculated fuel flow became low enough that the FADEC demanded additional fuel flow to prevent flame-out of the combustor. The additional fuel flow to the combustor was sufficient to result in N1 reaching the FADEC overspeed limit.

(4) The FADEC then experienced a control system oscillation as it competed between reducing fuel flow (closing the FMV) to protect against N1 overspeed, which functioned as intended, and increasing fuel flow (opening the FMV) to prevent flame-out of the combustor.

(5) In response to the overspeed warning, the flight crew commanded the engine to idle. However, the control system oscillation persisted, and the engine did not follow the N1 command.

(6) To sum up, the fuel leakage from the P1 bypass valve port fitting of the FMU caused the N1 to reach the overspeed limit.

### 2.4.2.2. Phase 2: In-flight Fire

(1) Referring to the study of the fuel system leakage after engine shutdown in Section 1.16.5, the fuel leak at this point was a

high-pressure spray/mist/vapour combination but was carried out of the vent areas by the under-cowl air flow before it had time to ignite.

(2) The flight crew commanded the shutdown of the engine due to the loss of N1 control. The fuel shut-off command closed both the HPSOV in the FMU, and the aircraft spar valve, with fuel trapped in the circuit between the two valves.

(3) The engine windmilling speed continued to drive the main fuel pump (MFP) which continued to recirculate fuel upstream of the HPSOV. The fuel leak also affected the bypass valve position after shutdown and allowed it to close, rather than stay open as intended.

(4) This resulted in high pressure in the fuel circuit upstream of the HPSOV instead of low pressure.

(5) With the engine at windmill speed, the under-cowl air flow was greatly reduced. The fuel leak remained at high pressure in form of a spray/mist/vapour combination, and had sufficient time to ignite adjacent to the hot engine surfaces.

(6) The engine fire warning alerted, and the flight crew pulled the fire handle and discharged both fire extinguisher bottles. The high-pressure fuel leak persisted after the fire extinguisher bottles were deployed and fuel continued to reignite on the hot engine surfaces.

(7) Over the course of about 9.5 minutes, the pressure/flow of the trapped volume of fuel feeding the fuel leak decreased until it could no longer sustain the fire. The fire warning was turned off approximately 20 seconds before landing.

(8) To sum up, the fuel leakage from the P1 bypass valve port fitting of the FMU in the engine fire zone caused the in-flight fire.

#### 2.4.2.3. Phase 3: Ground Fire

(1) After landing, the AFC attended the aircraft and noticed no indication of fire. Approximately 22 minutes after landing, the AFC on the ground noticed white smoke and then a fire in the No. 1 engine as when water was being applied to the engine surrounding to maintain a cooling effect. The AFC extinguished the ground fire after about 40 seconds using fire suppressants.

(2) Referring to the powerplant examination in Section 1.16.1, as a result of the in-flight fire, there was likely secondary damage to some of the fuel-carrying components in the under-cowl area.

(3) Referring to the study of the fuel system leakage after engine shutdown in Section 1.16.5, while on the ground, a small amount of residual fuel continued to leak/drip out of those fuel-carrying components where seals or lines had been compromised by the in-flight fire.

(4) Based on the flight test result for post-shutdown surface temperatures described in Section 1.16.4., some surface temperatures were above the auto-ignition threshold for fuel vapour (450 $^{o}$F) for more than 22 minutes after landing.

(5) Referring to the study of the fuel system leakage after engine shutdown in Section 1.16.5, the 3.3 gallons of remaining fuel at landing was available for the 30-40 second ground fire.

(6) There was sufficient fuel vapour accumulated to potentially create a deflagration, which is subsonic combustion propagating through heat transfer where hot burning material heats the next layer of cold material and ignites it.

(7) To sum up, the ground fire was likely due to secondary damage to the fuel-carrying components in the under-cowl area.

## 2.5. Solution for the Improper Installation of P1 Bypass Valve Port Fitting

(1) Referring to 1.16.7, the assembly process at production had been changed to include the 100% torque verification procedure of the P1 bypass valve port fitting on 30 December 2019, which was about one month after the event FMU was manufactured.

(2) Referring to 1.16.7, not only the production, the repair and overhaul had also established the 100% torque verification procedure of the P1 bypass valve port fitting on 4 October 2021. The fitting is independently verified to proper torque value by an independent operator prior to safety cabling and final inspection.

(3) The investigation team concurred that the 100% torque verification procedure in place minimises the likelihood of an improper installation of P1 bypass valve port fitting.

(4) Referring to 1.16.6, improper Installation of the P1 bypass valve port fitting can be detected by a 0.005” shim check, i.e. inserting a feeler gauge into the gap between the fitting and the housing.

(5) Referring to 1.18.2.1, GE issued SB 73-0092 R00 and 73-0100 R00 to inspect the population of FMUs through the 0.005” shim check inspection in order to ensure the proper installation of the P1 bypass valve port fitting.

(6) Referring to 1.18.2.2, FAA issued AD No. 2022-04-07 to mandate the shim check inspection within 150 flight cycles after the effective date of this AD, 9 March 2022.

(7) The investigation team agreed that the 0.005” shim check inspection can be used for both on-wing and off-wing to ensure the proper installation of the P1 bypass valve port fitting on the FMU.

# 3. Conclusions

*From the evidence available, the following findings are made with respect to this occurrence. These findings should not be read as apportioning blame or liability to any particular organisation or individual.*

## 3.1. Findings

(1) The flight crew were licensed and qualified for the flight in accordance with regulations and the operator's requirements. (2.1.1.)

(2) The flight crew handled the situation of N1 exceedance and engine fire warning in accordance with the operations manual. (2.1.2.)

(3) The weather conditions were within the limits of the flight. (2.1.3.)

(4) Ground-based navigation aids and aerodrome visual ground aids were serviceable. (2.1.4.)

(5) All communications between Hong Kong ATC and the aircraft were good. (2.1.5.)

(6) The aircraft held a valid FAA Standard Airworthiness Certificate and was maintained in accordance with the regulations. (2.2.)

(7) The examination identified the fuel leak from the supply pressure (P1) bypass valve port fitting on the FMU. (2.3)

(8) The inspection revealed that the P1 bypass valve port fitting was loose with a gap between the fitting and the FMU housing. (2.3)

(9) If the P1 bypass valve port fitting was properly installed, there should be no gap between the fitting and the FMU housing. (2.3)

(10) As the safety issue on the FMU was identified, the AAIA issued two safety recommendations to the FAA on 24 September 2021 to take necessary safety actions in order to prevent future occurrences. (2.3)

(11) The fuel leakage from the P1 bypass valve port fitting of the FMU caused the N1 to reach the overspeed limit. (2.4.2.1.)

(12) The fuel leakage from the P1 bypass valve port fitting of the FMU in the engine fire zone caused the in-flight fire. (2.4.2.2)

(13) The ground fire was likely due to secondary damage to fuel -carrying components in the under-cowl area. (2.4.2.3)

(14) The 100% torque verification procedures of the P1 bypass valve port fitting had been added to production, repair and overhaul since 4 October 2021. (2.5)

(15) Improper Installation of the P1 bypass valve port fitting can be detected by a 0.005" shim check. (2.5)

(16) GE issued SB 73-0092 R00 and 73-0100 R00 to introduce the 0.005" shim check inspection to ensure the proper installation of the P1 bypass valve port fitting on 3 December 2021. (2.5)

(17) The FAA mandated the shim check inspection within 150 flight cycles after the effective date of AD No. 2022-04-07, 9 March 2022. (2.5)

## 3.2. Cause

This serious incident was caused by improper installation of the P1 bypass valve port fitting on the fuel metering unit, resulting in a fuel leak that rendered the engine fire. [3.1.(7)–(9) & (11)–(13)]

# 4. AAIA Safety Recommendation Report

*When a safety issue is identified at any stage of the investigation, AAIA issues Safety Recommendation Report to relevant organisation(s) to recommend preventative action that has to be taken promptly to enhance aviation safety.*

## 4.1. Issue of Safety Recommendation Report

(1) During the investigation, the AAIA identified the safety issue on the FMU. The AAIA worked with the NTSB and the technical advisors to identify any safety actions in order to prevent future occurrences.

(2) The investigation team was advised that:

a) The assembly process had been changed since December 2019, which should minimize the likelihood of an improper installation of P1 bypass valve port fitting.

b) Based on the product life data analysis using the Weibull distribution, the shape parameter of the distribution, beta (β), which represents the failure rate behaviour, is 0.4. Thus, an "infant mortality" condition was identified, which the product could quickly fail at the initial period and the failure probability will reduce to a low and stable stage past this initial period.

c) The fuel metering units with sufficient cycles, i.e. 800 engine cycles, likely do not have the "infant mortality" condition.

(3) Based on the above technical advice, the AAIA issued a Safety Recommendation Report 02-2021 on 24 September 2021 to release Safety Recommendations 10-2021 and 11-2021 to the Federal Aviation Administration, as follows.

### 4.1.1. Safety Recommendation 10-2021

It is recommended that the Federal Aviation Administration require General Electric to develop instructions for continuing airworthiness for inspection of the supply pressure (P1) bypass valve port fitting on fuel metering units, General Electric part number (PN) 2459M17P02, Woodward PN 8062-1177, that were delivered, produced, or repaired before December 2019 and those with less than 800 cycles to ensure proper installation and to mandate a one-time inspection based on those instructions.

**Safety Recommendation Owner:** Federal Aviation Administration

### 4.1.2. Safety Recommendation 11-2021

It is recommended that the Federal Aviation Administration require General Electric and Woodward:

(1) To review the assembly and repair procedures of the Maintenance, Repair, and Overhaul (MRO) and Component Maintenance Manual (CMM) for the installation of the supply pressure (P1) bypass valve port fitting on fuel metering units, General Electric part number (PN) 2459M17P02, Woodward PN 8062-1177, and

(2) To make necessary changes and incorporate post assembly inspections to ensure proper installation.

**Safety Recommendation Owner:** Federal Aviation Administration

# 5. Implementation of AAIA Safety Recommendations

## 5.1. Safety Actions Taken in Response to Safety Recommendations 10-2021 & 11-2021

### 5.1.1. Safety Actions Taken by the FAA

(1) The FAA issued the Airworthiness Directive (AD) 2022-04-07 on February 22, 2022, with an effective date of March 9, 2022, to require a shim check inspection of the FMU BPV fitting and, depending on the results of the inspection, replace the FMU.

(2) The sample of affected FMUs subject to the AD are those with less than 500 cycles. The 800 cycle recommendation was reduced to 500 once it was determined the root cause of the fuel leak was improper torquing. Units with lower time cycles are at a higher risk of having the improperly torqued P1 bypass valve port fitting. After 500 cycles, FMUs have flown long enough without incident that the risk becomes minimal.

### 5.1.2. Safety Actions Taken by the Woodward

The containment actions in the form of torque verification have been in place at the supplier of the FMU (Woodward Inc.) since the end of 2019 at production, and at repair facilities since October 4, 2021. This torque audit will verify that all threaded fittings, including the P1 BPV fitting, are independently verified to their proper torque values by independent operators prior to safety cabling and final inspection.

### 5.1.3. AAIA Assessment on the Safety Actions Taken

In consideration of the safety actions taken by the FAA and the Woodward, the investigation team confirmed that there were no new discoveries of incomplete safety actions. Hence, the Safety Recommendations 10-2021 and 11-2021 were closed.

# 6. General Details

## 6.1. Occurrence Details

| | |
|---|---|
| Date and time: | 20 July 2021 at 1252 hrs Local |
| Occurrence category: | Serious Incident |
| Primary occurrence type: | Propulsion System Fire (SCF–PP–PSF) |
| Location: | Hong Kong International Airport, Hong Kong |
| Position: | 22° 19' 5" N, 113° 55' 13" E |

## 6.2. Pilot Information

### 6.2.1. Pilot Flying (PF)

| | |
|---|---|
| Age: | 59 |
| Licence: | Airline Transport Pilot, FAA |
| Aircraft ratings: | Boeing 747-4, 757 and 767 |
| Date of the first issue of aircraft rating on type: | August 2018 |
| Instrument rating: | Yes |
| Medical certificate: | Class 1 |
| Date of last proficiency check on type: | June 2021 |
| Date of last line check on type: | June 2021 |
| Date of last emergency drills check: | June 2020 |
| ICAO Language Proficiency: | Class VI |
| Limitation: | Circling Approach – VMC Only |
| Flying Experience: | |
| Total all types: | 14,747 |
| Total on the type (B747-8F) : | 1562.14 (UPS hours only listed below) |
| Total in last 90 days: | 55.59 |
| Total in last 30 days : | 28.81 |

| | |
|---|---|
| Total in last 7 days: | 0 |
| Total in last 24 hours: | 0 |
| Duty Time: | |
| Day up to the incident flight (Hours: Mins) : | 1:30 |
| Day prior to the incident (Hours: Mins) : | 0:00 |

### 6.2.2. Pilot Monitoring (PM)

| | |
|---|---|
| Age: | 47 |
| Licence: | Airline Transport Pilot, FAA |
| Aircraft ratings: | Boeing 747 |
| Date of the first issue of aircraft rating on type: | June 2021 |
| Instrument rating: | Yes |
| Medical certificate: | Class 1 |
| Date of last proficiency check on type: | June 2021 |
| Date of last line check on type: | July 2021 |
| Date of last emergency drills check: | April 2021 |
| ICAO Language Proficiency: | Class VI |
| Limitation: | Circling Approach – VMC Only |
| Flying Experience: | |
| Total all types: | 13,900 |
| Total on the type (B747-8F) : | 114.31 (UPS hours only listed below) |
| Total in last 90 days: | 114.31 |
| Total in last 30 days : | 114.31 |
| Total in last 7 days: | 45.74 |
| Total in last 24 hours: | 12.54 |
| Duty Time: | |
| Day up to the incident flight (Hours: Mins) : | 1:30 |
| Day prior to the incident (Hours: Mins) : | 0:00 |

### 6.2.3. Relief Pilot

| | |
|---|---|
| Age: | 54 |
| Licence: | Airline Transport Pilot, FAA |
| Aircraft ratings: | Boeing 747-4, 757, 767 |
| Date of the first issue of aircraft rating on type: | May 2017 |
| Instrument rating: | Yes |
| Medical certificate: | Class 1 |
| Date of last proficiency check on type: | February 2021 |
| Date of last line check on type: | May 202 |
| Date of last emergency drills check: | February 2020 |
| ICAO Language Proficiency: | Class VI |
| Limitation: | Circling Approach – VMC Only |
| Flying Experience: | |
| Total all types: | 16,366 |
| Total on the type (B747-8F) : | 2804.05 (UPS hours only listed below) |
| Total in last 90 days: | 221.31 |
| Total in last 30 days : | 89.74 |
| Total in last 7 days: | 28.16 |
| Total in last 24 hours: | 0 |
| Duty Time: | |
| Day up to the incident flight (Hours: Mins) : | 1:30 |
| Day prior to the incident (Hours: Mins) : | 0:00 |

## 6.3. Aircraft Details

| | | |
|---|---|---|
| Manufacturer and model: | Boeing 747-8F | |
| Registration: | The United States of America, N624UP | |
| Serial number: | 63784 | |
| Year of Manufacture: | 2020 | |
| Engine: | Four General Electric GEnx-2B67/P | |
| Engine Serial Number: | 959767 | |
| Operator: | United Parcel Service Company (UPS) | |
| Type of Operation: | Commercial Air Transport (Cargo) | |
| Certificate of Airworthiness | Issued on 5 November 2020 by the FAA, Standard Airworthiness Certificate | |
| Departure: | Hong Kong International Airport (VHHH) | |
| Destination: | Dubai International Airport (OMDB) | |
| Maximum Take-off Weight | 987,000 lbs | |
| Total Airframe Hours | 2905:18 | |
| Total Airframe Cycles | 447 | |
| Persons on Board: | Crew – 3 | Passengers – 0 |
| Injuries: | Crew – 0 | Passengers – 0 |
| Aircraft Damage: | Minor Damage | |

# 6.4. Aerodrome Information

## 6.4.1. Aerodrome of Departure

| | |
|---|---|
| Aerodrome Code | VHHH |
| Airport Name | Hong Kong International Airport |
| Airport Address | Chek Lap Kok, Lantau Island |
| Airport Authority | Airport Authority Hong Kong |
| Air Navigation Services | Approach Control, Aerodrome Control,<br>Ground Movement Control, Zone Control,<br>Flight Information Service,<br>Clearance Delivery Control, and<br>Automatic Terminal Information Service |
| Type of Traffic Permitted | IFR / VFR |
| Coordinates | 22° 18' 32" N, 113° 54' 53" E |
| Elevation | 28 ft |
| Runway Length | 3,800 m |
| Runway Width | 60 m |
| Stopway | Nil |
| Runway End Safety Area | 240 m x 150 m |
| Azimuth | 07L / 25R, 07R / 25L<br>(At the time of the occurrence) |
| Category for Rescue and Fire Fighting Services | CAT 10 |

# 7. Abbreviations

| | |
|---|---|
| °F | Degrees Fahrenheit |
| AAIA | Air Accident Investigation Authority |
| AD | Airworthiness Directive |
| ADIRU | Air Data Inertial Reference Unit |
| AFC | Airport Fire Contingent |
| AFSO | Airframe Shutoff |
| ALF | Aft Looking Forwards |
| AOC | Air Operator’s Certificate |
| ATP | Acceptance Test Procedure |
| BPV | Bypass Valve |
| BSI | Borescope Inspection |
| Cap. 448B | Hong Kong Civil Aviation (Investigation Of Accidents) Regulations |
| cc | Cubic Centimetres |
| CCC | Core Compartment Cooling |
| CMM | Component Maintenance Manual |
| CVR | Cockpit Voice Recorder |
| EEC | Electronic Engine Control |
| EICAS | Engine Indicating And Crew Alerting System |
| EMU | Engine Monitoring Unit |
| FAA | Federal Aviation Administration |
| FADEC | Full Authority Digital Engine Control |
| FDR | Flight Data Recorder |
| FFT | Fuel Flow Transmitter |
| FMU | Fuel Metering Unit |

| | |
|---|---|
| FMV | Fuel Metering Valve |
| FSV | Flow Split Valve |
| GE | General Electric |
| gpm | Gallons Per Minute |
| HPC | High-Pressure Compressor |
| HPSOV | High-Pressure Shut-Off Valve |
| HPT | High-Pressure Turbine |
| IFSD | In-flight Shutdown |
| KSDF | Louisville Muhammad Ali International Airport |
| LOTC | Loss Of Thrust Control |
| LPC | Low-Pressure Compressor |
| LPT | Low-Pressure Turbine |
| LVDT | Linear Variable Differential Transformer |
| METAR | Meteorological Aerodrome Weather Report |
| MFF | Main Fuel Filter |
| MFO HEx | Main Fuel Oil Heat Exchanger |
| MFP | Main Fuel Pump |
| MIS | Manufacturing Integration System |
| MRO | Maintenance, Repair, And Overhaul |
| N1 | Fan Speed |
| No. 1 | Left Outboard Engine |
| NTSB | National Transportation Safety Board |
| OMDB | Dubai International Airport |
| O-ring | Primary Black Packing |
| OWS | On-Wing Support |
| P1 | Supply Pressure |

| | |
|---|---|
| PB | Bypass Pressure |
| PF | Pilot Flying |
| PHS | Heated Servo Pressure |
| PM | Pilot Monitoring |
| PN | Part Number |
| PPH | Pounds Per Hour |
| PSEC | Pilot Secondary Fuel Manifold |
| psi | Pound Per Square Inch |
| psid | Pounds Per Square Inch Differential |
| psig | Pounds Per Square Inch Gauge |
| PSO | Pressure Shutoff |
| QRH | Quick Reference Handbook |
| SB | Service Bulletin |
| SBV | Start Bleed Valve |
| SN | Serial Number |
| T/R | Thrust Reverser |
| TRA | Thrust Resolver Angle |
| UPS | United Parcel Service Company |
| UTC | Coordinated Universal Time |
| VBV | Variable Bleed Valve |
| VHF | Very High Frequency |
| VHHH | Hong Kong International Airport |
| VSV | Variable Stator Vane |
| Wf | Metered Flow |
| Wi | Inlet Flow |
| $\Delta P$ | Pressure across the metering valve |

# 8. Table of Figures, Photos, Tables