Air Accident Investigation Unit Ireland

SYNOPTIC REPORT

SERIOUS INCIDENT
Airbus A330-202, EI-LAX
On Take-Off, Dublin Airport
28 December 2017

An Roinn Iompair
Turasóireachta agus Spóirt
Department of Transport,
Tourism and Sport

Foreword

This safety investigation is exclusively of a technical nature and the Final Report reflects the determination of the AAIU regarding the circumstances of this occurrence and its probable causes.

In accordance with the provisions of Annex 13[1] to the Convention on International Civil Aviation, Regulation (EU) No 996/2010[2] and Statutory Instrument No. 460 of 2009[3], safety investigations are in no case concerned with apportioning blame or liability. They are independent of, separate from and without prejudice to any judicial or administrative proceedings to apportion blame or liability. The sole objective of this safety investigation and Final Report is the prevention of accidents and incidents.

Accordingly, it is inappropriate that AAIU Reports should be used to assign fault or blame or determine liability, since neither the safety investigation nor the reporting process has been undertaken for that purpose.

Extracts from this Report may be published providing that the source is acknowledged, the material is accurately reproduced and that it is not used in a derogatory or misleading context.

[1] **Annex 13**: International Civil Aviation Organization (ICAO), Annex 13, Aircraft Accident and Incident Investigation.
[2] **Regulation (EU) No 996/2010** of the European Parliament and of the Council of 20 October 2010 on the investigation and prevention of accidents and incidents in civil aviation.
[3] **Statutory Instrument (SI) No. 460 of 2009**: Air Navigation (Notification and Investigation of Accidents, Serious Incidents and Incidents) Regulations 2009.

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In accordance with Annex 13 to the Convention on International Civil Aviation, Regulation (EU) No 996/2010 and the provisions of SI No. 460 of 2009, the Chief Inspector of Air Accidents on 28 December 2017, appointed John Owens as the Investigator-in-Charge to carry out an Investigation into this Serious Incident and prepare a Report.

Aircraft Type and Registration:	Airbus A330-202, EI-LAX	
No. and Type of Engines:	2 x General Electric (GE) CF6-80E1A4	
Aircraft Serial Number:	269	
Year of Manufacture:	1999	
Date and Time (UTC)[4]:	28 December 2017 @ 15.38 hrs	
Location:	On Take-Off from Dublin Airport	
Type of Operation:	Commercial Air Transport, Scheduled Passenger	
Persons on Board:	Crew - 11	Passengers - 267
Injuries:	Crew - Nil	Passengers - Nil
Nature of Damage:	No. 2 engine 14th stage bleed air spacer failure, resulting in overheat damage to the No. 2 engine compartment and impact damage to the No. 2 engine's main fuel feed line	
Commander's Licence:	Airline Transport Pilot Licence (ATPL), Aeroplanes (A) issued by the Irish Aviation Authority (IAA)	
Commander's Details:	57 years	
Commander's Flying Experience:	19,000 hours, of which 7,200 were on type	
Notification Source:	Shannon Airport Duty Manager	
Information Source:	Field Investigation	

[4] **UTC**: Co-ordinated Universal Time. All timings in this report are quoted in UTC, which was the same as local time on the date of the incident.

SYNOPSIS

Just after take-off from Runway (RWY) 28 at Dublin Airport (EIDW), on a scheduled passenger flight to Los Angeles International Airport (KLAX), the Flight Crew of the Airbus A330 aircraft received a No. 2 (right-hand) engine fire (ENG 2 FIRE) warning, which required the No. 2 engine to be shut down. Following the shutdown, the fire warning ceased. The Flight Crew declared a MAYDAY (state of emergency) to Dublin Air Traffic Control (ATC) and also pressed the AGENT 1 pushbutton, thereby discharging an engine fire extinguisher into the engine compartment.

Following a review of the situation, the Flight Crew elected to proceed to Shannon Airport (EINN), which had a longer runway than those at EIDW. A holding pattern was entered near EINN to consume fuel and lighten the aircraft for landing. After approximately 20 minutes in the hold, an overweight landing was performed on RWY 06. The aircraft was brought to a stop on the runway, and was inspected by the Airport Fire Service (AFS), who advised that there was no apparent damage. The aircraft then taxied to its parking stand, where all passengers disembarked normally. No injuries were reported.

The ENG 2 FIRE warning was subsequently found to have been caused by hot, high pressure bleed air escaping into the No. 2 engine compartment as a result of the fatigue failure of a short section of No. 2 engine's high pressure bleed air ducting.

NOTIFICATION

The Shannon Airport Duty Manager notified the AAIU Inspector-On-Call (IOC) at approximately 16.21 hrs, when the aircraft was in a holding pattern over EINN. The AAIU IOC contacted the aircraft Operator to obtain further details and to request that the aircraft's Cockpit Voice Recorder (CVR) and Digital Flight Data Recorder (DFDR) be preserved once the aircraft had landed. Two AAIU Inspectors travelled to EINN and arrived there at approximately 20.00 hrs to inspect the aircraft and commence an Investigation.

1. FACTUAL INFORMATION

1.1 History of the Flight

A three-person Flight Crew was operating the flight: a Commander (Pilot Monitoring – PM), a Relief Commander (Pilot Flying – PF), and a First Officer. The Commander reported that when the landing gear was being retracted, following a normal take-off from RWY 28 at EIDW, a LAND ASAP[5] message was displayed on the aircraft's Electronic Centralised Aircraft Monitor (ECAM). This was followed by an ENG 2 FIRE warning and an ENG 2 NACELLE TEMPERATURE advisory message[6].

[5] **LAND ASAP:** This message requires flight crews to land as soon as possible at the nearest suitable airport at which a safe approach and landing can be made.
[6] **ENG 2 NACELLE TEMPERATURE:** This message is displayed on the ECAM if the temperature in the engine compartment area exceeds 260^{o} Celsius (C).

The Flight Crew shut down the No. 2 engine as per the ECAM checklist, which caused the ENG 2 FIRE warning to cease. The Commander declared a MAYDAY to Dublin ATC to inform them that the aircraft had "*an engine problem*" and advised that the aircraft was climbing straight ahead. ATC acknowledged the MAYDAY declaration and asked the Commander what his intentions were after climbing straight ahead. The Commander requested ATC to standby. A short while later, ATC advised that all runways at Dublin were available. The Commander, who subsequently reported that the Flight Crew were aware from their pre-flight calculations and briefing that they were "*unable to land back at Dublin*" and had pre-planned to divert to EINN if required, advised ATC that they were "*going to continue climbing straight ahead to 3,000 feet* [ft]" and that most likely they would be *"diverting to Shannon due runway requirements*".

Dublin ATC informed the Commander that smoke had been seen coming from the aircraft – possibly from its left-hand side. The Commander replied to ATC that it was actually the No. 2 (right-hand) engine that had a "*failure*" and had been shut down. ATC replied stating that "*there is smoke visible from the aircraft*". With ATC's permission, a climb to 3,000 ft was commenced.

The Commander stated that the Flight Crew reviewed the occurrence and concluded that the situation was stable and updated the Cabin Manager using the aircraft's interphone. The Commander reported that a short time later, the Flight Crew became concerned that they had [what appeared to be] an engine fire, but that they had not pushed the ENG 2 FIRE pushbutton, nor had they discharged an engine fire extinguisher. The Flight Crew reviewed the procedure that had been followed and concluded that the ECAM had not called for these actions. The Commander said that the engine parameters were reviewed and it was noted that all were as expected from a shutdown engine, but that as a precaution he pushed the ENG 2 FIRE pushbutton (see **Section 1.5.6** for system details). This action was completed at 15.46 hrs. The AGENT 1 pushbutton was also pressed, which discharged a fire extinguisher into the No. 2 engine compartment.

The Commander stated that the Cabin Manager was requested to come to the flight deck, where she was given a NITS briefing[7] regarding the diversion to EINN and was advised that the flight would take approximately 35 minutes. The Commander reported that the Cabin Manager was informed that a normal landing was planned, but that as a precaution an emergency briefing was to be given to the passengers. The Commander stated that he then made a PA[8] to the passengers to explain the situation. The Flight Crew also declared a MAYDAY to Shannon Approach (ATC), advising that they had "*an engine failure on number two*" and had received "*indications of a fire*", but that there were "*no signs of fire now*". The AFS was requested to attend on landing as a precaution. Shannon Approach confirmed that the AFS would be present. The Flight Crew advised Shannon Approach that it was intended to land on RWY 06, but that they would like to "*burn off some fuel beforehand*" and therefore requested to enter a holding pattern at 4,000 ft. When closer to the holding area, the Flight Crew requested permission to descend to 3,000 ft to enter the hold. This was granted by Shannon Approach, who, a short while later, informed the Flight Crew that "*the tower observed no smoke coming out of that engine at all*".

[7] **NITS Briefing**: An emergency briefing given by the Flight Crew to the Cabin Crew. N: Nature of the situation, I: Intentions of the Commander, T: Time remaining to landing, S: Special Instructions, if any.
[8] **PA:** Public Address.

The Commander stated that when the aircraft was overhead EINN, they were advised that the runway was wet. The Flight Crew reviewed the aircraft's performance calculations and concluded that they would need to "*burn-off*" 4,000 kg of fuel. The Commander noted that the aircraft's landing gear had been extended while en route to EINN to increase the aircraft's fuel consumption, but that for speed management reasons while in the hold, the landing gear was retracted and the aircraft's flaps were extended. The aircraft remained in the hold for approximately 20 minutes. Before leaving it, the Flight Crew sought an update from Shannon Approach regarding runway surface wind and conditions. Shannon Approach advised that the surface wind was "*one three zero degrees eleven knots*" and that the runway surface "*appears to be damp*". An approach to RWY 06 was commenced. When the aircraft was established on the approach, Shannon Tower ATC advised that the runway surface was "*wet*" and that the braking action was "*good*".

The Commander reported that the Flight Crew performed the checklist items for an overweight landing and that the Cabin Manager was updated on the situation. The Commander stated that he took over as PF for the landing, which was carried out manually (with the autopilot and auto-thrust selected to off). The aircraft landed at 16.37 hrs. The Commander stated that the aircraft was brought to a stop approximately halfway along the runway and that a PA was made to advise the passengers to remain seated and the Cabin Crew to remain at their stations. Contact was made with the AFS to request an inspection of the aircraft and to advise that it was the Flight Crew's intention to keep the No. 1 engine running during the inspection. AFS advised the Flight Crew that there was no apparent damage and the aircraft was taxied to its parking stand, where the passengers disembarked normally.

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1.2 Injuries to Persons

No injuries were reported to the Investigation.

1.3 Personnel Information

1.3.1 Aircraft Commander (PM)

Age:	57 years
Licence:	ATPL, issued by the IAA
Total all Types:	19,000 hours
Total on Type:	7,200 hours

1.3.2 Relief Commander (PF)

Age:	46 years
Licence:	ATPL, issued by the IAA
Total all Types:	13,300 hours
Total on Type:	3,000 hours

1.3.3 First Officer

Age:	43 years
Licence:	ATPL, issued by the IAA
Total all Types:	11,780 hours
Total on Type:	2,415 hours

1.4 Airport Information

There are two runways at EIDW: RWY 10/28, which is 2,637 metres (m) long and RWY 16/34, which is 2,072 m long. EINN is located approximately 105 Nautical Miles (NM) to the south-west of EIDW and has one runway: 06/24, which is 3,199 m long.

1.5 Aircraft Information

1.5.1 General

EI-LAX, an Airbus A330-202, was manufactured in 1999 and was fitted with two GE CF6-80E1A4 engines. Its most recent Certificate of Airworthiness was issued by the IAA on 12 May 2008. The Airworthiness Review Certificate (ARC) in force at the time of the occurrence was issued on 13 June 2017 and was valid until 18 June 2018. The aircraft had operated for 82,228 hours and 14,374 flight cycles[9] from the date of manufacture until the occurrence date.

The Airbus A330-202 aircraft type is type-certified by EASA for ETOPS[10] operations beyond 180 minutes. According to EASA, in order to maintain a level of safety consistent with the overall safety level achieved by modern aircraft, it is necessary for two-engine aircraft used in extended range operations to have an acceptably low risk of significant loss of power/thrust for all design and operation-related causes.

1.5.2 Aircraft Maintenance History

The most recent scheduled maintenance inspection performed on the aircraft (not including its daily inspection), was a "*Weekly Check*" (now known as an 8-day check), which was carried out on 22 December 2017. Detailed inspections of the aircraft's engines are not required to be performed during scheduled Weekly/8-day checks or routine daily inspections.

1.5.3 Engine Bleed Air System

The aircraft's engines and/or the Auxiliary Power Unit (APU) supply bleed air to various aircraft systems. Engine bleed air is extracted through a system of valves, manifolds, and ducts from two of the 14 stages of each engine's compressor section: the Intermediate Pressure (IP) (8^{th} stage) and the High Pressure (HP) (14^{th} stage). According to the Engine Manufacturer, HP bleed air may reach a temperature of 646^{o} C and a pressure of 496 PSI[11] at take-off power (approximate values).

The following applies to each engine: The engine has three 14^{th} stage bleed air outlet ports (lower, middle and upper) located on its right-hand side (aft, looking forward) (**Figure No. 1**). A manifold is connected to the three ports. A straight section of steel ducting, described in the Engine Manufacturer's Illustrated Parts Catalogue (IPC) as a "*Spacer – Flow Bleed Bias*" and hereafter referred to as a "*spacer*", is fitted between the upper port and the 14^{th} stage manifold.

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[9] **Flight Cycle:** A flight cycle is one take-off and landing.

[10] **ETOPS:** Extended Twin-Engine Operation permits operation during which a portion of a flight is conducted beyond 60 minutes from an adequate airport for turbine-engine-powered aircraft with two engines.

[11] **PSI/PSIG:** Pounds per Square Inch/Pounds per Square Inch Gauge – Units of pressure.

According to the Engine Manufacturer, the spacer is "*not a tracked or life limited part*". The spacer incorporates a flange at each end to allow it to be clamped to the engine and 14th stage manifold. The flange at the engine side of the spacer is recessed to permit the installation of a sealing gasket (**Photo No. 1**). The manifold side of the spacer is not recessed (**Photo No. 2**), as the gasket for this joint is fitted into a recess in the manifold. Gaskets are also fitted between the manifold and the middle and lower bleed ports. The joints are secured by steel couplings (clamps), consisting of two halves joined at a dual hinge point on one side, and a bolt (known as a T-bolt) and self-locking nut on the other side.

The HP bleed valve is connected to the outlet of the 14th stage manifold. A Tolerance Take-Up Unit (TTU) provides an adjustable interface between the HP bleed valve and an intersect duct. A Pressure Regulating and Shut-Off Valve (PRSOV) is fitted between the intersect duct and the interface duct. An IP check valve is connected between the intersect duct and the 8th stage manifold. The interface duct connects the engine bleed air system to the engine pylon.

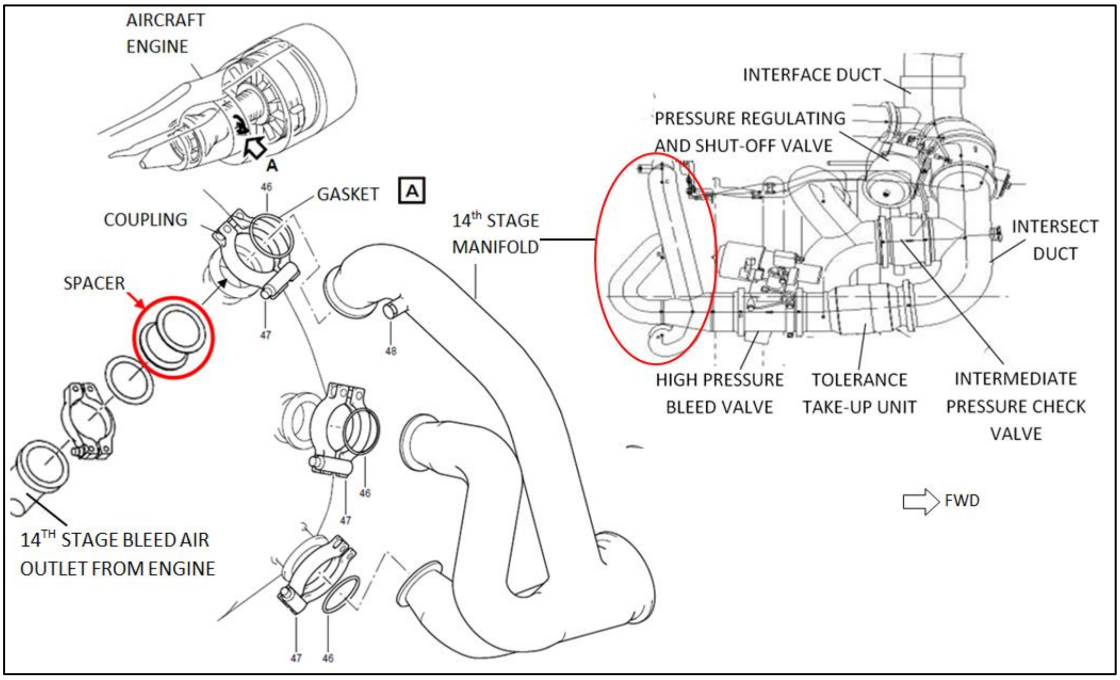


Figure No. 1: Location of 14th stage manifold and other bleed air system components

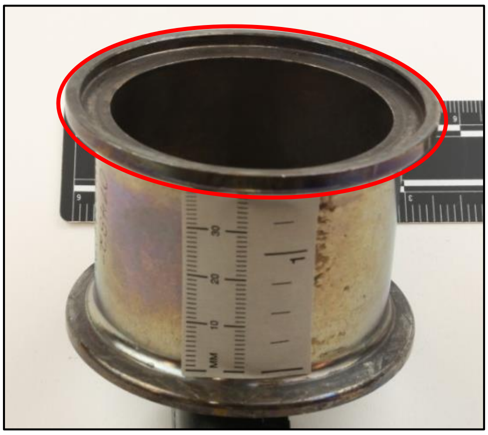


Photo No. 1: Recessed flange on engine side of spacer (circled)

Photo No. 2: Non-recessed flange on manifold side of spacer (circled)

1.5.4 Engine Fuel Supply

The following applies to each engine: The main fuel inlet line is routed circumferentially around the right-hand side of the engine (aft, looking forward), from a connection in the engine pylon, to the fuel pump inlet on the lower part of the engine (**Figure No. 2**). The fuel line is made up of solid and flexible sections. Each flexible section consists of a hose, supported internally by a metal coil and covered externally by a woven wire braid, which is in turn covered by a layer of silicone rubber. Part of the fuel line is located within close proximity to the 14th stage manifold.

The pressure of fuel in the line is approximately 45 PSI. According to the manufacturer of the fuel line, it is capable of operating at pressures of up to 250 PSI. At take-off power, fuel flow through this fuel line is approximately 3.2 kg per second (11,520 kg per hour).

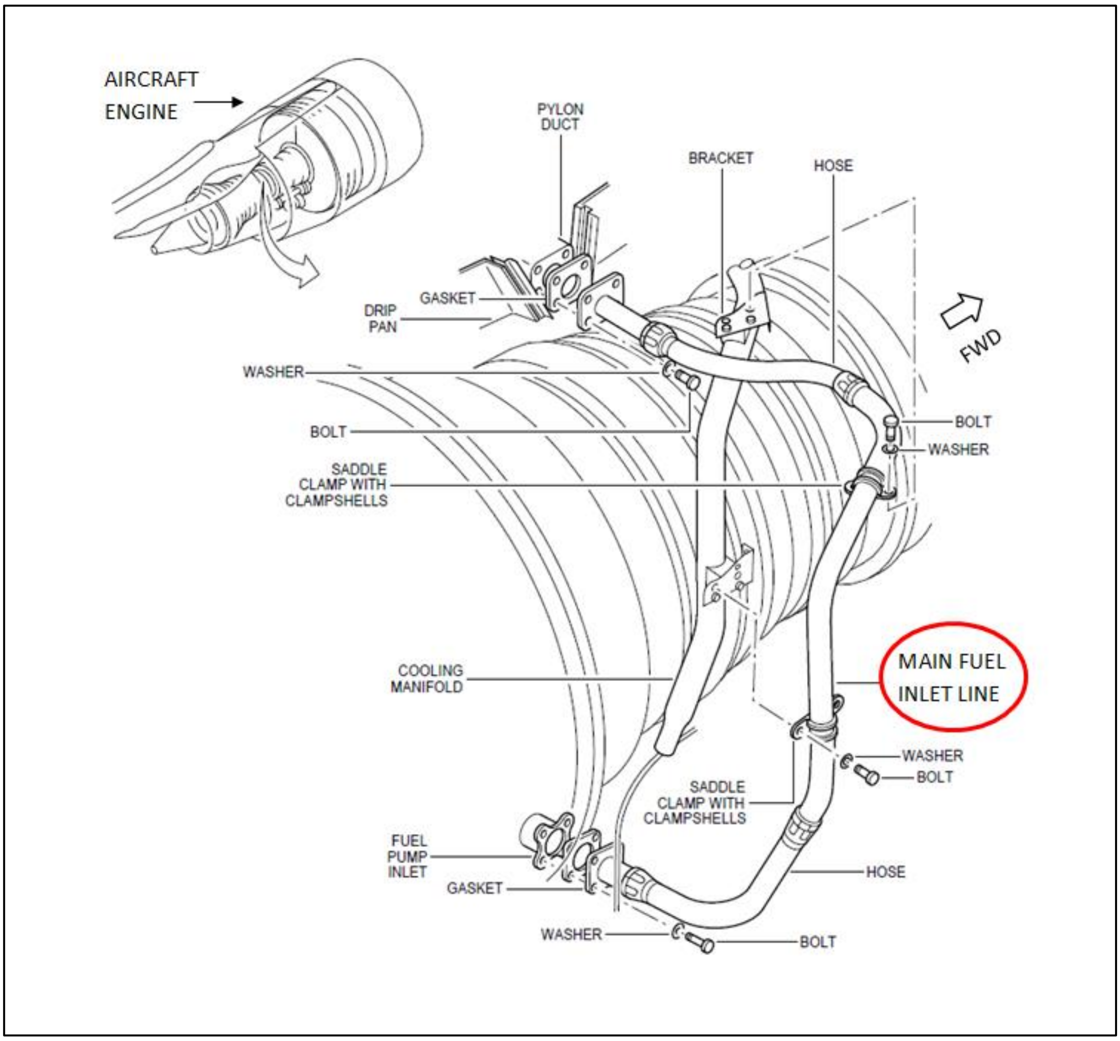


Figure No. 2: Location of main fuel inlet hose assembly (adapted from the Aircraft Manufacturer's Aircraft Maintenance Manual (AMM) 73-11-00)

1.5.5 Engine Maintenance History

The CF6-80E1 engine type went into service in January 1994. The subject engine (S/N 811116) was manufactured in October 1994 and at the time of the occurrence had operated for 77,587 hours and 15,205 flight cycles since manufacture. According to the Engine Manufacturer, these total operating hours and flight cycles are not unusual for an engine of this age.

The engine underwent maintenance at an approved engine overhaul facility from 17 April 2017 to 4 August 2017 and was fitted to the No. 2 position (right-hand) on EI-LAX on 8 November 2017. The engine had operated for 754 flight hours and 87 flight cycles since installation. A task card within the work pack associated with the work carried out during the shop visit, records that the bleed "*tubes*" were removed from the engine and visually inspected in accordance with the Engine Manufacturer's Engine Manual requirements at the time. The 14^{th} stage bleed air outlet spacer (Part Number 1440M41P01) is specifically mentioned in the parts list attached to the task card.

According to the engine overhaul facility, the task card '*INSTALL R/H DELTA AIR TUBE*' (Engine Manual Section 72-00-00-430-238) within the work pack relates to the refitting of the spacer to the 14^{th} stage bleed air outlet. However, the installation instructions for the spacer are actually contained within a separate sub task of the Engine Manual – '*Install the flow spacer*' (72-00-00-430-239). The '*Install the flow spacer*' subtask instructs to "*put the clamp* [coupling] *with the T-bolt down and the nut aft*". The procedure does not specify that a new coupling should be used. Following the occurrence, the Investigation noted that the coupling had been installed with the T-bolt forward and the nut up (**Section 1.6**, **Photo No. 3**). The Investigation brought this to the attention of the engine overhaul facility. The facility acknowledged that the direction of clamp was not in accordance with the Engine Manual requirements and advised that it is a requirement of the associated task card to be "*double checked by QC* [Quality Control] *after installation*". The Engine Manufacturer was asked what the adverse effects of incorrect orientation of the clamp would be. The Engine Manufacturer replied that the orientation requirements were to provide "*best wrench access during installation and removal*" and that "*there is no adverse impact to the hardware as a result of a rotated clamp*".

The '*INSTALL R/H DELTA AIR TUBE*' task card, which the engine overhaul facility deemed to refer to the installation of the spacer, contains a specific section to record the reference number of the torque wrench[12] used during the task. However, the Investigation established that the torque wrench referenced was in the calibration shop when the task was being performed. The engine overhaul facility identified three other torque wrenches that could have been used for the task; the Investigation reviewed the calibration reports for each of these torque wrenches, which indicated that the torque wrenches were correctly calibrated.

The task card associated with the installation of the 14^{th} stage manifold, which attaches to the other side of the spacer, refers to the Engine Manual requirement to "*use new couplings* [clamps]" when installing the manifold. Three couplings are required to install the 14^{th} stage manifold and one is required to install the spacer to the engine. A parts '*Issue Document*' provided to the Investigation by the engine overhaul facility indicates that four new couplings (clamps) were ordered while the engine was in the workshop.

[12] **Torque Wrench:** A tool used to apply a specific torque to a fastener such as a nut or bolt.

The task card for the installation of the 14th stage manifold also contains instructions (with reference to the Engine Manual) regarding the correct alignment of the manifold during the installation procedure and the correct torque to be applied when tightening the couplings. The referenced Engine Manual section (71-00-02, dated 15 March 2017) instructs technicians to fit the manifold to the lower bleed port and to tighten its coupling sufficiently to hold the manifold in position and then check the clearance and offset at the two other ports (**Figure No. 3**). The Engine Manual states that the maximum permitted clearance at the centre and upper ports is "*0.020 inch (0.50 mm)*" and the maximum permitted alignment offset is "*0.060 inch (1.52 mm)".* The task card includes a specific section to record these measurements following installation. The clearance is recorded as "*0.008"* [inch]. The offset is recorded by what appears to be 0.025 inch (i.e. within Engine Manual limits).

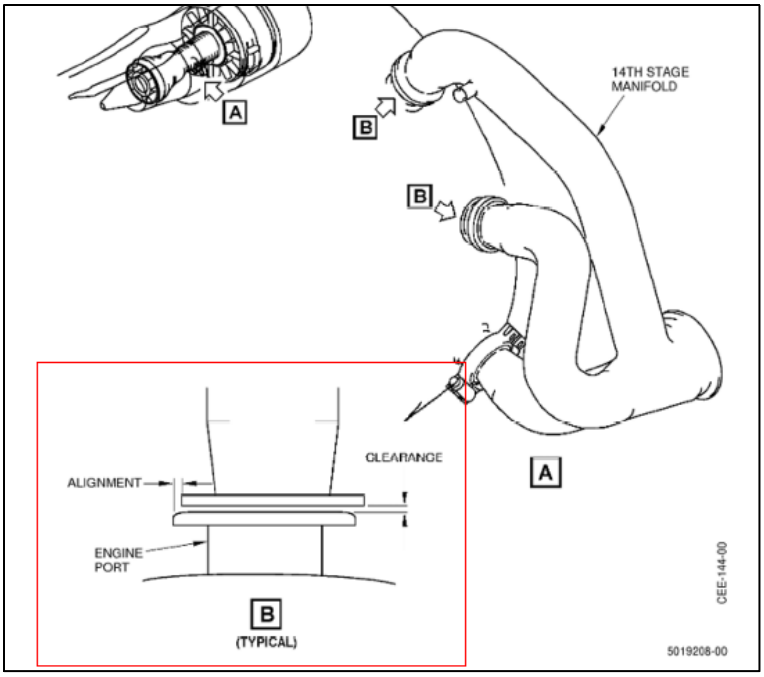


Figure No. 3: Manifold installation instructions regarding clearance and alignment

The next step in the Engine Manual describes the procedure for torqueing (tightening) the three couplings. The following caution is included:

> *"MAKE SURE THAT YOU TORQUE THE COUPLINGS IN BOTTOM-TO-TOP ORDER OR THE MANIFOLD CAN BECOME MISALIGNED".*

The Engine Manual procedure describes the torqueing of the coupling nut, followed by tapping the coupling with a fibre mallet before re-torqueing and then repeating this operation. These instructions are also contained on the task card. However, the task card did not include the Engine Manual caution, to tighten the couplings in "*BOTTOM-TO-TOP ORDER*". Since the occurrence, the engine overhaul facility has revised the task card, to include this caution.

The use of a fibre mallet was not referred to in the '*Install the flow spacer*' subtask of the Engine Manual (72-00-00-430-239) in use when the spacer was installed. Since the occurrence, this subtask now refers to '*V-Coupling Assembly Techniques*' as contained in the Engine Standard Practices Manual. This referenced section describes the correct process to follow, which includes tapping the coupling with a fibre mallet during the torqueing process.

Following an engine shop visit, an engine may be shipped with some ancillary components missing, which must then be fitted during engine installation. A '*SHOP IN/OUT'* list is used by the engine overhaul facility to record components that were found installed when the engine arrived in the shop (SHOP-IN) and whether or not a component was present when the engine left the shop (SHOP-OUT). The list forms part of the post-shop report that accompanies the engine when it leaves the shop. In the case of the subject engine, the '*SHOP IN/OUT'* list identified that two bleed air system components – the PRSOV and the interface duct – were not installed. In addition, the engine overhaul facility reported that a placard was fitted to the TTU to identify that it was "*LOOSE*" and therefore required adjustment at engine installation when all valves and air ducts were installed and secure. This was not referred to in the post-shop report. The engine overhaul facility provided a photograph to the Investigation showing the placard installed on the engine.

The Operator's engine change workpack, which documents the installation of the subject engine, indicates that the IP check valve fitted to the engine was defective and was replaced during the engine change. The associated workorder refers to the Aircraft Maintenance Manual (AMM) installation procedure used. The procedure requires the TTU to be adjusted as part of the task. AMM subtask 36-11-49-420-066-A relates to the installation/adjustment procedure for the TTU. The following caution is included:

> "*DO NOT EXTEND THE TOLERANCE TAKE-UP UNIT BEYOND CONTINUOUS FLANGE CONTACT WITH THE HP BLEED VALVE. TOO MUCH LOAD CAN CAUSE DAMAGE TO THE BLEED AIR SYSTEM COMPONENTS*".

The Investigation asked the Engine Manufacturer to give an opinion on whether or not an over-extended TTU could result in overloading the spacer. The Engine Manufacturer stated that "*since the 14th stage, 8th stage, and Intersect ducts are very stiff*", they would not expect adjustments of the TTU to "*adversely impact loading to the spacer*".

1.5.6 Engine Fire Detection and Protection

When a No. 2 (1)[13] engine fire warning signal is triggered by the engine's Fire Detector Unit (FDU), the following cockpit alerts are generated (the engine fire warning is inhibited between V1[14] and take-off (all landing gears in the air) +15 seconds):

- Continuous repetitive chime.
- MASTER WARNing[15] light.
- ENGine/FIRE/FAULT annunciation on the aircraft's ECAM system and the displaying of the ENG 2 (1) checklist.
- Illumination of the ENG 2 (1) FIRE PUSH button on the No. 2 (1) engine fire panel located on the overhead panel in the cockpit.
- Illumination of the FIRE warning on the FIRE/FAULT annunciator located below the two-position (ON/OFF) ENG 2 (1) master switch on the engine master panel located on the pedestal between the Pilots' seats.

[13] **2 (1):** This numbering convention is used to indicate that the description also refers to the No. 1 engine.
[14] **V1:** Take-off decision speed – the speed above which a take-off will continue even if an engine fails.
[15] The capital letters indicate how the warning/component identification actually appears in the aircraft. Lower case letters are added to aid clarity.

Selecting the ENG 2 (1) master switch to OFF shuts down the No. 2 (1) engine by closing both the No. 2 (1) high pressure fuel valve, which controls fuel flow from the No. 2 (1) engine's Hydro-Mechanical fuel control Unit (HMU) and the No. 2 (1) low pressure fuel valve, which controls fuel flow from the relevant fuel tank. When the ENG 2 (1) FIRE PUSH button is released out, the continuous repetitive chime is cancelled, the MASTER CAUTion illuminates, and an associated single chime is generated, due to the deactivation of other systems associated with the engine that was shut down. In addition, closure of No. 2 (1) low pressure fuel valve is confirmed and the SQUIB[16] lights illuminate on the AGENT pushbuttons fitted to the No. 2 (1) engine fire panel, to indicate that the AGENT 1 and AGENT 2 pushbuttons can be used. Each engine is fitted with two fire bottles. Pressing an AGENT pushbutton discharges its associated fire bottle into the No. 2 (1) engine compartment. When the fire is extinguished, the ENG 2 (1) FIRE PUSH button light, the MASTER WARNing light, and the FIRE indication on the ENGINE MASTER panel no longer illuminate.

1.5.7 Flight Recorders

The aircraft type is fitted with a CVR and a DFDR. The subject aircraft was also fitted with a Quick Access Recorder (QAR), which permits easy access to flight data for maintenance and fleet monitoring purposes. The DFDR is capable of recording up to 25 hours of data, while the CVR records the most-recent two hours of cockpit voice recordings. The CVR system includes a CVR control unit, which controls its operational logic.

The CVR records when any of the following conditions are met:

- During the first five minutes of the aircraft's electrical system being energised, when the aircraft is on the ground.
- At least one engine running, when the aircraft is on the ground.
- Up to five minutes after the last engine is stopped, when the aircraft is on the ground.
- When the aircraft is in flight.
- When the aircraft is powered and the CVR CTL (control unit) CB is pulled.

The recorder systems are fitted with Circuit Breakers (CBs) to protect against electrical failures and to allow systems to be isolated when required. The CBs are located in the avionics compartment below the forward cabin/cockpit floor. Following notification of an occurrence involving a flight recorder-equipped aircraft, the AAIU routinely requests that the recorders are preserved by the operator. This is normally achieved by pulling the relevant CBs.

AMM task 23-71-00-040-801-A contains the deactivation procedure for the CVR. The procedure requires the CVR or CVR DC SPLY CB to be pulled, depending on the aircraft's serial number. AMM task 31-33-00-040-801-A contains the deactivation procedures for the DFDR. This procedure requires the FDIU/DFDR CB to be pulled.

AMM Task 23-71-35-000-801-A contains the removal procedure for the CVR and requires two CBs to be pulled: CVR CTL [control] and CVR. The removal procedure for the DFDR is contained in AMM 31-33-55-000-801-A. This procedure also requires two CBs to be pulled: the CVR CTL CB and the FDIU/DFDR CB. The removal procedure does not warn that pulling the CVR CTL CB may result in inadvertent CVR operation.

[16] **Squib**: A small pyrotechnic device used to release the agent from a fire extinguisher.

1.6 Damage to Aircraft

The AAIU inspected the aircraft at EINN. The spacer, which links the upper port of the No. 2 engine's 14^{th} stage bleed air outlet to the 14^{th} stage bleed manifold, was found to be fractured at the recessed flange close to the clamp which secured the spacer to the bleed air outlet (**Photo No. 3**). This resulted in the engine compartment being exposed to high temperature (646^{o} C)/high pressure (496 PSI) bleed air from the No. 2 engine's 14^{th} stage bleed air outlet, which caused heat damage to adjacent wiring looms.

The flange and coupling remained attached to the engine's 14^{th} stage bleed air outlet. However, the 14^{th} stage manifold buckled, resulting in the coupling, which secured the other (main) portion of the fractured spacer to the manifold, becoming partially embedded in a flexible section of the engine's main fuel feed line (**Photo No. 4** and **Photo No. 5**). This caused damage to the fuel line (**Photo No. 6** below and **Section 1.7.8**); however, the fuel line did not rupture and there was no fuel leak. Impact and heat damage to the engine cowlings were also evident. The pressure relief door on the right-hand aft engine cowling was found in the open position.

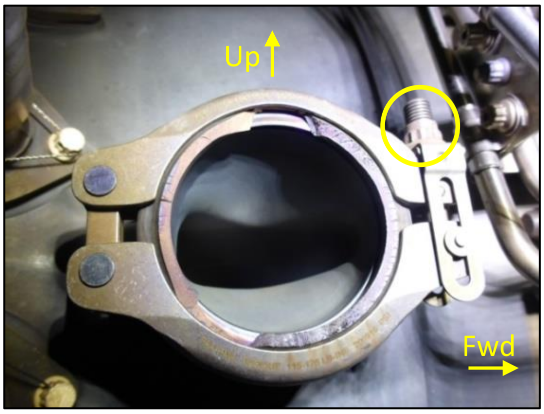


Photo No. 3: Fractured spacer flange at coupling which secured spacer to 14^{th} stage bleed air outlet (self-locking nut circled)

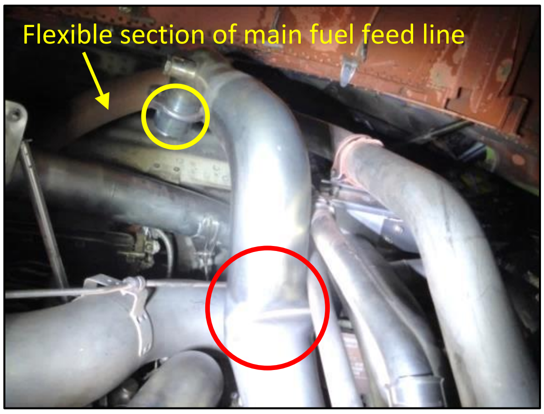


Photo No. 4: Looking up at buckled 14^{th} stage bleed manifold (circled in red). Main portion of fractured spacer (circled in yellow). Fuel line also highlighted

Photo No. 5: Coupling securing main portion of fractured spacer to the manifold partially embedded in flexible section of main fuel feed line

Photo No. 6: Damage to flexible section of main fuel feed line

The Engine Manufacturer informed the Investigation that the event was the first separation of this spacer "*in the history of the 80E1 and 80C2 engine programs (over 255 million engine flight hours, 58.5 million engine flight cycles). The part is common to both engine models*".

1.7 Component Examination

1.7.1 Visual Examination of Fractured Spacer

The AAIU requested the removal of the damaged spacer and other components to facilitate further examination. The self-locking nut on the coupling, which secured the spacer to the bleed air outlet (**Photo No. 3**) was found not to be loose, and once the self-locking nut was loosened by maintenance personnel to release the coupling latch, percussion was required to remove the coupling itself.

The Investigation examined the minimum and maximum dimensions of the outside diameter of the flange of the fractured spacer to determine if any distortion (out-of-roundness) was evident (**Photo No. 7** and **Photo No. 8**). The maximum out-of-roundness was found to be 0.25 mm (72.11 mm - 71.86 mm). The out-of-roundness of the flange of an exemplar spacer was also evaluated (**Photo No. 9** and **Photo No. 10**). The maximum value was 0.19 mm (72.43 mm - 72.24 mm). The Engine Manufacturer's component specifications did not contain a tolerance for out-of-roundness. However, the specifications included a manufacturing tolerance for the spacer's outside diameter of +/- 0.010 inch (0.25 mm) and a maximum "*run-out*" between one diameter and another diameter concentric to the same axis of 0.005 inch (0.127 mm).

Photo No. 7: Maximum diameter of fractured spacer flange (72.11 mm)

Photo No. 8: Minimum diameter of fractured spacer flange (71.86 mm)

Photo No. 9: Maximum diameter of exemplar spacer flange (72.43 mm)

Photo No. 10: Minimum diameter of exemplar spacer flange (72.24 mm)

1.7.2 Metallurgical Examination of Fractured Spacer and Retention Coupling

With the assistance of the National Transportation Safety Board (NTSB) of the United States (representing the State of design and manufacture of the engine), the Investigation sent the fractured spacer to the Engine Manufacturer for detailed metallurgical examination (**Photo No. 11** and **Photo No. 12**).

Photo No. 11: Fractured Spacer (*GE*)

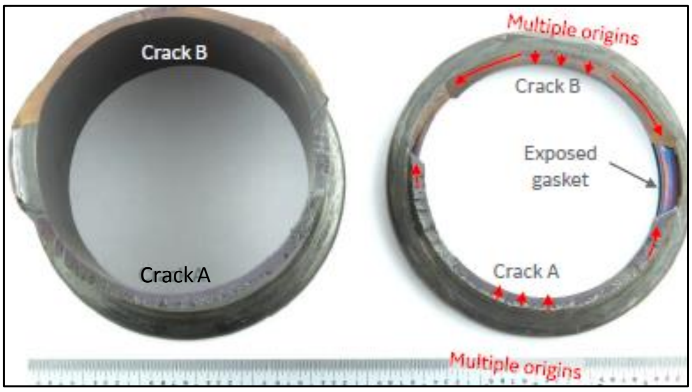


Photo No. 12: Fractured Spacer – location of main cracks: Crack A and Crack B (*GE*)

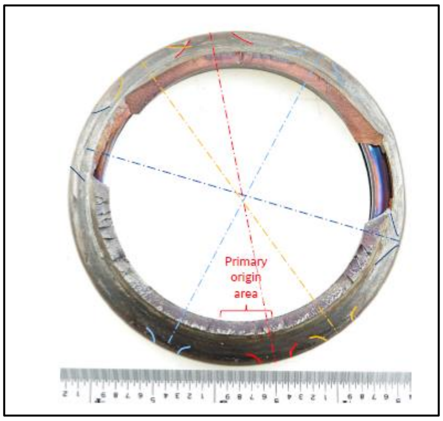
The subsequent examination identified two main cracks (A and B in **Photo No. 12**). Metallurgical analysis of Crack A identified fatigue striations[17] with a striation density of between 27,000 and 100,000 striations per inch, which the associated report deemed to be consistent with high alternating stress, High Amplitude Fatigue (HAF) crack propagation.

Analysis of Crack B revealed features consistent with lower alternating stress, High Cycle Fatigue (HCF[18]) crack propagation. The metallurgical analysis report deemed Crack A to be the primary origin of the failure. The report summarised that:

> "*The fracture initiated from multiple origins on the outer diameter surface with features consistent with high alternating stress, high amplitude fatigue (HAF), and propagated in reverse bending HAF and low alternating stress, high cycle fatigue (HCF). There was no observed material anomalies or corrosion at the primary crack origin area. The material microstructure, hardness and chemistry were consistent with* [drawing] *requirements*".

The examination found indentations on the surface of the broken flange at eight locations, which the Engine Manufacturer attributed to be due to where the spacer retention coupling had been tightened onto the spacer at four separate locations (indicated by the coloured dashed lines in **Photo No. 13**). The position of the coupling at the time of the event is shown in **Photo No. 3** in **Section 1.6**. The metallurgical examination noted that the indentation of the flange due to the coupling impression at this clamping position (dashed red line in **Photo No. 13**), was approximately 4.9 thousandths of an inch deep (0.124 mm). Crack A, which was found to have multiples origins, was located close to where the coupling latch was situated (**Photo No. 14**).

[17] **Striations:** Striations are marks that are found on a material, which has failed due to fatigue. Each striation is usually indicative of a fatigue cycle that propagated the fatigue crack further through the base material.
[18] **HCF:** High Cycle Fatigue – material failure that occurs under the influence of repeated, cyclic tensile stresses, which are normally well below the yield stress of the material.



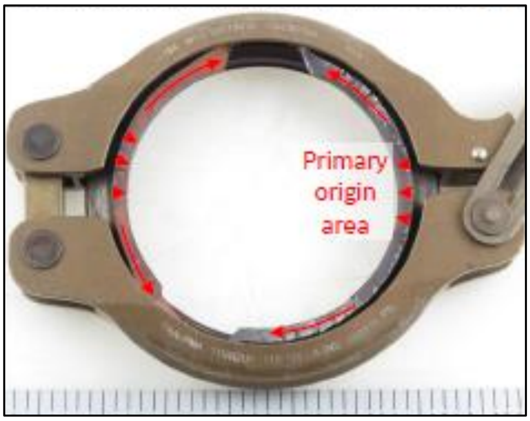


Photo No. 13: Indentations on flange attributed to be due to locations where coupling had been previously tightened onto the spacer (indicated by the coloured dashed lines) (*GE*)

Photo No. 14: Location of primary origin of failure adjacent to where coupling latch was located (*GE*)

Metallurgical analysis of Crack A also identified local discolouration below the fracture surface, consistent with bleed air leakage (**Photo No. 15**).

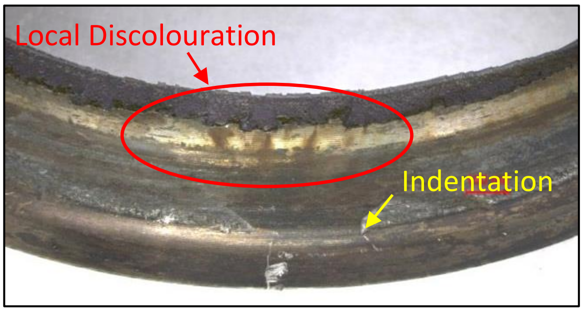


Photo No. 15: Local discolouration and indentation on flange adjacent to Crack A (*GE*)

The spacer-retention coupling was also examined by the Engine Manufacturer. "*Witness marks*"[19] were found on the spacer side of the coupling mating surface. A longitudinal cross-section through the coupling bolt determined that the material's microstructure was consistent with the material specification. No cracks were observed within the thread roots.

1.7.3 Engine Manufacturer's Examination of Exemplar Components

For comparison purposes, the Engine Manufacturer also examined three exemplar (field-returned) spacers, gaskets and clamps. The examination report noted that the field-returned gaskets had similar dimensions and discolouration to the gasket removed from EI-LAX. The returned spacers showed flange deformation up to "*approximately 2.8 mils* [thousandths of an inch]" (0.071 mm). Examination of one of the returned spacers identified "*local discolored regions consistent with surface corrosion and pitting*[20]", but that no cracking was found. It was also noted that the returned couplings had less wear on their inside surfaces adjacent to the hinge and connection points than that found on the event coupling, but the Manufacturer could not determine if this difference was primary or secondary to the event.

[19] **Witness marks:** In this case, the term refers to evidence of contact.

[20] **Pitting:** A form of localised corrosion, which can result in cavities or holes in the material.

1.7.4 Independent Metallurgist's Assessment

To further analyse the failure, the Investigation sought an opinion from an independent metallurgist, based on the details contained in the Engine Manufacturer's report. The following information is extracted from the independent metallurgist's observations and analysis:

> *"The spacer failed in reversed bending fatigue. This is indicated by the fact that there are two fatigue cracks* […]*, which initiated at diametrically opposite locations on the OD* [Outside Diameter] *and propagated in opposite directions to each other. There were no pre-existing material defects associated with fatigue crack initiation.*
>
> *There were depressions in the flange of the spacer, caused by the clamp* [coupling]. *However, the fatigue cracks appear to have initiated on a plane which was remote from them*. […] *it is most likely that the depressions were the result of fretting*[21] *wear between the clamp* [coupling] *and the flange, rather than being static indentations, caused by over-tightening of the clamp* [coupling] *on assembly. If that is the case, then it would follow that the indentations were probably a secondary result of the cyclic reversed bending loads, rather than being a primary cause of fracture.*
>
> *Having eliminated pre-existing material defects and/or mechanical damage, we would arrive at abnormal loading conditions as the most likely cause of the failure. The respective descriptions of Cracks A and B* […] *provides information about the loading conditions under which they initiated and grew, as follows:*
>
> *Crack A – '….consistent with high alternating stress, high amplitude fatigue crack propagation'. This suggests a cyclic stress range of relatively high magnitude, in the direction of bending which caused Crack A.*
>
> *Crack B – '....consistent with lower alternating stress, high cycle fatigue crack propagation'. This suggests a cyclic stress range of lower magnitude, in the direction of bending which caused Crack B.*
>
> *From the above, we can infer conditions of cyclic reversed bending, where the magnitude of the bending stress range was not equal in both directions. The stresses in the bending direction which caused Crack A were greater than those in the bending direction which caused Crack B. Consequently, Crack A probably initiated first and grew faster than Crack B. This is supported by the local discolouration* […]*, on the OD just below the plane of Crack A. It is likely that Crack A had penetrated through the wall thickness some time before the spacer finally separated and the discolouration was caused by air leakage during subsequent engine running.*

[21] **Fretting:** A wear process that occurs at the contact area between two materials under load, which are subject to minute relative motion due to vibration or some other force.

The independent metallurgist summarised by stating:

1. *The spacer failed in reversed bending fatigue.*

2. *There were no pre-existing material defects or mechanical damage, at the sites of crack initiation. By elimination,* ***this suggests abnormal loading conditions as the most likely cause of the fatigue cracking*** [emphasis added].

3. *The magnitude of the cyclic bending stresses was unequal in the two directions of bending. They were greater in the direction of Crack A than they were in the direction of Crack B. This could be explained by* ***the presence of a static bending stress*** *in the direction of Crack A, upon which the cyclic, reversed bending stresses were superimposed* [emphasis added].

The Investigation also sought the independent metallurgist's opinion regarding the depressions found on the failed spacer and whether or not they formed stress-raisers which contributed to the failure. The Investigation highlighted that such depressions were also found on the exemplar spacers inspected by the Engine Manufacturer. In response, the metallurgist stated the following:

> *"It is quite possible that a correctly tightened clamp could cause such fretting wear depressions* [indentations]. *Fretting occurs in nominally stationary joints, due to very small amplitude reciprocal movement between the surfaces. Vibration loads may be enough to cause fretting* […]. *If the depressions had participated in crack initiation, by acting as points of stress concentration, then it would be expected that the cracks would have initiated at the depressions themselves. However,* [the cracks] *actually initiated some distance away from the depressions. Therefore, I don't think that the depressions were directly responsible for the cracking* […]. *I note that on the incident spacer, the depth of the depressions was 4.9* [thousandths of an inch]. *On three example spacers, not involved in the incident* [**Section 1.7.5** below]*, the maximum depth of the depressions was 2.8* [thousandths of an inch]. *The fact that the depressions were so much deeper on the incident spacer is probably an indication that the loading on this spacer was abnormally high".*

The Investigation shared the observations of the independent metallurgist with the Engine Manufacturer. The Engine Manufacturer agreed that the observations could support the scenario proposed by the metallurgist.

1.7.5 Spacer Examination Performed on behalf of the Operator

The Operator sent three spacers that were removed from engines within its fleet to an Approved Maintenance/Repair Organisation (MRO) for Non-Destructive Testing[22] (NDT). The MRO performed a Fluorescent Dye Penetrant Inspection[23] (FPI), in addition to visual examination.

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[22] **Non-Destructive Testing (NDT):** A range of examination techniques used to analyse a material, component or system without causing damage.

[23] **Fluorescent Dye Penetrant Inspection:** A type of NDT. The process involves cleaning the part to be examined, before it is coated with a fluorescent penetrant. Following a '*dwell*' period, the excess penetrant is removed, the component is dried and a '*developer*' is applied. If defects are present, the developer causes the penetrant within the defect to be drawn to the surface and become visible with the aid of an ultraviolet light source.

No cracking was evident on any of the three spacers examined. However, indentation damage, similar to that identified by the Engine Manufacturer was found on both flanges of each of the three spacers examined. In addition, pitting, 3 mm in length, was found on one of the spacers, adjacent to one of its flanges.

1.7.6 Spacer Examination Performed by Engine Overhaul Facility

Subsequent to the occurrence, the engine overhaul facility performed an FPI inspection on two spacers removed from engines in the work shop. The associated workorders noted that no defects were found.

1.7.7 Visual Inspection of In-Service Spacers

In addition to the FPIs outlined above, the Operator also initiated a visual examination of the spacers installed on aircraft within its fleet and those fitted to its spare engines. At the time of writing, a total of 25 spacers have been inspected. The Operator reported that no defects were found during these visual inspections.

1.7.8 Examination of Damaged Fuel Line

Substantial damage was sustained to a flexible section of the No. 2 engine's main fuel inlet line during the occurrence. The damage did not result in a fuel leak. However, due to the potential for a fuel-fed engine fire, if a fuel leak had occurred, the Investigation sought to establish the extent of the reduction of the integrity of the fuel line. With the assistance of the Aircraft Manufacturer, the Bureau d'Enquêtes et d'Analyses (BEA) (representing the State of the Aircraft Manufacturer), and the NTSB, the Investigation sent the fuel hose to the Component Manufacturer for examination and testing.

In addition to the damage sustained to the exterior of the flexible hose as shown in **Figure No. 4**, the Component Manufacturer found that the internal support coil had also sustained significant damage at the site of the external impact, with approximately five spiral wraps of the support coil indented toward the centre of the assembly (**Photo No. 16**). Following visual examination, the hose was "*proof tested with water at 500 PSIG* [twice its design maximum operational pressure] *for 2 minutes with no signs of leakage*".

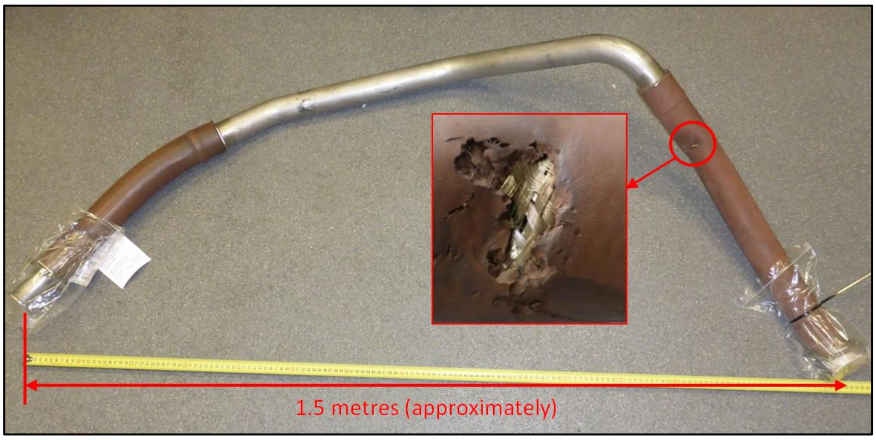

Figure No. 4: Damage to exterior of flexible section of No. 2 engine's main fuel feed line

Photo No. 16: Damage to interior of flexible section of No. 2 engine's main fuel feed line

1.8 Recorded Data

1.8.1 Attempted Isolation of Flight Recorders Post - Occurrence

Immediately following notification of the subject event by the Shannon Airport Duty Manager, the AAIU IOC contacted the Operator to seek further information and to request that the flight recorders be preserved once the aircraft had landed. Upon arrival at EINN at approximately 20.00 hrs, the AAIU inspected the aircraft. The Operator's maintenance personnel removed the DFDR and CVR from the aircraft and provided these to the AAIU. Both recorders were downloaded at the AAIU's recorder facility the following day.

When the data was reviewed, it was found that the CVR data from the occurrence flight had been overwritten. The Operator was immediately informed of this. The Investigation was advised that the Operator's maintenance personnel based at EINN, prior to removing the DFDR, noted that the removal procedure in the AMM that the personnel were following required the '*CVR CTL*' (control) and the '*FDIU/DFDR*' CBs to be pulled. It was mistakenly thought that pulling the CVR CTL CB would inhibit the CVR. The maintenance personnel advised that the CBs were pulled approximately half an hour after the aircraft arrived on stand.

1.8.2 Loss of a Foreign Operator's CVR Data

On 3 June 2013, a pressurisation-related event occurred on a foreign operator's Airbus A330 aircraft. The aircraft subsequently landed safely. However, according to the Aviation Safety Council's (Taiwan) summary of the associated investigation report, [in an attempt to preserve the CVR data for investigation purposes], maintenance personnel pulled the CVR CTL CB, but did not pull the CVR CB. This resulted in the CVR operating and overwriting the data from the occurrence flight. According to the Aircraft Manufacturer, specific CVR and DFDR deactivation procedures (as described in **Section 1.5.7**) were added to the AMM following the 2013 occurrence.

1.8.3 Recorded Data available to Investigation

The DFDR data for the occurrence flight was successfully downloaded. The data was analysed by the Aircraft Manufacturer, who subsequently provided a report to the Investigation. In addition, the Operator provided the Investigation with a copy of the Flight Data Monitoring (FDM) data for the flight and the aircraft's self-generated Post-Flight Report (PFR). ATC voice and radar recordings were also obtained by the Investigation. The available data indicates the following:

- At 15.26:12 hrs, the No. 1 engine was started, followed at 15.27:01 hrs, by the No. 2 engine.
- At 15.38:15 hrs, the thrust levers were advanced to the take-off position.
- At 15.38:29 hrs, when the aircraft's airspeed was approximately 67 kts, the No. 2 engine's Exhaust Gas Temperature (EGT) began to increase more rapidly than the No 1.
- At 15.38:40 hrs, the No. 2 engine fuel flow (consumption) became higher than the No. 1 by approximately 200 kg per hour.
- The aircraft took-off (all landing gears in the air) at 15.39:00 hrs.
- At 15.39:01 hrs, the No. 2 engine's EGT was 970^{o} C (the maximum value reached), whereas at that stage, the No. 1 engine's was 874^{o} C.
- Five seconds after take-off, the landing gear was selected up and 10 seconds after that, at 15.39:15 hrs, an ENG 2 FIRE warning was displayed when the aircraft was approximately 550 ft Above Ground Level (AGL).
- The engine was shut down at 15.39:33 hrs, when the aircraft was approximately 1,370 ft AGL.
- The ENG 2 FIRE pushbutton switch was released at 15.46 hrs, when the aircraft was approximately 28 NM west of EIDW.

The Investigation also obtained a video taken on a mobile phone by a person who witnessed the aircraft taking off. This video shows what appears to be smoke or vapour coming from the No. 2 engine during the initial climb from EIDW.

1.9 Coupling (Clamp) Failures

The Engine Manufacturer informed the Investigation that the failure of the spacer was the first time such an event occurred in the history of the engine type. However, failures of couplings securing the 14th stage manifold have occurred. At a technical symposium held by the Engine Manufacturer in May 2016 in relation to the subject engine type, the Engine Manufacturer outlined that there had been six 14th stage manifold coupling failures reported since 2011.

At another symposium in October 2017, the total number of reported failures rose to seven. It was noted by the Engine Manufacturer in documentation associated with the October 2017 symposium that the events typically result in engine fire warning indications, followed by an In-Flight Shut-Down (IFSD) and an Air Turn Back (ATB). At both symposiums, the Engine Manufacturer outlined that no material anomalies were identified in subsequent metallurgical examinations of the failed couplings and that the failure mode was HCF.

The Engine Manufacturer noted that 14th stage engine bleed ports have "*non-piloted flanges*" (features which would assist with component alignment during installation and minimise loading on the flange) and that couplings can be subjected to elevated side loading due to port/duct misalignment. The Engine Manufacturer highlighted that the lower duct port was the primary[24] location for the coupling failures because the highest loads were present at this location (three times greater than the loads experienced by the middle and upper ports). It was also noted that the couplings should be replaced at engine shop visit and that amendments had been made to the 14th stage manifold installation procedure in relation to the alignment of the manifold and the tightening sequence of the couplings.

According to the Engine Manufacturer, a previous procedure required the centre coupling to be attached first (not torqued) to check the alignment at the other ports, before the upper coupling was then torqued. At the time of the engine shop visit the procedure required that the lower coupling was attached first, the alignment at the other ports checked, and then the lower coupling torqued first. This revision was introduced to "*mitigate port/manifold misalignment in the lower port*". The Engine Manufacturer outlined that additional support links for the high pressure bleed valve had been introduced to reduce loads on the couplings and that the alignment procedure and torqueing sequence will "*complement the* [support] *links to lower vibratory loads and clamp wear*". The subject engine (S/N 811116) had the HP bleed valve support links installed.

The AAIU investigated a 14th stage manifold coupling failure event involving an Airbus A330 aircraft, which occurred on 4 June 2004 (AAIU Report No. 2006-006). In that case, the cause of the failure was deemed to be due to the 14th stage manifold becoming unsupported following the failure of the TTU, which "*initiated a fatigue fracture of the coupling, which then failed*".

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[24] When requested by the Investigation to clarify this point, the Engine Manufacturer advised that **all** coupling failures had occurred at the lower port.

1.10 Action Taken Subsequent to the Occurrence

1.10.1 Action Taken by the Engine Manufacturer

The Engine Manufacturer included an article in its '*CF 6 Fleet Highlites*'[25] publication, dated "*Third Quarter 2018*" (July), in relation to the event. It notifies operators of the engine type regarding Engine Shop Manual assembly and inspection changes in response to the subject event. The publication states the following:

> "*Metallurgical investigation was unable to determine root cause of the fracture. Examination of the failed components suggests that the clamp was not seated properly during the last SV* [shop visit] *assembly, creating high alternating stresses which led to the eventual fracture of the spacer. However, it is also possible that even with a properly seated clamp* [coupling]*, the clamping loads may have resulted in the development of stress concentration areas or damage to the duct*".

The publication highlights that an FPI is now required during shop visits:

> "*FPI requirements for high pressure ducts (Category b tubing*[26]*) have been added to 72-09-03 of the 80C and 80E ESMs* [Engine Shop Manuals]. *Additionally, caution notes regarding the proper assembly of the spacer has been amended to the 72-00-00 80E and the 72-00-02 80C2 Assembly sections*".

The caution note added regarding proper assembly of the spacer for the 80E engine (subject type) is as follows:

> "*<u>CAUTION:</u> MAKE SURE THAT THE 14TH STAGE MANIFOLD SPACER AND THE ENGINE PORTS ARE CORRECTLY ALIGNED. IF THE MANIFOLD AND ENGINE PORTS ARE INCORRECTLY ALIGNED, DAMAGE TO THE PART CAN OCCUR*".

In addition, a note has been added referring installers to ESM task 70-10-02-800-801 (V-Coupling Assembly Techniques) "*to make sure that the installation of V-clamps is correct*".

Furthermore, the Investigation identified a discrepancy between two sequential sections of the Engine Manual regarding the manifold alignment procedure (task 71-00-02-430-077 F '*Prepare to install the 14th stage manifold*' and task 71-00-02-430-078 G '*Connect the 14th stage manifold*'). The first procedure (correctly) required the clearance and alignment to be checked at the "*centre and upper engine ports*". The second procedure required the clearance and alignment to be checked "*across the three engine ports*". The Manufacturer was informed of this discrepancy and advised that procedure 71-00-02-430-078 G would be amended to reflect the content of task 71-00-02-430-077 F.

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[25] **CF 6 Fleet Highlites:** The Engine Manufacturer's support publication for the CF6 engine family.
[26] **Category b tubing:** High pressure/high temperature air tubes (ref. Engine Manual 72-09-03).

1.10.2 Action Taken by the Engine Overhaul Facility

Since the occurrence, the engine overhaul facility introduced a new task card, which specifically relates to the installation of the spacer. This task card instructs technicians to "*use a new clamp* [coupling]" and also, in accordance with the Engine Shop Manual, to "*Put the clamp with the T-bolt down and the nut aft*".

The engine overhaul facility revised the task card relating to the installation of the 14th stage manifold to include the caution from the relevant Engine Manual section to "*MAKE SURE YOU TORQUE THE COUPLINGS IN BOTTOM-TO-TOP ORDER OR THE MANIFOLD CAN BECOME MISALIGNED*".

The engine overhaul facility also produced a read and sign memo in relation to what it referred to as a "*torque wrench typo*" recorded on the task card, which recorded the installation of the subject spacer. The memo required each "*shop leader*" to re-emphasise that all staff must carefully verify [tool] ID numbers before they are recorded on a task card. The memo also stated that clarification must be sought if an ID number was unclear.

1.10.3 Action Taken by the Operator

Following the occurrence, the Operator initiated a visual examination of the spacers installed on aircraft within its fleet and those fitted to its spare engines. The Operator reported that no defects were found during these visual inspections.

Records indicate that the engine left the overhaul facility with the TTU identified as being "*LOOSE*". The Operator did not highlight this as a task requiring action during the engine change. Consequently, the Operator revised its Company Manual '*ENGINE PROCESS CONTROL*' procedure to highlight the requirement to raise workorders for "*Warnings/Notices/Labels/Tags identified by the engine MRO* [Maintenance Repair Organisation] *requiring follow up maintenance prior to and during engine installation* […]".

As a result of the CVR data being inadvertently overwritten, the Operator also revised its Company Manual '*AIRCRAFT INCIDENT/ACCIDENT - DFDR/CVR DATA RETRIEVAL*' procedure, which refers to the AMM CVR and DFDR sections to be followed when there is a requirement to deactivate/remove a DFDR or CVR following an occurrence.

1.10.4 Action Taken by the Aircraft Manufacturer

As a result of the loss of CVR data, the Investigation's Draft Report included a proposed Safety Recommendation to the Aircraft Manufacturer. This recommended that the Manufacturer considers amending Section 31-33-55 (DFDR Removal) of the Airbus A330 Aircraft Maintenance Manual (AMM), and the AMMs of its other aircraft types as required, to include a warning to maintenance personnel that pulling the Cockpit Voice Recorder (CVR) CTL Circuit Breaker (CB) may result in inadvertent CVR operation. In response, the Aircraft Manufacturer informed the Investigation that it will implement an appropriate warning during the "*next AMM revision opportunity*". The Aircraft Manufacturer also advised that it reviewed the DFDR removal procedures for its other aircraft types, and that only the subject aircraft type was affected.

2. ANALYSIS

2.1 Fire Warning

The aircraft Commander reported that when the landing gear was being retracted following take-off from EIDW, a "*Land ASAP*" warning was displayed on the aircraft's ECAM system. This was quickly followed by an ENG 2 FIRE warning. On a take-off roll, once V1 speed is reached, it is unlikely that an aircraft would be able to stop before the end of the runway following a rejected take-off. Therefore, on this aircraft type, engine fire warnings are inhibited between V1 and take-off +15 seconds.

The recorded data indicates that in the case of this occurrence, the ENG 2 FIRE warning was generated in the cockpit exactly 15 seconds after take-off. The data indicates that approximately 30 seconds before take-off (15.38:29 hrs), with the engines at take-off power and the aircraft's airspeed at approximately 67 kts, the No. 2 engine's EGT began to increase more rapidly than the No. 1. This was likely due to the 14th stage bleed spacer beginning to separate and adversely affecting the engine's efficiency (and fuel-air mixture ratio), with a corresponding increase in fuel consumption, as the engine's control system attempted to compensate.

Once the spacer began to separate, the engine compartment would have been exposed to gases in excess of 600^{o} C. Hot gas leakage sufficient to trigger a fire warning signal likely occurred sometime after V1, with the associated cockpit warning being inhibited, as designed, until 15 seconds after take-off. The smoke/vapour visible on the witness video may have been due to the escaping hot gasses and/or the increased fuel consumption/changes to the engines fuel-air mixture ratio.

2.2 Diversion to EINN

Following the ENG 2 FIRE warning, the Flight Crew shut down the engine as per the ECAM checklist, which caused the ENG 2 FIRE warning to cease. The Commander declared a MAYDAY to Dublin ATC to inform them of the engine problem and advise that the aircraft was climbing straight ahead. ATC acknowledged the MAYDAY declaration and asked the Commander what his intentions were after climbing straight ahead and advised that all runways at Dublin were available.

A return to the departure airfield would normally be performed following a significant event such as the subject occurrence, at, or just after, take-off. The "*Land ASAP*" ECAM message would also prompt such an action. However, due to the weight of the aircraft, which was carrying fuel sufficient to travel non-stop to KLAX on the west coast of America, the Flight Crew elected to divert to EINN, which has a runway that is 562 metres longer than the main runway (10/28) at EIDW. According to the Commander, such a possibility formed part of the Flight Crew's pre-flight briefing. It should be noted that the subject aircraft type is type-certified for ETOPS operations beyond 180 minutes and engine reliability must be such that the aircraft can be safely operated on one engine for that time period.

2.3 Fractured Spacer

2.3.1 Introduction

The spacer fractured at its recessed flange close to the coupling which secured it to the 14^{th} stage upper bleed air outlet port of the No. 2 engine. The Engine Manufacturer's metallurgical examination of the fractured spacer identified two main cracks, denoted as Crack A and Crack B (**Section 1.7.2**, **Photo No. 12**). Local discolouration was found outboard of the fracture surface of Crack A (**Section 1.7.2**, **Photo No. 15**), which was likely due to bleed air leakage as the crack propagated. Metallurgical examination of Crack A identified features consistent with high alternating stress crack propagation. Analysis of Crack B revealed features consistent with lower alternating stress, HCF crack propagation.

The Investigation determined that Crack A originated close to where the T-bolt side of the coupling had been located. Crack B was situated diametrically opposite to Crack A and was determined to be located close to where the coupling's dual hinge point had been located. The cracks were therefore situated adjacent to locations on the spacer flange that were not completely in contact with the clamping surfaces of the coupling. Crack A was forward of Crack B, with reference to the engine's longitudinal axis.

2.3.2 Possible Causes of Spacer Fracture

The engine was installed on the aircraft on 8 November 2017. The aircraft subsequently operated for 754 flight hours and 87 flights before the spacer failed. Records indicate that the spacer, which according to the Engine Manufacturer is not a tracked or life-limited part, had been removed from the engine, before being examined and reinstalled while the engine was undergoing a shop visit between April and August of 2017 at an approved engine overhaul facility.

It is possible that this pattern of removal, inspection and reinstallation was repeated at each shop visit throughout the engine's life. Therefore, the spacer may have been the same age as the engine, which was manufactured in October 1994 and had operated for 77,587 hours and 15,205 flight cycles since manufacture. If the failure was purely age-related, in terms of the spacer's operating hours and cycles, it is likely that the same part would have failed on other in-service engines of the same type. However, the Engine Manufacturer advised that the event was the first separation of this spacer "*in the history of the 80E1 and 80C2 engine programs (over 255 million engine flight hours, 58.5 million engine flight cycles). The part is common to both engine models*".

When the AAIU inspected the aircraft following the occurrence, it was found that the coupling securing the fractured part of the spacer to the 14^{th} stage bleed air outlet was not orientated in accordance with the requirements of the Engine Manual ("*T-bolt down and the nut aft"*). The Investigation asked the Engine Manufacturer what effect this incorrect orientation would have. The Manufacturer advised that the specified orientation was to facilitate "*wrench access*" and that there would be "*no adverse impact to the hardware as a result of a rotated clamp*". Therefore, the Investigation considers it unlikely that the incorrect orientation contributed to the fracture of the spacer.

The Engine Manufacturer's metallurgical examination found indentations on the surface of the fractured flange at eight locations. These were likely due to where the spacer retention coupling had been tightened onto the spacer over the course of its lifetime. The examination noted that the indentations, which appeared to be due to where the coupling was installed at the time of the occurrence, were approximately 4.9 thousandths of an inch deep. Indentations were also noted on the flanges of three exemplar spacers. However, the maximum depth of these indentations was approximately 2.8 thousandths of an inch.

A review of the Engine Manufacturer's metallurgical analysis by an independent metallurgist noted that the cracks on the fractured spacer initiated some distance away from the indentations attributable to where the coupling was last installed. It was considered unlikely that the indentations initiated the cracking. However, the independent metallurgist stated that the depth of the indentations on the fractured spacer compared to the depth of the indentations on the exemplar spacers was *"probably an indication that the loading on this spacer was abnormally high".* The metallurgist noted that "*abnormal loading conditions"* were the *"most likely cause of the fatigue cracking".* The possible presence of a *"static bending stress"* was also identified. The Investigation examined several possible causes of the abnormal loading conditions. These are outlined below.

2.3.2.1 Coupling not at Specified Torque

The engine overhaul facility stated that the '*INSTALL R/H DELTA AIR TUBE*' task card referred to the installation of the spacer. However, the '*Install the flow spacer*' and the '*Install R/H delta air tube*' are separate sub tasks of the Engine Manual and consequently, it was not clear if the task card actually recorded the installation of the spacer. In addition, the Investigation established that the torque wrench referred to on the '*INSTALL R/H DELTA AIR TUBE*' task card, which the overhaul facility deemed to relate to the installation of the spacer, was in the calibration shop when the task was being performed.

It is possible therefore that the coupling was not tightened to the specified torque. However, records for the other torque wrenches that could have been used during the task indicated that these torque wrenches were correctly calibrated. Therefore, it is also possible that the coupling was torqued using one of these wrenches and that the torque wrench referenced on the task card was a typographical error, which was what the engine overhaul facility believed to be the case.

Under-Tightening

Records associated with the work carried out during the shop visit indicate that new couplings were used for the installation of the spacer and the 14th stage manifold. However, the Engine Manufacturer's examination noted that there was more wear on the inside surface of the occurrence coupling adjacent to its hinge and connection points than other couplings examined. The Engine Manufacturer could not determine if this difference was primary or secondary to the event. It is possible that an under-tightened coupling could result in a larger degree of relative movement than that which would occur as a result of a correctly tightened coupling. Such relative movement could result in fretting leading to the indentations on the flange and also more wear on the coupling's inner surfaces.

However, following component failure so close to a fastened joint, the fastened joint itself can become loose and therefore any subsequent tightness check of a fastener may be unreliable. In this case, when the damaged components were being removed at the request of the Investigation, the coupling's self-locking nut was found not to be loose. Also, once the nut was loosened by maintenance personnel to release the coupling latch, percussion was required to remove the coupling itself, indicating that the indentations and wear were not due to a loose coupling.

Over-Tightening

The Investigation inspected the fractured spacer for evidence relating to an over-tightened coupling, such as out-of-roundness (distortion). Due to the stiffness of the spacer, it is unlikely that permanent distortion would result from an over-tightened coupling. Nevertheless, for completeness, the Investigation compared the out-of-roundness of the fractured spacer flange to the flange (engine-side) of an exemplar spacer. The maximum out-of-roundness of the fractured flange was 0.25 mm, which was only 0.06 mm greater than the figure of 0.19 mm for the exemplar spacer.

The manufacturing tolerance for the spacer's outside diameter was +/- 0.010 inch (0.25 mm). However, this would generally refer to a uniform maximum or minimum dimension; the maximum run-out figure of 0.005 (0.127 mm) is probably more applicable in this examination. The figure of 0.25 mm, as calculated by the investigation, exceeds the limit specified by the Manufacturer by 0.123 mm. While over-tightening cannot be ruled out, the Investigation considers that when the measured dimensions of the exemplar spacer and the manufacturing tolerances are also reviewed, there is insufficient evidence of distortion due to over-tightening.

2.3.2.2 Coupling Installation Procedures

The tightening procedure for the 14th stage manifold couplings, as contained in the Engine Manual in use when the engine was undergoing maintenance at the engine overhaul facility, and repeated on the 14th stage manifold installation task card, required coupling nuts to be torqued, followed by tapping the couplings with a fibre mallet before re-torqueing and repeating the operation. Such a procedure would ensure that couplings are correctly seated and that the clamping loads are evenly distributed.

However, this procedure was not referred to in the Engine Manual sub task relating to the installation of the spacer when it was fitted during the shop visit carried out in April-August 2017. It is possible therefore, that the indentations on the flange of the fractured spacer attributed to where the coupling was last installed, occurred as a result of the coupling installation procedure. While the indentations themselves did not initiate the fracture, they could be an indication of non-uniform clamping loads. The witness marks found on the spacer side of the coupling mating surface could also be an indication of non-uniform clamping loads. Furthermore, the Engine Manufacturer noted, in its '*Fleet Highlites*' publication for the engine type, that component examination "*suggests that the clamp* [coupling] *was not seated properly*".

The Engine Manual procedure for the installation of the spacer now refers maintenance personnel to the Engine Standard Practices Manual section which describes the correct coupling installation technique.

2.3.2.4 14th Stage Manifold Misalignment

The Engine Manufacturer outlined at a technical symposium in October 2017 that there had been seven failures of 14th stage bleed manifold couplings since 2011. The Engine Manufacturer stated that all failures occurred at the lower duct port because the highest loads were present at this location.

The Engine Manufacturer outlined that couplings can sustain elevated side loading due to port/duct misalignment and that in addition to the HP bleed valve support links previously installed, amendments had been made to the 14th stage manifold installation procedure regarding the alignment of the manifold and the tightening sequence of the couplings. The 14th stage manifold is directly connected to the spacer and any excessive loads as a result of misalignment of the manifold or incorrect clearance during installation could be transferred to the spacer. However, the task card relating to the installation of the 14th stage manifold during the most-recent shop visit, recorded that the alignment and clearance dimensions were within Engine Manual specifications.

Manuals, such as the Engine Manual, are primary reference documents for maintenance personnel, and task cards would not necessarily duplicate all information contained in such manuals. Notwithstanding this, the Investigation notes that although the task card referred to the correct torque to be applied when tightening the 14th stage manifold couplings and also the Engine Manual procedure to follow regarding tapping the coupling with a fibre mallet during the torqueing procedures, the task card did not refer to the caution contained in the Engine Manual regarding the "*bottom-to-top or*der" tightening sequence. The Engine Manual states that if this sequence is not followed, the manifold could become misaligned. The engine overhaul facility's task card relating to the installation of the 14th stage manifold has since been amended to include this caution.

The Engine Manufacturer outlined the revised (bottom-to-top) tightening sequence at a symposium in 2016 and the Investigation also considered the possibility that the revised tightening sequence resulted in abnormal loading that may have been previously experienced at the lower coupling, being transferred to the upper coupling and hence to the spacer. However, as stated earlier, according to the Engine Manufacturer, this is the first reported case of a spacer failure.

The AAIU investigated a 14th stage manifold coupling failure event, also involving an Airbus A330 aircraft, which occurred on 4 June 2004. In that case, the cause of the failure was deemed to have been due to the 14th stage manifold becoming unsupported following the failure of the TTU, which "*initiated a fatigue fracture of the coupling, which then failed*". The TTU provides an adjustable interface between the HP bleed valve and an intersect duct. Records indicate that the engine, as fitted to EI-LAX, left the overhaul facility with the TTU identified as being "*LOOSE*". It therefore required adjustment during the subsequent engine installation process. The associated AMM procedure includes a caution that when extending the TTU, too much load (caused by over-extension) "*can cause damage to the bleed air system components*".

The Investigation notes that the Operator's engine change workpack did not record that the TTU was loose and needed to be adjusted during the engine change process. However, the Operator's engine change workpack indicates that the IP check valve was replaced during the engine change. The associated workorder refers to the AMM installation procedure used, which requires the TTU to be adjusted as part of the task. The Engine Manufacturer informed the Investigation that adjustments performed on the TTU would be unlikely to adversely impact the loading on the spacer. Therefore, the Investigation considers that TTU adjustment was not a factor in the subject occurrence. The Operator has since revised its procedures to highlight the requirement to raise workorders for "*Warnings/Notices /Labels/Tags identified by the engine MRO* [Maintenance Repair Organisation] *requiring follow up maintenance prior to and during engine installation* […]". Therefore, no Safety Recommendation is made to the Operator in this regard.

2.3.3 Failure Summary

The Investigation examined a number of potential causes for the fatigue failure of the spacer, including the indentations found on the spacer's recessed flange; the age of the spacer; incorrect seating of the coupling which secured the spacer to the engine's upper bleed port; incorrect torqueing of the coupling's self-locking nut (under/over-tightening); misalignment of the 14th stage manifold; and incorrect adjustment of the TTU during engine installation.

Independent metallurgical examination identified that abnormal loading conditions were the "*most likely cause of the fatigue cracking".* Possible causes of the abnormal loading include incorrect seating of the coupling, over-tightening of the coupling's self-locking nut, or misalignment of the 14th stage manifold. While a definitive cause could not be established, several process improvements were implemented as a result of the Investigation. These are summarised below.

2.3.4 Process Improvements

Subsequent to the occurrence, the engine overhaul facility developed a new task card, which specifically relates to the installation of the bleed spacer and the associated Engine Manual section to follow. The new task card also refers to the correct orientation of the coupling at installation. Notwithstanding that records indicate that a new coupling was used to secure the spacer to the engine's upper bleed port at the last shop visit, the new task card also instructs technicians to use a new coupling when installing the spacer.

The engine overhaul facility has also revised the task card for the installation of the 14th stage manifold, to include the Engine Manual caution to tighten the couplings in "*bottom-to-top order*". Furthermore, as a result of an unavailable torque wrench being referred to on the task card, which was considered by the engine overhaul facility to relate to the installation of the spacer, the engine overhaul facility issued a read and sign memo. This memo required each "*shop leader*" to re-emphasise that all staff must carefully verify [tool] ID numbers before they are recorded on a task card. The memo also stated that clarification must be sought if an ID number was unclear. As a result of these actions, no safety recommendation is made to the engine overhaul facility.

The use of a fibre mallet was not referred to in the '*Install the flow spacer*' subtask of the Engine Manual (72-00-00-430-239) in use at the time. This subtask now refers to '*V Coupling Assembly Techniques*', as contained in the Engine Standard Practices Manual. This section describes the correct process to follow. The Engine Manual procedure for the installation of the spacer now also includes a caution, highlighting that misalignment during installation can result in damage.

Also subsequent to the occurrence, the Engine Manufacturer has introduced a requirement for an FPI to be performed on the spacer during each shop visit. However, metallurgical examination identified that the failure did not initiate at the indentations on the spacer which were attributable to the coupling. It is therefore possible that causal defects were not present during spacer examination prior to installation and the entire failure sequence, from crack initiation, through stable fatigue crack growth, to final separation, took place within 87 flight cycles. Under such a scenario, the FPI at each shop visit would be ineffective in preventing other failures from a similar cause. Notwithstanding this, such an inspection could help prevent failures from other causes. As outlined above, the Engine Manufacturer has also revised the spacer installation procedures as contained in the Engine Manual. As a result of these actions, no safety recommendation is made to the Engine Manufacturer.

2.4 Damage to No 2 Engine Fuel Feed Line

The No. 2 engine's main fuel feed line was substantially damaged following the fracture of the bleed air spacer and the subsequent buckling of the 14th stage manifold. At take-off power, fuel flow through this fuel line is approximately 3.2 kg per second (11,520 kg per hour). Notwithstanding the functionality of the engine's fire protection system, a fuel leak in a line carrying fuel with such a high rate of flow, combined with a high pressure/high temperature air leak (646^{o} C/496 PSI), could have resulted in a fuel-fed engine fire.

In this case, there was no fuel leak and no engine fire. Nevertheless, the Investigation sought to establish the extent of the reduction of the integrity of the fuel line and returned the line to the component manufacturer for further examination and testing. The manufacturer of the line pressure-tested it to twice its design maximum operational pressure for two minutes and no leaks were evident.

The Investigation acknowledges that it is not practicable to predict all failure scenarios and therefore protect against them. However, this occurrence demonstrates the need for careful consideration in relation to the routing of high volume fuel lines during engine design.

2.5 Loss of CVR Data

Following notification of the occurrence by the Shannon Airport Duty Manager, the AAIU IOC contacted the aircraft Operator to obtain further details and to request that the aircraft's CVR and Digital Flight Data Recorder DFDR be preserved. When the AAIU arrived at EINN approximately three and a half hours after the aircraft landed, the Operator's maintenance personnel removed the DFDR and CVR from the aircraft and provided these to the AAIU. When the CVR was downloaded by the AAIU the following day, it was found that the voice recordings from the occurrence flight had been overwritten.

The Operator advised the Investigation that prior to removing the DFDR, the EINN-based maintenance personnel reviewed the AMM DFDR removal procedure. The DFDR removal procedure (AMM task 31-33-55-000-801-A) requires the CVR CTL CB and the FDIU/DFDR CB to be pulled. Maintenance personnel mistakenly thought that pulling the CVR CTL CB would inhibit the CVR. The CVR recording logic is such that the CVR will record during the first five minutes of the aircraft's electrical system being energised when the aircraft is on the ground. However, pulling the CVR CTL CB will result in the CVR continuing to record for as long as the aircraft remains powered. This is what occurred in this case, with the result that all voice data for the occurrence flight was overwritten. Other recordings were available to the Investigation and the loss of the CVR data did not greatly impede the Investigation. However, its availability would have facilitated a better understanding of the occurrence and the subsequent diversion to EINN.

The Investigation notes that CVR data was also overwritten as a result of the CVR CTL CB being pulled following a serious incident in 2013 involving a foreign operator's aircraft. According to the Aircraft Manufacturer, CVR and DFDR deactivation procedures were added to the AMM following the 2013 event. However, in the case EI-LAX, maintenance personnel were following the DFDR removal procedure (AMM 31-33-55-000-801-A). At the time of the occurrence, there was no warning in this section of the AMM to highlight to maintenance personnel that pulling the CVR CTL CB, as required by the removal procedure, may result in inadvertent CVR operation, which could overwrite data that may have been critical to an investigation.

The Investigation acknowledges the Aircraft Manufacturer's planned amendment of the A330 AMM to include an appropriate warning in the DFDR removal procedure. The Aircraft Manufacturer also advised the Investigation that it reviewed the DFDR removal procedures for its other aircraft types and that only the subject aircraft type was affected. Consequently, no Safety Recommendation is made in this regard.

3. CONCLUSIONS

3.1 Findings

1. The airworthiness certification for the aircraft was valid.

2. An ENG 2 FIRE warning was received by the Flight Crew 15 seconds after take-off.

3. As required by the associated emergency checklists, the Flight Crew shut down the No. 2 engine.

4. The aircraft diverted to Shannon Airport (EINN) and entered a local holding pattern in order to consume fuel to reduce the weight of the aircraft, before performing an overweight landing on RWY 06 at EINN.

5. Following an inspection of the aircraft by the Airport Fire Service, the aircraft taxied to a parking stand, where the passengers and Crew disembarked the aircraft normally.

6. The aircraft was inspected by maintenance personnel at EINN, who identified that the fire warning was due to a fractured spacer at the 14th stage bleed air outlet on the No. 2 engine, which permitted hot, high pressure air to escape into the engine compartment.

7. The forces exerted during the fracture and subsequent air leak were such that the 14th stage bleed air manifold was buckled, resulting in the coupling which secured the manifold to the fractured spacer, becoming partially embedded in the No. 2 engine's main fuel feed line.

8. The No. 2 engine's main fuel feed line was damaged by the coupling that secured the manifold to the spacer, but was not perforated and therefore there was no fuel leak.

9. The No. 2 engine had been installed on the aircraft on 8 November 2017, and had operated for 87 flights since installation.

10. The spacer, 14th stage bleed air manifold, and several other air bleed system components had been fitted to the engine when it was undergoing maintenance at an approved engine overhaul facility from 17 April 2017 to 4 August 2017.

11. The spacer fractured adjacent to its recessed flange, close to the coupling which secured it to the No. 2 engine's 14th stage upper bleed air outlet.

12. The fracture initiated close to where the spacer retention coupling's T-bolt and self-locking nut had been located.

13. The coupling securing the spacer to the No. 2 engine's 14th stage bleed air outlet was not positioned in accordance with Engine Shop Manual requirements. The Investigation does not consider this to be a factor in the fracture of the spacer.

14. The task card that the engine overhaul facility deemed to refer to the installation of the spacer related to a different sub-task. A new task card, specific to the installation of the spacer has since been introduced.

15. The torque wrench referred to on the task card that the engine overhaul facility deemed to relate to the installation of the spacer was not available for use on that date.

16. Metallurgical analysis identified that the spacer fractured as a result of reversed bending fatigue.

17. Metallurgical analysis found indentations at several locations on the spacer flange, which were attributed to be from where the coupling had been installed throughout the life of the spacer. The deepest indentations were located at the position the coupling was found following the occurrence. These indentations did not initiate the fracture.

18. Indentation damage, similar to that identified on the fractured spacer was found on both flanges of each of three other removed spacers examined. In addition, pitting, 3 mm in length, was found on one of the spacers examined, adjacent to one of its flanges.

19. The engine was manufactured in October 1994. Spacers may be removed, inspected and re-installed during engine shop visits. It is possible therefore that the spacer was the same age as the engine.

20. Engine maintenance records indicate that the spacer was visually inspected at the last shop visit (April 2017-August 2017).

21. At the time of the occurrence, there was no requirement to perform Non-Destructive Testing (NDT) of the spacer at engine shop visit. However, a Fluorescent Penetrant Inspection (FPI) is now a requirement.

22. The Operator visually inspected a total of 25 in-service spacers (without removal). The Operator reported that no defects were found during these inspections.

23. The CVR data was inadvertently overwritten as a result of the CVR CTL CB being pulled as required by the AMM DFDR removal procedure. There was no warning in the DFDR removal procedure highlighting this possibility.

3.2 Probable Cause

Fatigue failure of the No. 2 engine's 14^{th} stage bleed air spacer, which allowed hot, high pressure bleed air to escape into the No. 2 engine compartment, resulting in a No.2 engine fire warning and the Flight Crew shutting down the No. 2 engine and diverting the flight.

3.3 Contributory Cause(s)

Metallurgical examination and analysis identified that abnormal loading conditions were the most likely cause of the fatigue cracking.

4. SAFETY RECOMMENDATIONS

As a result of the actions taken by the Engine Manufacturer, the engine overhaul facility, and the Operator, in addition to the action planned by the Aircraft Manufacturer, this Investigation does not sustain any Safety Recommendations.

- END -

In accordance with Annex 13 to the Convention on International Civil Aviation, Regulation (EU) No. 996/2010, and Statutory Instrument No. 460 of 2009, Air Navigation (Notification and Investigation of Accidents, Serious Incidents and Incidents) Regulation, 2009, the sole purpose of this investigation is to prevent aviation accidents and serious incidents. It is not the purpose of any such investigation and the associated investigation report to apportion blame or liability.

A safety recommendation shall in no case create a presumption of blame or liability for an occurrence.

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