Serious Incident

Aircraft Type and Registration:	Boeing 787-9 Dreamliner, G-ZBKF
No & Type of Engines:	2 Rolls-Royce Trent 1000-J2 turbofan engines
Year of Manufacture:	2016 (Serial no: 38622)
Date & Time (UTC):	29 April 2017 at 1040 hrs
Location:	En route from London Heathrow to New Delhi airport
Type of Flight:	Commercial Air Transport (Passenger)
Persons on Board:	Crew - 13 Passengers - 124
Injuries:	Crew - None Passengers - None
Nature of Damage:	None
Commander's Licence:	Airline Transport Pilot's Licence
Commander's Age:	50 years
Commander's Flying Experience:	14,200 hours (of which 1,238 were on type) Last 90 days - 175 hours Last 28 days – 48 hours
Information Source:	AAIB Field Investigation

Synopsis

The aircraft was on a scheduled flight from London Heathrow to New Delhi, India. The aircraft was dispatched in accordance with the Minimum Equipment List (MEL) with the left air conditioning (AC) system disabled. Shortly after reaching FL350 the crew were alerted by EICAS that the cabin altitude was increasing above normal, triggered at 8,500 feet. With no additional Environmental control system (ECS) actions available to control cabin altitude, the flight crew initiated a descent. During this descent the cabin altitude exceeded 10,000 ft and the crew completed the relevant emergency actions.

The loss of cabin pressurisation was caused by detachment of the lower right air conditioning recirculation fan duct on a sector where the left air conditioning system had been disabled before flight. As a consequence of this finding, the Aircraft Maintenance Manual has been amended to alter the process of replacing the relevant recirculation fan and maintenance procedures to react to a related Maintenance Alert Message have been altered.

The investigation also identified a software problem related to the volume of the cabin decompression pre-recorded announcement (PRA) in the passenger cabin which is being addressed by the Operator's safety action. Three Safety Recommendations are made concerning the testing of the installed performance of CVR systems.

History of the flight

Flight crew

The aircraft was scheduled to operate from London Heathrow to New Delhi, India. The aircraft flight crew, which consisted of three pilots, reported as normal at 0755 hrs for a scheduled departure time of 0925 hrs. The sector was planned under Extended-range Twin-engine Operational Performance Standards (ETOPS) rules and, due to the forecast of thunderstorms near Delhi, additional 'holding' fuel was added to the flight plan.

When the flight crew boarded the aircraft, they noted that the aircraft's electronic technical log reflected that the left AC system had been disabled, in accordance with the MEL. This was because the left No 2 (L2) CAC (Cabin Air Compressor) shaft had failed, which had subsequently damaged the left No 1 (L1) CAC. As a result of this unserviceability the aircraft no longer qualified for ETOPS[1] and a new flight plan was requested, with a maximum altitude limit of FL350 to enable the overhead crew rest areas to be used during the flight. The amended flight plan meant an additional two tonnes of fuel was added.

The aircraft took off at 1007 hrs and the climb was largely uneventful, although the crew noted a higher than usual temperature and lower than normal airflow in the cockpit. As the aircraft climbed through FL200 the third pilot left the cockpit for the flight crew rest area.

At 1032 hrs the aircraft levelled off at the planned cruise level of FL350. Two minutes later, the 'CABIN ALTITUDE PRESSURE BLOCK' was automatically[2] displayed on the EICAS display. The crew immediately responded, confirming that the cabin altitude was increasing at a rate of about 300 fpm and that both outflow valves were indicating closed. The crew then selected the 'SYSTEM STATUS' page and noted that the 'RECIRC FAN LWR R' status message was displayed.

The crew discussed remedial options and initially requested a descent to FL310 to see whether the cabin altitude would stabilise. They began a descent in flight level change (FLCH) mode, at idle power. However, the cabin altitude continued to increase and the commander asked the co-pilot to speak to the cabin service director (CSD) on the interphone, to brief her on the situation and request that the cabin service be stopped. The co-pilot initially called the first-class cabin but the CSD was not there so he spoke with another member of the cabin crew, whom he advised to stop the cabin service. The co-pilot then called the interphone in the next cabin, to locate the CSD.

As the aircraft descended through FL330, the commander advised the co-pilot that the cabin altitude was still increasing and he would be declaring a PAN, requesting a further descent. Just as the commander transmitted the PAN, the cabin altitude reached 10,000 ft and the EICAS cabin altitude warning activated. This coincided with the co-pilot speaking to the CSD, whom he advised to stop the cabin service and ensure passengers and crew were

Footnote

[1] The MEL requires that the aircraft remain within 60 minutes of landing at an airfield.
[2] The cabin altitude pressure block is automatically displayed on EICAS when the cabin altitude reaches 8,500 ft. It contains system information and graphics pertaining to cabin altitude, cabin altitude rate, differential pressure, landing altitude, and outflow valve position.

seated near an oxygen mask. The CSD replied, stating "ON OXYGEN MASKS OKAY", to which the co-pilot responded "NO NOT ON OXYGEN, NOT ON OXYGEN, JUST BY YOUR SEATS WITH THEM", before ending the call to don his oxygen mask. In the meantime, the commander had donned his oxygen mask. The crew completed the QRH memory items, with the cabin oxygen system being manually deployed.

Having established communications with each other, the crew declared a MAYDAY and made a rapid descent to FL100 with speedbrakes deployed. The aircraft was approximately 25 nm east of Brussels, Belgium. As the aircraft descended through FL258 the cabin altitude reached a maximum value of 10,429 ft before starting to reduce. During the descent the CSD, wearing a portable oxygen system, entered the cockpit.

After levelling at FL100, and having confirmed that the cabin altitude was at 7,000 ft and reducing, the crew removed their oxygen masks and completed the QRH checklist for 'Excessive Cabin Altitude'. The commander then asked the CSD to advise the third pilot, who had remained in the flight crew rest area on a fixed 'drop down' oxygen mask, that he could return to the cockpit and that the cabin crew and passengers could remove their oxygen masks if required.

The cabin altitude continued to reduce to about 3,700 ft, where it stabilised. Having evaluated the status of the aircraft, the crew decided to return to Heathrow. Before the CSD returned to the cabin, the commander gave her a briefing on the plan to return.

Whilst en route, approximately four tonnes of fuel was jettisoned to reduce the aircraft weight below the Maximum Landing Weight (MLW). The approach and landing at Heathrow were uneventful and the aircraft was taxied to the terminal where the passengers disembarked normally.

Cabin crew

From a cabin crew perspective, the flight progressed normally up to cruise altitude, other than that the CSD reported that she was feeling a little unwell. At cruise altitude a normal cabin service was underway. The cabin crew in the first-class cabin recalled receiving an interphone call from the co-pilot and the request to stop the cabin service and return to their seats. However, before this message could be passed on to the other cabin crew, the cabin oxygen masks deployed. The deployment of the oxygen masks is accompanied by a PRA that advises of the emergency over the cabin loudspeakers, and contains instructions to don the oxygen masks. However, while the PRA was triggered in the cabin, its volume over the speakers was so low that the content of the message could not be heard above the background cabin noise.

As a result of not hearing the PRA, and in the absence of any other serious indications of depressurisation, the cabin crew were confused as to what was happening. Many thought the oxygen masks had deployed inadvertently, possibly because of turbulence. The cabin crew did not follow their depressurisation actions but returned their cabin service carts to the galleys and took their seats there.

The passengers appeared unaware of the emergency. Some remained asleep and many did not fit their oxygen masks. Of those that did fit the masks, some fitted them incorrectly. As the cabin crews' awareness of the situation developed, they began shouting instructions to the passengers to fit their oxygen masks.

Due to the uncertainty of the situation, the CSD took a portable oxygen system and went to the cockpit to ascertain what was happening. During this period several of the cabin crew also used portable oxygen systems. Several of them reported that the systems were difficult to extract from their stowage locations and to use due to the "cumbersome" oxygen bottle. They also found it difficult to tell whether the portable oxygen systems were working.

During the return to Heathrow several of the cabin crew and passengers reported feeling unwell, although none required medical attention.

Planned Route

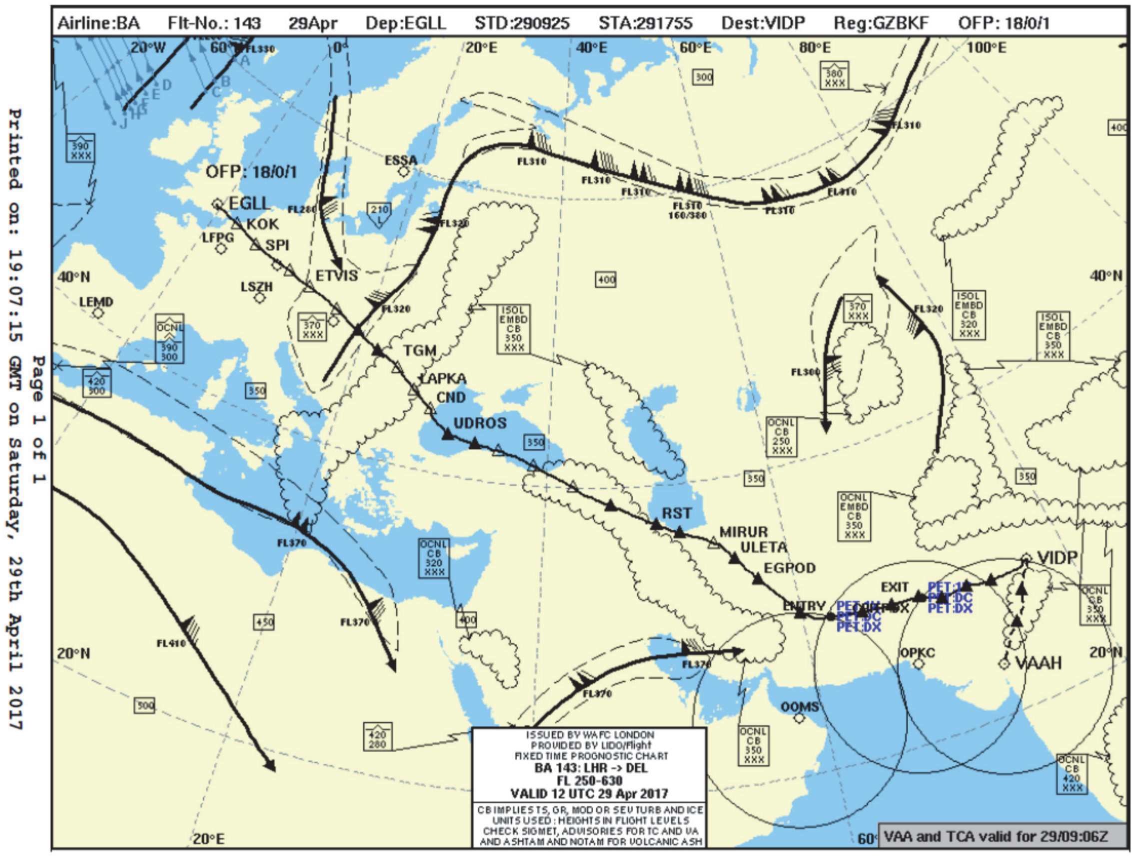

Figure 1

Planned route, BA143 London-Delhi 29 April 2017

Recorded information

Sources of recorded information

The aircraft was equipped with two Enhanced Airborne Flight Recorders (EAFR), one installed at the front of the aircraft and the other at the rear. The EAFR is a multifunction recorder that records 25 hours of FDR data and 120 minutes of CVR audio into a crash-protected solid-state memory.

The CVR audio record for the flight commenced at 1016 hrs, when the aircraft was climbing through FL110, and ended after the aircraft had landed. Flight data was available for the entire incident flight. Both EAFRs record the same flight data, with just over 2,200 parameters available. Parameters of significance included cabin altitude, status of cabin oxygen mask deployment, EICAS and system status display information and the speed of the air conditioning recirculation fans. System fault log information was also available from the aircraft's Central Maintenance Computing Function (CMCF) and the Aircraft Health Monitoring (AHM) ground-based software service.

Recorded data

Figure 2 shows pertinent parameters recorded during the incident. The data shown is for the period just before the aircraft reaches FL350, to shortly after the aircraft descended to FL100. Additional information not included in the earlier section 'History of the flight' is included below.

The Boeing 787 AHM is a ground-based software service that collects, analyses and presents aircraft-generated data to operators to assist them in determining current and future serviceability of their aircraft. Information, which includes 'low level' faults that do not require crew action, are presented to the crew as status messages by on-board systems. When a status message is triggered, the crew are made aware on the EICAS, which displays the word 'STATUS' in blue text. Selection of the system status page 'SYS' presents the associated message on the Multifunction Display (MFD).

At 1029:54 hrs, as the aircraft was climbing through FL320, the air conditioning lower right recirculation fan stopped. The cabin altitude was 7,000 ft at this time and at 1033 hrs system status message 'RECIRC FAN LWR R' was triggered by the CMCF. This message was subsequently referred to by the crew about a minute later, after they had been alerted to the abnormal cabin pressure on EICAS.

The aircraft manufacturer later reviewed the 'RECIRC FAN LWR R' status message and its associated fault code '1031 Motor Driver Current Fault'. The manufacturer stated that the fan shut down, after which the air conditioning system attempted to restart it. After three consecutive failed attempts to restart, the status message 'RECIRC FAN LWR R' is triggered. This is a latched fault that cannot be cleared in flight. The aircraft manufacturer stated that the fault with the fan was most likely associated with it having become detached from the inner duct.

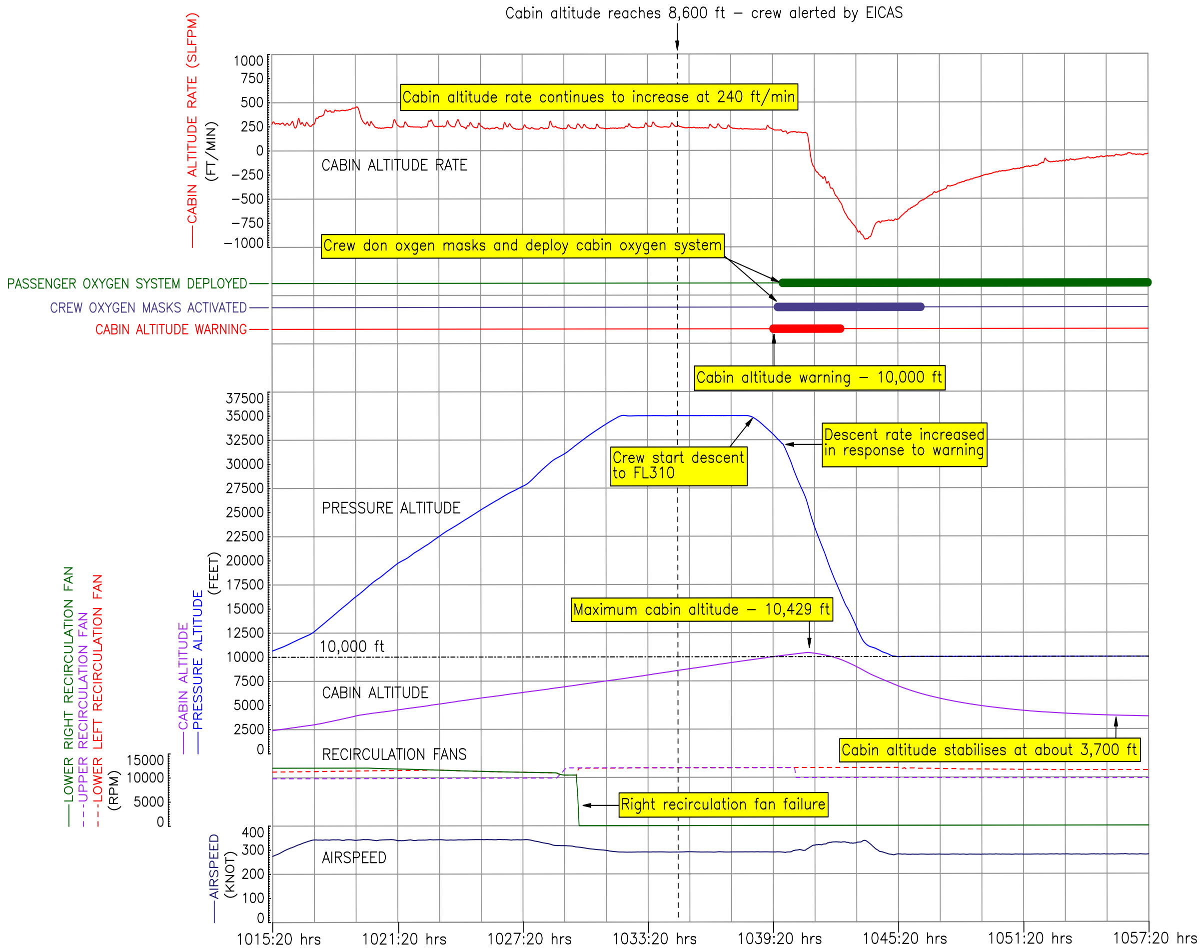

Figure 2

Descent from FL350 following cabin altitude warning

Aircraft information

Cabin pressurisation system

The cabin pressurisation system fitted to the Boeing 787 is different from earlier aircraft types, in that it does not utilise air bleeds from the engine compressors but is equipped with electrically driven centrifugal impellers, known as cabin air compressors (CACs). Four CACs are fitted, with two CACs (referred to as L1 and L2) providing compressed air to the left air conditioning unit and two CACs (R1 and R2) to the right air conditioning unit. The left and right air conditioning units can each function with only one CAC per side operating.

The system includes two recirculation fans, one each in the left and right air conditioning units. These fans are referred to as the 'left lower' and 'right lower' recirculation fans respectively. The main air conditioning unit components, including the left and right lower recirculation fans, are positioned in non-pressurised areas within the lower fuselage, just forward of the wing box structure.

The left and right lower recirculation fans are each connected by ducts to their respective left and right heat exchangers. The fan assemblies are connected to the ducts at both ends by sleeved couplings and these ducts are connected to the rest of the system by conventional 'V-band' clamps (Figure 3). Access to the right recirculation fan is more restricted, compared to the left fan, due to the left and right air conditioning systems being geometrically similar, rather than 'handed'. The right unit thus requires reaching through an extensive system of ducting and components to effect fan installation and removal.

Cabin decompression Pre-Recorded Announcement (PRA)

Manual deployment of the oxygen masks by the crew causes a cabin decompression PRA to be played over the cabin speakers by the passenger address system. This recorded announcement is intended to be heard clearly above the ambient noise in the cabin to alert passengers and cabin crew that they are to don oxygen masks.

Passenger privacy screens

The operator's business-class cabin seats fitted to its Boeing 787 fleet are installed with retractable privacy screens. Unlike other aircraft types in this operator's fleet, the privacy screens on the Boeing 787 do not automatically retract when the cabin oxygen masks are deployed, and are not required to do so.

Aircraft examination

During the flight sector into Heathrow which preceded the incident flight of 29 April 2017, the crew had reported a status message 'CABIN AIR CPRSR L2'. Engineers attended the aircraft and carried out troubleshooting in accordance with the Fault Isolation Manual (FIM), but initially could not identify the cause of the fault message. Following further investigation, it was found that the L2 CAC shaft had failed and part of it was missing. The inlet of the L1 CAC was removed for comparison and the missing material from the L2 CAC was found at the inlet with damage sustained to the blades of the L1 CAC. This was discovered shortly before the scheduled departure. It was therefore decided to dispatch the aircraft with the left AC system disabled, in accordance with the MEL.

Following the return of the aircraft to Heathrow after the incident, an examination took place monitored by the AAIB. It was found that the right-hand inner recirculation duct was disconnected from the lower right-hand recirculation fan (Figure 3). Once the duct and fan unit were removed, there was evidence that the coupling and seal joining the two had been incorrectly aligned when last assembled. The V-band clamp joining the other end of the duct to the heat exchanger was correctly fitted.

Examination of the coupling system used to connect the recirculation fan to the inner duct showed that if the coupling were not installed correctly, there was less visible evidence and a reduced tactile feel compared to that of the V-band clamp used at the opposite end of the duct. The connection of the right-hand recirculation fan is located in a position that requires reaching through an extensive system of ducting and components to install it. Viewing of the connection between the duct and fan is also restricted. Figure 3 shows the relative position of the recirculation fan and the disconnected duct.

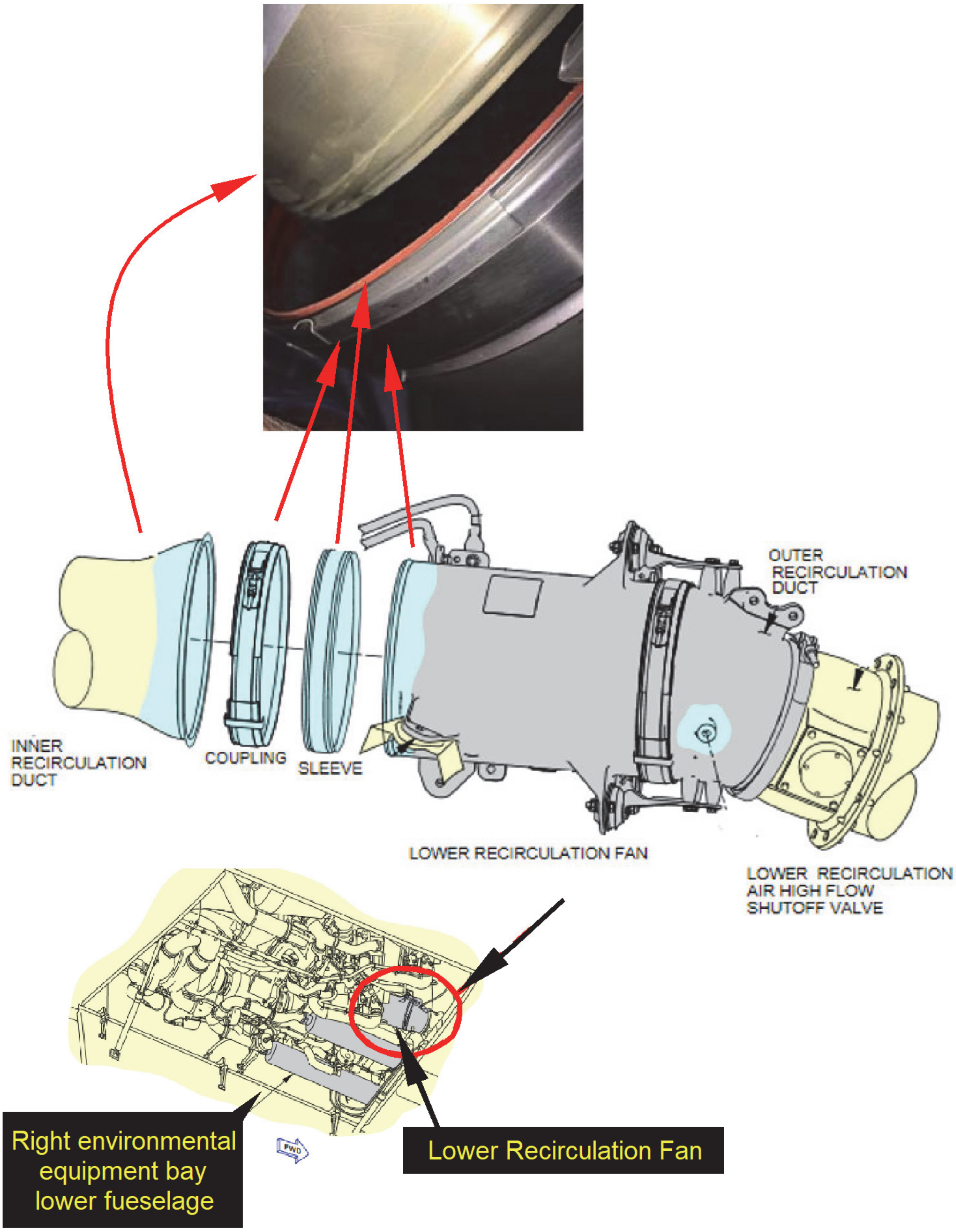

Figure 3

Position of Right Lower Recirculation Fan and photograph of disconnected duct

Previous maintenance activity

Examination of the aircraft records showed that the right-hand lower recirculation fan had been disabled on 8 April 2017 due to a fault and the fan was subsequently changed on 18 April 2017, 11 days before the incident flight. The following day, when the aircraft returned to service, the aircraft's AHM system sent Maintenance Alert Message 21-0209-C740[3] to the operator's ground-based data system, indicating that a 'high leakage/low inflow' of the cabin pressurisation system had been detected. This message is not displayed to the flight crew.

The AHM message 21-0209-C740 was assessed by the operator's engineering department and on 20 April 2017 a work request, D7 32165109 titled 'CABIN PRESSURISATION CHECKS', was raised to carry out a pressurisation leak check of the aircraft. The recent work carried out on the aircraft's right air conditioning pack (8 and 18 April) would have been available by accessing the aircraft's electronic flight log details. The end date for completion of work request D7 32165109 was set at 5 May 2017.

Thereafter, during all of the subsequent flights of G-ZBKF, of which there were 15 prior to the incident flight, Maintenance Alert Message 21-0209-C740 was sent by the aircraft to the operator's AHM ground-based data system. The end date (5 May) for the completion of work request D7 32165109 was not altered. The operator later stated that the AHM system provides just over 1,200 maintenance alerts. From experience, some maintenance alert messages are inadvertently triggered, which has led to refinements to improve the robustness of the system and reduce the level of 'nuisance' alerts. The operator had seen alert message 21-0209-C740 triggered 'intermittently' on other aircraft before and this had caused maintenance staff to question the reliability of this particular alert message.

The engineer who had disabled the left air conditioning pack on the morning of the incident had been provided with documentation that included outstanding maintenance activities. This included work request D7 32165109. The operator stated that it was not a requirement that engineers review this particular information as it was included for information purposes only.

Cabin decompression Pre-Recorded Announcement (PRA)

Under normal operation, the cabin decompression PRA is output at a peak level equivalent to the level of someone shouting. When a cabin announcement is made by the flight crew the PRA is paused and after completion of the cabin announcement the PRA continues.

Testing of the cabin audio system, and further investigation by its manufacturer[4], found that on recommencement of the cabin decompression PRA (following a cabin announcement from the flight crew), the source of the PRA announcement had reduced the amplitude of the input announcement to the passenger address system to a level just above normal conversation. The manufacturer of the passenger address system verified the system volumes were per design and operated correctly but could not produce the output at the right amplitude with the input signal reduced by the amount stated above. This caused the low level that previously stated was not intelligible. The manufacturer of the In Flight Entertainment System (IFES - which is the source of the PRA announcement) is releasing a software update to correct this deficiency of the PRA source audio levels being supplied at a lower value than specified by the manufacturer.

Footnote

[3] This fault message is triggered if the outflow valves are less than 5° open in flight.
[4] Thales: www.thalesgroup.com

Passenger privacy screens

It was found that passenger safety cards carried on the operator's fleet of Boeing 787 aircraft incorrectly indicated that privacy screens would automatically retract when the passenger oxygen masks deployed. Cabin crew training also did not reflect this difference.

EAFR CVR audio recording quality

On 21 November 2014, the National Transportation Safety Board (NTSB) of the USA published report NTSB/AIR-14/01 on an accident to a Boeing 787-8, JA829J that suffered an auxiliary power unit battery fire. During the investigation, the NTSB identified the following discrepancies with the EAFR's CVR audio recordings:

- '*only a small percentage of the dynamic range*' was used to record the crew audio channels
- The cockpit area microphone (CAM) channel had *'excessive cockpit background noise that obscured the inter-crew's conversations both during the airborne and ground portions of the flight'.*
- Superimposed on the crew channels were multiple *'full volume clicks and pops that appeared randomly throughout the recording'.*

The NTSB categorised the quality of CVR recordings using its *'CVR Quality Rating Scale'* which has five ratings: 1) unreadable 2) poor 3) fair 4) good and 5) excellent. The NTSB categorised the EAFR CVR recordings for the Boeing 787-8 registration JA829J as *'Fair'* which it defines as:

> *'The majority of the crew conversations were intelligible. The transcript that was developed may indicate passages where conversations were unintelligible or fragmented. This type of recording is usually caused by cockpit noise that obscures portions of the voice signals or by a minor electrical or mechanical failure of the CVR system that distorts or obscures the audio information.'*

The NTSB concluded that:

> *'The poor audio recording quality of the enhanced airborne flight recorder could impede future aircraft investigations because the recorded conversations and other cockpit sounds might be obscured.'*

To address this the NTSB made the following Safety Recommendation to the FAA:

> *'Require Boeing to improve the quality of (1) the enhanced airborne flight recorder radio/hot microphone channels by using the maximum available dynamic range of the individual channels and (2) the cockpit area microphone airborne recordings by increasing the crew conversation signals over the ambient background noise. (A-14-126)'*[5]

Footnote

[5] The *'radio/hot microphone channels'* as stated in NTSB Safety Recommendation A-14-126 refer to the three crew audio channels.

As of April 2018, NTSB Safety Recommendation A-14-126 remains 'OPEN', awaiting a final response from the FAA.

When both EAFRs fitted to G-ZBKF were replayed by the AAIB, the CVR recordings exhibited the same characteristics to those previously identified by the NTSB, with approximately 10% of the available dynamic recording range used when the crew headset microphones were in use. Subsequently the AAIB became aware that the Australian Transport Safety Bureau (ATSB) and the Bureau d'Enquêtes et d'Analyses pour la Sécurité de l'Aviation Civile (BEA) of France had also experienced the same issues when reviewing CVR recordings from Boeing 787 aircraft.

Further to the previous findings of the NTSB, the AAIB also identified that when the flight crew of G-ZBKF had used their oxygen masks, the full dynamic recording range of the crew CVR channels was used, with occasional clipping of the signal. Figure 4 reflects the difference in dynamic recording range when the flight crew used the headset and oxygen mask microphones.

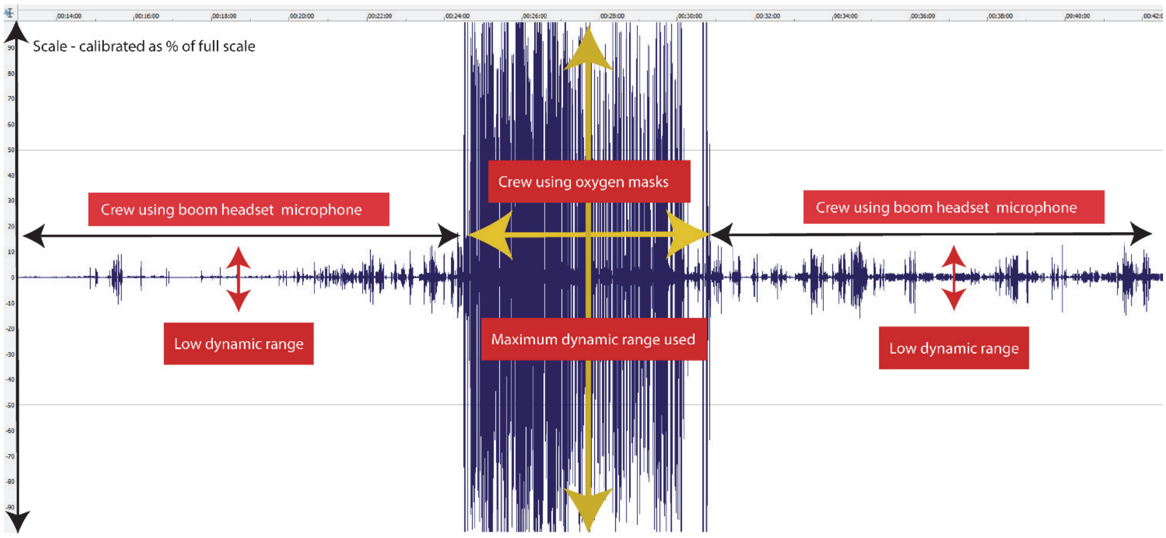

Figure 4

G-ZBKF – CVR waveform of crew channel showing difference in use of available dynamic recording range between headset and oxygen mask microphone signals

EAFR operation and readout

The aircraft is fitted with three audio control panels (ACPs), one for each crew position (commander, co-pilot and observer). Each ACP digitises the respective crew member's communications and transmits this as digital audio data packets over the aircraft's Avionics Full Duplex Switched Ethernet (AFDX) network to the EAFR. The data packets include a 'time stamp' that is acquired from an integral time reference source within each ACP. The CAM signal is provided as an analogue voltage, which the EAFRs digitise prior to recording.

Due to transport latencies of the AFDX network, and 'drift' between the ACPs internal time reference sources, corrections are required to ensure that the crew and CAM audio channels are synchronised[6] during replay. The EAFR CVR readout is made using a ground-based software utility called the Integrated Ground Software (IGS), which is produced by the manufacturer of the EAFR. IGS is used by the AAIB, other safety investigation authorities and operators.

The AAIB initially replayed the EAFRs fitted to G-ZBKF using IGS software version 2.11. Analysis of the audio found that each crew channel contained erroneous '*full volume clicks and pops'*. The AAIB subsequently contacted the manufacturer of IGS for assistance, who provided IGS version 2.14, advising that this included several refinements to the alignment process applied to the crew and CAM channel. The recordings from G-ZBKF were reprocessed and the '*full volume clicks and pops'* were no longer present. The IGS manufacturer subsequently confirmed that version 2.11 and earlier versions of IGS had inadvertently incorporated '*full volume clicks and pops'* into the audio.

The AAIB has notified the NTSB, other safety investigation authorities, and the operator of G-ZBKF of these findings. The IGS manufacturer is also considering notifying other operators of the need to update the IGS software to resolve this anomaly.

Certification of Boeing 787 EAFR CVR system

The certification of the Boeing 787 EAFR CVR system consisted of two distinct parts. The first related to the certification of the EAFR itself, which was certified by its manufacturer as meeting the requirements of FAA Technical Standard Order (TSO) C123B, 'Cockpit Voice Recorder Equipment'. The second part of the certification process related to the CVR system fitted to the aircraft, which was certified by the aircraft manufacturer as meeting the FAA operating rules contained in Title 14 of the Code of Federal Regulations (14 CFR) PART 25, Subpart F, 25.1457 – Cockpit Voice Recorders.

TSO-C123B required that the EAFR met the minimum performance standard as defined in the European Organization for Civil Aviation Equipment (EUROCAE) document ED-112[7] which includes aspects such as the minimum crash survivability of the recorder. ED-112 also included Chapter I-6 that provided requirements for verifying the installed performance of the CVR system. This included:

- *'For each newly installed system, the quality of the recording shall be established by analysis of information recorded on the ground and in flight.*
- *Position the microphone for recording general cockpit sounds, voice communications originating at the pilot and co-pilot stations, voice communications of other flight crew members in the cockpit when directed to those stations…..*

Footnote

6 IGS calculates time synchronisation adjustments using a combination of the recorded arrival time of each ACP audio data packet at the EAFR, and the time that each data packet was transmitted from the ACPs. IGS then adds or removes audio samples from the three crew channels so that they align with the CAM channel, which is used as the master time source.

7 ED-112 - Minimum Operational Performance Specification for Crash-Protected Airborne Recording Systems.

- *In general, the proper recording level will be confirmed using the oscilloscope to show that the full recording dynamic range has been achieved without excessive clipping of peak signals. A check should be made to confirm that adequate signal to noise ratios exist for all significant input signals*[8]
- *The presence of cockpit sounds, crew speech and audible warnings should be confirmed on the area microphone channel.'*

However, in TSO-C123B, the FAA permitted a number of exemptions, including the requirement to meet the performance standards in ED-112 Chapter I-6. The FAA advised that the rationale for the exception was that TSOs normally relate to the specification and performance of equipment as 'standalone' units, and that guidance on the installed performance of systems is typically provided in an Advisory Circular (AC)[9]. When the Boeing 787 CVR system was certified, AC 25.1457-1A dated 1969 was applicable to the CVR system. This provided guidance on the position of the CAM relative to the cockpit loud speakers, but it did not provide guidance on how to verify the installed performance of the CVR system.

As a result of the exception to comply with ED-112 Chapter I-6, and a lack of guidance in AC 25.1457-1A, there was no requirement for the aircraft manufacturer to demonstrate that the performance of the Boeing 787 CVR system met any industry approved guidance or standard.

Following the NTSB's findings on the performance of the CVR system fitted to aircraft registration JA829J, it made this Safety Recommendation to the FAA:

'Either remove the current exception to European Organization for Civil Aviation Equipment ED-112A, "Minimum Operational Performance Specification for Crash Protected Airborne Recording Systems" chapter I-6 in Technical Standard Order 123B, "Cockpit Voice Recorder Equipment," or provide installers and certifiers with specific guidance to determine whether a cockpit voice recorder installation would be acceptable. (A-14-127)'

The FAA responded to NTSB Safety Recommendation A-14-127 by publishing AC 20-186. This provides guidance on determining that CVR and FDR systems '*perform as intended*' and defines the test requirements as those specified in ED-112A Chapter I-6 (CVR) and Chapter 2-5 (FDR). However, AC 20-186 is not applicable to the CVR system fitted to the Boeing 787 as the EAFR was certified prior to the applicability of the AC.

Footnote

8 In this context, the dynamic range of the audio recording is the ratio between the largest and smallest recorded signals. A non-optimised use of the dynamic range can affect the overall 'quality' of a digital recording due to a low signal to noise ratio and quantisation noise.

9 An AC is not mandatory or a regulation, but can provide information on an acceptable means of compliance when applying for certification.

On 15 November 2016, the NTSB responded to the FAA, stating:

> *'We believe that the AC [20-186] contains good guidance, and that, if the guidance were applied to the Boeing 787 CVR installation, the installation would fail in multiple ways.'*

However, the NTSB concluded that AC 20-186 met the intent of the Safety Recommendation and classified it as '*CLOSED-ACCEPTABLE ACTION*'.

In August 2017, the AAIB and NTSB met with the aircraft manufacturer and FAA to discuss the certification process applied to the Boeing 787 CVR system. The FAA advised that the evaluation of the system performance was delegated to the aircraft manufacturer, who carried out a series of ground tests and a 'scripted' flight test (based on that provided in ED-112, which was applicable at the time). The recordings from these tests were evaluated by an Authorized Representative (AR)[10] who had worked on previous CVR certification programmes with the manufacturer.

The acceptance criteria applied by the AR focused on the intelligibility of 'voice communications', in accordance with the regulation[11] that states '*voice communications of flight crewmembers'* shall be recorded. Aural alerts, such as those generated by TAWS, were also confirmed as being recorded. The AR subsequently provided confirmation that the system performance was acceptable and the FAA granted approval.

The aircraft manufacturer further commented that the evaluation process applied to CVR systems is 'subjective' as it considered that ED-112 and the updated version ED-112A, lacked detail in providing 'objective' measurements.

Dynamic recording range of crew channels

The aircraft manufacturer stated that it had been aware of the difference between the recorded dynamic ranges of the boom headset and oxygen mask signals prior to certification of the Boeing 787. The manufacturer advised that the reason for this difference is that in normal operation the output signal from the headset microphone is about 0.1 volt, whereas, the output signal from the oxygen mask microphone is much higher, at about 2.0 volt. The ACP microphone input is designed[12] to accept an analogue voltage range of between 0 volt and 2.1 volt (peak-to-peak) and therefore when digitised, the boom headset microphone signal is at a much lower level than the oxygen mask signal.

The Boeing 787 audio system combines the crew headset/oxygen mask microphone signals with the sidetone[13] signal. The aircraft manufacturer advised that during the system design

Footnote

[10] An AR is a qualified individual who may act, for certain functions, on behalf of the regulator (FAA).
[11] (14 CFR) PART 25, Subpart F, 25.1457.
[12] RTCA DO-214 'audio systems characteristics and minimum operational performance standards for aircraft audio systems and equipment'.
[13] The sidetone signal is the audio reproduced through the headsets speakers consisting of sound of the pilots own voice, RTF and interphone communications. It may also include other background sounds picked up by the headset microphone.

it had aimed to comply with the requirement in ED-112 that stated '*at the summing point, the microphone signal exceeds the level of its corresponding sidetone signal on a high percentage of occasions*'. This was to ensure that crew speech would not be inadvertently masked by higher amplitude RTF signals, such as ATC transmissions.

During development, the aircraft manufacturer found that the sidetone signal level exceeded the crew headset microphone signal when combined. The manufacturer resolved this by attenuating the sidetone signal, which resulted in the signal using about 5% of the available recordable dynamic range.

Analysis of the G-ZBKF incident recording shows that when the sidetone signal is combined with the oxygen mask microphone signal, the sidetone is predominantly masked by the much higher amplitude oxygen mask signal.

Certification process used in Europe by the EASA

For aircraft certified by the EASA, the performance of CVR systems is to be measured against the requirements currently specified in ED-112A[14]. For aircraft manufactured in France, the BEA participate informally in the approval process by reviewing pre-certification CVR recordings, and providing feedback on areas that the manufacturer may consider improving upon. The review process is 'subjective' in nature.

European certification guidance material

EASA has advised that as part of Rule Making Task (RMT).0249 it intends to update its guidance material on demonstrating that the quality of the CVR recording complies with the corresponding certification standards. The update is based on EASA Certification Memorandum (CM)-AS-001, which is to be consolidated with views provided by the European Flight Recorder Partnership Group (EFRPG)[15].

Review of CVR recordings from B787 and other aircraft types

The AAIB performed a comparative review of the Boeing 787 EAFR CVR recordings against a range of other turbofan powered aircraft, which included the Boeing 747-400, 777, 767, 737-800, 737-300, Airbus A380, A340, A330, A320 and Embraer 190. These recordings were all from solid-state CVRs, meaning that the relative use of the dynamic recording ranges were directly comparable.

The results of the review indicate significant variation between aircraft types of the 1) recorded dynamic range of the crew channels and 2) ambient background noise levels compared to crew speech recorded on the CAM channel. Figure 5 and 6 show the difference between the crew and CAM channels of nine different aircraft types.

Of the recordings, the lowest recorded dynamic range when the headset microphone was in use was the Boeing 787 and the highest was the Boeing 757. For the CAM channel, the

Footnote

[14] or '*any later equivalent standard produced by EUROCAE*'

[15] The EFRPG is an independent voluntary group of European flight recorder experts represented by manufacturers, national aviation authorities and safety investigation authorities.

Boeing 787 and Airbus A380 had the highest levels of background ambient noise which, depending on the phase[16] of flight, could mask crew conversation. The Airbus A320 CVR system provided a reasonable balance of the use of the dynamic recording ranges and level of ambient noise on the CAM channel that meant that the majority of sounds and communications could be readily transcribed.

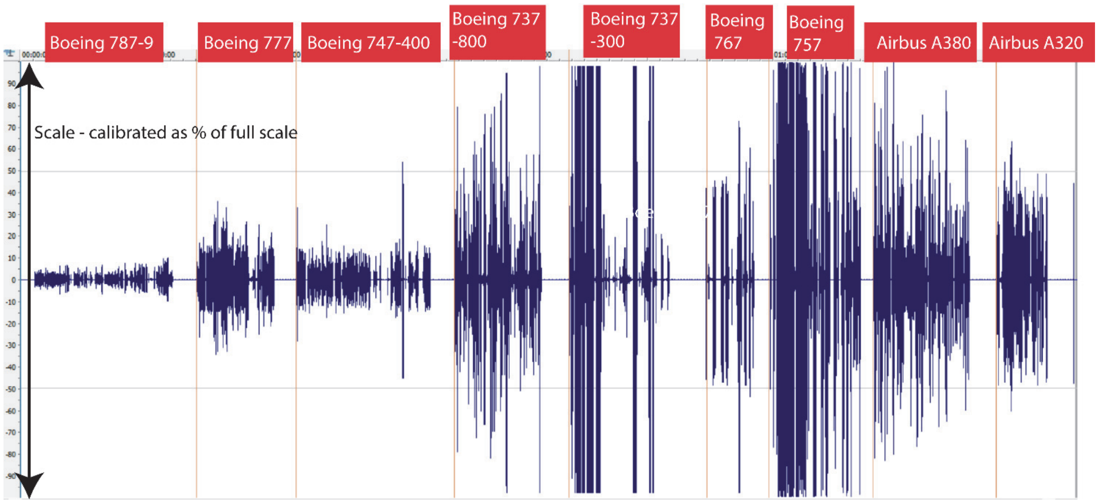

Figure 5

Nine aircraft types - differences in dynamic range used for recording of crew channels

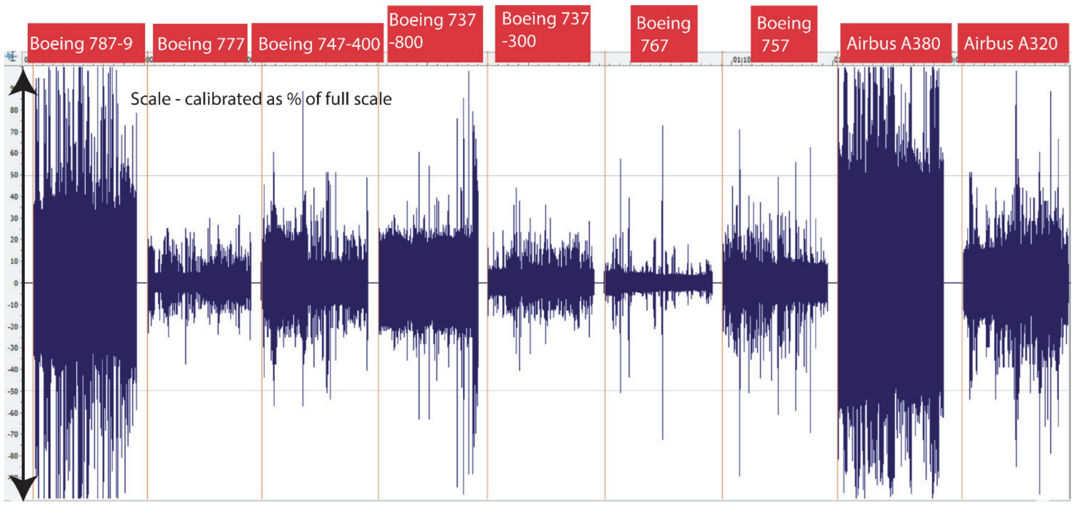

Figure 6

Nine aircraft types - differences in dynamic range used for recording of CAM channel

Footnote

16 Background sound levels were significantly increased during takeoff, when the aircraft was configured for landing and when high engine power settings were used in conjunction with reverse thrust.

During the meeting in August 2017 (between the AAIB, NTSB, aircraft manufacturer and FAA), several CVR recordings[17] were replayed, which included the Boeing 787-8 EAFR CVR flight test recording. It was noted that the intelligibility of the crew communications recorded on the CAM channel during the flight test appeared 'clearer' compared to the CAM recording from a 'routine flight'.

The difference between the two recordings may have been due to the 'scripted' nature of the flight test, resulting in the crew speaking louder and placing more emphasis on clarity than normal. However, evaluation of the Boeing 787 recordings also showed that when the aircraft equipment cooling system was turned 'off' after flight, there was a notable reduction in the ambient noise recorded on the CAM channel. This indicates that airflow from the equipment cooling system in the cockpit was contributing significantly to the 'high' ambient noise on the CAM. It was also commented that the CAM recording gave the impression that the cockpit environment was noisy and did not truly represent the actual ambient sound if a human observer were listening in the cockpit.

Speech Transmission Index (STI) analysis

There are several types of objective analysis technique that can be applied to audio to ensure that a minimum standard of speech intelligibility is achieved. One such technique is the STI, which uses a combination of test tones that are recorded and analysed to provide an index score. An index of one represents perfect speech intelligibility and zero is unintelligible.

ED-112, and the later ED-112A[18], both specify that an STI test is performed on the CVR unit, with the crew channels and CAM channel requiring a minimum index score of 0.75 (good to excellent) and 0.85 (excellent) respectively. However, this STI test is not applicable to the installed performance of the CVR system.

Analysis

Operations

The flight crew were appraised of issues related to the cabin pressurisation system during their ground briefing before the incident flight on 29 April and discussed those relating to temperature control again during the climb. Shortly after establishing the aircraft in the cruise, the crew were alerted to a higher than normal cabin altitude by the EICAS. They quickly recognised the relevance of this and promptly took action to avoid a cabin altitude exceedance by requesting a descent to FL310. The passenger oxygen was manually deployed. The cabin altitude continued to increase and as it reached 10,000 ft, the commander initiated an emergency descent to FL100. The cabin reached a maximum altitude of 10,429 ft.

When the pressurisation warning occurred, the crew carried out the appropriate QRH drills in a timely and comprehensive manner. The emergency descent was conducted in accordance with SOPs and was well co-ordinated with ATC.

Footnote

[17] Recordings from routine flights, not from safety events.
[18] Chapter I-3 'minimum performance specification under standard test conditions'.

In the cabin, the cabin decompression PRA was reported as not being audible. Whilst the passenger oxygen masks deployed, the lack of an apparent accompanying PRA caused confusion amongst the cabin crew as to the exact nature of the situation. Accordingly, the initial response by the cabin crew was uncoordinated and ineffective, with the majority of the cabin crew reacting by returning their service carts to the galleys. The unstructured response of the cabin crew meant the reaction of the passengers was not effective and some passengers did not don their oxygen masks.

The relatively low altitude exceedance of just over 10,400 ft, which lasted for only a short duration due to prompt flight crew action, reduced the possibility of medical effects on cabin crew and passengers. However, had the cabin altitude continued to climb the effects of not donning oxygen masks would have been more serious.

The CSD recognised that the situation was confused and took the initiative to enter the cockpit to clarify with the flight crew. She was, however, unable to return to the cabin until the aircraft levelled at FL100, so the situation in the cabin was not resolved until after the conclusion of the emergency descent.

Engineering

The loss of cabin pressure was due to a compromised ECS. This was because of a number of factors:

1. The incorrect fitment of the sleeve and coupling joining the replaced lower recirculation fan to the inner recirculation duct in the right air conditioning (AC) system allowing a leak of cabin air.
2. The maintenance organisation did not identify that the continuing air leakage, which persisted as a consequence of this incorrect fitment of the sleeve on the right AC system, would affect the pressurisation system performance if the aircraft were flown with the left AC unit disabled.
3. Fracture of a component (tie-rod) within the L2 CAC of the left air conditioning system, resulting from a manufacturing quality control shortfall.
4. Damage to the L1 CAC of the left AC system as a result of ingestion of a liberated part of the failed L2 CAC tie-rod and its nut, leading to the disabling of the left AC system before flight.

It is not known whether further physical movement of the components of the incorrectly fitted coupling, on the right AC unit, occurred during the incident flight, when the right unit was called upon to pressurise the aircraft on its own.

The incorrect fitment of the coupling and sleeve was partly a consequence of the inaccessibility of those components in the right AC unit and the lack of tactile feel enabling an incorrectly assembled coupling to be easily identified. The resulting leakage from the recently assembled coupling was identified by the AHM Customised Alert and analysed by the operator's Technical Support department. It was decided that, as the aircraft was operating satisfactorily with the leakage present, there were no other abnormal indications and a planned maintenance input was scheduled for the near future, investigation of the leak could be aligned with that input. This decision in turn appears to have been influenced by the perception of the high frequency of data and messages received by AHM on the 787 fleet.

The manufacturing quality shortfall in the L2 CAC has been identified by the component supplier as a batch problem and the location of components from that batch established. The potential for damage to the L1 CAC resulting from the ingestion of the failed part of the L2 CAC was not explicitly considered during the original system Fault Mode Effects Analysis (FMEA) carried out by the manufacturer. However, other system-level failures that can cause loss of both CACs in one pack had been considered and accounted for at the design stage and the manufacturer is not aware of any other event where the failure of a CAC has resulted in damage to, or failure of, the second CAC on the same AC pack.

The decision to dispatch the aircraft

The decision to dispatch the aircraft with the left AC system disabled did not take account of the unresolved leakage problem on the right AC system. Procedures of the operator, common within the industry and consistent with the approved MEL, permitted dispatch of the aircraft with one AC unit disabled provided certain flight routing constraints were observed. In this instance the procedures did not ensure that the operating system would continue to function, with the normal level of reliability. Although the individual who authorised the dispatch with one AC system disabled was provided with information, including details of the status of the right system, that individual was not aware of the incorrect fitment of the sleeve and coupling or its influence on the performance of the pressurisation system.

CVR performance

The full volume clicks and pops that appeared randomly throughout the recording on the crew channels on the incident flight was later confirmed as being introduced by the EAFR manufacture's ground-based replay software, IGS. A later version of the software, version 2.14, resolved this anomaly.

The review of CAM recordings for the Boeing 787 indicated that airflow in the cockpit from the equipment cooling system appeared to contribute to the high level of ambient background noise, as a significant reduction in background noise is apparent on the CAM recording when the system was turned off. Discussions further indicated that the level of ambient background noise recorded by the CAM may not truly represent that experienced by a human observer in the cockpit. This indicates that the CAM installation is not optimised.

The NTSB has previously made Safety Recommendation A-14-126 to address the performance of the CAM recording on the Boeing 787. As of April 2018 this Safety Recommendation remains 'OPEN', awaiting a final response from the FAA. Therefore, although issues were found in this incident that are similar to those that caused the NTSB to issue Safety Recommendation A-14-126, the AAIB considers that it is not necessary to make a further Safety Recommendation on this subject.

However, this AAIB investigation has highlighted an additional issue with the Boeing 787 CVR performance. A significant difference exists between the recorded dynamic range when the headset and oxygen mask microphones are used. The aircraft manufacturer attenuated the sidetone signal so that ATC communications did not inadvertently mask the crew speech when using the headset microphone. However, when the oxygen masks are used, the sidetone signal can be easily obscured due to the much higher signal level of the oxygen mask microphone. The aircraft manufacturer was aware of this during certification, but considered that it was acceptable.

Although audio processing techniques may be applied to reduce the effect of the issues identified with the CVR recordings of the crew and CAM channels, it is not always possible to recover quieter background sounds and speech. Consequently, information that may be of significance to an investigation may be lost. Therefore, the following Safety Recommendation is made:

Safety Recommendation 2018-008

It is recommended that the Federal Aviation Administration require Boeing to modify the audio system fitted to the Boeing 787, so that sidetone signals recorded on the cockpit voice recorder crew channels are not masked when flight crew oxygen mask microphones are in use.

The review of CVR systems from different aircraft types, including the Boeing 787, has highlighted the significant variation in the installed performance of these systems, with differences in the use of the available dynamic recording range and levels of background noise on the CAM channel that can affect the intelligibility of the recordings.

The CVR unit is subject to qualitative performance testing in ED-112A that includes an 'objective' measurement in the form of an STI index test. However, the installed performance of CVR systems is currently evaluated using a 'subjective' process. Therefore, differences in opinion can exist as to whether the performance of the CVR system is acceptable.

If an 'objective' analysis measurement, such as the STI index, could be applied to the testing of the installed performance of the CVR system, this would enable the setting of a minimum standard of performance that manufacturers could demonstrate. However, it is not known whether such qualitative measurements can be successfully applied to CVR system recordings. Therefore, the following Safety Recommendation is made:

Safety Recommendation 2018-009

It is recommended that the European Aviation Safety Agency initiate a review to consider whether a repeatable and objective analysis technique can be applied to audio recordings to establish consistent installed performance of cockpit voice recorder systems.

If this review shows that a qualitative measurement can be successfully applied, the EUROCAE document ED-112 (currently ED-112A) should be updated to include this information. Therefore, the following Safety Recommendation is made:

Safety Recommendation 2018-010

It is recommended that the European Organization for Civil Aviation Equipment (EUROCAE) amend their document '*Mininimum Operational Performance specification for Crash Protected Airborne Recorder Systems*' (currently ED-112A) to include a repeatable and objective analysis technique to establish consistent installed performance of cockpit voice recorder systems.

Conclusions

Loss of cabin pressure

The inability of the aircraft to maintain normal cabin pressure was found to be have been caused by the right lower recirculation fan becoming detached from the inner duct, which allowed air from the AC unit to leak to atmosphere rather than provide the required cabin pressure on a sector where the left air conditioning system had been disabled before flight.

When the aircraft was operated during the incident flight with only the right air conditioning system available, the system did not have sufficient capacity to overcome the effect of the leak. It was concluded that the lower right recirculation fan had not been correctly attached to the inner duct when the fan had been installed on 18 April 2017.

Cabin PRA

The deployment of the oxygen masks in the cabin was accompanied by the cabin decompression PRA. However, the level of the PRA was reported as not being audible. The apparent lack of an accompanying PRA caused confusion amongst the cabin crew as to the exact nature of the situation and the initial response by the cabin crew was uncoordinated, with some passengers not donning their oxygen masks.

The cause of the low volume of the PRA was subsequently identified as a software issue in the cabin audio system, whereby the volume of the announcement was attenuated following use of the cabin address system from the cockpit.

CVR performance

Digital 'spikes' evident in the crew channels, as identified by the NTSB during the readout of the EAFRs fitted to accident aircraft registration JA829J, has been subsequently confirmed as being introduced by the EAFR manufacturers ground replay software, IGS. This issue has now been resolved and the AAIB has communicated this to other accident investigation laboratories.

The NTSB has previously identified deficiencies in the quality of the CVR recordings on the Boeing 787 and issued Safety Recommendation A-14-126 to address these. The AAIB has further identified that ATC communications can be masked when the flight crew are using the oxygen masks, due to the disparity in the recorded dynamic range of the sidetone and oxygen mask signals. A Safety Recommendation has been made to address this.

Testing of the installed performance of CVR systems is currently largely subjective, which has led to variation in their performance. Three Safety Recommendations are made to address this.

Safety actions

Following the serious incident to G-ZBKF on 29 April 2017 a number of safety actions have been taken:

- The aircraft manufacturer has revised the Aircraft Maintenance Manual (AMM) installation procedure for the lower recirculation fans.
- The aircraft manufacturer has made changes to its Fault Isolation Manual for Maintenance Message 21-34127, the message triggered by Maintenance Alert Message 21-0209-C740 from the AHM. This includes checking for recent maintenance activity on the cabin pressurisation system, including the lower recirculation fans.
- The aircraft manufacturer has made an update to the AHM 'maintenance alert' logic for message 21-0209-C740. This logic helps to filter out only those instances that are deemed valid and should be presented to the airline.
- The operator of G-ZBKF has revised its process for dealing with AHM 'maintenance alert' message 21-0209-C740.
- The operator of G-ZBKF is updating the audio system software fitted to its fleet of Boeing 787 to prevent the volume of the cabin decompression PRA from being attenuated.