INCIDENT

Aircraft Type and Registration:	Boeing 757-204, G-BYAO
No & Type of Engines:	2 Rolls-Royce RB211-535E4-37 turbofan engines
Year of Manufacture:	1994
Date & Time (UTC):	22 October 2006 at 0835 hrs
Location:	Over North Sea/London Stansted Airport, Essex
Type of Flight:	Commercial Air Transport
Persons on Board:	Crew - 7 Passengers - 160
Injuries:	Crew - None Passengers - None
Nature of Damage:	None
Commander's Licence:	Airline Transport Pilot's Licence
Commander's Age:	43 years
Commander's Flying Experience:	11,000 hours (of which 6,000 were on type) Last 90 days - 206 hours Last 28 days - 39 hours
Information Source:	AAIB Field Investigation

Synopsis

Shortly after reaching cruise altitude on a scheduled passenger flight from Newcastle to Larnaca, a blue haze was observed in the passenger cabin. A precautionary diversion was made to London Stansted, where an emergency evacuation was carried out successfully. One cabin crew member initially had difficulty in opening the rear cabin doors, due to insufficient force being used.
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The blue haze could not be reproduced on initial investigation, which included engine ground runs. A planned post-maintenance proving flight was aborted during the takeoff roll when smoke entered the flight deck and cabin. Further investigation, which included ground runs at higher engine power settings, identified the source of the smoke to be the No 2 (right) engine. The cause was determined to be a fractured No 1 bearing floating seal ring, which had allowed engine oil to leak into the compressor airflow path and to be ingested into the bleed air system, which provides air to the cabin air conditioning system.

Two Safety Recommendations are made.

History of the flight

The aircraft was operating a scheduled passenger flight between Newcastle and Larnaca. The takeoff and climb were uneventful. Approximately five minutes after reaching its cruising level of FL 370 over the North Sea, the cabin manager (CM) contacted the flight crew via interphone to report a "haze" and an unusual smell in the cabin. She commented that the haze seemed worse in the rear of the cabin, but could not smell anything from her position at the front galley. On inspecting the cabin the commander saw a fine blue-grey haze, but could not detect any unusual smells. He returned to the flight deck, having requested that the CM report any change. She contacted him again shortly afterwards to advise that the smoke was getting worse.

The commander instructed the co-pilot to declare a 'PAN' to Maastricht ATC, with whom they were already in contact, to request a descent and direct routing to Stansted, approximately 100 nm distant. The CM then entered the flight deck to be briefed.

Having established the aircraft in a descent, the pilots commenced the Quick Reference Handbook (QRH) *'SMOKE OR FUMES – AIR CONDITIONING'* checklist. The first item on the checklist related to the use of oxygen masks and smoke goggles; these were not used initially, as no fumes could be detected on the flight deck at this time. In accordance with the operator's training, but not specified in the QRH procedure, the pilots paused for a few minutes between specific checklist items, to determine if the actions taken had been effective. When this checklist was complete the flight crew actioned the '*SMOKE OR FUMES REMOVAL*' QRH procedure.

Whilst descending through FL200 the aircraft was handed over to the London Terminal Control Centre (LTCC). The CM advised the flight crew that the haze appeared to be worsening and that some passengers were starting to feel unwell. Fumes were then detected on the flight deck, which prompted the pilots to don oxygen masks and declare a 'MAYDAY'. LTCC gave immediate clearance for a further descent and provided radar vectors to position the aircraft for an 8 nm final for Runway 23 at Stansted. The commander briefed the CM, giving the time to touchdown and stating his intention to stop on the taxiway after landing before determining if an evacuation was required. He also briefed ATC of his intentions. The passengers were informed via the Passenger Address (PA) system of the intention to divert to Stansted.

The landing was uneventful and the aircraft vacated the runway using the first available exit. When clear of the runway, but still remote from the terminal area, the commander brought the aircraft to a halt, as briefed, and set the parking brake. The CM reported via the interphone that smoke and fumes were still present in the cabin and as no airstairs were readily available, the commander chose to order an evacuation. He shut down the engines, checked that the aircraft was unpressurised and then gave the command over the PA system to evacuate.

The front right (R1) cabin door was not opened because the senior cabin crew member seated adjacent to it noted that few passengers were seated nearby, and those that were could evacuate via the front left (L1) door. The cabin crew member operating the rearmost doors first attempted to open the left rear door (L4), but was unable to do so. She then attempted to open the right rear door (R4) and had the same problem. She returned to the L4 door and, by pushing it "really hard" was able to activate the door power assist mechanism. The door then opened fully and the escape slide deployed automatically. She was then able to do likewise with the R4 door and passengers then used both rear exits. All the escape slides deployed satisfactorily on those doors that were opened.

After completing the shutdown checks the commander and co-pilot inspected the cabin to check that the evacuation was complete, before exiting via the L1 door.

Airport Fire and Rescue Service (AFRS) personnel marshalled passengers on the ground and directed them to waiting coaches. Some passengers received minor abrasions when descending the slides, but there were no other reported injuries.

Aircraft information

Cabin exits

The aircraft had eight cabin doors. These were designated L1 to L4 sequentially along the left side from front to rear and R1 to R4 for the corresponding doors on the right side. All eight exits were available for use in emergency and were equipped with inflatable escape slides and 'door assist' pressure bottles; the latter are designed to drive the door hinge mechanism to force the doors open during evacuation. 'Arming' a door (ie placing it in automatic mode) engages the activation mechanism for the escape slide and also arms the door power assist mechanism. When the door is opened, the door power assist operates and the escape slide is deployed automatically, allowing rapid egress of the passengers in an emergency.

Powerplant

The aircraft was powered by two Rolls-Royce RB211-535E4-37 turbofan engines. The engines supply compressed 'bleed' air to various aircraft systems, including the cabin pressurisation and air conditioning systems.

The left and right bleed air systems normally receive air from their respective engine compressor via a 'low stage' valve, positioned close to the forward end of the compressor. At lower engine power settings, the pressure available from the early stages of the compressor may be insufficient for the requirements of the air conditioning and other systems. A second, 'high stage' valve located in the later compressor stages then opens to supply higher pressure bleed air. The 'changeover' occurs at an Engine Pressure Ratio (EPR) of approximately 1.14 at sea level.

The engine lubrication system supplies pressurised oil to the main shaft bearings. Various methods are used to ensure that the air pressure external to the bearing chambers exceeds the local oil pressure, to prevent engine oil from escaping and contaminating the compressor air flow. If this should occur, oil mist can enter the bleed air system causing odour, fumes or smoke to enter the cabin via the air conditioning system. The forward (No 1) bearing on the low pressure (LP) shaft utilises a continuous cast iron seal ring as part of its sealing arrangement. Its purpose is to ensure that a positive air pressure gradient is maintained to prevent oil from escaping from the bearing housing.

Air conditioning system

Air conditioning is achieved by identical left and right air conditioning packs that are supplied with bleed air from the respective engines. Conditioned air from the packs flows into a common mix manifold where it is mixed with recirculated cabin air. The mixed air is then supplied to the passenger cabin. The flight deck is provided with conditioned air taken from the left pack duct, upstream of the mix manifold.

Each air conditioning pack is controlled via its own pack control rotary selector switch. The pack switches are normally set to the 'AUTO' position, which provides fully automatic control of the pack outlet air temperature. When a pack is operating, its pack control valve is modulated to control the pack airflow to a scheduled rate based on altitude. Selection of the pack control switch to OFF closes the pack control valve, shutting off the flow from the respective air conditioning pack.

Aircraft examination

Aircraft initial examination

Initial visual and borescope examination of the engines did not reveal any evidence of oil contamination in the compressor airflow path. The Boeing 757 Fault Isolation Manual (FIM) procedure for troubleshooting air conditioning smoke and/or fumes in the cabin was actioned. This culminated in engine ground runs being performed at EPR settings of 1.1 and 1.14, whilst selecting different bleed air sources and air conditioning packs, to try to isolate the source of the smoke/fumes. The latter engine power setting is just high enough for the high stage bleed valve to close, allowing air to be supplied via the low stage valve.

Examination of the 4L and 4R cabin doors did not identify any reason why the door operating forces should have been higher than expected.

The aircraft operator then planned to conduct a proving flight. During the takeoff roll, smoke appeared on the flight deck, causing the flight crew to abandon the takeoff at around 121 kt. Smoke was also visible in the cabin in the region of the L3 and R3 exit doors. At idle power no further smoke was generated on the flight deck.

Aircraft further examination

The aircraft was then subjected to further examination and testing to identify the source of the smoke; this included engine ground runs at higher power settings than previously used. This proved successful in generating smoke in the cabin and it was established that smoke was associated with the No 2 engine. After completion of these engine runs it was observed that the No 2 engine oil level indication was significantly lower than that of the No 1 engine.

Engine strip examination

The No 2 engine was removed and strip examined by the manufacturer under AAIB supervision. Pooling of oil was visible in the fan casing; this had emanated from the Intermediate Pressure Compressor (IPC) splitter fairing. Borescope examination revealed streaking of oil on and aft of the IPC Stage 5 compressor blades. When the fan assembly was removed, oil wetting of the internal bore of the LP compressor disc and the front of the LP shaft was visible. These are areas which are not normally lubricated. Removal of the LP shaft revealed that the No 1 bearing floating seal ring had fractured in two places.

The fractures were found to be orientated both radially and longitudinally, permitting the seal ring to open out in diameter. This had increased the clearance around the journal and created gaps in continuity of the seal ring, allowing oil to escape from the LP shaft front bearing housing. Examination by the manufacturer suggested that the cause of failure was tensile fracture, with a possible fatigue mechanism at the origin. It was considered that both fractures were initiated by the drag between the static seal ring carrier plates and the rotating LP shaft. The bore of the seal ring was uniformly worn and had no obvious areas of concentrated heavy rub. Magnetic particle inspection showed no other cracks to be present. The material properties, microstructure and hardness of the seal ring were found to be satisfactory. Its cross-sectional dimensions were in accordance with the drawing, with the exception of the outer diameter chamfers which were oversize, but this was not considered to be influential in this event.

The hours and cycles of the fan module did not place it near the lower or higher ends of the fleet experience. Records showed that only three other known seal ring failures had occurred in the operating history of the RB 211-535 engine series, which had completed over 52 million flight hours at December 2008. Given that this engine type has been in widespread use for about 20 years, a very large number of operating hours and cycles have been accumulated with only a small number of failures of this particular component.

Recorded data

The aircraft was equipped with a Flight Data Recorder (FDR) and Cockpit Voice Recorder (CVR) capable of recording a minimum duration of 25 hours of data and 30 minutes of audio respectively. Both were successfully replayed at the AAIB.

The FDR data indicated the following:

- The thrust setting on both engines at the time the in-flight haze in the cabin was reported was about 86% N_1, corresponding to an EPR of 1.6.
- During the initial troubleshooting after the diversion to Stansted, except for the time spent at idle thrust, the engines were predominantly operated at either 45% or 52% N_1, corresponding to EPRs of 1.1 and 1.14 respectively. The thrust setting for the No 2 engine momentarily reached 72% N_1 (1.29 EPR). This was the highest recorded during these initial engine runs.
- The engine thrust was stabilised at 89% N_1 (1.5 EPR) when the takeoff was rejected on the planned proving flight.
- During the subsequent troubleshooting the engines were operated at up to 89% N_1 (1.5 EPR).

The recorded data were consistent with the flight crew's recollection of the events during the incident, with the exception of the recorded positions of the air conditioning pack control valves. From shortly after engine start to the time the aircraft was shut down prior to evacuation, both left and right air conditioning pack control valves indicated they were in the open position. This was inconsistent with the flight crew's actions in accordance with the QRH, which required them to select each pack off in turn, to attempt to identify the source of the smoke or fumes. It was subsequently determined that the positions of the left and right pack control valves were incorrectly recorded due to a wiring error; this is believed to have occurred at aircraft build.

It was determined that the left and right pack control valve open and closed position signal wires had been erroneously connected at a point between the outputs from the left and right pack flow control cards and the inputs to the left and right bleed configuration cards. These signals should have been electrically isolated. This had the effect that when only one of the pack control valves was in the open position, both valves would indicate open, irrespective of the position of the other valve. Both valves would have also had to be in the closed position before a closed indication would have been provided. The wiring error would potentially result in the Flight Management Computer (FMC), Thrust Management Computer (TMC) and FDR being supplied with incorrect information. The aircraft manufacturer established that the operation of these systems would not have been significantly affected, with the exception of the FMC, where the performance calculations for single-engine operations would have given a maximum cruise altitude that was reduced by 200 ft. The aircraft manufacturer has since revised Chapters 22 and 34 of the Boeing 757 Aircraft Maintenance Manual to include tests to verify that the correct pack control valve position indications are provided to the thrust and flight management systems.

Additional information

Smoke/fumes removal procedures

The procedure actioned by the crew was contained in the operator's Quick Reference Handbook under the heading *'SMOKE or FUMES – AIR CONDITIONING'*; see Figure 1.

In order to identify a pack as a source of smoke, a pause is required after each pack control is selected OFF to determine if there has been any reduction in the amount of smoke or fumes. However, no such pause was specified in the procedure at the time of the event. The operator's pilots are advised during initial and recurrent training, which includes periodic revision of the procedure in a simulator, that a pause of some minutes may be required. In October 2007, Boeing revised the 757 QRH procedure to include the following statement after each pack selection to OFF:

> *'Wait 2 minutes unless the smoke or fumes are increasing'*

Previous AAIB investigation

AAIB bulletin EW/C2005/08/10 reported on an incident to a DHC-8-402 registration G-JECE, on 4 August 2005. Soon after initiating a descent, an oily smell was noticed on the flight deck, followed almost immediately by a build-up of smoke in the flight deck and cabin. The cabin crew donned smoke hoods, which caused appreciable communication difficulties. The flight crew actioned the initial part of the smoke checklist procedure, declared an emergency and carried out a diversion. The source of the smoke was determined to be an oil leak from the No 2 engine, which had caused an oil mist to enter the cabin air supply.

SMOKE OR FUMES – AIR CONDITIONING

Condition: A concentration of air conditioning system smoke or fumes is identified.

OXYGEN MASKS AND SMOKE GOGGLES
(If required).. ON

CREW COMMUNICATION (if required)........ ESTABLISH

RECIRCULATION FAN SWITCHES (Both)............... OFF
[Removes fans as possible source of smoke or fumes. Stops recirculation of smoke or fumes and increases fresh air flow.]

APU BLEED AIR SWITCH.................................... OFF

If smoke or fumes continue:

ISOLATION SWITCH.................................... OFF
[Isolates left and right sides of bleed air system.]
RIGHT PACK CONTROL SELECTOR........... OFF
[Removes right side of air conditioning system as possible source of smoke or fumes.]

If smoke or fumes continue:

RIGHT PACK CONTROL SELECTOR....... AUTO
[Restores right side of air conditioning system.]
LEFT PACK CONTROL SELECTOR...........OFF
[Removes left side of air conditioning system as possible source of smoke or fumes.]

Do not accomplish the following checklists:

PACK OFF
RECIRCULATION FAN

If smoke or fumes are persistent:

Declare an emergency and plan to land at the nearest suitable airport.

Accomplish SMOKE or FUMES REMOVAL checklist on page 757.11.10.

CHECKLIST... COMPLETE

Figure 1

QRH: Smoke or Fumes - Air Conditioning Checklist

Recognising the difficulty that flight crews often experience in identifying the source of smoke or fumes in the cabin, the bulletin contained the following safety recommendations to the European Aviation Safety Agency (EASA) and the US Federal Aviation Administration (FAA):

Safety Recommendation 2007-002

It is recommended that the EASA consider requiring, for all large aeroplanes operating for the purposes of commercial air transport, a system to enable the flight crew to identify rapidly the source of smoke by providing a flight deck warning of smoke or oil mist in the air delivered from each air conditioning unit.

Safety Recommendation 2007-003

It is recommended that the FAA consider requiring, for all large aeroplanes operating for the purposes of commercial air transport, a system to enable the flight crew to identify rapidly the source of smoke by providing a flight deck warning of smoke or oil mist in the air delivered from each air conditioning unit.

To date, the AAIB has not received formal responses to these recommendations.

Door operation in emergency

Appendix 1 to EU-OPS 1.1010 (Conversion and Differences Training) section (c) '*Operation of doors and exits*' contains training requirements for cabin crew members in respect of cabin door/exit operation. This states that:

'An operator shall ensure that:

(1) Each cabin crew member operates and actually opens all normal and emergency exits for passenger evacuation in an aeroplane or representative training device…'

In practice, cabin crew members will not often have the opportunity on aircraft to operate cabin doors and emergency exits with the door or exit armed. Training is therefore usually accomplished in a simulator. The initial force to open a door when its escape slide is armed (ie in automatic mode) may be greater than when it is opened in the disarmed or manual mode. It is therefore important that the door operating forces on the simulator are representative of the forces required on the aircraft. This issue was previously raised during the investigation of the accident to an Airbus A340-311, G-VSKY on 5 November 1997, when the AAIB made the following Safety Recommendation to the UK Civil Aviation Authority (CAA), the FAA and the Joint Aviation Authorities (JAA):

Safety Recommendation 2000-33

The CAA, FAA and JAA should review the requirements for public transport aircraft cabin door simulators used for crew training to require that they accurately simulate any non-linear characteristics of the associated aircraft doors and to require that full instruction is given to cabin crews regarding the door operating characteristics to be expected when operating the doors in an emergency.

In response to this recommendation, the CAA published Flight Operations Department Communication (FODCOM) 05/2001. This stated in part:

'Differences in door operating characteristics between actual aeroplane doors and the doors installed in cabin simulators can be of critical importance during an emergency evacuation, especially if an incorrect door operation procedure is used. In the worst case scenario, the crew member may not be able to effectively open a fully functional door or exit if incorrect or inadequate procedures have been specified in the Operations Manual and are repeated during training.

Consideration should be given to:

a. Retrospective modification of existing cabin simulators to address these potential problems.

b. Purchase of new cabin simulators to take into account the need for the equipment to accurately simulate all characteristics of aeroplane door operation.

c. Highlight anomalies between the operating characteristics of actual aeroplane doors and cabin simulator doors during training (e.g. by use of video) and in the Operations Manual. This is especially important where it is recognised that a cabin door simulator cannot, or does not, exactly replicate the actual aeroplane door operating characteristics.

Operations Manuals should be reviewed to ensure that information on aeroplane door operation is fully compliant with the procedures recommended by the relevant aeroplane manufacturer. In addition, operators should provide full instructions to their flight and cabin crew, based on information provided by the aeroplane manufacturer, regarding door operating characteristics that might be expected when operating an aeroplane door in an emergency.'

The CAA also submitted a proposal to the JAA Operation Steering Team (OST) that the requirements for door/exit training for cabin crew should be enhanced and clarified. The JAA OST agreed and the JAA Cabin Crew Steering Group was tasked with this. The rule material in JAR-OPS (now EU-OPS) 1.1010/15 and associated material was enhanced and formed part of Amendment 11 to JAR-OPS issued in August 2006. In light of these measures taken, the FODCOM was subsequently cancelled.

The current requirements for representative training devices are contained in document ACJ OPS 1.1005/1.1010/1.1015/1.1020. With respect to cabin exits, paragraph 2 (c) requirements state that such training devices should accurately represent the aeroplane in the following particulars:

'Exits in all modes of operation (particularly in relation to their mode of operation, their mass and balance and operating forces) including failure of power assist systems where fitted…'

Analysis

Source of haze/smoke

The origin of the haze and smoke in the flight deck and cabin was determined to be the No 2 engine. A fractured seal ring in the No 1 bearing on the LP shaft had allowed engine oil to leak into the compressor air path. The reason for the failure could not be determined but the seal ring contained no material defects and did not diverge significantly from design dimensions or geometry. The affected engine module was neither newly overhauled, nor had it accrued excessively high hours in relation to the remainder of the fleet of RB211-535 engines. As there have been only three recorded similar failures of this seal ring during the considerable service life of the large fleet, it was considered that modification action was not warranted.

Crew identification of source of smoke/fumes

Smoke or fumes in the flight deck or passenger cabin present the crew with a potentially hazardous situation, which requires prompt action. In this case the crew quickly decided that a diversion was the best course of action. They correctly identified the air conditioning smoke drill as being appropriate and initiated the actions. In this event, the procedure did not allow the crew to identify the source of the haze and thus it could not be isolated. The fact that they had promptly initiated the diversion meant that the aircraft could be landed as quickly as possible, before the situation became more serious.

The fact that such procedures have not always proved effective in identifying the source of air conditioning fumes and smoke prompted the AAIB to issue previous Safety Recommendations 2007-002 and 2007-003 to the EASA and FAA respectively. These recommended that large commercial transport aircraft be equipped with sensors that can provide the flight crew with a reliable indication of the source of air conditioning smoke/fumes. Had such equipment been fitted to G-BYAO, the crew may have been able to identify and isolate the source of the blue haze. Furthermore, this equipment would enable flight crews to more readily differentiate between air conditioning smoke and an actual fire within the aircraft.

When actioning the air conditioning smoke drills, the operator advised its pilots that a pause is required after each pack control is selected OFF, in order to determine if this has resulted in a reduction in smoke or fumes. Boeing has since amended the 757 QRH procedure to instruct flight crews to wait for two minutes after selecting each pack to OFF, to determine if the action has been effective in isolating the source of the smoke/fumes.

Troubleshooting procedures

The Boeing 757 FIM procedures employed during initial troubleshooting failed to reproduce the haze in the cabin that led to the diversion, as the engines were not run at a high enough power setting. The smoke did, however, manifest itself at the higher power settings used during the takeoff roll on the planned post-maintenance flight and during subsequent troubleshooting.

This suggests that the procedures contained in the FIM may not always be effective in reproducing smoke or fumes. The maximum EPR of 1.14 called for in the FIM is only sufficiently high for the high stage bleed valve to close and pressurizing air to flow via the low stage valve. This EPR value was demonstrated to be insufficiently high to exploit the seal ring failure. The following Safety Recommendation is therefore made:

Safety Recommendation 2009-041

It is recommended that the Boeing Commercial Airplane Company consider revising the procedures in the Boeing 757 Fault Isolation Manual to introduce a requirement for ground running at higher engine power settings, if initial testing fails to identify the source of smoke or fumes in conditioned air.

Boeing has responded to this safety recommendation, stating that the 757 troubleshooting procedures are being reviewed with a view to adding a requirement to conduct higher power engine runs when troubleshooting reports of smoke or fumes in the cabin and/or flight deck. A decision is expected by the end of the third quarter 2009.

Cabin door simulation

The CAA and JAA had taken previous measures intended to enhance cabin crew training in the operation of cabin doors and exits. The operational requirements state that training must be carried out either on the aircraft or in a representative simulator which accurately reproduces door and exit operating characteristics. However, in the light of this incident, it is not clear whether these measures remain effective in ensuring that cabin crew are aware of the different operating characteristics of cabin doors and exits when operated in the armed mode. The following Safety Recommendation is therefore made:

Safety Recommendation 2009-042

It is recommended that the European Aviation Safety Agency ensure that effective measures are in place for cabin crews to become, and remain familiar with, the different opening procedures and characteristics of aircraft exits in both normal and emergency modes of operation.

Conclusions

The source of the blue haze which caused the diversion and the smoke which resulted in the rejected takeoff was determined to be the No 2 (right) engine. A fractured floating seal ring on the No 1 bearing on the LP shaft had allowed engine oil to leak into the compressor airflow path; the oil mist was ingested into the bleed air system, which provides air to the cabin air conditioning system.

The flight crew actioned the appropriate QRH procedure, which required each air conditioning pack to be selected off in turn, but this was ineffective in identifying the source of the blue haze. In response to previous events of smoke and fumes in the cabin where the emergency procedures proved similarly ineffective, the AAIB issued Safety Recommendations 2007-002 and 2007-003 calling for large commercial air transport aeroplanes to be equipped with systems to indicate to flight crews the source of air conditioning smoke or oil mist.

Although the operator's flight crews were trained to wait for a period after selecting a pack to OFF, to establish if there is any reduction in the amount of smoke or fumes, the QRH did not reflect this requirement. In addition, no published information was available at the time which specified how long flight crews should wait after selecting a pack to OFF.

Although the evacuation was completed successfully, the cabin crew member responsible for opening doors 4R and 4L was initially unable to open the doors, being unaware that significant additional force would be required to open the door in order to activate the escape slide and door assist mechanisms.

The troubleshooting procedures provided in the Boeing 757 Fault Isolation Manual were, on this occasion, ineffective in identifying the source of the smoke/fumes, as they did not require engine ground runs at a high enough power setting for smoke to be generated.