

Boeing 737-3Q8, G-OBML, 1 November 1996

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Aircraft Type and Registration:	Boeing 737-3Q8, G-OBML
No & Type of Engines:	2 CFM56-3B1 turbofan engines
Year of Manufacture:	1989
Date & Time (UTC):	1 November 1996 at 1121 hrs
Location:	Runway 27L, London Heathrow Airport
Type of Flight:	Public Transport
Persons on Board:	Crew - 8 - Passengers - 133
Injuries:	Crew - None - Passengers - None
Nature of Damage:	Severe internal damage to No 2 engine
Commander's Licence:	Airline Transport Pilot's Licence
Commander's Age:	54 years
Commander's Flying Experience:	10,169 hours (of which 1,082 were on type) Last 90 days - 180 hours Last 28 days - 57 hours
Information Source:	AAIB Field Investigation

The flight crew had adequate pre-flight rest and reported for duty at 0610 hrs to operate four sectors on the Heathrow-Dublin route. The aircraft allocated for these flights was G-OBML. The aircraft had one relevant carried forward defect entered in the Technical Log, *ie* the No 2 Power Management Control (PMC) was inoperative. The operator's Minimum Equipment List indicated that one or both PMC systems may be inoperative for flights provided that both PMC's remained OFF and that Take-off Performance and Brake Energy adjustments were applied as given in the relevant Volume of the Operations Manual. It was also a requirement under these conditions to use full rated thrust for each take off.

The first two sectors were uneventful, with the autothrottle system used to set the full take-off thrust setting for each departure. On the third sector, the aircraft was cleared for take off from Runway 27L at Heathrow with a surface wind of 270°/12 kt, good visibility, no significant cloud, temperature +13°C and QNH 1024 mb. The take off was normal, but between 400 and 500 feet in the initial

climb the flight crew heard a very loud 'bang' from the No 2 engine. The aircraft began to yaw and roll to the right, but this was quickly controlled by the commander who was the handling pilot for the sector. He observed that the N1 engine (fan) speed indication for the No 2 engine was reducing rapidly and that the corresponding exhaust gas temperature (EGT) indication was in excess of 900°C, with the associated red warning light illuminated. There was no engine fire warning indication.

At this stage, the aircraft was still within the boundaries of the airport and the event had been observed by the crews of other aircraft and by several witnesses around the airport, all of whom noted that for a brief period flames and smoke had appeared from the rear of the No 2 engine. This information was transmitted to the aircraft by ATC and the commander issued a MAYDAY advising of the engine failure. The aircraft climbed straight ahead to 2,000 feet initially while the recall items of the Engine Fire/Severe Damage/Separation checklist were carried out. An expeditious left hand circuit was then flown for a visual approach to Runway 27R while the appropriate checklist items were carried out from the Quick Reference Handbook (QRH). After positioning the aircraft onto final approach at about 6 nm, an uneventful Flap 15° single engine landing was carried out. After landing, the aircraft vacated the runway and stopped on an adjacent taxiway while the Airport Fire Service carried out an inspection of the aircraft to confirm that there was no fire present. The aircraft then taxied to a parking stand and the passengers disembarked normally.

In the post-incident debrief, the crew commented that the bang associated with the engine failure was significantly louder than that experienced during the practice of failures of a similar nature in the flight simulator. The non-handling pilot also commented that there was a very high workload associated with the completion of all of the required checklist items within the time available. The short flight time also precluded confirmation of the nature of the failure by reference to the secondary engine instruments and an overall review of related actions prior to the commencement of the final approach.

Flight Recorders

The aircraft was fitted with a Sundstrand Universal Flight Data Recorder (UFDR) and a Sundstrand Cockpit Voice Recorder (CVR). Upon inspection of the aircraft in the hangar it was determined that the CVR circuit breaker had not been pulled and that the CVR had continued operating, thus recording over the period of the incident flight. Both recorders were removed from the aircraft and the UFDR replayed by AAIB satisfactorily. The UFDR recording included all of the incident flight, from engines start to shutdown.

The data from the UFDR showed that the aircraft had commenced the take off roll at 11:21 hrs with Flap 5° on a magnetic heading of 275°. With both engines indicating N1 speeds of 93%, the aircraft had left the runway at a speed of 160 kt and had started to climb with a stable pitch-up attitude of 17°. The landing gear was retracted at a radio altitude of 100 ft agl.

Twelve seconds after take off, at a radio altitude of 438 feet and airspeed of 176 kt, the N1 indication for engine No 2 decayed rapidly over a period of three seconds and stabilised at 10%. At the same time the N2 indication started to decay towards zero, but over a longer period of approximately 45 seconds.

In the four second period subsequent to the onset of the event, the aircraft momentarily rolled 8° to the right and the airspeed started reducing. Corrective roll and rudder input were applied to bring the

wings level and maintain heading. The nose of the aircraft was lowered to a pitch attitude of between 6° to 7.5°, which arrested the reducing airspeed at 170 kt and the aircraft started to accelerate.

Flap retraction was initiated at a radio altitude of 1,300 feet. The aircraft climbed to a radio altitude of 2,000 feet and commenced a left-hand circuit. Between 4° and 6° of left rudder was maintained throughout the remainder of the flight and the aircraft made an uneventful landing with Flap 15° at 1135 hrs. As the airspeed reduced during the rollout, the N1 reading for No 2 engine started to reduce from 10% and decayed to zero once the aircraft had slowed to taxi speed.

Engine description (Figure 1)

The CFM 56 series of turbofan engines are based on a two shaft design, and offer a thrust range of 18,500 lbs to 34,000 lbs, depending on the model. All engines utilise a four stage low pressure turbine (LPT) which drives a single stage fan and three stage (four on the -5B and -5C) low pressure compressor (LPC) through the LPT shaft. A single stage high pressure turbine (HPT) drives the nine stage high pressure compressor (HPC). The subject engine was a -3B-1 variant, rated at 20,000 lbs static sea level thrust and flat rated to 30°C. The -2 and -3 models are built with identical core components, including the LPT shaft, and these engines are installed on aircraft such as (-2 series) DC-8-Super70, re-engined KC-135 tankers, E-3 AWACS, and (-3 series) Boeing 737-300, -400, -500. Later versions (-5 series) are fitted to the Airbus A319/320/321/340 family of aircraft and (-7) to the Boeing 737-600, -700 and -800. By January 1995, approximately 7,000 engines had been delivered and some 2,400 aircraft had logged in excess of 59 million flight hours. The -5A1, fitted to the A320, has achieved 120 minute extended range operations (EROPS) certification.

Engine examination

After the aircraft had been towed to the maintenance hangar an initial, on-wing, examination of the engine was carried out. This indicated that the low pressure (LP) shaft had failed since the fan, which appeared undamaged, was able to rotate freely whilst the low pressure turbine (LPT) did not rotate. The LPT fourth stage, the only stage visible at this time, showed gross evidence of overheating. The high pressure rotor had not failed, but was stiff to turn. There were indications on the engine that it had experienced severe vibration, in particular on the exhaust cone buckling and tearing of the skin was present around its complete circumference, close to its attachment flange. After removal, the No 2 engine was initially transported to the operator's maintenance base before being dispatched to an overhaul facility where a strip examination was conducted under the supervision of the AAIB, and with the assistance of the manufacturer.

Upon strip of the rear of the engine it quickly became apparent that the No 4 bearing had failed, there being clear evidence of gross overheating associated with severe damage to the rollers, inner and outer tracks. Bearing Nos 1, 2, 3 and 5 were all found to be in good condition. The position of the damage on the No 4 outer track was some 4 mm further aft than the normal roller path, part of which had not been obscured, indicating that the rear section of the LP shaft had moved aft prior to the bearing failure. This was supported by evidence of contact between the trailing edges of the LPT blades and the leading edges of their nozzle guide vanes. All four LP turbine discs had remained intact, although all LPT blades had been affected by overheating. (Later examination by the manufacturer established that there had been no growth in the bore diameter of the LPT discs, and thus that the LPT had not oversped). Further disassembly of the engine confirmed that the LP shaft had failed over a length between, approximately, the No 3 bearing and the aft end of the HPC (see

Figure 1). In this area the shaft had fragmented into some seven segments of various sizes (Figure 2), this break-up having also caused fragmentation of the Central Oil Vent Tube (CVT) and an outer cylindrical cooling air shroud. All other damage apparent throughout the engine appeared to have resulted from the effects of the LP shaft failure.

LP shaft examination

The forward section of the shaft was disassembled from the fan, and all the available shaft fragments were removed from the engine and visually examined. The external surface of the shaft showed clear evidence, over its full length, of an aluminum-loaded protective paint finish, except where it had been damaged during the failure and there were no obvious signs of corrosion. The inner surface, however, was devoid of this protective paint throughout its sealed length, bounded by the front and rear centre vent tube (CVT)/LPT shaft seals, and the shaft had been affected by surface corrosion over this same length. This corrosion was most severe in the fragmented region close to the areas of contact made by the forward CVT support ring, although there was evidence of the protective paint within the front and rear support ring areas of contact. Detailed examination showed the paint in these areas to have adhered to the surface, indicating that the corrosive attack on the inner paint surface had occurred after painting and that the whole length of the shaft had probably been coated in paint. The shaft's inner surface was covered in compacted patches of a dark brown powdery deposit, the nature of which suggested that the whole surface had been so covered prior to the failure. A subsequent metallurgical examination was carried out on the shaft fragments, which necessitated these being cleaned in chloride solutions. This revealed that the shaft had failed as a result of a torsional fatigue mechanism, from multiple origins, precipitated by corrosion pitting of the shaft inner surface, as indicated in the diagram at Figure 3. Sections of the fracture surfaces also exhibited a brown discolouration. A fluorescent penetrant check revealed the presence of many small cracks in this area which had not been exploited by the main fracture paths, but which showed evidence of corrosion on their fracture surfaces (Figures 4 and 5), with significant 'mouth-open' due to corrosion. A microsection taken near to the primary origin (Figure Figure 6) revealed the presence of multi-branched stress-corrosion cracking in addition to the fatigue mechanism. The extent and characteristics of the failures and the high incidence of cracks suggested that the cracking mechanisms had been relatively long term. The relevant parts of this engine were transferred to the manufacturer's plant in France where the detailed investigation was pursued, in conjunction with the various investigative and airworthiness authorities involved.

The protective paint applied to the shaft is of the manufacturer's proprietary type, but is essentially a silicon-based paint loaded 40% with aluminium. The paint is not intended to be sacrificial and the painting process involves, after degreasing, the application of several layers with curing over specific times and temperatures. The degreasing process involves the use of chlorine based solvents (such as trichlorethylene) but all traces of solvents are removed before painting and tests conducted by the manufacturer have shown the applied paint not to be affected by such solvents. An elemental analysis of the corrosion deposits, however, revealed the presence of chlorine in the form of aluminium (and other) chlorides. Evidence of chlorides were also found in the pits of the LPT shaft inner surface and at the tips of some cracks, and generally throughout the sealed region of the LPT shaft. The titanium CVT had failed as a direct result of the LPT shaft failure, but the characteristics of the fractures in the vicinity of the forward CVT support ring were unusual. Detailed examination of these by the manufacturer showed that significant fragmentation had occurred due to hydrogen embrittlement of the titanium, with the outer surface showing the presence of many small oxidised cracks in which chlorine enrichment was detected. Chemical and spectrometric analysis performed by gas chromatography to identify the origin of the chlorine and hydrogen contamination has led the manufacturer to believe that it originated from a chlorine

aromatic derivative from the chlorobenzene family. This potentially corrosive agent is commonly used as a paint stripper and the manufacturer has stated that it is not used during the manufacture or assembly of the engine. They consider that the presence of chlorobenzene did not result from atmospheric pollution, but that it probably derived from an agent introduced inadvertently, or used as a temporary alternate, at some time in the engine's history. As a result, the engine manufacturer investigated the compositions of all products used during manufacture or assembly, or available as temporary alternatives, or recommended in their documentation, without identifying any chlorobenzene.

Detailed examination of the shaft by the manufacturer also revealed the presence of additional pitting corrosion, but no cracks, to a maximum depth of 11 micrometres in a region not otherwise affected by the chlorobenzene contamination. It was determined that this pitting had resulted from several areas of damage to the protective paint on the inner surface, close to the forward end of the shaft, and was associated with the use of an alignment fixture used during engine assembly.

Engine history

The subject engine was a CFM 56-3B1, serial no 725248. It was constructed in 1989 and delivered to the operator as a spare engine in April of that year. At a total time of 251 hours, the engine was removed from service for replacement of the No 3 bearing, and associated light maintenance, at an overhaul facility. The engine remained serviceable, although it was not required for use for a period of approximately one year between 1993/4, during which time it was reportedly stored under normal workshop conditions. In September 1995, when at a total time of 11,597 hours and 12,485 total cycles, it was partially disassembled, again at an overhaul facility, following damage to stage seven HPC blades. At this time a pressure check was carried out on the CVT, as required due to previous instances of associated cracking and failure in CFM56 engines, and found to be serviceable. The CVT was not removed at this time or during its previous shop visit (nor was it required to be removed), and thus no visual inspection of the LP shaft inner surface had been carried out since manufacture. At the time of failure, the engine had accumulated 15,453 hours and 14,222 cycles. The LPT shaft is life-limited to 30,000 cycles.

Safety Recommendation

This was the first failure of this nature to have occurred on this engine type, the LP shaft and its protective treatment being common (or similar) to most variants, although cracks in at least one shaft had been detected, during a shop visit, in the outer surface resulting from an area of fretting. Up to the time of this failure, the interior of LPT shafts had not been (specifically) inspected during overhaul shop visits, and never whilst the engines were installed on-wing, due to the presence of the CVT, the main length of which may only be removed during a shop visit. Although the manufacturer has now instigated inspection of all shafts during engine shop visits, with some 100 inspection reports having been received by January 1997 with no reports of corrosion (1,000 reports are expected by the end of 1997), the condition of most in-service LPT shafts is not known. Therefore, during the early stages of this investigation, the following Safety Recommendation was made.

96-78: The FAA and DGAC, in conjunction with the manufacturer of CFM56 turbofan engines, should require the earliest introduction of an effective in-service inspection procedure to check the LP shafts on all variants of these engines for the condition of the aluminium protective coating on the bore surface of these shafts and for any associated corrosion and cracking of the parent steel material.

Additional Information

The inner diameter of an LPT shaft is difficult to inspect with the engine installed, since only the forward section of the CVT may be removed (Figure 1). Trials at the manufacturer, overhaul shops and operator facilities demonstrated that it is possible to inspect the internal diameter of LPT shafts on assembled engines using a suitable flexible borescope, and some UK operators have initiated on-wing inspection programmes. In response to Safety Recommendation 96-78, the CAA issued Additional Airworthiness Directive (AAD) No 001-02-97 on 21 February 1997, applicable to CFM International CFM56-3 and -5 engines which meet certain age and installation criteria. Figure 7 shows three views taken from such an inspection and illustrates typical differences in the surface texture of the paint and discolouration evident around several of the support ring contact areas. The AAD acceptance standards* are as follows:-

Inspect/Check Maximum Serviceable Limit

Cracks Not serviceable

Corrosion Not serviceable **

Missing paint, peeling, blistering Total surface area not to exceed 10 sq ins

Scratches in paint

(parent metal not affected) Any number

* The acceptance standards are extracted from the Engine Shop Manual. These standards may be varied by CFMI when assessing the suitability of individual shafts for continued service.

** In case of doubt refer to CFMI for interpretation and advice.