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

AAIB Bulletin No: 4/97 Ref: EW/C96/11/1 Category: 1.1

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 forduty at 0610 hrs to operate four sectors on the Heathrow-Dublinroute. The aircraft allocated for these flights was G-OBML. Theaircraft had one relevant carried forward defect entered in theTechnical Log, *ie* the No 2 Power Management Control (PMC)was inoperative. The operator's Minimum Equipment List indicatedthat one or both PMC systems may be inoperative for flights providedthat both PMC's remained OFF and that Take-off Performance andBrake Energy adjustments were applied as given in the relevantVolume of the Operations Manual. It was also a requirement underthese conditions to use full rated thrust for each take off.

The first two sectors were uneventful, with the autothrottle systemused to set the full take-off thrust setting for each departure.On the third sector, the aircraft was cleared for take off fromRunway 27L at Heathrow with a surface wind of 270°/12 kt,good visibility, no significant cloud, temperature +13°Cand QNH 1024 mb. The take off was normal, but between 400 and500 feet in the initial climb the flight crew heard a very loud'bang' from the No 2 engine. The aircraft began to yaw and rollto the right, but this was quickly controlled by the commanderwho was the handling pilot for the sector. He observed that theN1 engine (fan) speed indication for the No 2 engine was reducingrapidly and that the corresponding exhaust gas temperate (EGT)indication was in excess of 900°C, with the associated redwarning light illuminated. There was no engine fire warning indication.

At this stage, the aircraft was still within the boundaries ofthe airport and the event had been observed by the crews of otheraircraft and by several witnesses around the airport, all of whomnoted that for a brief period flames and smoke had appeared fromthe rear of the No 2 engine. This information was transmittedto the aircraft by ATC and the commander issued a MAYDAY advisingof the engine failure. The aircraft climbed straight ahead to2,000 feet initially while the recall items of the Engine Fire/SevereDamage/Separation checklist were carried out. An expeditious lefthand circuit was then flown for a visual approach to Runway 27Rwhile the appropriate checklist items were carried out from theQuick Reference Handbook (QRH). After positioning the aircraftonto final approach at about 6 nm, an uneventful Flap 15°single engine landing was carried out. After landing, the aircraftvacated the runway and stopped on an adjacent taxiway while theAirport Fire Service carried out an inspection of the aircraftto confirm that there was no fire present. The aircraft then taxiedto a parking stand and the passengers disembarked normally.

In the post-incident debrief, the crew commented that the bangassociated with the engine failure was significantly louder thanthat experienced during the practice of failures of a similarnature in the flight simulator. The non-handling pilot also commentedthat there was a very high workload associated with the completionof all of the required checklist items within the time available.The short flight time also precluded confirmation of the natureof the failure by reference to the secondary engine instrumentsand an overall review of related actions prior to the commencementof the final approach.

Flight Recorders

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

The data from the UFDR showed that the aircraft had commencedthe take off roll at 11:21 hrs with Flap 5º on a magneticheading of 275º. With both engines indicating N1 speeds of93%, the aircraft had left the runway at a speed of 160 kt andhad 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 feetand airspeed of 176 kt, the N1 indication for engine No 2 decayedrapidly 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 airspeedstarted reducing. Corrective roll and rudder input were appliedto bring the wings level and maintain heading. The nose of theaircraft was lowered to a pitch attitude of between 6° to7.5°, which arrested the reducing airspeed at 170 kt andthe 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 commenceda left-hand circuit. Between 4° and 6° of left rudderwas maintained throughout the remainder of the flight and theaircraft made an uneventful landing with Flap 15° at 1135 hrs.As the airspeed reduced during the rollout, the N1 reading forNo 2 engine started to reduce from 10% and decayed to zero oncethe aircraft had slowed to taxi speed.

Engine description (Figure 1)

The CFM 56 series of turbofan engines are based on a two shaftdesign, and offer a thrust range of 18, 500 lbs to 34,000 lbs,depending on the model. All engines utilise a four stage low pressureturbine (LPT) which drives a single stage fan and three stage(four on the -5B and -5C) low pressure compressor (LPC) throughthe LPT shaft. A single stage high pressure turbine (HPT) drivesthe nine stage high pressure compressor (HPC). The subject enginewas a -3B-1 variant, rated at 20,000 lbs static sea level thrustand flat rated to 30°C. The -2 and -3 models are built withidentical core components, including the LPT shaft, and theseengines are installed on aircraft such as (-2 series) DC-8-Super70, re-engined KC-135 tankers, E-3 AWACS, and (-3 series) Boeing737-300, -400, -500. Later versions (-5 series) are fitted tothe Airbus A319/320/321/340 family of aircraft and (-7) to theBoeing 737-600,-700 and -800. By January 1995, approximately 7,000engines had been delivered and some 2,400 aircraft had loggedin excess of 59 million flight hours. The -5A1, fitted to theA320, has achieved 120 minute extended range operations (EROPS)certification.

Engine examination

After the aircraft had been towed to the maintenance hangar aninitial, on-wing, examination of the engine was carried out. Thisindicated that the low pressure (LP) shaft had failed since thefan, which appeared undamaged, was able to rotate freely whilstthe low pressure turbine (LPT) did not rotate. The LPT fourthstage, the only stage visible at this time, showed gross evidenceof overheating. The high pressure rotor had not failed, but wasstiff to turn. There were indications on the engine that it hadexperienced severe vibration, in particular on the exhaust conebuckling and tearing of the skin was present around its completecircumference, close to its attachment flange. After removal,the No 2 engine was initially transported to the operator's maintenancebase before being dispatched to an overhaul facility where a stripexamination was conducted under the supervision of the AAIB, andwith the assistance of the manufacturer.

Upon strip of the rear of the engine it quickly became apparentthat the No 4 bearing had failed, there being clear evidence ofgross overheating associated with severe damage to the rollers,inner and outer tracks. Bearing Nos 1, 2, 3 and 5 were all foundto be in good condition. The position of the damage on the No4 outer track was some 4 mm further aft than the normal rollerpath, part of which had not been obscured, indicating that therear section of the LP shaft had moved aft prior to the bearingfailure. This was supported by evidence of contact between thetrailing edges of the LPT blades and the leading edges of theirnozzle guide vanes. All four LP turbine discs had remained intact,although all LPT blades had been affected by overheating. (Laterexamination by the manufacturer established that there had beenno growth in the bore diameter of the LPT discs, and thus thatthe LPT had not oversped). Further disassembly of the engine confirmedthat 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 segmentsof various sizes (Figure 2), this break-up having also causedfragmentation of the Central Oil Vent Tube (CVT) and an outercylindrical cooling air shroud. All other damage apparent throughoutthe engine appeared to have resulted from the effects of the LPshaft 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 engineand visually examined. The external surface of the shaft showedclear evidence, over its full length, of an aluminum-loaded protectivepaint finish, except where it had been damaged during the failureand there were no obvious signs of corrosion. The inner surface,however, was devoid of this protective paint throughout its sealedlength, bounded by the front and rear centre vent tube (CVT)/LPTshaft seals, and the shaft had been affected by surface corrosionover this same length. This corrosion was most severe in the fragmentedregion close to the areas of contact made by the forward CVT supportring, although there was evidence of the protective paint withinthe front and rear support ring areas of contact. Detailed examinationshowed the paint in these areas to have adhered to the surface,indicating that the corrosive attack on the inner paint surfacehad occurred after painting and that the whole length of the shafthad probably been coated in paint. The shaft's inner surface wascovered in compacted patches of a dark brown powdery deposit,the nature of which suggested that the whole surface had beenso covered prior to the failure. A subsequent metallurgical examinationwas carried out on the shaft fragments, which necessitated thesebeing cleaned in chloride solutions. This revealed that the shafthad failed as a result of a torsional fatigue mechanism, frommultiple origins, precipitated by corrosion pitting of the shaftinner surface, as indicated in the diagram at Figure 3. Sectionsof the fracture surfaces also exhibited a brown discolouration.A fluorescent penetrant check revealed the presence of many smallcracks in this area which had not been exploited by the main fracturepaths, but which showed evidence of corrosion on their fracturesurfaces (Figures 4 and 5), with significant 'mouthing-open'due to corrosion. A microsection taken near to the primary origin(Figure Figure 6) revealed the presence of multi-branched stress-corrosioncracking in addition to the fatigue mechanism. The extent andcharacteristics of the failures and the high incidence of crackssuggested that the cracking mechanisms had been relatively longterm. The relevant parts of this engine were transferred to themanufacturer's plant in France where the detailed investigationwas pursued, in conjunction with the various investigative andairworthiness authorities involved.

The protective paint applied to the shaft is of the manufacturer'sproprietary type, but is essentially a silicon-based paint loaded40% with aluminium. The paint is not intended to be sacrificialand the painting process involves, after degreasing, the applicationof 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 removedbefore painting and tests conducted by the manufacturer have shownthe applied paint not to be affected by such solvents. An elementalanalysis of the corrosion deposits, however, revealed the presenceof chlorine in the form of aluminium (and other) chlorides. Evidenceof chlorides were also found in the pits of the LPT shaft innersurface and at the tips of some cracks, and generally throughoutthe sealed region of the LPT shaft. The titanium CVT had failedas a direct result of the LPT shaft failure, but the characteristicsof the fractures in the vicinity of the forward CVT support ringwere unusual. Detailed examination of these by the manufacturershowed that significant fragmentation had occurred due to hydrogenembrittlement of the titanium, with the outer surface showingthe presence of many small oxidised cracks in which chlorine enrichmentwas detected. Chemical and spectrometric analysis performed bygas chromatography to identify the origin of the chlorine andhydrogen contamination has led the manufacturer to believe thatit originated from a chlorine aromatic derivative from the chlorobenzinefamily. This potentially corrosive agent is commonly used as apaint stripper and the manufacturer has stated that it is notused during the manufacture or assembly of the engine. They considerthat the presence of chlorobenzene did not result from atmosphericpollution, but that it probably derived from an agent introducedinadvertently, or used as a temporary alternate, at some timein the engine's history. As a result, the engine manufacturerinvestigated the compositions of all products used during manufactureor assembly, or available as temporary alternatives, or recommendedin their documentation, without identifying any chlorobenzine.

Detailed examination of the shaft by the manufacturer also revealedthe presence of additional pitting corrosion, but no cracks, toa maximum depth of 11 micrometres in a region not otherwise affectedby the chlorobenzine contamination. It was determined that thispitting had resulted from several areas of damage to the protectivepaint on the inner surface, close to the forward end of the shaft,and was associated with the use of an alignment fixture used duringengine assembly.

Engine history

The subject engine was a CFM 56-3B1, serial no 725248. It wasconstructed in 1989 and delivered to the operator as a spare enginein April of that year. At a total time of 251 hours, the enginewas removed from service for replacement of the No 3 bearing,and associated light maintenance, at an overhaul facility. Theengine remained serviceable, although it was not required foruse for a period of approximately one year between 1993/4, duringwhich time it was reportedly stored under normal workshop conditions.In September 1995, when at a total time of 11,597 hours and 12,485total cycles, it was partially disassembled, again at an overhaulfacility, following damage to stage seven HPC blades. At thistime a pressure check was carried out on the CVT, as requireddue to previous instances of associated cracking and failure inCFM56 engines, and found to be serviceable. The CVT was not removedat this time or during its previous shop visit (nor was it requiredto be removed), and thus no visual inspection of the LP shaftinner surface had been carried out since manufacture. At the timeof failure, the engine had accumulated 15,453 hours and 14,222cycles. The LPT shaft is life-limited to 30,000 cycles.

Safety Recommendation

This was the first failure of this nature to have occurred tothis engine type, the LP shaft and its protective treatment beingcommon (or similar) to most variants, although cracks in at leastone shaft had been detected, during a shop visit, in the outersurface resulting from an area of fretting. Up to the time ofthis failure, the interior of LPT shafts had not been (specifically)inspected during overhaul shop visits, and never whilst the engineswere installed on-wing, due to the presence of the CVT, the mainlength of which may only be removed during a shop visit. Althoughthe manufacturer has now instigated inspection of all shafts duringengine shop visits, with some 100 inspection reports having beenreceived by January 1997 with no reports of corrosion (1,000 reportsare expected by the end of 1997), the condition of most in-serviceLPT shafts is not known. Therefore, during the early stages ofthis investigation, the following Safety Recommendation was made.

96-78: The FAA and DGAC, in conjunction with the manufacturerof CFM56 turbofan engines, should require the earliest introductionof an effective in-service inspection procedure to check the LPshafts on all variants of these engines for the condition of thealuminium protective coating on the bore surface of these shaftsand for any associated corrosion and cracking of the parent steelmaterial.

Additional Information

The inner diameter of an LPT shaft is difficult to inspect withthe engine installed, since only the forward section of the CVTmay be removed (Figure 1). Trials at the manufacturer, overhaulshops and operator facilities demonstrated that it is possibleto inspect the internal diameter of LPT shafts on assembled enginesusing a suitable flexible borescope, and some UK operators haveinitiated on-wing inspection programmes. In response to SafetyRecommendation 96-78, the CAA issued Additional AirworthinessDirective (AAD) No 001-02-97 on 21 February 1997, applicable toCFM International CFM56-3 and -5 engines which meet certain ageand installation criteria. Figure 7 shows three views taken fromsuch an inspection and illustrates typical differences in thesurface texture of the paint and discolouration evident aroundseveral of the support ring contact areas. The AAD acceptancestandards* are as follows:-

Inspect/Check Maximum Serviceable Limit

Cracks Not serviceable

Corrosion Not serviceable **

Missing paint, peeling, blistering Total surface area not to exceed10 sq ins

Scratches in paint

(parent metal not affected) Any number

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

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