Boeing 737-5L9, G-MSKC

AAIB Bulletin No: 2/99 Ref: EW/C97/12/6 Category: 1.1

Aircraft Type and Registration:	Boeing 737-5L9, G-MSKC
No & Type of Engines:	2 CFM56-3B1 turbofan engines
Year of Manufacture:	1991
Date & Time (UTC):	23 December 1997 at 1946 hrs
Location:	East of Belfast Aldergrove Airport
Type of Flight:	Public Transport
Persons on Board:	Crew - 6 - Passengers - 63
Injuries:	Crew - Nil - Passengers - Nil
Nature of Damage:	Minor damage to aircraft, severe engine damage
Commander's Licence:	Airline Transport Pilot's Licence
Commander's Age:	54 years
Commander's Flying Experience:	5,920 hours (of which 658 hours were on type)
	Last 90 days - 136 hours
	Last 28 days - 50 hours
Information Source:	AAIB Field Investigation

History of flight

The crew were scheduled to fly three sectors in G-MSKC and had completed one uneventful flight from Birmingham Airport to Belfast. There were no significant unserviceabilities in the technical log and the aircraft was fully serviceable on this first sector. After a turnaround of approximately 30 minutes, G-MSKC was pushed back for the return flight to Birmingham. The first officer had been designated as the handling pilot for the first two sectors. The weather was good with a surface wind of 230°/13 kt, visibility of 25 km, cloud scattered at 2,200 feet agl, a temperature of 10°C and dew point of 9°C.

After the pushback and with the aircraft pointing into wind, the commander started the No 2 and then the No 1 engine; both starts were normal. The aircraft was taxied to Runway 25 and the crew received clearance for take off. With the anti-ice off, a normal reduced power take off was made and the crew followed ATC instructions onto a south easterly heading. In the initial part of the climb, the crew noticed some light cloud and used the engine anti-ice for a short period. Then, as G-MSKC was climbing through FL145 with an indicated airspeed of 300 kt and approximately 5° Total Air Temperature (TAT), the crew noticed that the aircraft was approaching some more cloud and decided to re-activate the engine anti-ice. The ignition select switch was selected to 'IGN L' and the first officer selected the engine start switch to 'CONT' and then selected both engine anti-ice switches to 'ON'. As the No 2 engine anti-ice was selected, the first officer immediately heard a series of three short bursts of "Popping" noises; coincident with these noises, he also saw three "Illuminations" from the area of the No 2 engine; he recalled that he may have deselected No 2 engine anti-ice when he heard the noises but reselected it almost immediately. The commander also heard the noises and saw the illumination. When the commander checked the engine instruments, he noted that the vibration gauge was indicating between 2.5 and 3.5 units and that No 2 engine NI was indicating between 50% and 60%; the first officer confirmed these figures but neither pilot could recall the indications from the other engine instruments. There were no audio or caution lights illuminated. The first officer felt the aircraft bank to the right and applied left control wheel and rudder to counter this and then used rudder trim to offset the control loads.

The commander declared a 'Mayday' to Scottish Control and then, with the agreement of the first officer, slowly retarded the No 2 thrust lever. Neither crew member noted a difference on the engine indications as the lever was retarded although the first officer was aware of a slight change in roll and yaw. The commander then advanced the No 2 thrust lever slightly and noted an immediate increase in aircraft vibration and associated increase in vibration gauge indication. With No 1 engine indicating and operating normally, the crew agreed to shutdown No 2 engine. With the first officer flying the aircraft, but monitoring the procedure, the commander completed the appropriate 'Recall' actions for ENGINE FIRE, SEVERE DAMAGE OR SEPARATION and then completed the actions from the Quick Reference Handbook (QRH).

Thereafter, the crew received the fullest co-operation from both Scottish Control and Aldergrove ATC for the recovery to Belfast Aldergrove Airport. Additionally, the commander briefed the purser and then made a PA to the passengers to inform them of the situation. G-MSKC was then radar vectored for an ILS approach and, once established with the landing checks complete, the commander took control for the landing. After landing, the aircraft was followed by the AFS to the allocated parking stand where the passengers disembarked normally.

Flight recorders

The Cockpit Voice Recorder (CVR) and Flight Data Recorder (FDR) were removed from the aircraft and replayed at Farnborough. Further engine data was made available by the operator in the form of an engineering advisory report which was printed out on the flightdeck after the event.

The CVR circuit breaker had not been pulled subsequent to the landing after the event and so the CVR had recorded over the period of the incident. Recording had ceased when the aircraft was shutdown by the crew.

Recorded FDR data showed that the aircraft departed at 19:42 hrs. One and a half minutes later, during the climb, the TAT temporarily reduced to +9°C and anti-ice was selected to 'ON' for both engines for 40 seconds. The recorded TAT value then rose to +15°C before falling again. At 19:47 hrs, with the aircraft climbing through FL145 at 299 kt and TAT reducing through +1.75°C, anti-ice was selected to 'ON' for both engines. Simultaneously, various recorded parameters on No 2 engine began to change: N1 reduced from 90% to 49%, N2 reduced more slowly from 94% to 82% and all four engine vibration monitoring transducers showed increased levels of between 1.8 and 4.4 with the higher values originating from the rear of the engine. The Exhaust Gas Temperature (EGT) progressively rose from 750°C to 919°C over a period of 15 seconds and stabilised at the higher temperature.

At the onset of the event the aircraft rolled 7.6° to the right and was corrected with opposite aileron and rudder. Airspeed reduced to a minimum of 284 kt before the nose up pitch attitude was reduced and the aircraft levelled at 15,400 feet. Forty five seconds after the event the thrust lever for engine No 2 was brought back to flight idle and the EGT started to reduce, eventually stabilising at 650°C. The N1 and N2 for engine No 2 also reduced to 28% and 70% respectively. After the thrust lever was retarded the engine No 2 vibration levels reduced to values of 1.0 for the front section of the engine and 2.5 for the rear. The aircraft started a descent towards 10,000 feet and banked left to return to Belfast.

Six and a half minutes later, at 10,000 feet, engine No 2 thrust lever was advanced briefly by 11° and the associated engine vibration levels increased. The engine was shutdown shortly afterwards at 19:55 hrs.

During the descent to Belfast between 1° and 3° of left rudder was used which increased on finals to between 4° and 8° degrees with flap 15 selected. The aircraft made an uneventful flap 15 landing on Runway 25 at 20:14 hrs using left thrust reverse and 4° of right rudder. The FDR recording stopped when engine No 1 was shutdown at 20:20 hrs.

Engineering information

Secondary damage to the aircraft included some minor top coat paint chips to the underwing area and a small dent and hole in the leading edge of the starboard stabilator.

On-wing examination of the engine showed debris in the exhaust duct and considerable damage to the Low Pressure Turbine Rotor (LPTR) blades, however the LPT and fan were still connected and could be turned together. The operator nominated an independent engine overhaul facility to allow the engine to be stripped in the presence of an AAIB Inspector. This operation revealed extensive internal damage caused by the release of a section of the High Pressure Turbine Rotor (HPTR) rear shaft seal.

The HPTR rear shaft seal is a rotating seal which, in conjunction with a stationary honeycomb seal attached to the low pressure turbine stage 1 nozzle, provides an air seal at the HPT/LPT interface. See Figure 1.

On CFM56-3 engines fitted to Boeing 737s, series 300, 400 and 500, there have been a total of seven airborne failures of the HPTR rear shaft seal since 1995; additionally, three cracked seals were also found by eddy current non-destructive examination (NDE) during access provided to the seal by other work on the engine. The flying hour life consumed by those seals which failed in the air ranged from 10,405 hours/9,765 cycles on the youngest disk, to 20,540 hours and 14,305 cycles on two of the eldest disks. The times to failure of the seals rejected by the NDE inspections were 7,768 hours/5,026 cycles to 26,872 hours/19,365 cycles.

All the seals involved in the separations and rejections were supplied by one manufacturer and the serial numbers cover a numerical range of 2,199. A total of 2,326 CFM56-3 shaft seals have been supplied by the manufacturer. A further CFMI overview dated 9 April 1998 indicated a clustering of serial numbers, with one outlying seal that may have been nicked.

Examination of the dates the seals were supplied by the subcontractor showed that of the ten failed disks, seven were supplied in 1990, but the other three were supplied in 1984 and 1988.

The data appeared to indicate a potential batch problem from one manufacturer. There has been one rejected seal from another manufacturer since the event seal investigation, potentially negating a batch problem theory.

CFMI had provided an overview of the failure modes observed (CFM56 HPTR Rear Shaft Separation, 17/12/97) in which they suggested that the *low cycle fatigue* stresses are low in the location of the initiation site, and that a 2.5 mm long defect would be required for fatigue propagation at the predicted stress level. Moreover, a 5.3 mm long defect would be required for the fatigue propagation at the predicted stress level and within the observed cycles. The report also stated that the hardness, grain size and microstructures conformed to specification and that no geometric abnormalities were observed. A later document from CFMI suggested that, from striation spacing measurements, up to 55,000 propagating fatigue cycles had occurred; a figure well in excess of the maximum number of low cycle fatigue cycles consumed by any of the failed components. It is therefore possible that the failure contains a high cycle fatigue component. It was noted that the final failure on G-MSKC coincided with the selection of anti-icing but there is no evidence to support a direct relationship.

The failed shaft seal was manufactured from a double vacuum melted nickel 718 alloy, the seal racks of the component had a nickel-aluminium bond coat and an alumina wear coat applied by a thermal spray process. Two CFM56-3 HPTR rear shaft seals were sent to DERA Farnborough for examination with the objective of determining the failure mode and to characterise the material condition of the failed seal. One of these was the failed shaft seal, Serial No DED22284, which had consumed 12,438 cycles/16065 flying hours since new. The other shaft, Serial No DED21747, had been retired from service after 17158 cycles as serviceable but uneconomic to refit, and was examined as an example of a high time shaft which may contribute information to the mode of failure of shaft Serial No DED22284. Examination of the shaft seals revealed the following:

<u>Serial No DED22284</u> The shaft seal contained a circumferential fracture through a 200 degree arc around the forward seal rack retaining arm. Visual, scanning electron microscope, and chemical examinations were carried out and led to the conclusion that:

* The fracture was likely to have been initiated by fatigue in the forward tooth of the outer seal rack, which propagated into the retaining arm and then by overload failure in the radial direction.

* No initiation site for the fatigue in the forward tooth of the outer seal rack was identified.

* The hardness, microstructure, and grain size of the base alloy in the outer seal rack conformed to specification.

* The nickel-aluminium bond coat on the outer seal rack was not in optimum condition, and disbonding and lack of adherence were observed between the nickel aluminium bond coat and the nickel substrate.

* The alumina outer coating exhibited good adherence to the nickel bond coat and no disbonding was observed.

* It was considered unlikely that this failure was from low cycle fatigue alone, but a full explanation of the cause of the failure was not determined.

<u>Serial No DED21747</u> This shaft was visually inspected and the only defect observed was an isolated region of light surface coating wear. Non-destructive examination was completed in the seal front tooth area using an eddy current test set, however, no further defect indications were evident.

General Electric Aircraft Engines (GEAE), as the seal designer within the CFMI organisation, reviewed the DERA report and the metallurgical findings. After examining the metallographic samples used by DERA, GEAE also declared that the seal coatings had met the required specification, and that the delamination damage appeared to be associated with the rub damage sustained by the tips of the seal teeth. GEAE also stated that their experience with the bond coat and aluminium oxide top coat, as applied to alloy 718 components had been excellent, and that prior events of seal tooth cracking associated with alloy 718 components have always been attributed to *either unexpected vibratory loading or severe rub damage*.

This statement aligned with the DERA conclusion that it was unlikely that the failure was caused by low cycle fatigue (ie low cycle, high stress) alone.

<u>Hazard Ranking Criteria</u>

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A draft FAA Advisory Circular, "Continued Airworthiness Assessments of Turbine Engines, Propellers, and APUs - Revision 9" defines the FAA's position on best practice for addressing continued airworthiness issues. This advisory circular provides guidance, and a method, acceptable to the FAA, to identify, assign priorities and resolve safety related problems occurring on aircraft turbine engines for use on FAR Part 25 certified aircraft.

The circular draws on a database of engine malfunctions and their consequences, and provides a listing of standardised definitions of propulsion system hazard levels based on the consequences to the aircraft, passengers and crew. The circular recognises that a probability exists that a significant hazard will result for each propulsion system failure mode. However, this probability is sufficiently remote for most failure modes that mandatory corrective actions by the manufacturer are not warranted. The hazard ranking process therefore provides a method whereby the manufacturer can apply his resources to resolve the failure modes that represent the greatest potential hazard to the aircraft.

A total of four hazard levels are defined:

Level 4 -Severe consequences:

Forced Landing.

Loss of Aircraft (Hull Loss).

Serious Injuries or Fatalities.

Level 3 - Serious consequences:

Substantial damage to the aircraft or second unrelated system.

Uncontrolled fires - not extinguished by on-board aircraft systems.

Rapid depressurisation of the cabin.

Permanent loss of thrust or power greater than one propulsion system.

Temporary or permanent inability to climb and fly 1,000 feet above terrain along the intended route.

Any temporary or permanent impairment of aircraft controllability.

Level 2 - Significant consequences:

Nicks, dents and small penetrations of the aircraft primary structure.

Slow depressurisation.

Controlled fires (ie extinguished by on-board aircraft systems).

Fuel leaks beyond normal extinguishing capabilities, if fire had resulted.

Minor injuries.

Multiple propulsion system/APU malfunctions, or related events, where one engine remains shutdown but continued safe flight at an altitude 1,000 feet above terrain along the intended route is possible.

Any high speed take off abort.

Separation of propulsion system, inlet, reverser blocker door, translating sleeve inflight without Level 3 damage consequences to the aircraft structure or systems.

Partial inflight reverser deployment or propeller pitch change malfunction(s) which do not result in loss of aircraft control or damage to aircraft primary structure.

Level 1 - Minor consequences:

Uncontained nacelle damage confined to affected nacelle/APU area.

Uncommanded power increase, or decrease, at an airspeed above V1 and occurring at an altitude below 3,000 feet.

Multiple propulsion system malfunctions or related events, temporary in nature, where normal functioning is restored on all propulsion systems and the propulsion systems function normally for the rest of the flight. Includes common cause environmental hazard induced events.

Separation of propeller/components which cause no damage.

Uncommanded propeller feather.

The FAA has stated that although the draft advisory circular has been rewritten, the process for addressing engine malfunctions remains their best practice, and they expect that the revised circular will be sent out later this year for public comment.

In the meantime the Aviation Industries of America trade organisation has promulgated the guidelines for use by the industry, and CFMI have categorised the HPTR rear shaft seal failure, and earlier events, as Hazard 1-2 events. This conclusion was based on their findings that all events only resulted in a single engine inflight shutdown, no uncontained debris, and no fires. CFMI concluded from the data that the potential for a dual engine failure was extremely remote. However, the AAIB's understanding is that the root cause leading to the failure is not understood by the design authority, and that as a consequence no procedural or hardware solution has yet been identified.

The adoption of the methodology derived from the FAA Advisory Circular has given CFMI the confidence to allow the search for a solution to the problem to extend over a period of several years by tailoring the allocation of resources to match the perceived risk.

The development of a new seal would require an understanding of the mechanism of failure. Such a seal could be incorporated into new build engines, and a decision on retrospective embodiment of the new seal on in-service engines would be needed. The implementation of a periodic NDE of the seal would require an understanding of the failure mechanism to determine a safe flying hour life between inspections. The wide spread of the seal lives to failure would indicate that such a procedure may require an uneconomically high periodicity to ensure detecting any incipient failure.

Both the periodic use of NDE or the retrofitment of a new seal would require an engine strip, after which many hot-end components would need replacing as they would not pass the inspection criteria to allow their reuse. The adoption of either of these two strategies would therefore have significant financial repercussions.

CFMI programme

CFMI state that: 'They have a cross-functional engineering team with project, design, metallurgy, and customer support addressing all possible root causes for the crack initiation. All possible causes are being considered and all available data is used to support or contradict differing scenarios. This team has been in place for over a year and continues to drive towards the root cause or possible design changes that will address several probable causes. CFMI is evaluating a more robust seal design. Specifically, the seal tooth coating process was extensively researched. Several process differences and changes were investigated. The data could not conclusively support the seal tooth coating as the most probable cause and other scenarios are still being considered. Meetings are periodically held with the FAA to review the progress and address any continued airworthiness concerns.'

CFMI believe that this is a proactive environment and will lead to effective design changes.