Airbus A300B4-605R, G-MONS, 18 May 2001

AAIB Bulletin No: 11/2002	**Ref: EW/C2001/5/5**	**Category: 1.1**
Aircraft Type and Registration:	Airbus A300B4-605R, G-MONS	
No & Type of Engines:	2 General Electric (GE) CF6-80C2A5 turbofan engines	
Year of Manufacture:	1989	
Date & Time (UTC):	18 May 2001 at 1120 hrs	
Location:	In the cruise, near Casablanca	
Type of Flight:	Public Transport (Passenger)	
Persons on Board:	Crew 15	Passengers - 262
Injuries:	Nil	
Nature of Damage:	Uncontained failure of the No 2 engine, associated minor impact damage to the wing, skin panels and inboard aileron	
Commander's Licence:	Airline Transport Pilots Licence	
Commander's Age:	55 years	
Commander's Flying Experience:	14,128 hours (of which 6,281 were on type)	
	Last 90 days - 156 hours	
	Last 28 days - 56 hours	
Information Source:	AAIB field investigation	

Synopsis

The aircraft was on a scheduled flight from London Gatwick Airport to Banjul, in the Gambia, when it experienced an uncontained failure of the No 2 (right-hand) engine. The aircraft was diverted to Faro in Portugal, where an uneventful landing was made. There were no injuries to the crew or passengers.
The engine failure was precipitated by the detachment of a single High Pressure Turbine (HPT) Stage 2 blade due to fatigue and subsequent tensile overload, caused by the presence of a 0.25 inch deep notch worn into the leading edge of the blade. This notch was produced by an HPT Stage 2 Nozzle Guide Vane (NGV) segment which had 'sagged' rearwards and made contact with the HPT

Stage 2 turbine blades, due to the propagation of thermally induced fatigue cracks in the NGV aerofoil outer fillet.

This AAIB Bulletin contains Safety Recommendation 2001-60, which was originally issued in AAIB Special Bulletin S2/2001, which recommended that the on-wing inspection of the CF6-80C2 HPT Stage 2 NGVs, in accordance with GE Service Bulletin CF6-80C2 S/B 72-0952, be expeditiously mandated. One new Safety Recommendation, regarding improvement of the containment capabilities of the Low Pressure Turbine (LPT) case, is also made in this AAIB Bulletin.

History of the flight

The aircraft was on a scheduled passenger flight from London (Gatwick) Airport to Banjul, in the Gambia. In stabilised cruise conditions at FL290, abeam Casablanca, there was a sudden onset of a very noticeable vibration which was accompanied by some thrust loss from the No 2 engine. This was concurrent with the No 2 engine N2 vibration indication rising rapidly to 5.8 units. Manual throttle was selected, Maximum Continuous Thrust applied on the No. 1 engine and the No 2 engine throttle was retarded to idle. The N2 vibration decreased and settled at 4.4 units. A 'PAN' call was broadcast to Casablanca and approval was obtained for a descent and precautionary diversion to Faro in Portugal. A positioning A300 crew travelling on G-MONS provided assistance to the flight crew during the diversion.

In accordance with checklist procedures, the No 2 engine throttle was kept at idle and the engine parameters were carefully monitored. With the exception of the N2 vibration, these remained normal. An uneventful overweight landing at 150 tonnes was carried out at Faro with the Airport Fire Service (AFS) in attendance. The aircraft was taxied off the runway and the No 2 engine was shut down but, as the AFS reported that there was no sign of fire or obvious damage, the aircraft was taxied onto the stand. It was subsequently noticed that there were several holes in the No 2 engine cowl.

Aircraft and engine information

The No 2 engine was a CF6-80C2A5 turbofan, serial number 695-323. According to the engine data plate, the engine has a maximum take-off thrust rating of 60,100 lbs and a Maximum Continuous Thrust rating of 56,210 lbs. At the time of the incident, the engine had completed a total of 7,778 hours and 2,513 cycles since previous overhaul in December 1998. A review of the aircraft Technical Log reports did not highlight any significant defects on the No 2 engine, nor were there any recent reports of bird or foreign object ingestion. Flight Data Recorder and engine trend monitoring data did not show any significant trends prior to the engine failure.

The engine had completed 717 hours and 237 cycles since the previous routine boroscope inspection of the combustion chamber and HPT on 13 March 2001. According to the record sheets for this inspection, two of the HPT Stage 2 blades had cracks 0.080 inch in length in the tip cap area, which was within Maintenance Manual limits, but there was no record of any other damage to the HPT Stage 2 blades. The operator's engine maintenance programme required the HPT module to be boroscoped at each 'A' Check (every 43 calendar days). At the time of this incident, there was no requirement in the operator's engine maintenance programme to inspect the HPT Stage 2 NGVs
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Aircraft damage

(Note: For simplicity, all circumferential locations on the engine are referred to as positions on the clock, as viewed from the aft of the engine looking forward (ALF)).

Photographs of the aircraft damage taken at Faro were sent to the AAIB and the aircraft was later examined by the AAIB on its return to the United Kingdom. A large hole was visible in the 10 o'clock position on the left hand core cowl of the No 2 engine. The hole measured approximately 12 inch circumferentially and was located in the plane of the LPT Stage 5 rotor. A circular hole, some 3 inch in diameter, was visible in the right hand core cowl at the 2 o'clock position, in the same axial plane and the edges of both of these holes were noticeably petalled outwards. A 0.5 inch wide breach was visible in the LPT case, extending over an arc of approximately 330°, in the plane of the LPT Stage 5 rotor. Debris released radially outwards through the breach had struck the lower surface of the starboard wing, causing minor penetrations to the inboard aileron and access panels behind the leading edge on the underside of the wing, but no damage was sustained by the fuselage or any of the aircraft systems.

Engine strip examination

The engine was sent to GE's engine overhaul facility in Prestwick, Scotland, where it was stripped and examined by the AAIB and investigators from GE's Commercial Flight Safety Department. Representatives from the CAA and FAA were also present. Parts of the LPT and HPT assemblies were subsequently returned to the engine manufacturer for more detailed examination and metallurgical testing.

LPT Module Findings

The most evident damage to the LPT module was an approximately 0.5 inch wide circumferential breach in the LPT case extending over a 330° arc, from the 5 o'clock to 3 o'clock positions, in the plane of the LPT Stage 5 rotor. The centre of the breach was located approximately 1.25 inch forward of the Turbine Rear Frame mounting flange. The edges of the opening were curled outwards and heavily blued and scored. Most of the LPT outer shrouds were missing, except for a few fragments which remained in their shroud retainer grooves. The edges of these fragments were also heavily blued and scored. All of the LPT Stage 5 blades were still attached, but were missing the tip shrouds and the outer 1 inch of the aerofoil. One LPT Stage 5 blade tip shroud was found lodged in the opening in the LPT case. Two of the LPT Stage 5 blades were significantly bent opposite to the direction of rotation and many exhibited slight buckling between 3 inch and 4.5 inch from the blade root. It was evident that the LPT outer shrouds and the LPT case had been worn through and that debris had been ejected through the breach.
Metallurgical examination of the LPT case identified a heat affected zone approximately 0.6 inch wide, extending 360° around the case in the plane of the LPT Stage 5 rotor. Measurements of the local hardness in the heat affected zone gave a value 10 HRC (Rockwell Hardness), which is significantly lower than the specification limits of 37 - 48 HRC. The hardness elsewhere on the LPT case was within specification, as was the material composition. The fracture surface of the opening was intergranular, this was indicative of a high temperature overload failure. It was thus concluded that debris wedged under the LPT Stage 5 blade tips had been spun around the inside of the LPT case for a short period, probably for less than 1 second, and that this, through friction, had generated large amounts of heat. This had softened the material of the LPT outer shrouds and the LPT case causing them to fail in tensile overload. One of the LPT Stage 5 blades had been bent back such that it was supported by the adjacent trailing blade, and this possibly provided a stiffer

support more readily able to trap and drive debris around the inside of the LPT case than a single unsupported blade.

The LPT case was also punctured at the 12 o'clock location in the plane of the LPT Stage 1 rotor. The dimensions of the puncture were 0.75 inch circumferentially and 0.5 inch axially. There was a further 0.5 inch by 0.25 inch puncture at the 1 o'clock position in the same plane. The edges of both punctures were petalled significantly outwards. The debris had penetrated the engine cowl and caused punctures in the pylon heat shield. A further puncture of the LPT case was also visible at the 4 o'clock position in the plane of the LPT Stage 4. The dimensions of this puncture were 1.5 inch circumferentially and 1.0 inch axially. This puncture did not exhibit such noticeable petalling of the edges. The liberated fragment of case was recovered from inside the engine cowls. Metallurgical tests confirmed that the LPT case material composition and hardness in the puncture areas was in compliance with the design specifications.

All of the LPT Stage 1, 2, 3, and 4 blades had broken off at various heights along their span, releasing large amounts of aerofoil debris. Much of this debris was trapped by the NGVs of the next downstream stage, but sufficient debris was able to pass through and cause severe damage to the next stage of the LPT.
Approximately 40 aerofoil and tip shroud fragments were recovered from within the engine cowls and these ranged in size from small fragments to complete blade tip shrouds with sections of aerofoil attached. Many were heavily scored and blued. Metallurgical examination of a number of the fragments indicated that they had originated from various stages of the LPT.

HPT Module Findings, Figure 1 *(jpg 155kb)*

On disassembling the HPT module, it was observed that one of the HPT Stage 2 turbine blade aerofoils had completely separated approximately 0.125 inch above the root platform, Figure 2. The missing aerofoil was not recovered. The plane of the fracture was aligned with the apex of a notch which had been worn into the leading edge of the blade. The notch was 'V' shaped, parallel to the blade platform and approximately 0.25 inch deep in a chord-wise direction. Metallurgical analysis of the fracture surface on the remaining part of the blade, Figure 3 *(jpg 112kb)*, showed the presence of a fatigue crack that had originated in the notch, with the final failure resulting from tensile overload. Similar notches were found on the remaining 73 HPT Stage 2 blades. The trailing edge of the inner platform of the NGV segment at the 12 o'clock position was worn to the extent that it was almost entirely missing, Figure 2. This NGV segment had 'sagged' rearwards by approximately 5/8 inch, allowing the NGV inner platform trailing edge to come into contact with the leading edges of the HPT Stage 2 blades and wear, or machine, notches into the blades. Five NGV segments located at and adjacent to the 12 o'clock position were observed to have severe cracking in the fillet where the aerofoil meets the outer platform, Figure 4.

The NGV segments (24 in total) are comprised of two aerofoil sections which share a common inner and a common outer platform. The NGVs are cantilever-mounted to the HPT case from their outer platform and rely on the structural integrity of the aerofoils to resist the aerodynamic loading from the gas stream. On the NGV which had 'sagged', the cracks in the aerofoil outer platform fillets had grown to the point that insufficient residual strength remained to prevent the NGV segment from 'sagging' backwards and contacting the HPT Stage 2 blades. The depth of the notches machined in the HPT Stage 2 blades increased, as the cracks continued to propagate around the NGV aerofoil outer platform fillets, and this allowed the NGV segment to 'sag' further.

Examination of all of the HPT Stage 2 NGVs showed that several exhibited thermally induced fatigue cracking in the aerofoils. The cracks typically originated at the aerofoil leading or trailing edge, at a distance of between 0.125 inch and 0.75 inch from the outer platform. The cracks propagated perpendicularly to the leading or trailing edge for a short distance, before running out into the aerofoil outer fillet. The cracks then propagated around the fillet between the aerofoil and the outer platform, following the line of greatest stress. The cracking was noted to be more predominant on the trailing aerofoil (ie, the right-hand aerofoil, as viewed ALF). On the NGV segment in the 12 o'clock position, the trailing aerofoil had cracked around 360° of the outer platform fillet and significant cracking was present in the outer fillet of the leading aerofoil.

HPT Stage 2 NGV modification history

The early HPT Stage 2 NGVs (part number 9373M80G28 and earlier), referred to as pre-G29/G30 NGVs, originated from the original engine certification and were manufactured between 1983 and December 1993. In-service experience did not highlight any problems with the basic design of these NGVs, but problems of aerofoil mid-span cracking and fragmentation were experienced on NGVs which had been subject to multiple repairs.

In December 1993, Service Bulletin CF6-80C2 S/B 72-0716 was issued, which modified the NGVs to reduce the amount of internal cooling airflow. This was in order to improve the specfic fuel consumption of the engine. In service, the aerofoils of these NGVs, part number 9373M80G29/G30, suffered from severe thermal distress, including mid-span cracking and leading edge burning. In response to this, the engine manufacturer released Service Bulletin CF6-80C2 S/B 72-0959 in June 1999, recommending that operators replace the G29 and G30 NGVs at next HPT module exposure.

Service Bulletin CF6-80C2 S/B 72-0904, released in September 1997, introduced a new insert which restored the amount of NGV internal cooling air to pre-G29/G30 levels and redistributed the air onto the desired surfaces. This changed the NGV part numbers to 9373M80G33/G34, and these are referred to as 'Phase 1a' NGVs. Service Bulletin CF6-80C2 S/B 72-0921, issued in August 1998, introduced the same cooling insert but with an additional thermal barrier coating applied to the NGV aerofoils, and these are referred to as G35/G36, or 'Phase 1b' NGVs. Recent in-service experience shows that all of these post-G29/G30 NGVs tend to suffer from thermal fatigue cracking in the aerofoil outer fillet. As with earlier modification standard NGVs, cracking is more prevalent on NGVs that have been previously repaired. In-service experience also shows that NGVs located in the 12 o'clock and 6 o'clock positions are more likely to suffer from thermal distress due to hot spots caused by fuel nozzle spray pattern distortion. This can occur at these positions from fuel pressure variation due to an internal build-up of carbon deposits within the nozzles.

All 24 of the HPT Stage 2 NGVs on the engine from G-MONS were established to be post-G29/G30 modification standard, ie, they were in the category which is most prone to outer platform fillet cracking. The NGV in the 12 o'clock position, which had 'sagged' and damaged the Stage 2 HPT blades, had been repaired three times. Sixteen of the HPT Stage 2 NGVs on the engine were established to be post-G29/G30 modification standard having accumulated in excess of 10,000 cycles, ie, they were in the category which is most prone to outer fillet cracking because of age and configuration. The other eight NGVs, which had never been repaired, were post-G29/G30 standard and were not distressed.

In June 1999, a new design of NGV was introduced by service bulletin CF6-80C2 S/B 72-0978. These NGVs, part number 2080M12G01/G02, are referred to as 'Phase 2' NGVs, and feature a new casting with a more blunt aerofoil leading edge and compound aerofoil fillet radii. These are now the current production standard and, to date, there have been no reported problems of aerofoil cracking with this standard of NGV.

Effect of multiple repairs on NGV distress

Studies by the engine manufacturer have identified that the repair process can significantly reduce the wall thickness of the NGV aerofoil section: aggressive stripping and cleaning can produce a reduction in the aerofoil wall thickness of up to 22%. This increases the mechanical and thermal stresses within the NGV, thereby increasing the probability of cracking, but more so if the NGV has been repaired more than once. Studies also show that twice and three-time repaired NGVs installed in the 6 and 12 o'clock positions have a 30% probability of failure by 2,500 engine cycles.

Detailed examination of HPT Stage 2 NGV fragments recovered from previous NGV failures (though not necessarily due to cracks in the aerofoil outer fillet) revealed aerofoil wall thicknesses reduced by up to 36%. There had been no requirement to check the aerofoil wall thickness during NGV overhaul and this would not always have been practicable. Many NGVs have large amounts of braze alloy added to the aerofoil surfaces during repair and NDT techniques cannot differentiate between repair material and the parent material. The engine manufacturer is, however, amending the Engine Shop Manual to require aerofoil wall thickness checks on those NGVs which are at first repair or overhaul.

In-service history of HPT Stage 2 NGV cracking

The engine manufacturer advised CF6-80C2 operators of the problem of NGV aerofoil distress and cracking in Commercial Engine Service Memorandum No. 42 (CESM 42), which was issued in June 2000. This document informed operators of eight in-flight engine shut down incidents which had occurred since March 1998 and which were attributable to pre-G29/G30 HPT Stage 2 NGV distress. Whilst most of these were due to aerofoil mid-span cracking and aerofoil burning, one of the events was attributed to cracking in the NGV aerofoil outer fillet. Of the eight failures, two had resulted in penetrations of the LPT case. All of the NGVs involved had been previously repaired.

Revision 1 of CESM 42 was issued in August 2001, following the G-MONS incident. Details were included of six previous cases of NGV aerofoil outer fillet cracking and HPT Stage 2 blade notching which had occurred since April 2000. These had been discovered either during on-wing inspections or at engine overhaul.

On July 25 2001 an A330-301, registration OO-SFM, en route from Brussels to Montreal, experienced a failure of the No 2 engine in the climb. The aircraft was equipped with CF6-80E1A2 engines with HPT Stage 2 NGVs of an equivalent standard to the post-G29/G30 NGVs installed on G-MONS. The engine failure was established, on engine strip examination, to have been caused by aerofoil outer fillet cracking. This failure also resulted in a rub-through of the LPT case in the plane of the LPT Stage 5 but, on this occasion, the released debris was contained within the nacelle. This failure is being investigated by the Belgian Air Accident Investigation authority.

Inspection Service Bulletin CF6-80C2 S/B 72-0952

Due to the history of in-service problems of HPT Stage 2 NGV cracking, the engine manufacturer issued Service Bulletin CF6-80C2 S/B 72-0952 in December 1998, recommending that operators introduce a repetitive boroscope inspection of the HPT Stage 2 NGVs to inspect for thermal distress and cracking. At the time of the G-MONS incident, this Service Bulletin was at Revision 4. This revision was issued on June 30 2000, and provided inspection limits and recommended inspection intervals for the particularly problematic G29/G30 NGVs. However, the pre- and post-G29/G30 NGVs were to be inspected at the operator's convenience. At the time of the failure, the operator of G-MONS had already taken the decision to introduce a routine inspection of the HPT Stage 2 NGVs and was in the process of incorporating this into the engine maintenance programme. The inspection was not assigned a high priority, as S/B 72-0952 did not seem to indicate that it was an airworthiness issue for the non-G29/G30 NGVs. Prior to the release of S/B 72-0952 there had been no requirement to carry out special inspections of the HPT Stage 2 NGVs.

Revision 4 of S/B 72-0952 illustrated the various types of NGV distress typically seen, such as mid-span cracking and bulging, and leading edge burning, but did not specifically highlight the problem of outer fillet cracking, as this had only recently become a significant issue. This was addressed in Revision 5 of the Service Bulletin, which was issued on 7 August 2001, and which highlighted the outer platform fillet as being an area of primary distress and provided limits for acceptable crack lengths. Inspection intervals for the pre- and post-G29/G30 NGVs were also introduced in Revision 5 of S/B 72-0952.

It is possible that, if S/B 72-0952 Revision 4 had placed more emphasis on the inspection of the post-G29/G30 HPT Stage 2 NGVs and included inspection intervals, rather than a recommendation that they be inspected at the operators discretion, the operator would have assigned the NGV inspection a higher priority. If the NGVs had been inspected during the previous HPT inspection, 237 cycles prior to the incident, there is also a high probability that the NGV aerofoil outer fillet cracking might have been identified.

LPT containment issues

The release of engine debris as a result of the LPT Stage 5 rub-through is a cause for concern as the debris possessed sufficiently high energy to be able to penetrate the engine cowls and puncture panels on the underside of the wing. (The wing panels which were punctured, however, were not the thicker/reinforced panels used under critical wing components). Rub-through containment issues were not considered in the design of the LPT. The LPT case penetrations at the 12 and 1 o'clock positions in the plane of the LPT Stage 1, and the case penetration at 4 o'clock in the plane of the LPT Stage 4, also give cause for concern, given that the engine was operating below its maximum thrust setting when the failure occurred.

The NTSB has investigated two cases of CF6-80C2 LPT case non-containment, one originating from a thermocouple probe failure and the second from a Stage 1 LPT air seal segment failure. Both of these cases resulted in LPT non-containment downstream of the failures, and this led them to conclude that the "...design containment capability of the [CF6-80C2] LPT case is inadequate". As a result of these and previous events on both the CF6-80 and the CF6-50 series engines, the NTSB issued Safety Recommendation A-98-126 on 03 December 1998, which recommended that the FAA:-

'Require General Electric Aircraft Engines to improve the ability of the CF6-50 and the CF6-80 series engines to prevent fractured low pressure turbine blades from being liberated through the engine cowling'

The CF6-80C2 was certificated to the United States Title 14 Code of Federal Regulations, Part 33 requirements. 14 CFR 33.19 a) states in part that:

'The design of the compressor and turbine rotor cases must provide for the containment of damage from rotor blade failure'

In the G-MONS event, the HPT case contained the initial HPT Stage 2 blade failure and therefore met the design requirements. However, the LPT case was unable to contain the energy of the debris produced from the consequential damage to the LPT. To interpret the regulation as purely referring to containment of the initial event would be unrealistic in light of the experience from this incident and previous CF6-80C2 engine failures. These incidents indicate that the consequences of an initial failure may sometimes be the more testing scenario for LPT containment, rather than the initial failure itself. The LPT case rub through is a new phenomenon with this engine, and is one that the manufacturer will be addressing.

As a result of the NTSB concerns over LPT containment issues, the engine manufacturer introduced several changes intended to improve the containment capability of the CF6-80C2 LPT case. In 1998 the thickness of the LPT case was increased and this design change was incorporated into production engines, beginning in September 1998. New limits were also added to the Engine Shop Manual to specify minimum allowable thicknesses for repaired LPT outer shrouds. Finally, new LPT outer shrouds manufactured from a tougher material were introduced by service bulletin CF6-80C2 S/B 72-1006, issued in April 2001. The FAA has issued a Notice of Proposed Rulemaking with the intention of mandating the installation of the new shrouds by December 2006.

Preventative actions

Immediately after the G-MONS event, the operator instigated a fleet inspection of its CF6-80C2 engines. This inspection identified two other engines with significant cracking of the HPT Stage 2 NGV aerofoil outer fillets which could, ultimately, have caused a similar failure to that on G-MONS. These engines were removed for repair.

Concurrently, the AAIB issued Special Bulletin S2/2001, containing Safety Recommendation 2001-60, which recommended that the CAA and FAA expeditiously mandate the boroscope inspection of the CF6-80C2 HPT Stage 2 NGVs in accordance with GE Service Bulletin CF6-80C2 S/B 72-0952.

On 07 June 2001, the engine manufacturer issued an All Operators Wire to CF6-80C2 operators, informing them of the G-MONS incident. In this wire it was recommended that operators implement an inspection programme of the HPT Stage 2 NGVs, with priority to be given to higher thrust engines which have more than 2000 cycles since HPT overhaul and which have multiple-repaired NGVs installed.

In August 2001, the engine manufacturer issued Revision 1 of CESM 42 to highlight to operators the increased probability of HPT Stage 2 NGV cracking occurring on post-G29/G30 standard NGVs with multiple repairs. This document provided recommendations on how to avoid NGV failures in service, including the introduction of on-wing inspections of NGVs per S/B 72-0952,

limiting the number of repairs to the NGVs and replacement of high-time pre-Phase 2 NGVs. CESM 42 also draws operators attention to Revision 72-0833 to the Engine Shop Manual, issued in July 2001, which contains revised, tighter, limits for the repair of the HPT Stage 2 NGVs.

Conclusions

The failure of the No 2 engine was caused by thermally induced fatigue cracking of the HPT Stage 2 NGV aerofoils around the aerofoil outer fillet. This allowed the NGV segment at the 12 o'clock position to 'sag' backwards and 'machine' notches in the HPT Stage 2 blades, ultimately causing the separation of a single blade due to fatigue and tensile overload. All of the HPT Stage 2 NGVs installed on the engine were post-G29/G30 modification standard, the standard which are prone to cracking of the aerofoil outer fillet. An additional factor was the fact that many of the NGV sections, but in particular the NGV segment at the 12 o'clock location, had been multiple-repaired, which further increased the probability of outer fillet cracking.

According to Service bulletin CF6-80C2 S/B 72-0952 Revision 4, the inspection of the HPT Stage 2 NGVs could be performed at the operator's convenience. The HPT on the G-MONS No 2 engine was boroscope inspected 237 cycles prior to the incident, but the Stage 2 NGVs were not inspected at that time. It is possible that, had the NGVs been inspected on this occasion, the aerofoil outer fillet cracking might have been identified and the incident could have been prevented. The engine manufacturer's recommendation that operators inspect the non-G29/G30 nozzles was not assigned a higher level of significance as, prior to the G-MONS event, there was no significant history of engine failures due to HPT Stage 2 NGV aerofoil outer fillet cracking.

The HPT case withstood the initial event of the release of a single HPT Stage 2 aerofoil and therefore met the engine certification requirements in this respect. However, LPT case penetrations in the planes of the LPT Stages 1 and 4, and LPT case rub-through in the plane of the LPT Stage 5, subsequently occurred due to the cascade of damage caused by engine debris travelling rearwards through the engine. This and previous events give cause for concern that, whilst the CF6-80C2 LPT case may satisfy the certification design requirement to contain a single blade-off, it cannot, in some cases, contain the debris subsequently generated within the LPT case as a consequence of an initial failure further upstream in the engine. This is particularly true for the LPT Stage 5 case rub-through condition, which was an unforseen failure mode and for which the LPT case was not designed. In-service experience of actual failures suggests that further improvements in LPT containment capability are desirable, and that these need to address the LPT case rub-through failure mode.

Safety Recommendations

In order to prevent further engine failures caused by HPT Stage 2 NGV aerofoil outer fillet cracking, the following Safety Recommendation 2001-60 was made during the course of this investigation, and was included in AAIB Special Bulletin S2/2001:-

Safety Recommendation 2001-60

> *'The FAA and CAA should expeditiously issue a mandatory instruction requiring operators to perform boroscope inspections of the CF6-80C2 HPT Stage 2 nozzles to check for nozzle cracking and distress in accordance with GE Service Bulletin CF6-80C2 S/B 72-0952.'*

The CAA accepted this Safety Recommendation and issued Additional Airworthiness Directive 003-07-2001 on 26 July 2001, requiring CF6-80C2 operators in the United Kingdom to perform boroscope inspections of the HPT Stage 2 NGVs, in accordance with Service Bulletin CF6-80C2 S/B 72-0952 Revision 4. The FAA have also agreed in principle to mandate the intent of CF6-80C2 S/B 72-0952, but only in respect of the aerofoil outer fillet inspections and therefore does not intend to mandate this service bulletin in its current form. The issuing of the FAA AD is awaiting the release of a new inspection service bulletin from the manufacturer, specifically addressing the primary concern of HPT Stage 2 NGV aerofoil outer fillet cracking. A similar service bulletin has already been issued for the CF6-80E1 engine (CF6-80E1 S/B 72-0217), in response to the OO-SFM incident in July 2001, and this was mandated by the FAA.

In order to reduce the likelihood of engine debris penetrating the engine cowls and potentially endangering the aircraft, the following new Safety Recommendation, which complements NTSB Safety Recommendation A-98-126 in respect of CF6-80C2 LPT containment, is made:-

Safety Recommendation 2002-08

The engine manufacturer, General Electric Aircraft Engines, should take actions to improve the ability of the CF6-80C2 to prevent fractured LPT blades from being liberated through the engine cowling. These actions should also address the LPT case rub-through mode of failure.

In a response to this recommendation the FAA have made a similarly worded Safety Recommendation, 02.170, and this is directed at two issues:

1. preventing ballistic type penetrations due to high energy blade debris, and

2. preventing rub-through and separation of the LPT case due to entrapment of accumulated debris.

The status of the FAA's activities, at the time of writing, with regard to each of these issues are quoted below:

1. 'GE released improved LPT shrouds for stages 2-4 via SB 72-1006 in 2001. These improved shrouds (material and thickness changes) will provide additional resistance to ballistic penetrations. The FAA issued a notice of proposed rule making (Docket # 2001_NE-19-AD) to require incorporation of these improved shrouds. The resulting final rule AD is in process, with publication planned for later this year [2002]

2 In February 2002, GE briefed the FAA, NTSB and AAIB on a multi-year program plan to understand the rub-through failure scenario, identify design solutions for prevention, define tests and analysis for verification, complete certification and introduce hardware to the field. The initial phase of this program is still in progress. Over the course of the program, the FAA will receive periodic updates from GE on the status. Once a design solution to prevent LPT case rub-through failure has been defined by GE, the FAA will work closely with the manufacturer to substantiate the design change in accordance with all applicable FAA regulations. Once certified, mandatory incorporation of the design improvement will be considered by the ECO [Engine Certification Office].

In addition to addressing the containment issues, GE and the FAA are taking action to address the root cause of this LPT uncontained engine event.'

The FAA's Safety Recommendation Review Board have classified recommendation 02.170 as "Closed-Acceptable Action".