Boeing 747-136, G-AWNG

AAIB Bulletin No: 12/98 Ref: EW/C97/5/8 Category: 1.1

INCIDENT

Aircraft Type and Registration:	Boeing 747-136, G-AWNG
No & Type of Engines:	4 Pratt & Whitney JT9D-7A turbofan engines
Year of Manufacture:	1971
Date & Time (UTC):	27 May 1997 at 1638 hrs
Location:	London Heathrow Airport
Type of Flight:	Public Transport
Persons on Board:	Crew - 18 - Passengers - Not Available
Injuries:	Crew - None - Passengers - None
Nature of Damage:	No 2 Engine Combustion Chamber Outer Case cracked
Commander's Licence:	Airline Transport Pilot's Licence
Commander's Age:	51 years
Commander's Flying Experience:	16,294 hours (of which 276 hours were on type)
	Last 90 days - 193 hours
	Last 28 days - 46 hours
Information Source:	AAIB Field Investigation

Flight

The aircraft was departing from Heathrow for New York. Shortly after take off, at an estimated height of 100 feet and an indicated airspeed of 172 kt, the flight crew was alerted to a No 2 engine problem by the illumination of an amber caution light on the No 2 Exhaust Gas Temperature (EGT) gauge. The light signifies EGT exceeding 915°C (engine shutdown required if EGT exceeds 940°C). The Flight Engineer immediately reduced the thrust lever setting, almost simultaneously noted that other No 2 Engine parameters had suffered a major decrease and informed the other crew members that the engine had failed. The crew shutdown the engine, completing the Engine Fire Checklist immediate actions by around 500 feet, and continued the climb to FL 100.

The aircraft take-off weight had been approximately 300,000 kg and the crew jettisoned 30,000 kg of fuel over the English Channel to reduce weight to below the Maximum Allowable Landing Weight. An uneventful three engine landing was made back at Heathrow 70 minutes after take off. Initial examination revealed a 69 inch long circumferential crack around the No 2 Engine Combustion Chamber Outer Casing (CCOC). The engine manufacturer considered that the resultant disruption of the engine gas flow was likely to have caused the engine to surge.

Flight recorders

At the time of landing the Cockpit Voice Recorder (CVR) had recorded over the recording of the take-off phase. The Flight Data Recorder (FDR) and an Optical Quick Access Recorder (OQAR) both provided parameter records for the whole flight. The only abnormal feature apparent during the take-off run was that the No 2 Engine N_2 (high pressure rotor rotational speed) was somewhat lower in relation to N_1 (low pressure rotor speed) than was usual for the engine type. At the point of take-off rotation the No 2 Engine parameters exhibited a sudden rapid change, with the following alterations occurring over a period of approximately 0.5 second:

Engine Pressure Ratio (EPR) decrease from 1.37 to 1.18

EGT increased from 860°C to 940°C

N_1 decrease from 91.5 to 80%

N_2 decrease from 91.1 to 86%

The EGT peaked at 945°C for 2 seconds and then began to slowly decrease in response to retardation of the thrust lever, accompanied by a slow further decline in EPR, N_1 and N_2. The thrust lever was fully closed 10 seconds after the initial event.

Engine description

The engine is a conventional twin spool modular turbofan (Figure 1.1). The CCOC forms part of the K-Module; it is a circular case, approximately 41 inches in diameter and 10.5 inches long, that surrounds the annular combustion chamber and forms the main structure of the engine carcass in this area (Figure 1.2). It is constructed of Inconel 718 (AMS 5663), a nickel-chrome-iron alloy. An internal flange (the L Flange) formed at the front of the CCOC is bolted to the diffuser case and an external flange (the M Flange) at the aft end is bolted to the high pressure (HP) turbine case. Under normal operating conditions the CCOC reaches a maximum temperature of approximately 550°C and has a maximum internal pressure in the order of 300 psig.

The CCOC has two basic configurations:

1. An early version fabricated case with welded axial seam and welded boroscope and drain bosses.

2. A later version integral one-piece case.

For both versions, the L Flange is integral with the forward part of the case, with a machine radiused internal fillet between the L Flange and the case wall (Figure 1.3). On most CCOC versions a single radius was cut, but some early versions had a dual radius profile (Figure 1.4). The CCOC fitted to G-AWNG's No 2 Engine was one of the earlier fabricated versions, with a dual radius fillet (Pratt & Whitney Part No (PN) 729237). For this case the required material thicknesses are 0.19 to 0.20 inch for the flange and 0.118 to 0.138 inch for the wall over most of its length, increasing to 0.290 to 0.350 inch at the forward end. The minimum permissible forward and aft radii for the L Flange fillet were 0.025 inch and 0.057 inch respectively.

Each engine bay is fitted with a dual loop nacelle overtemperature system. Each loop operates a flight deck temperature gauge and a nacelle fire warning system. A flight deck test of the system is scheduled prior to each engine start.

Powerplant examination

No clear signs of abnormal heating or other damage to the components mounted in the area of the CCOC crack were apparent. Both loops of the No 2 nacelle overtemperature system failed electrical continuity checks carried out after engine removal from the aircraft. Individual components checked satisfactorily and the system passed the checks after re-assembly. Checks of the No 2 Engine EGT indicating system and of the No 2 Engine oil system, including magnetic chip detectors (MCDs), filter debris and oil sample analysis, revealed no abnormalities.

The LP spool of the engine was tight to turn and fine metal fragments were evident in the exhaust system. Bulk strip examination of relevant engine components at the engine overhauler under AAIB supervision revealed significant internal damage, including heavy rotational rubbing between the blade tips and the outer airseal of the HP turbine and appreciable rotational rubbing between the LP and HP shafts. Both rivets attaching a locking plate for the HP turbine retaining nut had been sheared off and the nut had unscrewed approximately 10°. The severed rivets had lodged between the LP and HP shafts and were partially responsible for the damage to them but the shafts had also made direct contact with each other while rotating. Appreciable abnormal damage was present to the HP turbine first stage Nozzle Guide Vanes (NGV), consistent with overtemperature effects, with major leading edge burn through of six vanes and deposition of re-solidified material on the surface of most of the vanes. Assessment by an overhaul agency found no evidence of cooling passage airflow anomalies and concluded that the melted material had been present for only a brief period before the engine had ceased to operate.

Combustion chamber outer case examination

The CCOC crack ran around the L Flange fillet, extending over 195° of the circumference, from 050° to 245° (orientations throughout are relative to the top of the case, measured clockwise as viewed from the rear). It completely penetrated the section, separating the L Flange from the case wall over the 69 inch length of the crack, and in places a gap of around 0.25 inch had opened up. Fluorescent Dye Penetrant Inspection (FPI) of the unfractured part of the L-Flange fillet by the engine overhauler after removal of the CCOC from the module and cleaning of the surface indicated the presence of a number of unopened cracks. However, subsequent examination of a representative section from one of these areas by the Structural Materials Centre (SMC) of DERA at Farnborough found no signs of additional cracking. It was noted that a removable surface deposit present could have given false FPI indications.

Further assessment of the fracture was undertaken by SMC with a representative of the engine manufacturer present, followed by examination of the case in the USA by the engine manufacturer. L-Flange fillet forward and aft radii were 0.0287 inch and 0.0788 inch respectively, both of which exceeded the minimum requirements, and the case wall and flange thicknesses were also within limits. The material was found by Dispersive X-Ray Analysis to be consistent with Inconel 718, the hardness was within requirements, and the microstructure of a sample section was consistent with the required material in its properly heat treated state.

Optical examination of the separated fracture showed that the surfaces were generally clean and bright, typical of a fresh final fracture, but also exhibited a discoloured area over an approximately 5.5 inch circumferential length that had apparently been present for a period with the engine operating. This initial fracture passed through the forward radius of the fillet and was oriented approximately radially. It exhibited two distinct morphologies; a relatively smooth, blue-gold surface over an approximately 0.115 inch depth from the radius surface and a red-brown, more woody textured surface continuing for an additional 0.095 inch. The fracture terminated in a non-oxidised tensile shear lip through the flange chamfer.

Detailed examination of the initial fracture by Scanning Electron Microscopy (SEM) revealed striation marks in the blue-gold surface region, indicative of fatigue crack progression. The red-brown region did not show striations and was likely to have been a region where the fracture had progressed at a much higher rate. Surface detail near the origin of the fatigue crack had been obliterated by severe rubbing damage and oxidation, but the manufacturer assessed that the fracture had originated at multiple sites along the fillet radius at approximately the 135° position. It was assessed that the fracture had been due to Low Cycle Fatigue (LCF), *ie* step progression in response to stress cycles associated with a significant change in engine operating conditions and probably directly related to flight cycles, rather than High Cycle Fatigue associated with vibratory stresses. The total number of cycles involved in producing the initial crack, determined by integration of striation spacing versus distance from the origin, was estimated by the manufacturer as approximately 5,200 (predicted as accurate within ±10%). The SMC estimate was much higher.

No 2 engine history

The engine (SN P685964) had previously been owned by an overseas airline. During a shop visit to a UK engine overhauler in 1992 an FPI inspection and radius measurement check of the CCOC L-Flange fillet had been carried out. Ownership of the engine had passed to a United States leasing company in March 1995 and another shop visit to the same overhauler was made later that year for a repair. During this visit the engine strip included release of the CCOC as an individual part and it was inspected visually but not by FPI. When the incident occurred the CCOC had considerably exceeded the FPI interval recommended by the Pratt & Whitney (P&W) Overhaul Manual (paragraph 7); the CCOC service at the time of the incident represented 176% by hours and 145% by cycles of the recommended interval since the last FPI inspection.

The engine was leased by the airline operating G-AWNG shortly after the 1995 repair, sub-leased for a short period to another operator and then installed in G-AWNG's No 2 position on 11 July 1996, where it remained until the incident. The CCOC involved in the incident (SN BD5144) was originally produced as PN 644801 and subsequently modified to PN 729237 by three Service Bulletins, none of which concerned the L Flange. Details of the CCOC history are:

CCOC EVENT	DATE/ PERIOD yr	CCOC OPERATING HOURS	CCOC FLIGHT CYCLES

Manufacture	Dec 70	0	0
Time/cycles from New until:			
Last L Flange FPI and Radius Check	Dec 92	38,562	8,643
Last Shop Visit and L Flange visual inspection	Sept 95	43,683	10,077
At the time of the Incident, Time/Cycles since:			
Manufacture	26.5 yr	47,362	10,669
Last L Flange FPI and Radius Check	4.5 yr	8,800	2,026
Last Shop Visit and L Flange visual inspection	1.7 yr	3,679	592
Installation on G-AWNG	0.9 yr	3,602	560

The FDR information showed that the No 2 Engine N_2 was somewhat lower than usual in relation to N_1 and analysis of the operator's cruise performance monitoring data for the engine showed an incremental reduction of 1% in N_2 occurring in February 1997. Analysis of the data by the engine manufacturer concluded that, as no other parameters had altered at the same time, the shift had most likely been caused by a change in instrumentation or in variable stator vane scheduling. The abnormally low N_2 was not considered to have been indicative of a problem with the engine gas path.

Background

The fabricated CCOC of the type that ruptured in this incident was the first standard used on the JT9D engine, which was certificated in 1969. Pratt & Whitney Aircraft (PWA) Service Bulletin (SB) No 4482, issued 5 September 1975, introduced a modification to re-work the CCOC to provide a thicker L Flange with a single fillet radius. It noted that "Cyclic testing of the diffuser case has revealed high stresses in the inner radius of the outer combustion chamber case front flange (L Flange). Although there have been no field problems, a thicker flange has been provided to preclude the possibility of cracks developing in the L flange and to improve the durability of the outer combustion chamber case." SB No 4923, issued on 25 August 1978, introduced replacement of older types of CCOC with the one-piece case, along with replacement or rework of other components. The stated objective was "To remove an unnecessary maintainability feature and reduce air leakage"; the SB made no mention of any desirability of replacing the older type CCOC in order to reduce the likelihood of cracking. Compliance with both SBs was specified by the manufacturer as Category V (or 5, present day Category 8) "Optional - accomplish at a period based on operator's experience with prior configuration" and did not alter with subsequent SB revision. Approximately 29% of the JT9D engines operated by G-AWNG's operator have the original type of fabricated case without the thicker flange modification incorporated. No FAA or CAA directives in relation to this type of CCOC have been issued.

On 20 December 1991 an engine manufacturer's All Operator's Wire recommended an FPI of the L-Flange at 5,000 hr/1,400 cycle intervals; this was added to the Engine Overhaul Manual in March 1994. A medium sensitivity inspection standard (SPOP 62) was specified but it was believed that the overhauler involved had in fact opted for a more sensitive standard (SPOP 82), although this could not be categorically confirmed. Since the incident to G-AWNG the manufacturer has also recommended the higher sensitivity FPI (see below).

The engine manufacturer believed that the effects of extensive cracking of the CCOC would be for the engine carcass and shafts to bend and for the rotating assemblies to rub heavily and considered that there would be no significant effects on the engine mounts or the pylon and no concern for an engine non-containment. This incident and other similar cases (paragraph 8) suggested that rapid extension of the crack was likely to occur during take off, when the engine was at high power and components were relatively highly stressed.

Similar Cases

Three other cases of gross fracturing around the L Flange fillet have been reported. Two preceded the incident to G-AWNG and one followed it:

1 July 1991, JT9D-7A, CCOC PN 644801A.

Time since new - 54,331 hr/12,211 cycles

Time since last inspection (during overhaul) - 10,332 hr/2,300 cycles

A crack around the L Flange fillet that penetrated the case over a circumferential distance of 63 inches on its right side was discovered after the aircraft turned back with high EGT during climb. The engine manufacturer attributed the fracture to LCF that had originated at a toolmark in the L Flange fillet aft radius. The radius was poorly formed and did not conform to dimensional requirements (0.008 inch compared to the required 0.057 inch minimum). The engine manufacturer recommended a one-time check of all CCOCs with a dual radius fillet for correct radii dimensions and freedom from cracks, on the next occasion that this area became accessible (All Operators Wire AOW JT9/72-41/TS:RCB: 1-12-20-1 of 20 December 1991). The means of ensuring freedom from cracks were not specified.

2 December 1993, JT9D-7A, CCOC PN 729238.

Time since new - 57,809 hr/12,050 cycles

Time since last inspection (during overhaul) - 460 hr/121 cycles

A crack around the L Flange fillet that penetrated the case over a circumferential distance of 13 inches between approximately 208-247° was discovered during investigation of an ongoing problem of nacelle high temperature warnings. The crack had turned axial at both ends. The radii had previously been checked during a repair and found to be within limits. The engine manufacturer attributed the fracture to LCF that had originated at multiple origins in the L Flange fillet forward radius. Poor definition in some areas precluded a meaningful count of striations. The radii were found to be correctly dimensioned and there were no apparent material or processing abnormalities. The nacelle high temperature problem had begun shortly after the engine had been installed following its overhaul, indicating that a crack had been present when it had been released to service. No new recommendations were made.

3 July 1997, JT9D-7A.

Time since last inspection (during overhaul) - 64 cycles

A 40 inch long crack around the CCOC L Flange circumference was found after nacelle overtemperature indications had been experienced during take off. The engine was shutdown and the aircraft turned back. Features of the crack were very similar to those found on G-AWNG's CCOC and reportedly indicated that cracking had been present at the time of the last overhaul inspection.

Post-incident actions

Following the Incident to G-AWNG, the engine manufacturer re-analysed the structure of the CCOC and conducted rig and engine testing. A P&W All Operator Wire (AOW) (JT9D/72-41/TS:KDM: 7-11-12-2) issued on 12 November 1997 concluded that: "the fabricated cases are approaching their predicted fatigue life due to the considerable cycles and hours that have been accumulated in service. However, the continued use of fabricated cases in all JT9D-7/20 engine models does not pose a significant risk with regard to fracture and/or rupture provided the following management plan for this part is adhered to and/or a retirement plan for the cases be initiated." The plan specified:

1 A repetitive shop inspection that included a high sensitivity fluorescent penetrant inspection and eddy current inspection of the L Flange at intervals not to exceed 2,000 cycles. Cases with cracks found only in the L Flange will require flange replacement before return to service; those with cracks at the axial or boss welds must be scrapped.

2 For cases that had not had the shop inspection, an on-wing sonic inspection of the L Flange using newly developed sonic probe kits, at the earlier of the next A Check or 250 cycles. Manufacturer's recommendations for cases found cracked were stated to be under review.

3 For cases that remain on the wing for longer than 2,000 cycles since the last shop inspection, a repetitive sonic inspection of the L Flange at a cycle interval to be determined, with engine removal required if a crack were found.

The AOW recommended careful adherence to the management plan, encouraged retirement of the fabricated cases and offered a trade-in for a one-piece case for $50,000. The sonic probe kits were scheduled to be available in January 1998 but this was later revised to June 1998. Repetitive on-wing sonic inspection intervals (3. above) have not yet been promulgated.

A second P&W All Operator Wire (JT9D/72-41/TS:KDM:7-12-1-3), issued on 1 December 1997, provided information on the recommended eddy current inspection of the L Flange fillet. The special tooling necessary to conduct this inspection was offered free of charge and the AOW recommended that operators order the tooling and start performing the inspection at their earliest convenience to minimise the chance of releasing a part back to service with a crack in the flange. It also noted that P&W was working on improved procedures for cleaning the CCOC prior to inspection to minimise the possibility of the FPI failing to detect a crack.

G-AWNG's operator has opted to add X-Ray shop visit inspection of the fabricated CCOC L-Flange fillet to the above measures and to accept the possibility of a high rejection rate, depending on the rejection criteria set.

The above measures have not been mandated by the CAA or FAA. It has been reported that the engine manufacturer intends to issue an Alert Service Bulletin (ASB) in relation to improved measures for CCOC inspection and that, following this, the FAA will issue a Notice of Proposed Rulemaking (NPRM) with the intention of making incorporation of the ASB mandatory by means of an Airworthiness Directive (AD). The CAA requires UK operators to adhere to ADs issued by the airworthiness authority of the country of manufacture.

Discussion

It was apparent from the FDR data that the crew dealt expeditiously with the engine failure. The evidence indicated that the primary failure had been the sudden extensive growth of a crack in the No 2 engine CCOC from a pre-existing low cycle fatigue crack. The considerable internal damage to the engine was consistent with the effects of the CCOC rupture having subjected turbine components to abnormally high temperatures for a brief period, because of gas flow disturbance, and having resulted in heavy rotating contact between components, because of deformation of the engine carcass. There was some question as to whether the No 2 engine bay overtemperature/fire detection system had been functional at the time of the failure, but it was also possible that the location, size and/or duration of the hot gas leak were such that triggering of the system would not have been expected.

It was considered likely that incremental growth of the CCOC fatigue crack had been associated with flight cycles, although this could not be positively determined, and therefore that fatigue cracking had been present at the times of both the last shop visit visual inspection and the last FPI inspection. It was possible that the cracking may have been detected at the time of the last inspection 592 cycles before the incident had an FPI been carried out at this point, as recommended by the P&W Overhaul Manual. However, the failure of the FPI during the previous shop visit (probably to the higher sensitivity standard) to detect a crack together with the available evidence from other cases suggested that the inspection methods had not been totally reliable in detecting cracking.

The engine manufacturer had identified a problem of high stresses in the inner radius of the CCOC L Flange more than 21 years before the incident to G-AWNG and in 1975 had issued a SB modification to improve durability. A further SB modification replaced the older type CCOC with an improved version but without mention of increased CCOC durability as an objective. The 'Optional' categorisation of both SBs placed the onus for deciding on the necessity of accomplishing them on operators, based on the operator's experience with the existing configuration. Action recommended by the manufacturer before the incident had consisted of medium sensitivity FPI inspection and an L Flange radii check.

Recommendation

The effects of the CCOC cracking in the case of G-AWNG's incident and in the other known cases had apparently been largely confined to the engine and had not had major repercussions on other parts of the aircraft. However, there was a likelihood that such a failure would result in sudden complete loss of power from one engine at a critical stage of flight, as in G-AWNG's incident. Additionally, even though the effects in the cases so far had been relatively benign, the possibility that such an extensive rupture of a major structural component of the engine hot-section, with consequent leakage of high temperature gas and disruption of the high speed rotating assemblies, could hazard the aircraft could not be dismissed. In at least one of the other cases the crack direction had turned from circumferential to axial and this suggested the potential for an even more hazardous rupture. The following recommendation has therefore been made:

> **98-63** It is recommended that the CAA in conjunction with the FAA review the history and engineering analysis of the fabricated type of combustion chamber outer case used on the JT9D engine and mandate measures aimed at preventing recurrence of instances of extensive cracking of the case.