McDonnell Douglas DC-10-30, G-NIUK, 11 May 1997 at 2334 hrs (1934 hrs local)

AAIB Bulletin No: 4/99 Ref: EW/A97/5/1 Category: 1.1

Aircraft Type and Registration:	McDonnell Douglas DC-10-30, G-NIUK
No & Type of Engines:	3 General Electric CF6-50C2 turbofan engines
Year of Manufacture:	1974
Date & Time (UTC):	11 May 1997 at 2334 hrs (1934 hrs local time)
Location:	San Juan International Airport, Puerto Rico, USA
Type of Flight:	Public Transport
Persons on Board:	Crew - 14 - Passengers - 248+1
Injuries:	Crew - None - Passengers - Multiple minor evacuation injuries
Nature of Damage:	Damage to No 3 engine fuel cooled oil cooler
Commander's Licence:	Airline Transport Pilot's Licence
Commander's Age:	46 years
Commander's Flying Experience:	11,000 hours (of which 250 were on type) Last 90 days - 200 hours Last 28 days - 100 hours
Information Source:	Field investigation by the AAIB (see below)

The incident, which occurred within United States jurisdiction, was investigated by the NTSB with AAIB Inspectors' participation as accredited representatives. The NTSB issued a report on their investigation.

Description of the incident

The aircraft was operating a British Airways scheduled passenger service from San Juan, Puerto Rico, to London Gatwick Airport. The flight was being operated by Aircraft Management Ltd (AML), a joint venture company between British Airways PLC and Flying Colours Airlines Ltd. The flight deck crew was provided under contract from British Airways and the cabin crew from Flying Colours.

The aircraft had previously arrived at the end of the outbound sector from London Gatwick with no reported defects, and was refuelled for the return sector to a total of 78,000 kg contents. There was an administrative discrepancy in the amount of fuel uplifted as recorded in the Technical Log from fuel contents gauge readings and that for the measured volume uplifted. This apparent discrepancy was resolved by the flight deck crew prior to departure.

The aircraft pushed back from Stand 40 on the South Ramp at 2317 hrs. Engine No 3 was started first at 2319 hrs, followed by engines Nos 1 and 2. The passenger safety briefing had been completed and a seat belt check was in progress in the cabin as the aircraft started to taxi along taxiway 'N', towards Runway 08 for departure, just prior to 2324 hrs. As the aircraft began taxiing, the senior cabin crew member (SCCM) informed the commander of the presence of fumes in the cabin.

The crew considered that this was not unusual whilst on the ground but the commander initially asked the flight engineer to go into the cabin to investigate the problem. On his return, he confirmed that there was considerable haze in the cabin, particularly towards the rear, with a smell of fuel. The commander stopped the aircraft on the taxiway at 2325.5 hrs and applied the parking brake. ATC were informed and the flight deck crew switched off the pneumatic and air conditioning supplies, intending to restore each system in turn in an attempt to identify the source of the contamination.

The commander then went into the cabin to assess the situation for himself. The haze was still visible in the rear cabin accompanied by the smell of fuel, and this was causing some eye discomfort to the occupants. The commander returned to the flight deck and ordered the shutdown of engines Nos 1 and 3, which was accomplished just prior to 2328 hrs. The auxiliary power unit (APU) was started as a source of electrical power and uncontaminated air conditioning. Engine No 2 was shut down after the flaps had been retracted and as soon as the APU was on line. ATC were informed of the situation and the handling agency was requested to provide a tug to return the aircraft to the parking stand. The first officer informed the passengers of the situation and the commander returned to the passenger cabin to inform the cabin crew of the proposed return to the parking stand.

As the commander returned to the flight deck, the crew of another aircraft positioned behind G-NIUK observed that there was a fire in its right engine (No 3). They informed ATC and G-NIUK's crew on the Airport Ground frequency, although there was initially some confusion in terminology as to which engine was being referred to. There were no fire warnings or other abnormal indications apparent on the flight deck of G-NIUK and all three engines had been shut down by this time.

The Engine Fire Checklist was actioned for the No 3 engine. During this action, smoke was observed passing the right side of the flight deck. In view of the presence of smoke and the fuel fumes in the cabin, the commander ordered a passenger evacuation verbally to the SCCM who was standing on the flight deck at that time. The first officer activated the Evacuation Alarm. The flight deck crew carried out the Evacuation Checklist actions. At that time, the commander was not aware of the status of the fire, merely that it was confirmed as being present.

The aircraft had stopped on the taxiway only a short distance from the Airport Fire Station. The Fire Service were very quickly in attendance and discharged water onto the jet pipe area of the No 3 engine in order to quickly extinguish the fire. However, this was not reported to the flight crew prior to the initiation of the evacuation.

A witness who was driving on the airport stated that, as the aircraft taxied, white smoke was trailing from the No 3 engine. The smoke then turned black and flames some 6 feet long erupted from the rear of the engine. After several seconds the fire died down, becoming confined to the tail pipe and lower cowling. He reported that the fire vehicles had arrived at the aircraft just prior to the evacuation and had discharged water onto the rear of the No 3 engine, extinguishing the fire.

The recorded weather at the time was: surface wind 100° / 8 kt, good visibility, no significant low cloud and a temperature of +28°C.

Evacuation

It was dark outside the aircraft at the time of the evacuation and the cabin crew commented that it was difficult to check for adverse external conditions through the small viewing windows located in the doors prior to their opening. As the evacuation commenced, a fire vehicle was in attendance at the right wing which initially precluded the use of door 3R. The cabin crew member in charge of this door therefore redirected passengers to an alternative exit. The door was later opened and the slide deployed normally.

At the time that the evacuation commenced, the cabin crew member in charge of door 3L was away from the door attending to a distressed passenger. As the evacuation started, a passenger mistakenly partially disarmed this door in an attempt to open it. However the cabin crew member then regained control of the door, rearmed it and opened it for use.

There were no other difficulties encountered with the operation of the other six doors or their associated escape slide deployment systems. The cabin crew reported that the passengers were generally calm, except in 'Club Class' where there was some panic. A number of passengers delayed the evacuation while they retrieved personal items from the overhead lockers, contrary to the instructions in the safety briefing video which had been shown a short time earlier. This caused added stress to those passengers whose evacuation path was temporarily impeded by these actions. A staff passenger considered that the shouting of the cabin crew (in accordance with their training to give short assertive commands in a concise and positive manner) may have unnerved some passengers. The cabin crew commented that the large amount of newspapers scattered around the cabin floor rendered it somewhat 'slippery' under foot. Most of the passengers later commented that there was no assistance available at the bottom of the escape slides, although this function is not normally regarded as an aircraft crew task, there being eight exits to be managed internally by a complement of eleven cabin crew.

After all of the passengers had left the aircraft, the first officer evacuated from door 1R and the commander from door 1L, the commander taking his crew hat which he considered would be useful in aiding crew identification on the ground. The commander spoke to the Fire Chief, who confirmed that there had been a fire which had been extinguished. The evacuation was reported to have been completed within 70 to 90 seconds from initiation.

The crew attempted to marshal some passengers away from the aircraft and to keep them together away from other aircraft on the ramp and particularly from some turboprop aircraft which were taxiing in the vicinity.

There was high degree of confusion on the ramp after the evacuation, with no immediate assistance from ground staff or airport personnel and no ground transportation in attendance to return the passengers and crew to the terminal building. The passenger list reconciliation process was also delayed significantly, as was the offload of the passengers' personal effects and baggage. Many passengers commented adversely on the lack of ground staff available to respond to the post-evacuation tasks and on the fact that the flight crew were separated from the passengers once inside the terminal building.

The shortcomings of the Airport Emergency Plan in these respects were highlighted to the Airport Authority. The Operator also became aware of the shortcomings in the Station Emergency Procedures applicable to this type of event.

Technical investigation

On-site examination of the aircraft

No 3 engine

There were no visible signs of fire damage, but 'soot-like' fuel and oil residues were evident on the exhaust cone and in the jet pipe.

The fan and bypass duct, together with the exterior surfaces of the engine casing and the insides of the cowls, were heavily contaminated with oil and fuel which had evidently sprayed from various points in the lubrication vent system. Upon removing the lubrication system filler cap, neat fuel welled up from within and spilled out in a continuous flow, indicating that a major internal leak had occurred between the fuel and engine lubrication systems. It was evident that this had resulted in flooding of the lubrication system with fuel, causing a mixture of oil and fuel to enter the vent system in large quantities. The heat exchanger matrix within the fuel cooled oil cooler was judged to be the most probable point at which such a leak could have occurred, and the unit was therefore removed and subject to a visual inspection and preliminary testing for leakage; this confirmed the presence of a significant internal leak.

Following extended discussions with the engine manufacturer and operator, during which the implications of the discharge of water into the jet pipe by the fire service and the contamination of the lubricating oil were reviewed, a ferry flight was authorised subject to replacement of the failed oil cooler and appropriate oil system replenishment and flushing operations, and satisfactory engine ground runs. These operations were subsequently completed and the aircraft made an uneventful transit flight to Dallas International Airport where the No 3 engine was removed and shipped under quarantine to the operator's overhaul contractor in the UK. (Maintenance staff reported that when the oil sump was drained at San Juan, in preparation for replenishment and flushing operations, approximately 85% of the sump contents by volume was fuel.)

After further liaison with AAIB to identify areas of potential significance, the engine was subject to routine inspection and overhaul with no relevant defects or abnormalities reported.

Oil level rise

The Tech Log for G-NIUK showed that the recorded oil contents rose by 3 quarts in the interval between completion of the Gatwick to San Juan sector, and the previous (Tampa to Gatwick) sector. However, there was no recorded uplift of oil on either sector.

Detailed investigation of the fuel cooled oil cooler (FCOC)

The failed FCOC, Part No 158210-11 Serial No AEY 03403, was installed on the No 3 engine of G-NIUK in November 1996 to replace a unit removed following a discovery of fuel in the oil, during a routine '*sniff* check' (see later). Prior to its installation on G-NIUK, it had been received back from the manufacturer following routine inspection/repair, and had accumulated a total of approximately 2,098 hrs of operation since it was installed on G-NIUK. The FCOC was an 'on-condition' unit with no fixed life, its continued operation being subject to pressure testing and visual inspection at specified intervals.

Description and principles of operation

The cut-away diagram at Figure 1 shows the general form of construction. The FCOC comprised a cylindrical casing with a matrix of thin-walled aluminium tubes fixed into header plates at each end. The oil occupies the casing, and fuel passes through the matrix tubes.

A central divider plate (shown red in Figure 1) is positioned along the axis of the unit and engages slots in the header plates at either end, dividing the oil circuit into two main chambers. A series of three semicircular baffle plates (coloured green in Figure 1) are spaced equidistant along the length of the matrix tubes on each side of the central divider, sub-dividing the two main oil chambers into sub-chambers. The oil to be cooled enters the unit on one side of the divider via an oil manifold at one end of the casing, from which it flows along the length of the unit, working back and forth between the baffles, until it reaches the far end of the unit. From there it passes across to the opposite side of the unit, via a cut-out in the centre divider, before working its way back, between the baffles, to the outlet port. Fuel enters via the fuel manifold and passes to an inlet chamber in the divided end cap, from where it flows down one side of the unit through the first group of matrix tubes to reach the domed end cap at the opposite end; this cap has no divider and thus provides a *turn-around* chamber for the fuel, which then flows back along the second group of tubes to reach the exit chamber. A significant pressure differential exists between the fuel and oil circuits at all times, and consequently any leakage between the two will result in fuel entering the oil.

The FCOC is constructed throughout from 6061 aluminium alloy. The central divider plate is brazed to the casing of the unit. It has corrugated surfaces to accommodate the adjacent tubes and is a 'T' section at either side to accommodate the brazed joint to the case. The ends of the plate have locating tangs which engage in matching grooves in the header plates; a similar arrangement provides location for the domed end-cap divider. The matrix tubes are brazed into the header plates, and the headers into the casing. The baffles are a sliding fit on the tubes, and are located solely by cut outs in a series of thin locator channels (coloured orange in Figure 1) brazed onto the inside of the casing. Assembly is completed by welding the end caps to the casing. The FCOC is heat treated after the brazing processes are completed.

Examination of the FCOC

The failed FCOC was subject to X-ray examination, followed by progressively invasive investigation under AAIB direction, in close collaboration with the US manufacturer and its UK subsidiary. Due to the complexity of the unit's construction and the fragile nature of the matrix tubes within, sectioning was carefully planned and executed in stages. Following preliminary sectioning and examination, key elements were subject to detailed metallurgical examination by the manufacturer, and by specialists at DERA, Farnborough.

Physical and X-*ray examinations*

Preliminary X-ray examination showed that the end-most baffles in the oil circuit had migrated out of position by several millimetres at their *closed* ends, causing the baffles to adopt a slight angle in the casing.

The unit was not subject to the standard pressure test to avoid the risk of introducing further tube damage. Instead, the casing was filled with oil and set at an angle so that any internal leakage would be revealed by oil draining from the fuel circuit. This confirmed the presence of a large internal leak, at a rate of approximately 50cc per minute of oil under gravity alone.

After removal of the end cap to expose the header plates, the tubes were examined internally using a fibre optic probe. This revealed a large rupture in the wall of the third tube from the side of the unit. The pair of tubes on either side of the ruptured tube, also adjoining the centre divider, had been repaired at some time previously using the manufacturer's approved procedure, which involved stopping up the affected tubes at both ends with plugs of adhesive. Figure 2 identifies the ruptured tube, and the two pairs of plugged tubes on either side.

After further sectioning to expose the various internal components, full thickness fractures were visible on both sides of the central divider plate at the *manifold* end, these ran longitudinally in the radii of the 'T' sections at the brazed attachment to the casing. Dye penetrant inspection showed that these fractures extended for distances of 5.5cm and 8.0cm respectively from the header plate. Heavy fretting and wear was evident on the corrugated face of the divider, on the *outlet port* side at the cracked end of the divider; this was evidently caused by repeated contact between the divider and the fuel tubes as the cracked plate flexed under differential pressure loading. Fretting and wear was also apparent on the divider locating tang and its associated locating slot in the header plate, consistent with long term transverse flexing of the cracked divider. Figure 3 shows the divider fractures and the fretting and wear on the corrugations and locating tang.

Fretting and wear were also evident on the two rows of fuel tubes adjoining the cracked end of the divider (Figure 4a), where the divider had repeatedly contacted the tubes. Fretting of the tubes was particularly aggressive adjacent to the header plate, evidently due to the high stiffness of the brazed tube connections and the larger flexural displacements of the divider plate in this region, giving rise to higher contact pressures. This had caused severe thinning of the fuel tube walls immediately adjacent to the header plate, and one tube had burst creating a large aperture in the wall of the tube (Figures 4a and 4b). It was apparent that the failure of this tube had originated from a circumferential crack at its root end, which had subsequently become unstable and propagated rapidly to produce the large rupture. Because of the large positive pressure differential between the fuel and oil circuits, even when the engine is at idle, fuel was then able to leak at a high rate into the oil circuit. The surface of this tube, and the corrugated face of the divider adjoining the rupture, were slightly discoloured in a manner which suggested that there may have been long term leakage of fuel from the pre-cursor crack in the failed tube; however, this could not be confirmed. The two pairs of (similarly fretted) tubes on either side of the ruptured tube, which had been plug repaired at some previous stage, were also cracked at their root ends immediately adjoining the header plate; these cracks were visually very similar to the initial crack in the ruptured tube. Figure 4c shows a typical example. The repairs had evidently been carried out because of leakage from these cracks, detected at some earlier stage in the life of the unit.

The displacement of the oil baffles, noted first on the X-ray film, had resulted from fretting and wear at the interface between the baffle plates and the retaining slots in the locator channels. Slight wear of the tubes was also evident, caused by the relative movement of the baffle against the tubes.

Metallurgical examination of the cracked central divider

Preliminary visual and Scanning Electron Microscope (SEM) examination of the fractures in the divider plate radii revealed the presence of multiple cracks, propagating from both faces of the plate. The fracture surfaces, which exhibited multiple facets, had suffered heavy mechanical damage caused by rubbing as the divider flexed under load. Consequently, only one very small area of the fracture survived in which the original features were still evident. This region displayed clear evidence of fatigue.

Examination of a section through the cracked region showed that the facets were cleavage planes along which a large part of the fracture had progressed. Numerous cleavage cracks were also found running at acute angles to the fracture direction. Chemical etching did not reveal the microstructure grain boundaries, but the path length of the cleavage cracks was indicative of a large grain size.

Tests on the polished section showed that the hardness of the divider was 100HV(10kg), at which value cleavage fractures would be unlikely to occur, except as a result of 'Stage 1 mode' fatigue. Stage 1 fatigue is a mode of failure which is occasionally found in coarse grained, low strength aluminium alloys and which can result from thermal cycling. The presence of multiple cleavage cracks at an acute angle to the main fracture suggested that the plate may have been subject to a complex combination of bending, tension, and possibly compression, resulting from both thermal and pressure cycling in service. The large grain size of the divider, and the fact that the ultimate strength (implied by the hardness value) was low compared with that of the alloy in its fully aged condition, whilst being higher than that of the alloy in its fully annealed condition, suggested that the heat treatment of the divider following the brazing operations may have been poorly controlled.

Oil bypass valve tests

The oil bypass valve at the manifold was removed and function tested. No significant abnormally or defect was found and the unit functioned within specification. Additional tests were carried out in which the flow rates and pressures were adjusted in an effort to provoke the unit into any form of unstable operation, such as might induce pressure fluctuations in the oil circuit, but the unit functioned positively throughout and displayed no evidence of instability.

Design variations

On later versions of the FCOC, Part Nos 158210-14 and 158210-16, the tubes are swaged into the headers, instead of being brazed. Consequently, the divider could be brazed to the casing, and heat treated, before the tubes and headers were installed. This gave better access for the quenching fluid, and allowed better control of the heat treatment process than was possible with the *brazed tube* units.

Previous FCOC failures in service

CF6 engine 'events' *involving internal leakage of the FCOC*

The aircraft manufacturer's records included a total of 10 events associated with contamination of the engine oil with fuel on DC-10 aircraft, of which 8 involved GE engines. The first of these, on a DC-10-30, resulted in an internal sump fire and separation of the LPT rear stub shaft. The aircraft manufacturer advised that corrective actions included GE Service Bulletin (SB) 79-9, issued December 1974, requiring daily checks for the presence of fuel in the oil tank and laboratory analysis of oil every 150 hrs; FCOC reliability improvements introduced into production in 1977; and a centre vent extension to isolate the sump vent from internal ignition .

A total of 11 centre vent system fires have been reported to the engine manufacturer between the model's entry into service in December 1972 and April 1998. In 9 of these cases, the affected engines did not have the centre vent extension, introduced by SB 72-395 Revision 3. Of these 9 fires, 8 resulted in significant secondary damage, including one uncontained failure.

A search of the UK CAA's incident database produced at total of 5 GE CF6 engine incidents during the period 1988 to 1993 in which internal leakage of the FCOC was implicated. One of these, involving a CF6 installed on Boeing 747 aircraft, was caused by an internal leak in the FCOC which allowed fuel to enter the oil system, resulting in a 'D' sump fire, failure of the low pressure turbine (LPT) rear shaft and separation of turbine blades from the No 1 and No 4 stages of the LPT. This engine had not been modified to incorporate the centre vent tube extension, in accordance with SB 72-395.

Actions taken to address vent cavity / bearing fires

In-service experience of bearing cavity fires and associated shaft failures on CF6 series engines, caused by contamination of the oil lubrication system with fuel due to internal leakage at the FCOC, led to two Service Bulletins designed to address separate aspects of the problem, since they affected different models of the CF6 engine:

GE Service Bulletin 72-395

SB 72-395, applicable to the CF6-50/-45 series engines, introduced an extension tube to the centre vent system. This extension was designed to carry fuel vapours within the vent system clear of the LPT cavity; these vapours could otherwise ignite, potentially causing a bearing fire and separation of the LTP stub shaft. This Service Bulletin was mandated by Airworthiness Directive action. (The CF6-80A/-80C series engines incorporated centre cavity venting arrangements which performed the same function).

GE Service Bulletin 72-648

SB 72-648, applicable to CF6-80 series engines, introduced a flame trap designed to prevent a fire, which had initiated in the centre body cavity of the centre vent system, from travelling forward via the centre vent tube to reach the forward fan shaft cavity, with attendant risk of a fan mid-shaft separation.

Previous instances of matrix tube rupture and / or divider cracking

In 1988, the FCOC manufacturer carried out a detailed investigation of a matrix tube rupture on a -11 FCOC (ie the same type as fitted to G-NIUK) from a Canadian registered aircraft, which was removed for investigation following indications of excess oil contents. The investigation report attributed the tube failure to fretting between the centre divider and the adjoining tubes, close to the header plate. Wear marks were found on ten of the adjacent tubes and on the central divider, and on the divider plate tang and associated groove on the header plate, all on the *oil outlet* side of the divider. However, the report made no reference to cracking of the divider, or to displacement of the baffles.

In 1993, the cooler manufacturer investigated a defective unit which was found to exhibit displaced baffles and a cracked central divider. It is not known whether this unit also exhibited cracking or rupture of one or more tubes, or the extent of wear and fretting damage to the divider and/or tubes. This led the manufacturer to revise the Component Maintenance Manual to include a new inspection for cracks in the central divider of all *brazed tube* type units (described later).

Early symptoms of internal leakage at FCOC

A number of publications alert operators to the implications of increasing oil contents indications, including the following:

GE Operations Engineering Bulletin No 5, 15 January 1992

This document provides a description of the lubrication system and background information on the *normal* and *abnormal* procedures contained in the aircraft manufacturer's documents. The section headed 'Oil quantity malfunctions' draws attention to the fact that increasing oil contents indications may be caused by an internal leak in the fuel / oil heat exchanger (FCOC), or to a leak in the hydraulic shaft pump seal.

Aircraft manufacturers' and *operators' documentation*

Several aircraft manufacturers and operators are known to have published warnings to aircrew and engineering staff of the potential for fuel from a leaking FCOC to flood the oil system, and the attendant risk of oil vent system fires leading to uncontained engine failures in flight. For the most part these publications appear to have been based on the GE Operations Engineering Bulletin referred to above, and to have been first issued shortly after its publication, with subsequent re-issues.

Inspection requirements

Sniff test

The operator's Transit Check (to be completed at every stop) included a requirement to perform a '*sniff check*' of the oil when checking levels, to detect the presence of fuel in the oil tank. According to the company responsible for engineering and turn-round operations at San Juan, this check was carried out at San Juan but nothing abnormal was apparently found; however, the results were not recorded.

Component Inspection

The FCOC had no fixed life, continued service being subject to periodic inspections for condition and pressure testing for tube leaks at specified intervals. The Component Maintenance Manual detailed an approved repair procedure for units which failed the leak test which entailed cutting circular access holes in the end caps, plugging both ends of the affected tubes with adhesive and re-sealing the end caps by welding special plugs into place.

After the FCOC manufacturer's investigation of a cracked divider in1993 (described earlier), a revision to the Component Maintenance Manual (CMM) was introduced which detailed a new inspection, applicable to all *brazed tube* type heat exchangers, designed to locate cracks in the central divider. This inspection involved the insertion of a borescope probe into the casing through the oil port, which gave visual access to the corner region between the centre divider and the casing wall adjacent to the header plate. Units exhibiting cracks were required to be scrapped. However, owing to an administrative error, the Component Maintenance Manual at the FCOC manufacturer's UK factory did not list this revision in the master revisions list, and the revision therefore was not incorporated into the Manual. Consequently none of the units passing through the UK factory for routine pressure testing and inspection were checked for divider cracks; the affected tubes of leaking, and very probably cracked, units being simply *repaired* and returned as *serviceable* items. In contrast, the borescope inspection was implemented on all *brazed tube* FCOC units returned to US factories for routine inspection and repair, with units found to have cracked dividers being scrapped.

Follow-up safety actions

Review of inspection records

The UK FCOC manufacturer maintained records of all units which had passed through the UK factory for routine inspection/overhaul since January 1990. The information these records contained was limited, but a review showed that between January 1990 and June 1997 approximately 64% of the units had failed the pressure test, i.e. were found to have internal leaks. The records did not identify the location of the leaks, but it was believed that most would have been subject to the standard repair process, which involved plugging both ends of the affected tubes with adhesive. Anecdotal evidence suggested that in about 80% of the units which failed the pressure test, the defective tube was located adjacent to the central divider at the manifold end of the unit.

In-house requirement for X-ray inspection

On 20 June 1997, the FCOC manufacturer introduced a requirement that all units returned to its UK factory for routine inspection and testing would be subject to radiographic inspection to detect:

- displaced baffles
- any change in position of the central divider locating tang relative to its location in the header groove
- cracks in the central divider adjacent to the outer shell, running from the manifold end of the unit

FCOC units which exhibited any form of divider cracking were to be scrapped, as were units exhibiting baffle displacement in excess of 0.050 inch, with one or more leaking tubes. Units exhibiting baffle displacements of less than 0.050 inch, with or without leaking or previously repaired tubes immediately adjacent to the divider wall, could be repaired by plugging all 31 tubes adjoining the central divider and returned to service.

Service Bulletin 158210-79-2030

A revised inspection procedure, dated 28 July 1997, was implemented by SB 158210-79-2030, issued by the FCOC manufacturer with the approval of the engine manufacturer. This inspection effectively comprised an amalgamation of the existing borescope inspection contained in the Component Maintenance Manual and the in-house X-ray inspection of 20 June 1997. The inspection, which applied to all 'brazed tube' units (all dash numbers except Part Nos 158210-14 and 158210-16 series 1 and 2), required units exhibiting divider cracking or "excessive oil baffle movement to be scrapped". The amount of excessive baffle movement was not quantified.

Discussion

Loading environment

Both the fatigue cracking in the divider plate and the associated post-crack fretting and wear of the divider tang and header plate groove were consistent with cyclic variations in the differential oil pressure within the unit, caused by frictional resistance to the flow of oil. The maximum pressure differential would have been developed between the *start* and *end* points of the oil circuit, i.e. between the inlet and outlet ports, and consequently the end of the divider plate which separates these ports is the region most likely area to suffer fatigue damage, fretting and wear caused by plate movement.

Whilst it was not possible to establish the crack growth rate in this instance, it was evident that cyclic variations in both temperature-induced stress and differential pressure, potentially capable of initiating and driving fatigue cracks in the divider, will occur during normal operation as the oil pressure builds up during engine start and decays again during shutdown, and also due to normal fluctuations in oil pressure during each flight cycle. The possibility was considered that abnormal high frequency pressure fluctuations from the pump, the oil bypass valve, or some other component in the lubrication system were present, and that these may have initiated and/or contributed to the damage. However, tests on the oil bypass valve aimed at inducing '*chatter*' or instability tended to rule out valve instability in this case, and there was no evidence of significant abnormality found during the bulk engine strip and overhaul. Therefore, given this fact and taking into account the significant number of prior instances of divider cracking and the very high incidence of tube leakage (which implies divider movement and cracking in a majority of these cases) there appears to be no valid grounds for concluding that the cracking in this case was due to some *abnormal* loading environment peculiar to G-NIUK. Rather, it suggests that the cracking within the FCOC was caused by a loading environment common to all CF6 engines.

The fretting and associated migration of the baffles also matched the pressure distribution in the oil circuit, this having occurred only at the *closed* ends of the baffles where a differential pressure would have existed between adjacent chambers. The minimal contact area between the baffle plates and the locating channel cut-outs would have resulted in a large baffle displacements for a given volumetric rate of wear, and explained the relatively severe baffle migration seen in this and other cases.

Design issues

The design of the *brazed tube* type of FCOC is such that quenching operations during the heat treatment process cannot be controlled accurately in the area of the brazed join. As a consequence, satisfactory grain structure cannot be guaranteed in the affected parts of the divider. Poor grain structure was certainly a significant factor influencing adversely both crack initiation and propagation, and consequently the manufacturing process was undoubtedly a contributory factor in the failure of the unit.

It appears that the FCOC manufacturer presently perceives tube rupture as being a problem affecting only the *brazed tube* type of FCOC and that associated failures were caused solely by poor grain structure. The later *swaged tube* FCOCs, having better grain structure, are consequently regarded as being immune to divider cracking and consequential tube failure. This assessment appears to have been the justification by the FCOC manufacturer for the exclusion of all *non-brazed tube* units from both the original borescope inspection (introduced into the CMM following the 1993 instance of tube rupture) and the X-ray inspections (introduced after the failure on G-NIUK). However, as a result of these findings from this investigation it is considered that there is insufficient evidence available to safely reach such a conclusion, and that consequently the exclusion of the non-brazed units from the inspection program cannot be justified, even when considering the problem of divider cracking alone.

The exclusion of non-brazed FCOC units from the inspection program is even more difficult to justify in relation to the quite separate problem of baffle displacement and associated tube wear. The inspection requirements currently in force for the *brazed tube* FCOC units specify that all units found with significant baffle displacement must be scrapped, on the grounds that such movement implies possible tube abrasion and thinning. The latter, unlike the wear caused by divider plate movement, will potentially affect all tubes, not just the row adjacent to the divider. The pressure loading on the baffles, and the associated potential for baffle migration, tube wear and rupture, will be substantially the same on both types of FCOC unit. Therefore, since a high proportion of the *brazed tube* FCOC units inspected to date by the UK manufacturer are known to have suffered baffle displacement requiring the units to be scrapped, it is considered highly probable that a similar proportion of the *swaged tube* types of FCOC will be similarly affected, but are probably going undetected because they are not included in the current inspection program for cracking and baffle movement.

On the basis of the available evidence therefore, there appear no valid grounds for excluding *non-brazed* FCOC units from an inspection process which, in all other respects, appears to adequately address all of the problems affecting these units.

Safety recommendation

As a result of the findings arising from this investigation, the following safety recommendation is made:

Safety recommendation 99-4

In order to further reduce the incidence of internal cracking within General Electric CF6 turbofan engine Fuel Cooled Oil Cooler (FCOC) units, and related serious consequences of fuel ingress into the engine oil lubrication system, it is recommended that the FCOC manufacturer, AiResearch, takes action in conjunction with General Electric to extend the existing overhaul inspections for FCOC divider cracking and baffle displacement to include the *non-brazed* tube type of FCOC units, at least until statistical evidence of failure rates and characteristics allows valid assessment of the risks associated with each type of FCOC unit.