INCIDENT

Aircraft Type and Registration:	Boeing 737-528, G-GFFE
No & Type of Engines:	2 CFM56-3C1 turbofan engines
Year of Manufacture:	1995
Date & Time (UTC):	3 September 2005 at 0920 hrs
Location:	Stand 110, North Terminal, London Gatwick Airport
Type of Flight:	Public Transport (Passenger)
Persons on Board:	Crew - 6 Passengers - None
Injuries:	Crew - None Passengers - N/A
Nature of Damage:	APU failure with extensive axial ejection of turbine debris
Commander's Licence:	Airline Transport Pilot's Licence
Commander's Age:	Not known
Commander's Flying Experience:	18,500 hours (of which 9,400 were on type)
Information Source:	AAIB Field Investigation

Synopsis

During ground operation, the cast inflow turbine of the APU suffered a radially contained failure. This resulted in vanes separating from the casting as its two liberated halves came into rapid contact with the containment structure. The hot vane debris was ejected through the jet pipe and spread across the rear of the stand and the width of the adjacent taxiway. The failure was one of nine broadly similar events to the type of turbine wheel, each attributed to a casting defect. Efforts have been made to improve the manufacturing process, without proven success, and no reliable method has been found to detect the defect in new or existing turbines. No method of establishing a safe in-service life has been determined for this component but the hazard to airport staff remains very low.

History of the event

The aircraft was parked on Stand 110 adjacent to Pier 6 facing in a northerly direction. Immediately to the south of the stand was Taxiway K and beyond that were Stands 134 and 135 upon which aircraft are parked facing in a southerly direction. The orientation of the stands is shown in Figure 1.

G-GFFE was being refuelled and prepared for departure with the flight and cabin crew aboard. The passengers had been called for boarding but had yet to reach the aircraft. The commander instructed the co-pilot to start the APU and continue the associated checklist items. The commander then entered the cabin with the intention of carrying out the internal checks followed by the external inspection. Soon after entering the cabin, the lights

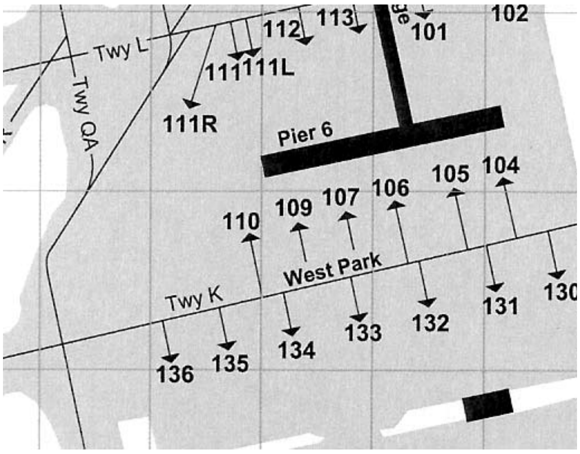

Figure 1

Orientation of Stands

extinguished so he returned to the flight-deck to be told that the APU had automatically shut down.

The flight crew then became aware of a commotion at the rear of the aircraft. On returning to the cabin the commander was informed by a cabin crew member that a sound of impact had been heard, the rear part of the aircraft had lurched, and a catering truck was presumed to have struck the fuselage. On looking out of the rear door, however, the commander observed members of the ground staff kicking bits of hot metal off the stand area and adjacent taxiway and realised that a major malfunction must have occurred to the APU. Having confirmed there was no sign of fire, the commander returned to the flight deck to supervise the co-pilot in making appropriate radio calls and completing APU failure procedures.

On completion of these activities, the commander went outside the aircraft to check the damage and to establish whether any personal injuries had occurred. None were observed or reported. Debris was observed extending over some 90 m (295 ft) aft of the aircraft, completely crossing the taxiway behind the aircraft. Larger items were collected by flight and ground crew and placed below the rear of the aircraft. A sketch diagram of the distribution of the remaining debris was made on part of a large-scale chart of the apron area before the smaller debris was swept up by the airport authority to bring the taxiway back into use. The diagram and some debris items were subsequently passed to the AAIB. It was noted that the general distribution formed a fan-shaped pattern extending behind the aircraft. A few fragments had travelled as far as the northern part of Stand 135 but none reached Stand 134. A photograph of the fragments collected is shown at Figure 2.

No airframe damage had occurred but on opening the APU access door, it could be seen that an internal failure had bulged and partly split the external casing of the unit. One of the two side-mounts had separated from the unit as a result of the deformation of the casing. Looking down the jet-pipe it could be seen that the turbine was damaged and displaced from its axis, whilst the exhaust duct within the APU had been seriously deformed by contact with high energy rotating turbo-machinery.

Figure 2

APU fragments

Component description

The APS 2000 APU utilises a centrifugal compressor feeding air to a reverse-flow annular combustion chamber. The combustion gasses are directed into a radial plane, flowing inwards into the vanes of a one-piece, cast, inflow turbine. The turbine is mounted directly behind the compressor and drives it via a curvic coupling[1]. The turbine turns the combustion gas flow through 90º enabling it to exit aft through a duct formed by the cylindrical inner face of the combustion chamber.

The manufacturer produces a number of different APU types having a similar layout and utilising cast inflow turbines of varying dimensions and power output. The APS 2000 and the APS 2100 are the largest units having this layout and they share identical turbine wheels. The APS 2100 is used in Boeing 717 aircraft.

The material of all the wheels of this class is IN 792 Mod 5A. It is an alloy developed specifically for this type of application. Turbine wheels are cast by a specialist company that also produces an inflow turbine of very similar mass and profile for another APU manufacturer. The other manufacturer developed its APU for a similar application considerably earlier than the development date of the APS 2000. Originally the other manufacturer's unit used a turbine cast from a different alloy. Following a series of turbine failures, however, the casting supplier recommended manufacturing future turbines from IN 729 Mod 5A. At about this time, the casting company also recommended this material to the manufacturer of the APS 2000, the type of unit installed in G-GFFE, an APU type which was then under development.

Footnote

[1] A joint between driving and driven shaft systems which transmits torque. It allows for small errors in alignment or angle but does not secure one shaft to the other. In its simplest form, it comprises two sets of meshing radial teeth of smooth curving profile.

Detailed examination

The damaged APU was removed from the aircraft and shipped to the European service and overhaul centre for the type. It was subjected to a strip examination in the presence of an AAIB Inspector. The gearbox and compressor section of the unit had suffered light damage but the turbine wheel was in two halves. Most of the housing, external casing and combustion chamber were severely damaged. The containment ring was severely deformed into an approximately oval shape but had successfully prevented any in-plane departure of turbine debris. Following separation from the wheel, most extremities of the inflow turbine had exited via the exhaust duct. This was the result of multiple impacts of the wheel casting halves with adjacent boundaries of the flow path. The two halves of the core of the turbine casting remained in the unit, were of approximately equal size and had separated as a result of a fracture at a face parallel with the casting axis.

The main fracture faces of the turbine appeared to exhibit overload characteristics. It was noted, however, that the failure appeared to have developed radially across the fracture face from a point on the centreline approximately mid-way along the longitudinal axis of the component. This was at or close to the centre of mass of the casting.

Information supplied by the APU manufacturer indicated that a number of similar failures had been experienced on other APS 2000/2100 units. All the failed turbines exhibited generally similar characteristics on their fracture faces. The fractured halves of the wheel from G-GFFE were forwarded to the manufacturer's laboratories in California for detailed analysis. The results of this analysis and a programme of earlier work were fully discussed during a subsequent visit to the manufacturer's plant by AAIB engineering personnel.

Similar events

The manufacturer has identified nine turbine failures in this type of wheel within APS 2000 and APS 2100 units. These occurred between February 1999 and January 2006. The service lives of the turbine wheels at the time of failure ranged from 890 to 14,931 hours and from 1,386 to 14,578 cycles. No reported failures have occurred in smaller turbine wheels of this geometry utilising similar materials and installed in other types of APU produced by this manufacturer. An earlier event at London Heathrow Airport, during which the complete turbine of an APS 2000 exited the rear of the unit and travelled a considerable distance across the apron, was the subject of an AAIB investigation which identified bearing failure as the cause. All reported turbine bursts have remained radially contained and the major portions of the failed turbines have remained within the unit. No information was received on the extent of the distribution of smaller debris following earlier failures.

As previously mentioned, another manufacturer produced a series of APU models which pre-dated the APS 2000 series and examples were extensively utilised in Boeing 737 aircraft. These units utilised an inflow turbine wheel design similar in mass and general profile (although different in detail design) to the component in the APS 2000 and 2001 units, cast by the same supplier. This original wheel design, manufactured from a Marum 247 casting, suffered a number of wheel failures. As a result of these problems, the casting supplier changed the material of the wheel to IN 792 Mod 5A and supplied IN 792 Mod 5A wheels for all APS 2000 and 2001 APUs, a family of models which entered production at about the time of the material change. None of the wheels manufactured from IN 792 Mod 5A in the other manufacturer's APUs are known to have failed in service. The highest working stress level in their APU turbines is, however, not known.

Manufacturer's action

The earlier bearing failure event at Heathrow Airport described above was the subject of modification action and no further departures of complete turbines from APUs have been reported.

The unit manufacturer reports that it has been working closely with the casting supplier over a number of years to eliminate the wheel failure/bursting problem on new turbines; this was the type of failure that occurred in G-GFFE. Also, in conjunction with the supplier, it has been reviewing possible NDI (Non Destructive Inspection) procedures to detect the initiating casting defects.

Examination of all the failed wheels returned to the manufacturer confirmed that the failures originated at small film inclusions of aluminium-magnesium oxides within the core of the casting. These led to initial fatigue crack growth before rapid failures occurred across the remainder of the cross-sections. Both failures involving separation into two approximately equal halves (bi-wheel) and into three approximately equal sized portions (tri-wheel failures) have occurred. In all instances the containment rings performed as designed.

The casting process is carried out to a specification aimed at preventing oxide formation during the melting, pouring and solidification process. An extensive laboratory programme of analysis of the manufacturing process was carried out, ending in 2003, using a large number of castings produced specifically for this purpose. These 'test' castings were sectioned and metallurgically analysed. This work showed that substantial deviations from the process specification had to be made in more than one parameter for detectible oxide inclusions to form within the wheel.

The material of the upper 'head' section of a number of test castings, a region to which impurities would be expected to migrate during the solidification process, revealed no correlation with oxide inclusions within the cores of the wheels. The head is subsequently removed during the finish machining process of the wheel.

As a result of the extensive process analysis completed in 2003, the casting supplier made a series of changes to redefine and improve the tolerances of the parameters of their casting procedures with a view to eliminating all conceivable causes of oxide inclusions. This more demanding production regime was introduced in 2003. Since then a further wheel, cast to this revised specification, has failed in service.

The possibility of adopting an NDT process to detect such inclusions was considered. The complex geometry of the turbine casting rendered most such processes unlikely to be effective whilst the nature of the particular defect leading to such failures, being a local lack of adhesion (ie not a homogenous microstructure) rather than a void, made it even less likely that any such process would be reliable. In particular an advanced Phased Array inspection method failed to detect a known Al/Mg inclusion in a wheel cast for test purposes.

It was noted that the two progressively smaller turbines of similar geometry used by the unit manufacturer in other APUs, although operating at similar working stresses, had no recorded history of failures.

It is also interesting to note that no instances have been reported to the casting supplier of any failures of the corresponding turbine wheel of similar mass and proportions cast in the same plant and of the same material for the other APU manufacturer. The working stresses of these wheels are, however, not known and it is possible that they could be sufficiently lower for the largest oxide inclusions, if present, not to be exploited.

None of the wheel failures known to the APU manufacturer, other than the G-GFFE failure, were accompanied by reports of significant amounts of debris being projected a large distance behind the aircraft concerned.

Jet aircraft flight statistics

Airclaims Limited provided the AAIB with estimates of the number of flights undertaken by western-built jet aircraft during the years 1999 to 2005 inclusive. The estimate for 1999 was 18.89 million rising to 23.53 million for 2005. The total number of flights during the seven year period was 145.75 million (1.4575×10^8). It was assumed that an APU was used on the ground during 90% of these flight departures. This assumption leads to an estimated APU usage on 1.31×10^8 occasions (departures only) in the 7 year period.

Discussion

The practical effect of this phenomenon was that turbines could be manufactured which were apparently free from significant defects whilst defective turbines manufactured during the same period succeeded in accumulating a varying but sometimes large number of operating cycles before failing without warning. No safe operating life for a defective turbine can be determined. No presently utilised method of NDI is thought to be capable of detecting this type of defect at this location before failure. In view of the high number of cycles achieved before failure by a number of in-service turbines, it is not clear whether and at what time during the production history of castings, that the first wheels were manufactured with the problem present. Neither is it easy to establish if and when process improvements significantly reduced the number of defects in all new production turbine wheels.

Smaller turbines can apparently be cast without defects, whilst a turbine of generally similar proportions, cast by the same supplier, using the same casting equipment and personnel, is either being cast without defects, operates at a significantly lower stress level or suffers failures which are not being effectively reported.

Neither this, nor any previous reported failures, have resulted in non-containment of the turbine, although hot fragments were ejected from the jet-pipe at considerable velocity on this occasion. These effects do not appear to constitute an airworthiness hazard and are within the certification requirements for such a unit. They can, however, pose a potential hazard for ramp personnel and for any aircraft, vehicle or person passing reasonably close behind an aircraft with this type of APU in use. This hazard remains and no short term method of eliminating it can be envisaged, given that no fully effective NDI method has been devised and guaranteed defect-free castings cannot be manufactured. It is understood that the 2000 series APU remains in production so the active population of such units is increasing. Although the amount of APU operation is being reduced at some locations for environmental reasons, it is not clear whether the world-wide number of fleet operating cycles is being similarly affected. There is thus no assurance that instances of such failures will decrease and, without a guarantee that the casting problem has been successfully eliminated on new turbines, the frequency of such failures may increase. This frequency is, however, low in terms of total number of cycles accumulated by this type of unit and the failure is not flight critical. Any attempt to carry out design or process changes cannot be guaranteed to reduce the already low risk of failure. On the contrary, design or process changes have the inherent possibility of increasing that risk.

Risk assessment

Since none of the 2000 series APU failures resulted in radial penetration of the APU casing, airport ground staff and crews were only at risk from such failures if they were downstream of the APU exhaust when hot, metallic debris was released. Of the nine failures between 1999 and 2005, none resulted in reports of injuries to staff.

Most western-built jets have the APU mounted in the tail section at heights well above the level of people working in close proximity to the aircraft. Consequently, the area of risk to staff is an ill-defined, fan-shaped region starting aft of the aircraft's tail and extending out to some 300 ft from it on either side of the aircraft's extended centreline. Staff may occasionally have to traverse this region in vehicles but they are not often required to work in or remain within the region because much of it is beyond the stand zone. However, staff working on one aircraft might be at risk from debris ejected by another aircraft's APU if the two aircraft were parked 'tail-to-tail', as they are at some airports.

Apron areas where aircraft are parked in a 'tail-to-tail' orientation usually have the aircraft well spaced to allow for pushback onto a central taxiway centreline. The minimum distance between Stand 110 and the stand opposite was 85 metres. No aircraft tail should protrude beyond the stand area so the minimum distance between aircraft tails would exceed 85 metres. Consequently, although in this incident the debris pattern extended across the adjacent taxiway, none penetrated the area of the opposite stands by more than few feet. Normally, staff would not be standing in this region whilst the APU was running.

Consideration was given to recommending procedures that minimised the risk to staff presented by hot metallic debris ejected from APU exhausts. However, staff could not be expected to know which aircraft were fitted with 2000 series APUs so any procedures would have to be relevant to all aircraft types. During the period of nine APU failures there were an estimated 138.5 million flight departures when an APU was run. Consequently, the risk of an APU disintegrating in a comparable manner to the APU fitted to G-GFFE would appear to be in the order of 1 in 15.4 million departures (1.539×10^7). Moreover, given that nobody was hurt during any of the nine failures, the injury risk to staff was considered to be too small to warrant special procedures aimed at protecting them solely from ejected debris.

Notwithstanding the minimal risk to people, airport operators could usefully remind ground staff not to linger downstream of APU exhausts.

Conclusions

The casting process of the turbine of APS 2000 and 2001 APUs produces occasional and unknown quantities of oxide films within the turbine core. The size and orientation of these films occasionally leads to fatigue crack initiation and growth to failure under working stresses. However, the number of hours/cycles to failure of turbines with such defects cannot be predicted.

Considerable experimental and analytical work has been carried out over an extended period by the APU manufacturer and the casting supplier to eliminate the oxide film problem. These efforts have not been successful.

APUs utilising cast inflow turbines have a history of occasional radially contained turbine bursts. No direct hazard to an aircraft is understood to have resulted from such contained failures of an installed APU and current certification requirements for containment appear to have been met. No other reports of large quantities of high speed debris travelling equivalent distances behind APS 2000 equipped aircraft have been received and nobody has been injured by ejected debris.

No changes to the design or manufacturing process of the APS 2000/2001 turbine can be envisaged that can be guaranteed to reduce the number of such failures without running the risk of making the situation worse. Revised apron procedures to protect staff from ejected debris were not considered necessary but staff could usefully be reminded to avoid lingering within 300 ft downstream of an operating APU.