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INCIDENT

Aircraft Type and Registration:	Boeing 747-136, G-AWNN
No & Type of Engines:	4 Pratt & Whitney JT9D-7A turbofan engines
Year of Manufacture:	1973
Date & Time (UTC):	4 October 1994 at 1330 hrs
Location:	Mid Atlantic (53° N, 020° 30' W)
Type of Flight:	Public Transport (Scheduled passenger)
Persons on Board:	Crew - 18 Passengers - 373
Injuries:	Crew - None Passengers - None
Nature of Damage:	Disintegration of starter, burning/heat damage to wiring harness and general heat effects on engine components
Commander's Licence:	Airline Transport Pilot's Licence
Commander's Age:	52 years
Commander's Flying Experience:	14,950 hours (of which 383 were on type) Last 90 days - 153 hours Last 28 days - 61 hours
Information Source:	AAIB Field Investigation

History of the Flight

G-AWNN took off from London Heathrow, as Flight BA 293 to Miami, at 1106 hrs. The takeoff and climb were uneventful and the aircraft levelled at FL 330, its final cruise level, at 1310 hrs. However, at 1330 hrs, with no prior indications of any engine malfunction, the fire warning system on No 3 engine activated. The crew carried out the fire drills from the checklist and, having discharged the first (left) fire extinguisher, the fire indications ceased after 28 seconds. When the fire had been extinguished, it was noted that the Nacelle Temperature Indicator on No 3 engine showed that a fault had developed in the 'B' loop of the fire protection system. The commander decided to return to Heathrow and so turned onto the reciprocal track and performed a three engine drift-down to FL 250. Having dumped 10 tonnes of fuel over the Irish Sea, the aircraft returned to Heathrow and landed without further event.

After landing, the aircraft was met by the AFS who said that there were no signs of fire remaining in No 3 engine. The aircraft was then taxied onto Stand T 8, where the ground engineers informed the crew that the starter motor of No 3 engine had burned out. No crew member recalls adjusting, at the time of the incident, any cockpit selection located at a control panel near the starter panel. Similarly no crew member recalls seeing the 'START VALVE OPEN' light illuminate, although this is not positioned in such a way as to be in the normal visual scan of any crew member, being above the head and to the left of the P2 position where it is shielded from the normal view of the flight engineer by the fire handle.

Examination of the Aircraft

Soon after arrival at Heathrow the No 3 engine cowlings were removed and the engine was examined. Evidence of a flash fire was observed at a variety of locations around the engine and at a number of points on the inside of the cowling panels. A splatter of molten metal had solidified on the lower part of the cowling adjacent to the starter. Examination of the starter revealed that it was severely damaged and overheated.

The No 3 engine starter and start valve (the latter incorporating the valve open warning light pressure switch) were removed, together with the right-hand engine start panel on the flight deck. The complete No 3 Engine Change Unit (ECU) was then removed from the aircraft.

The operator carried out extensive aircraft wiring checks and found no defects. A replacement ECU was fitted together with a replacement start panel. After the appropriate engine checks and ground runs, the aircraft was returned to service.

Description and Operation of Relevant Components

The starter takes the form of an air driven turbine, driving through an epicyclic reduction gear to an output shaft with a splined extension which engages in splines in a corresponding input shaft in the accessory gearbox. The starter output shaft incorporates a clutch, which takes the form of a ratchet type coupling, the transmission elements of which move out of engagement under centrifugal force when the output shaft revolves above a pre-determined speed with the drive disengaged. The turbine, reduction gearing, clutch and output shaft are all housed in the starter casing. The accessory gearbox is driven from the high pressure spool of the engine when the latter is running and that spool is thus turned when the start cycle is initiated.

The starter is supplied with air from the main aircraft manifold via a pylon valve and an engine start valve. The aircraft manifold is initially supplied from the APU. Once one or more engines are operating above a pre-determined thrust level, they supply bleed air to the aircraft manifold through the appropriate pylon valve(s) which act as non-return valve(s) unless an engine start cycle is underway. In the latter circumstances, the pylon valve of the engine to be started is powered to the open position, admitting high pressure air from the aircraft manifold to the pneumatic piping in the ECU. The relevant start valve is also signalled to the open position so high pressure air flows to the starter.

Once all engines have started operating, the aircraft manifold is prevented from supplying air to any ECU by the non-return features of the pylon valves. The pressure in the pneumatic piping of each ECU, however, is maintained by the bleed air supplied from the compressor of the corresponding engine. Thus under normal flight conditions, the starter is isolated from an air pressure source solely by the start valve.

Each start valve takes the form of a removable curved elbow in the pneumatic piping of the ECU, connected directly to the starter. A pivoted butterfly disc in the elbow is driven by links from a moving sleeve in an integral pneumatic actuator. Air, bled from the upstream side of the disc, is directed to a diaphragm which is mounted on the moving sleeve in such a way that the pressure normally drives the butterfly towards the closed position, isolating the starter from the pressure supply. When the ground start system is operated, air is supplied to an additional diaphragm in the actuator by way of a ball valve, which is opened against a spring by a pin projecting from an energised solenoid assembly. This second diaphragm is also mounted on the moving sleeve, is of greater area than the first diaphragm and, when pressurised, supplies an operating force in the opposite direction to that produced by the first diaphragm. Thus the net force from the two diaphragms drives the butterfly valve to the open position, allowing high pressure air to flow to the starter.

Normal starter operation is achieved via one of two start system panels situated in the flight deck overhead area. Each panel is associated with two engines, the right-hand panel being devoted to starting engines Nos 3 and 4. Each panel is equipped with four start switches, two for each engine, together with two start valve open warning lights, one for each engine. The start switches are normally used alternately and provide start system redundancy. A failure of a single switch and an element of the start system aircraft wiring will not therefore prevent a normal start from taking place. Each start switch has three positions; ground start, off, and air start. The ground start position operates the starter via the pylon valve and the start valve solenoid, as well as operating the igniters in the selected engine. The air start selection merely operates the igniters. The switches are spring loaded away from the ground start position but latch in the air start position to enable the igniters to be left on for extended periods during takeoff and during flight in turbulence or heavy precipitation. Each start valve open light is operated by a pressure switch downstream of the valve.

Each engine start valve solenoid unit has an external extension, enabling the starter to be operated manually in the event of failure of all electrical elements of the starter operating system. Such operation is achieved by ground personnel, in communication with the flight crew, pushing a screwdriver or similar object through a hole in the cowling aligned with the axis of the solenoid, thereby moving the solenoid shaft and lifting the ball valve off its seat.

Starter Overspeed Protection

Each starter turbine has a design burst speed of 150,000 RPM. As the energy at such a speed cannot be contained by the casing, provision is made for a benign failure to occur at approximately 95,000 RPM, a speed well above that reached on any normal start cycle. This failure is triggered by loss of bearing lubricant supply which causes immediate overheating of the ball/race contact track, resulting in almost immediate softening of the balls and bearing failure. The turbine disc is thus freed to move longitudinally under the thrust of the incoming airflow. This movement brings the disc into contact with a cutter ring which trepans the disc material away just below the blade roots, causing the blades to separate in tension from the disc, as a result of the centrifugal force acting on the reduced disc cross-section. At the normal separation speed, the blades have insufficient energy to escape through the case. The heat generated during the failure is, however, very considerable.

Initial Examination of Engine and Components

The ECU was examined to confirm that no errors had been incorporated in the assembly of the wiring harness. The unit was then shipped to its overhauler for further examination and repair.

The starter was strip examined and it was confirmed that failure had occurred in a manner consistent with the design provision for safeguarding the unit against uncontained failure during overspeed operation.

Examination of the Start Valve

The start valve was examined and it was found that the solenoid had a lesser amount of free play than other similar units when subjected to end load applied by finger pressure. When the solenoid was tested on a rig it was confirmed that it did not perform fully in accordance with its specification. In order to quantify the effect of the unusual solenoid behaviour, the unit was re-united with the remainder of the start valve and the latter subjected to the full acceptance test. Although it passed this, it was noted that carrying out manual operation only required light finger pressure on the solenoid extension, whereas carrying out a similar operation with other valves required a very firm force to be applied. A strip examination of the solenoid valve unit revealed that the installation of adjustment shims had allowed insufficient free movement of the solenoid before the ball valve was lifted clear of its seat. It appeared that the total shim thickness had been incorrectly set during the previous assembly of the unit.

Examination of the Start Switch Panel

Electrical tests were carried out on the switch panel. No defects were found, although one could not eliminate the possibility of some form of stray current energising an output cable when that output was not selected. Similarly, it was not possible to eliminate the possibility of switch connectors sticking in a different position from that selected by the switch lever. It did not prove possible to test this unit under realistic conditions of in-flight temperature and vibration, most standard tests being devoted to ensuring that correct functioning occurred on selection with the aircraft on the ground, rather than that incorrect function did not occur when no selection was being made whilst the aircraft was in flight. Nevertheless, a close examination of the unit gave no reason to believe that any malfunction or inadvertent operation would occur.

Examination of Wiring on the ECU

The cable loom between the ECU/aircraft pylon interface and the start valve solenoid was tested for any evidence of insulation failure. None was found. The loom was then dismantled and the individual cable between the pylon/ECU interface and the start solenoid carefully examined for evidence of chaffing. The insulation was found to be undamaged.

Other Incidents to G-AWNN

During the investigation it was found that the aircraft had suffered a series of previous related problems. Four sectors earlier, on 1 October, during an attempt to start No 3 engine at Chicago, the start valve warning light failed to illuminate and the engine failed to turn. It was found that the starter turbine had disintegrated. A new starter was fitted and the warning light switch replaced. The engine was then started successfully and the aircraft dispatched normally. Shortly after takeoff, however, during the after-takeoff checks, the flight engineer cancelled the igniters by moving the start switches from the air start to the off position. During this operation, which requires leaning forward and looking up past the fire handle, he noted that the start valve open light was illuminated for the No 3 position. The engine was therefore shut down in accordance with the standard procedure, fuel was jettisoned, and the aircraft landed back at Chicago. The No 3 start valve was then changed and the aircraft departed uneventfully, suffering no starter related problem until the event of 4 October.

Further information then became available that the aircraft had suffered a failure of No 3 engine to start at Toronto, approximately four sectors before the Chicago event. The starter was found to have disintegrated and had to be replaced before the No 3 engine could be started and the aircraft dispatched.

Incidents to Other Boeing 747-100 Series Aircraft

During the investigation, it was established that a series of incidents occurred in the period 1984 to 1988 involving destroyed starter motor turbines on UK registered Boeing 747-100 series aircraft. In most instances these were only noted when an engine start was attempted, although logic suggested that they had occurred sometime after engine start on the previous flight sector.

A study of the relevant documentation revealed that an investigation, involving extensive theoretical and practical analysis, was carried out at the time by both the aircraft and the starter manufacturer. No cause was determined but a series of modifications was proposed including one to improve the integrity of the aircraft start system wiring. These modifications were progressively implemented throughout the UK fleet, including on G-AWNN, and no instances were recorded on the Civil Aviation Authority Incident database after 1988.

Examination of Components from Chicago Incident

The No 3 engine starter motor and start valve open warning light switch removed after the Chicago starting incident, together with the start valve removed after the air turnback, were passed to the operator's base engineering organisation. The warning light switch was confirmed, on test, to be defective.

Strip examination of the starter motor, and metallurgical examination of the failed starter components, confirmed that their failure had occurred in the manner described in the section headed Starter Overspeed Protection. The general failure mode was similar to the Heathrow incident but with detail differences. Neither motor had sustained any damage to the epicyclic reduction gear or to the clutch. Both turbines had failed by a mechanism consistent with being air-driven rather than being driven by the output shaft and clutch.

The 'Chicago' start valve was found to have a small internal leak, allowing high pressure air to flow continuously into the volume between the two operating diaphragms, from where it exited via a venting hole. The records indicated that this start valve had been installed with new diaphragms fitted at engine overhaul, some 400 hours before the Heathrow incident. The start valve was strip examined and both diaphragms were found to be undamaged; it was presumed that leakage of air from within the actuator chamber was the result of poorly functioning chevron seals within the moving actuator sleeve. Some damage was found on an internal bore adjacent to the solenoid valve which could be attributed to scoring by an incorrectly installed roll pin. Since the installed roll pin had been correctly filed down so no protrusion was present, it was presumed that the damage had occurred during an earlier assembly of the unit. It was also noted that a small area of damage existed on the 'o' ring seal in this area. It was not clear what effect, if any, this scoring and possible internal leakage would have on the airflow distribution within the actuator. Examination of the solenoid confirmed that the amount of free movement available when the manual override was depressed was considerably less than on other units and thus had some similarity to the problem noted on the valve removed at Heathrow. It was also noted that pronounced 'stiction' existed in the movement of the override. The full strip examination of the 'Chicago' start valve was carried out after the engine tests described below.

Examination of Components from Toronto Incident

The only component removed at the time of the failure to start No 3 engine at Toronto was the starter. This was strip examined and it was confirmed that it had also failed in the same way as the 'Heathrow' and 'Chicago' starters ie by action of the cutter removing the turbine blade ring from the disc. The general condition of this unit suggested that most of its components had not reached as high a temperature as the corresponding parts in the starters involved in the other two incidents.

Other Common Factors

An assessment was made of possible remaining factors which could have caused operation at some time of both the start valves fitted in the No 3 position between the installation of the newly overhauled engine in August 1994 and the date of the Heathrow incident. The only further possibility was a badly fitting engine cowling, which might have had sufficiently small clearance from the solenoid override button to have caused fouling, leading to the start system operating, with either valve fitted, under some conditions of air-loading, temperature and vibration. The engine cowlings were accordingly removed from the No 3 position of G-AWNN and refitted on the subject engine, after it had been repaired by its overhaul company. (The repair included changing the accessory gearbox and replacing the entire ECU wiring harness, containing all the control and indicating wiring for the start valve). This trial fitting showed that a considerable clearance existed between the cowling and the override button and hence the possibility of fouling could be ruled out.

Tests

In order to assess the effect of the incorrect assembly of the solenoid of the start valve involved in the Heathrow incident, it was decided to carry out an engine test-bed run on the repaired No 3 unit from G-AWNN with the relevant start valve fitted. The start valve was installed after its solenoid unit had been re-fitted with the incorrect shimming re-instated so as to produce the reduced backlash originally observed. The test was done as part of the standard acceptance test running following completion of the engine repair.

After approximately one hour of running, shortly after the engine power setting was raised to a figure close to the take-off condition, it was noted that the 'start valve open' warning light was illuminated. The engine was rapidly shut down and the starter examined. Its very hot condition confirmed that it had been operating, although examination confirmed that no failure of the start turbine had taken place.

The start valve was removed, and the valve previously removed from G-AWNN at Chicago was fitted in its place. A successful start was then carried out, confirming that no major damage had been inflicted to the starter during its inadvertent operation on the bed. An extended run of approximately one further hour was carried out at various power settings. The start valve, in this instance, remained closed throughout this period.

Subsequent Events

The ECU in question was finally fitted with an overhauled start valve and starter unit and was released for service. It remained at the operator's base as a spare unit for approximately three weeks before it was fitted in No 3 position on a sister aircraft, G-AWNC. Shortly after entering service on this machine, it suffered a further series of three in-flight starter disintegrations before it was realised that these were occurring on the same ECU as the incidents to G-AWNN.

On each occasion the failed starter was replaced along with a replacement start valve. Immediately after the last such failure, the start valve solenoid operating wiring was replaced in the wiring loom on the ECU. It was realised immediately after this rewiring, however, that the ECU was the one involved in the previous incidents and the unit was accordingly removed from the aircraft and replaced before further flight.

The ECU was again transported to the premises of the overhaul company and carefully examined. Evidence of significant heat damage was noted on engine components in the area of the starter, and sheathing on the cables from the generator was again seen to be damaged. The failed starter units were also examined and compared with the remains of the previous wrecked starters removed after the incidents to G-AWNN. All six failed units appeared to have suffered the same modes of failure with only detailed differences in features of their eventual break-up.

It was decided to instrument three special parameters in the starter area of the engine and carry out further running in a test cell in order to establish more details of the conditions under which the inadvertent starter operation was occurring. Instrumentation displaying the start valve butterfly angle, duct pressure downstream of the butterfly valve and electrical current flowing to the start solenoid was devised and positioned such that these parameters could be observed from the test console in addition to the normal parameters available to the test personnel.

The engine was then subjected to extensive running using the start valve with the incorrect backlash previously used on the earlier successful test (the component removed after the original in-flight fire). During the run a vibration survey was carried to determine the conditions at which the highest vibration levels were present. Despite running for a total of some 12 hours under a variety of conditions, including the conditions producing the highest vibrations, no repeat of the inadvertent starter operation occurred. An additional start valve (the 'Chicago' valve) was fitted for a short period of running; the engine still operated without reproducing the in-flight defect. It was therefore not possible to usefully analyse the special instrumentation fitted to the start valve.

Summary

Since the basic incident, albeit without a recurring fire, was happening repetitively to the same ECU whilst installed on two different aircraft, and yet the defect could no longer be reproduced in the test cell, the investigation ceased at this point. During the total period of service difficulty associated with this ECU, the starter was changed five times, the start valve at least three times, the accessory gearbox once, the start valve wiring within the nacelle once (and a second time between the last in-flight failure incident and the final extended period of test cell running) and the unit was installed in two different aircraft, neither of which has experienced any related problems in recent years when this ECU was not fitted. As no further data or theories to account for the inadvertent operation could be produced the ECU has been withdrawn from service.