SERIOUS INCIDENT

Aircraft Type and Registration:	Bombardier DHC-8-402, G-FLBC
No & Type of Engines:	2 Pratt & Whitney Canada PW150A turboprop engines
Year of Manufacture:	2009
Date & Time (UTC):	16 December 2014 at 1832 hrs
Location:	En route Glasgow to Belfast
Type of Flight:	Commercial Air Transport
Persons on Board:	Crew - 4 Passengers - 76
Injuries:	Crew - None Passengers - 1 (Minor)
Nature of Damage:	Damage to left engine and engine nacelle
Commander's Licence:	Airline Transport Pilot's Licence
Commander's Age:	36 years
Commander's Flying Experience:	7,847 hours (of which 6,820 were on type) Last 90 days - 185 hours Last 28 days - 59 hours
Information Source:	AAIB Field Investigation

Synopsis

The aircraft was en-route from Glasgow to Belfast, when an oil pressure failure and subsequent fire in the left engine prompted a diversion to Belfast Aldergrove Airport. The fire indications on the flight deck cleared several minutes after both fire bottles had been discharged into the engine nacelle. However, observations from the cabin suggested that the fire returned shortly before arrival at Belfast. The aircraft landed safely and stopped on the runway, following which the Airport RFFS confirmed there was still signs of fire. Consequently, the passengers and crew were evacuated from the aircraft, while the fire was rapidly extinguished.

The investigation revealed that the left engine oil pump assembly had failed. This was the result of fatigue cracking in an engine bearing key washer, which caused a section of the washer to be released and migrate to the engine's oil pump. Consequent mechanical failure of the oil pump assembly upset the oil flow, resulting in engine lubrication failure, internal overheat and fire.

In December 2015, the engine manufacturer issued an Alert Service Bulletin requiring specialist internal inspection of engines to be carried out, in a time span dictated by the service life of the relevant key washer. In addition to this on-wing inspection, a revision to the engine manual has been made requiring replacement of the key washer upon access, and a Service Bulletin has been issued requiring replacement on engine shop visits, for any reason. A new, improved key washer has also been introduced.

History of the flight

At 1728 hrs, the aircraft pushed back from its stand at Glasgow Airport for the scheduled 1725 hrs service to Belfast City Airport. Before the ground crew disconnected the tug from the aircraft, with the right engine running and the left engine still shut down, the ground crew's headset operator informed the commander that the aircraft's nose landing gear oleo appeared to have lost its pressure. Consequently, the commander elected to return to the stand for the problem to be rectified. The aircraft eventually departed from Glasgow at 1812 hrs.

The flight proceeded normally until 1830 hrs, when a triple warning chime sounded and the red #1 ENG OIL PRESS warning caption (for the left engine) illuminated on the flight deck. The aircraft was passing FL151, climbing to its cruising altitude of FL160, and was VMC above cloud. The flight crew turned their attention to the oil pressure gauge and saw the reading fall to zero, then show three dashes, indicating invalid information. The crew understood that three dashes could mean there had been a loss of signal from the oil pressure transmitter, so they rechecked the engine instruments and warnings and confirmed the loss of oil pressure in the left engine.

The flight crew reduced power to level the aircraft at FL160, then started to action the Quick Reference Handbook (QRH) procedure for a loss of engine oil pressure in the left engine. As they retarded the left engine power lever there was a "judder through the airframe" and the fire warning audio chime sounded briefly. They expeditiously completed the procedure and shut down the left engine but did not discharge a fire bottle as there was no longer any indication of a fire.

Declaring a PAN, the crew advised ATC that it was their intention to return to Glasgow. As they commenced the turn back, the fire warning chime sounded again and the CHECK FIRE DET caption and left engine fire handle illuminated, indicating there was a fire in the left engine. The crew discharged the first fire extinguisher bottle into the left engine nacelle and upgraded their emergency to a MAYDAY, advising ATC that they now intended to divert to Belfast Aldergrove Airport, as it was the closest suitable airfield. After 30 seconds, the fire warning for the left engine remained, so the commander discharged the second fire bottle. The fire warning then remained illuminated for several minutes, before it cleared.

In the cabin, coincident with the judder felt through the aircraft, the passengers and crew heard what sounded to some like three large "whooshing" noises, in rapid succession, and reported seeing a large blue flame emitting from the left engine exhaust. Sparks and other evidence of a fire could also be seen originating from behind the left engine cowlings, just aft of the propeller.

A company First Officer, positioning to Belfast, was sitting in a window seat on the left side of the cabin and had a good view of the engine. He saw the fire and, after conferring with the senior cabin crew member, provided the commander with a commentary on what could be seen from the cabin. This enabled the cabin crew to concentrate on the passengers and preparing for the landing at Belfast Aldergrove. Following the initial "whooshing" noises, the fire in the exhaust disappeared, and several minutes later, the fire behind the engine cowlings was no longer visible to the cabin crew or the First Officer. One minute after the engine fire warning indications in the flight deck cleared, the cabin crew confirmed they could no longer see any signs of fire[1].

To lighten the flight crew's workload, Belfast Aldergrove ATC offered to retain the aircraft on their Approach radio frequency. The crew accepted this offer. This meant that the RFFS crews, who were moving to their standby positions on the airfield and were monitoring the ATC Tower radio frequency, were not able to listen to the flight crew's radio transmissions. Instead, relevant information was relayed to them by ATC.

On the flight deck the engine fire indications had extinguished, so the commander briefed the cabin crew to expect a normal landing at Belfast Aldergrove, followed by an inspection of the aircraft by the Airport RFFS.

Shortly before touchdown, the positioning First Officer thought he saw signs of fire behind the left engine cowlings and advised the commander accordingly. The commander informed ATC there were "reports of fire from the left engine again, from the cabin, no indications in the flight deck". This was relayed, through several people, to the Airport RFFS crews as "report that there is a fire now in the cabin, but it is not confirmed." As a result, the fire crews prepared themselves for the possibility that they would have to enter a burning aircraft, with several firemen donning breathing apparatus.

The aircraft landed at 1847 hrs and was brought to a halt on the runway, having turned into wind. The fire vehicles attended immediately and the flight crew tried to establish communications with them on 121.6 MHz. They were unable to do so[2] and ATC relayed their request for the RFFS to check the aircraft for signs of fire. The fire crew observed a small fire visible through a vent grill on the left side of the left engine nacelle and advised ATC that the left side of the aircraft was on fire. This was relayed to the aircraft and the commander ordered an evacuation at 1849 hrs, while the fire crew quickly extinguished the fire.

Evacuation

The landing seemed normal to those in the cabin and the call to evacuate was unexpected. At the front of the cabin, the senior cabin crew member opened the forward left door and, on seeing no signs of fire, instructed the passengers to start evacuating. Passengers in the front right seats, who had been briefed several times on how to operate the forward right emergency exit, if instructed to evacuate, departed via the forward left door. The forward right emergency exit remained closed throughout the evacuation.

The cabin crew member at the rear of the aircraft initially opened the rear left exit and, on seeing no signs of fire, instructed the passengers to evacuate. She then opened the rear right exit and passengers evacuated through both these exits. Some passengers were

Footnote

1 Some passengers believed they could still see signs of a small fire from behind the engine cowlings but this information was not communicated to the crew.

2 The ATC RTF recording contained the aircraft's transmissions but nothing from the fire vehicles.

surprised at the height they were required to jump, as the rear exits are not fitted with slides, and some passengers fell on landing, incurring minor cuts and bruises[3].

There was an airport vehicle on the runway with a large illuminated sign on its roof, which read: "PASSENGERS ASSEMBLE HERE" (see Figure 1). The same message was also broadcast through the vehicle's loudspeakers. Some of the passengers, particularly those who evacuated from the rear right exit, were confused as to where to go after leaving the aircraft. Most of the fire crew were on the left side of the aircraft, where the fire had been, and within a few minutes all of the passengers were safely on board airport buses, out of the rain. A head count was conducted and, initially, it appeared that a passenger was missing. This was quickly resolved, once it was realised that the positioning First Officer had remained with the crew.

The passengers were then taken to the terminal building, where they were assessed for any injuries. There were no serious injuries; however, one lady was taken to hospital as a precaution, suffering from anxiety and chest pains. She was released from hospital later that evening.

Figure 1
Airport 'Assemble Here' vehicle

Aircraft description

The DHC-8-402 is a twin turboprop powered aircraft having a typical capacity of 78 passengers. It has a high mounted wing and consequently a relatively low cabin floor, enabling emergency escape by jumping from the exit door sills in all cases except for the forward passenger exit, the door of which incorporates integral stairs.

The engines are mounted conventionally with an approximately vertical titanium alloy firewall protecting the wing structure from damage in the event of an engine fire. The engine mounting structure consists of titanium and stainless steel components clad in

Footnote

[3] EASA issue the certification standards for large aeroplanes in CS25. Subpart D, Para 25.810 states each non-over-wing landplane emergency exit more than 1.8 m above the ground must have an approved means to assist the occupants in descending to the ground. The rear emergency exits door sills in the DHC-8-402 are 1.6 m high. The safety briefing card clearly shows there are no slides fitted to the rear exits.

carbon composite panels and doors. The air intake of each engine is below and behind the propeller and takes the form of glass reinforced plastic trunking. A sheet metal decking is positioned below the hot section of the engine. Two fire bottles are positioned in the upper lobe of the fuselage, just aft of the wing box.

Engine description

The PW150A engine is one of a family of three-shaft units which have different power outputs, but broadly similar architecture. The 150A incorporates a centrifugal High Pressure (HP) compressor of titanium alloy, driven by the HP turbine, an axial Low Pressure (LP) compressor, driven by the LP turbine, and a power turbine/shaft assembly which drives the propeller via a reduction gearbox (RGB) (see Figure 2).

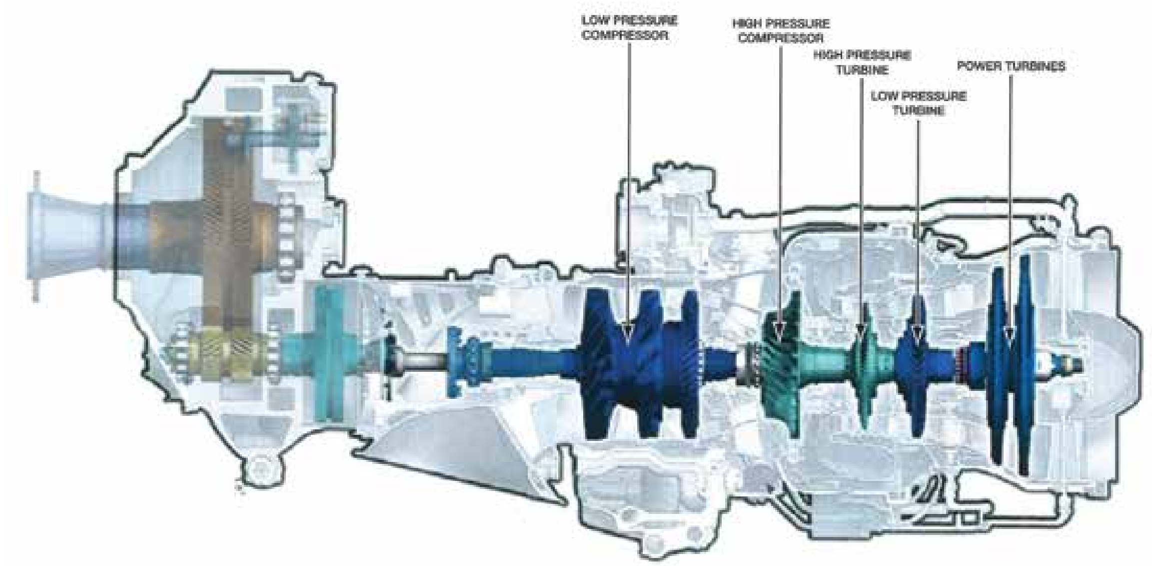

Figure 2

Major rotating assemblies in turbo-machinery and reduction gearbox

The combustor is of the reverse-flow type, with tubes (known as diffuser exit ducts) orientated circumferentially in a plane parallel with the HP compressor impellor carrying air from the tips of the impellor to 'fish-tails', which alter the flow direction to an approximately axial orientation.

The forward end of the HP shaft is located longitudinally and radially by a ball bearing at the No 4 position, in front of the impellor. The aft end of the shaft is located radially by a roller bearing (No 5), positioned forward of the HP turbine and enclosed by the reverse flow combustor (see Figure 3).

A number of parts of the HP spool rotate in close proximity to fixed parts of the engine structure in the vicinity of the No 5 bearing. Their operating clearance is assured by the No 4 bearing, preventing forward movement of the HP spool.

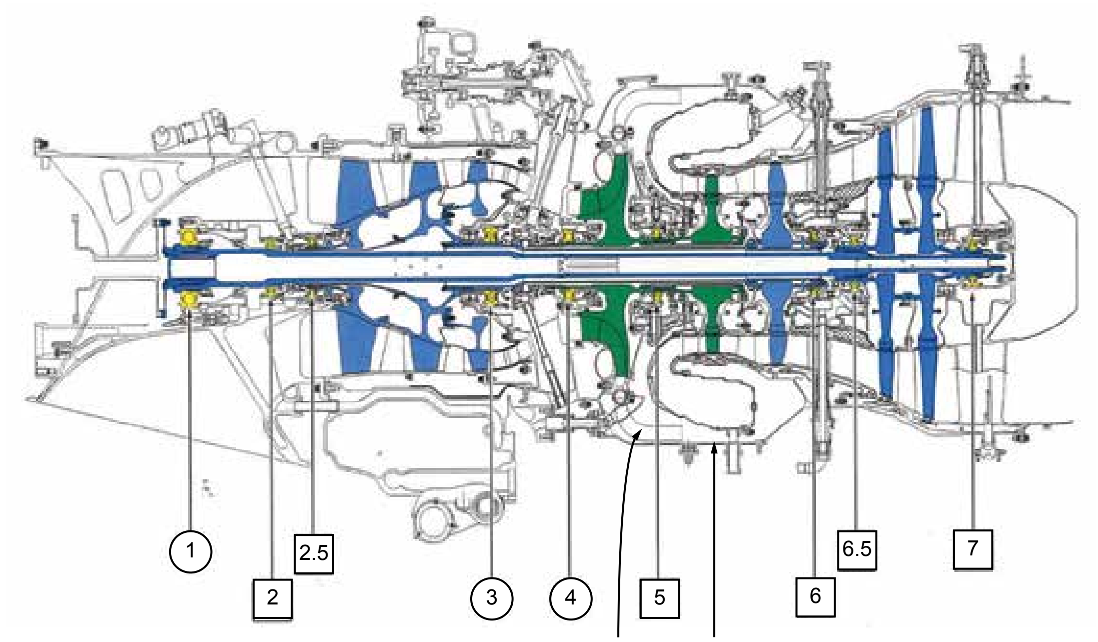

Figure 3

Layout of bearings and combuster in turbo-machinery section
(reduction gearbox not shown)

Lubrication

Lubrication is enabled by a vane pump assembly, incorporating a single pressure supply element and eight scavenge elements. The elements are arranged in two stacks, with the parallel axes orientated vertically and the individual elements joined by splined couplings (see Figure 4).

The assembly is driven by a shaft from the accessory gearbox which passes vertically into the 'driving' section and incorporates a shear neck. This driving section consists of the pressure supply element and four scavenge elements. A spur gear at the top of the driving section meshes with a similar spur gear at the top of the parallel 'driven' section. Four further scavenge elements are installed in the driven section of the unit. These include the scavenge pump for the RGB.

Air bled from the gas path (known as 'blowdown') pressurises some of the bearing cavities to increase scavenge flow when that created by the relevant scavenge pump is insufficient to prevent flooding of the cavity.

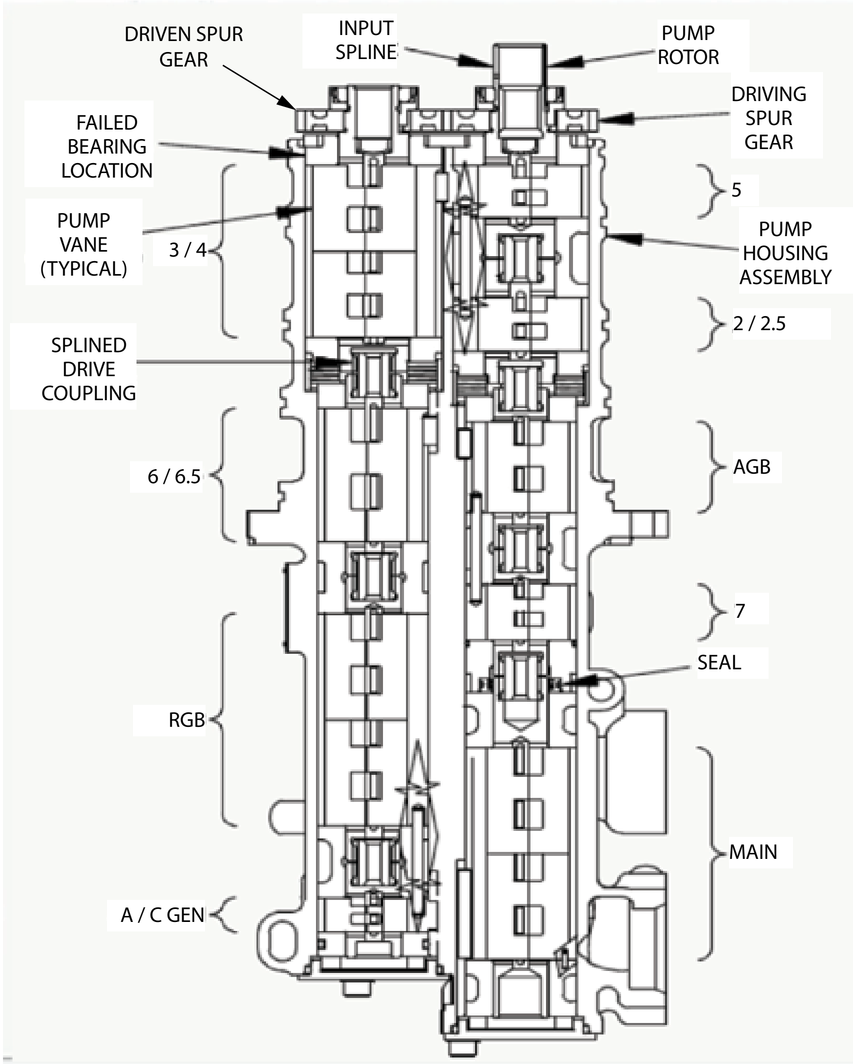

Figure 4
Layout of oil pump assembly

Engine fire detection system

In the event of a fire or overheat condition in the engine nacelles, the fire detection system provides indications and audio warnings on the flight deck. In the event of detection, the respective engine fire warning lights are illuminated and an audio warning triggered. The fire warning lights consist of an ENGINE FIRE PUSH TO RESET caption on each pilot's glareshield panel, PULL FUEL OFF handles, for each engine, in the overhead panel and a CHECK FIRE DET light on the Caution and Warning Panel (CWP). The latter is illuminated when the fire control system senses either an engine fire, APU fire, detector loop circuit malfunction or if the fire extinguisher levels are low. This warning is reversible, meaning that if any of the triggering parameters are reset the light will extinguish.

Other

The fixed structure of the engine is predominantly of titanium alloy. The engine mounting structure within the nacelle incorporates tubular stainless steel members, whilst the cowling materials are predominantly of titanium and composites.

Most power plant functions are controlled via a Full Authority Digital Engine Control (FADEC) and a Propeller Electronic Control (PEC). These supply data to the EMU, which can be downloaded for diagnostic purposes.

Additional engine information

The normal flow rate of oil into the RGB and bearings in the engine operating condition at the time of the event was such that a volume equivalent to that of the oil tank would be expected to enter the turbomachinery and gearboxes over a period of approximately 17 seconds. Consequently, with pressure supply to the RGB taking place and no corresponding scavenge occurring, the oil tank would empty and starvation of oil to the turbomachinery bearings would begin after a little over 17 seconds.

The titanium alloy materials used extensively in the engine have a low thermal conductivity. Consequently, rubbing contact can raise local temperatures rapidly, since the energy created results in heating at and close to the point of contact, and the heat dissipates slowly into more distant parts of the engine structure.

A sustained titanium fire requires a substantial supply of oxygen and will normally only continue within the core of an engine when the compressors are delivering air at an elevated pressure and flow rate.

Aircraft examination

The aircraft was examined by the AAIB the day after the event. It was noted that localised heat blistering of the paint was present on the external faces of both inboard and outboard aft engine access doors on the left nacelle. On opening the aft doors, extensive heat damage and/or smoke blackening was evident over the visible section of the engine, on the cowlings and numerous components mounted both on the engine and attached to the nacelle structure. The decking beneath the engine had suffered heat damage and distortion.

The section of the engine visible on opening the forward nacelle doors was relatively free from smoke and heat damage. It was noted, however, that the oil level was at the bottom of the range visible in the sight glass.

A number of services (pipes and cables) mounted on the engine and support structure appeared significantly heat damaged.

Examination of the engine outer casing revealed a series of holes in the insulation blanket around the lower part of the combustor unit, and a number of small 'fish-tail' components, from within the combustor, were lying on the decking below the engine casing. The intake system decking directly beneath the engine restricted the extent to which external damage on the underside of the engine could be viewed.

Viewed from the rear of the jet pipe, the power turbine could be seen to turn when the propeller was rotated by hand. Attempts at turning the LP compressor manually were unsuccessful, as were attempts at turning the accessory driveshaft, indicating that the HP shaft was probably seized.

Examination of the firewall did not indicate any significant heat damage.

Each of the three magnetic chip detectors on the engine was examined. Those from the reduction gear and the generator drive area were found to be clean. However, the detector from the turbomachinery lubrication area was found to be heavily contaminated with metallic debris. Oil samples were taken from the reduction gearbox volume and from the generator drive area. No oil could be extracted from the turbomachinery area.

Both flight deck fire-handles were found in the 'pulled' position and examination of the left LP fuel valve confirmed it to be at the 'closed' setting. Examination and weighing confirmed that both fire bottles had been fired and were fully discharged.

The aircraft was subsequently returned to service following removal and replacement of the complete left nacelle structure and systems forward of the firewall. A replacement left engine was also installed.

Engine examination

The engine was transported to the operator's engineering base for examination. The complete nacelle structure and the cowlings, from the firewall forward, were similarly transported to enable detailed examination to take place. Once the engine was suspended, without the intake system decking in position, it was possible to see the damage to the combustor area more clearly and large holes in the insulating cover could be observed close to the 6 o'clock position (see Figure 5).

Substantial burn damage and disruption was evident to pipes, cables and other services external to the engine casing at a number of locations. In particular, a hole was evident in a fuel pipe adjacent to the large hole in the combustor. The pipe in this area was coated in metal splatter.

Considerable heat damage to the fire protection shielding on the fuel manifold was evident. However, no other physical penetration damage or disruption was evident to the exterior of the engine casing.

The engine was then shipped to the manufacturer's facility for a strip examination. The lubricant was left in the engine during shipment.

Following arrival at the manufacturer's plant, the oil from the reduction gearbox was drained and it was noted that substantially more oil than normal was present in that unit.

Figure 5

Accelerated wear type failure was noted in a number of bearings, particularly the No 4 bearing. Unusual dryness was noted in undamaged bearings Nos 6.5 and 7, at the rear of the engine. Study of the internal engine features indicated that failure of the No 4 bearing would have permitted forward displacement of the HP spool, leading to extensive contact damage between the forward face of the HP compressor impellor and its casing. Such damage was clearly evident when the impellor and casing were examined.

A major proportion of the titanium alloy structure of the engine had been destroyed, apparently by fire. This damage was widespread, but particularly concentrated in the structural volume between the gas flow path and the centreline, behind the impellor and in the region of the No 5 bearing. The mounting web of the No 5 bearing had been destroyed by fire.

Gross tip damage to the HP turbine blades was evident. This was consistent with rotating blade tip contact with the casing, due to loss of location of the outer race of the No 5 bearing following destruction of its mounting web. It was also consistent with over-fuelling of the engine, as a result of non-standard flow conditions arising from turbomachinery damage and reduction of rpm below the demanded value, owing to impellor rubbing and elevated frictional torque in the HP shaft.

Examination of the combustor

Damage to the combustor casing took the form of a number of holes lying radially in the plane of the exit from the HP impellor. These punctures had occurred apparently as a result of hot debris passing through the casing, after first impacting and penetrating the inner faces of some of the 'fish-tails'. The diffuser exit ducts, leading from the impellor exits, appeared to have directed this high energy material - a number of 'fish-tails' had separated from the ducts and themselves passed through the largest of the holes in the combustor.

Detailed examination of the lubrication system and bearings

As previously noted, the oil tank was observed to be effectively empty when the aircraft was first examined. No oil was present in the turbo-machinery section of the engine but samples were successfully taken from the RGB and the accessory gearbox.

Examination revealed that the No 4 bearing had deteriorated as a consequence of a grinding effect on one of the races, permitting forward movement and contact of the titanium alloy impellor with its casing. The bearing condition was consistent with the effect of continuing operation, without any initial damage but an absence of lubricant. Nos 6.5 and 7 bearings were noted to be undamaged but unusually dry, as would be expected when oil starvation occurred for a short period of operation.

Preliminary examination of the oil pressure/scavenge pump assembly indicated that the upper bearing of the 'driven' element of the pump was damaged and internally deformed, allowing both axial and radial movement of the gear, thus permitting it to come out of mesh with the corresponding 'driving' gear. The complete pump assembly was seized ie none of the elements could be rotated.

The disengaged gears normally transfer the drive from the input shaft to a stack consisting of scavenge pumps for the Nos 3/4 and 6/6.5 cavities, AC (alternating current) generator drive and the RGB. The shear neck on the input drive to the combined pressure/scavenge pump assembly was intact and metallurgical examination indicated that its strength would have been in the normal range.

The oil pressure/scavenge pump unit was subjected to X-ray computed tomography (CT) scanning, before being forwarded to its manufacturer for examination. That examination revealed that a lateral breakout failure of the upper bearing of the driven stack (see Figure 6) had allowed its axis to be displaced, permitting disengagement of the gears.

This had resulted in loss of drive to all the scavenge pumps, except for No 2/2.5, 5 and 7, and that for the accessory gearbox. Dismantling revealed that numerous vanes were jammed in their slots in the rotors and evidence of significant overheating was present.

Laboratory examination of various items of debris from the pump initially indicated that the reason for vane seizure was the presence of re-solidified titanium in the slots and in the spaces below some of the vanes: titanium alloy is not used in the manufacture of the pump unit.

Figure 6
Failed upper bearing
No 3/4 scavenge pump

Further information

Coincidentally, another similarly burnt out PW150A engine, installed in another operator's aircraft, was received for investigation by the engine manufacturer. The damage was reported to be similar to that on the engine from G-FLBC, except that the shear neck of the drive to the oil pump had failed. Investigation of the second engine failure revealed a failed condition of the No 4 bearing key washer.

It appeared that debris from the failed washer had entered the No 3/4 scavenge pump section, leading to a condition which had overloaded and failed the shear neck on the pump driveshaft in that aircraft. Consequent loss of all oil pumping functions had caused starvation and led to total loss of delivery flow and pressure.

The close similarities between features of the above two engines led to a laboratory examination of the key washer salvaged during dismantling of the G-FLBC engine. It was confirmed that fatigue cracking had been present in the component (situated immediately forward of the No 4 bearing - see Figure 7). Consequently, overload failure had ultimately occurred, releasing part of the washer. The released fragment then appeared to have travelled through the gallery to the 3/4 cavity scavenge pump. Such an eventuality would normally result in seizure of the pump assembly and failure of the shear neck on the driveshaft. On this occasion, however, (in G-FLBC) it appeared that the action of lubricant within the pump assembly coupled with the geometry and orientation of the fragment did not create sufficient torque reaction to fail the shaft. Nonetheless, it created sufficient side load on the uppermost 3/4 cavity vaned scavenge pump to fail the top bearing in the driven scavenge pump stack.

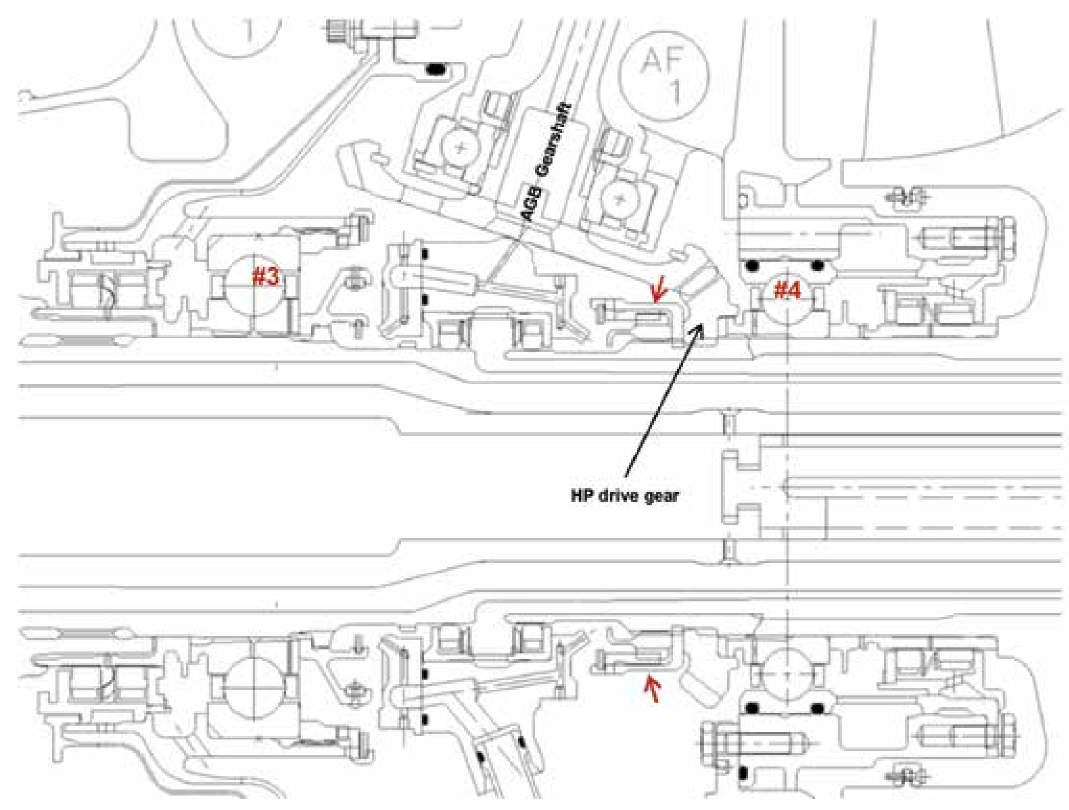

Figure 7

Red arrows show position of failed key washer
(between bearings #3 and #4)

The debris adhering to the magnetic chip detector for the turbomachinery was thought to include released material from the key washer. The similarity in the steel type employed to that forming components subsequently damaged by continuing operation of the inadequately lubricated engine, however, made it impossible to identify conclusively key washer debris.

Fire detection system

The fire detection loop from G-FLBC was tested, in accordance with the manufacturer's Aircraft Maintenance Manual (AMM), by the operator at their main engineering base. It was found to comply with the specified requirements.

Recorded information

The aircraft was fitted with a 2-hour CVR and a Flight Data Recorder (FDR) which recorded just over 26 hours of operation. Each engine also had an associated EMU which recorded fault and status events, along with a snapshot of engine parameters from two minutes before to one minute after each event. EMU data for the left engine was downloaded, decoded and analysed by the engine manufacturer. These recorded data sources were combined and are summarised in the 'History of the flight'.

A review of the FDR data during the taxi-out and initial climb confirmed that the recorded engine parameters were the same for both engines. During the climb, at 1827:37 hrs the EMU recorded a fault code corresponding to a *'turbo machinery chip detection'*. Two minutes and 43 seconds later, it recorded a *'main oil filter impending bypass'* fault code, followed fourteen seconds later by a *'low oil pressure'* fault code. The former is triggered when the oil filter is approaching its maximum capacity and bypass of the main oil filter is about to occur.

One second later, at 1830:35 hrs, the FDR recorded a MASTER WARNING and a left engine low oil pressure warning, which is triggered once oil pressure reduces below 44 psi. The EMU also recorded a *'main oil pressure exceedance flag'* which is triggered if the oil pressure is less than 45 psi. The CVR recorded the flight crew acknowledging this warning with the aircraft climbing towards its cruising altitude of FL160. Just after both engine power levers were retarded at the top of the climb, engine data started to differ between the left and right engines (see Figure 8). At 1831:36 hrs, the EMU recorded an *'engine flameout'* on the left engine. Thirteen seconds later, the FDR recorded a change of state in the CHECK FIRE DET light on the CWP, along with a MASTER WARNING. This was activated for five seconds, then cleared. The CVR recorded the flight crew acknowledging the warning, which occurred just after the left engine power lever had been retarded as part of the engine shutdown procedure.

At 1833:27 hrs, CHECK FIRE DET was again triggered and this time remained until the FDR recording ended, just over 13 minutes later. The status of the engine fire bottles was not recorded, although the CVR recorded the flight crew confirming that both fire bottles had been discharged. It also recorded them declaring a MAYDAY and requesting a diversion to Belfast Aldergrove Airport. Of the engine fire warning lights, only the CHECK FIRE DET status was recorded. However, at 1837:10 hrs, during the subsequent descent towards Belfast, the CVR recorded the commander saying "FIRE'S GONE OUT".

Analysis

Engineering

Initiating event

It was confirmed that fatigue cracking had been present in the engine's No 4 bearing key washer (situated immediately forward of the No 4 bearing). Consequently, overload failure ultimately occurred, releasing part of the washer. The released fragment then appeared to travel through the gallery to the No 3/4 bearing cavity scavenge pump in the oil pump assembly. It appeared that the action of lubricant within the pump, coupled with the geometry and orientation of the fragment, created sufficient side load on the uppermost 3/4 cavity scavenge pump to fail the top bearing in the driven scavenge pump stack. On this occasion, the particle did not create sufficient torque reaction to cause a failure of the shear neck on the oil pump's input driveshaft.

Failure of a No 4 bearing key washer also occurred in a similar engine during this investigation, leading to a generally similar outcome. In that event, the shear neck on the oil pump's input driveshaft failed.

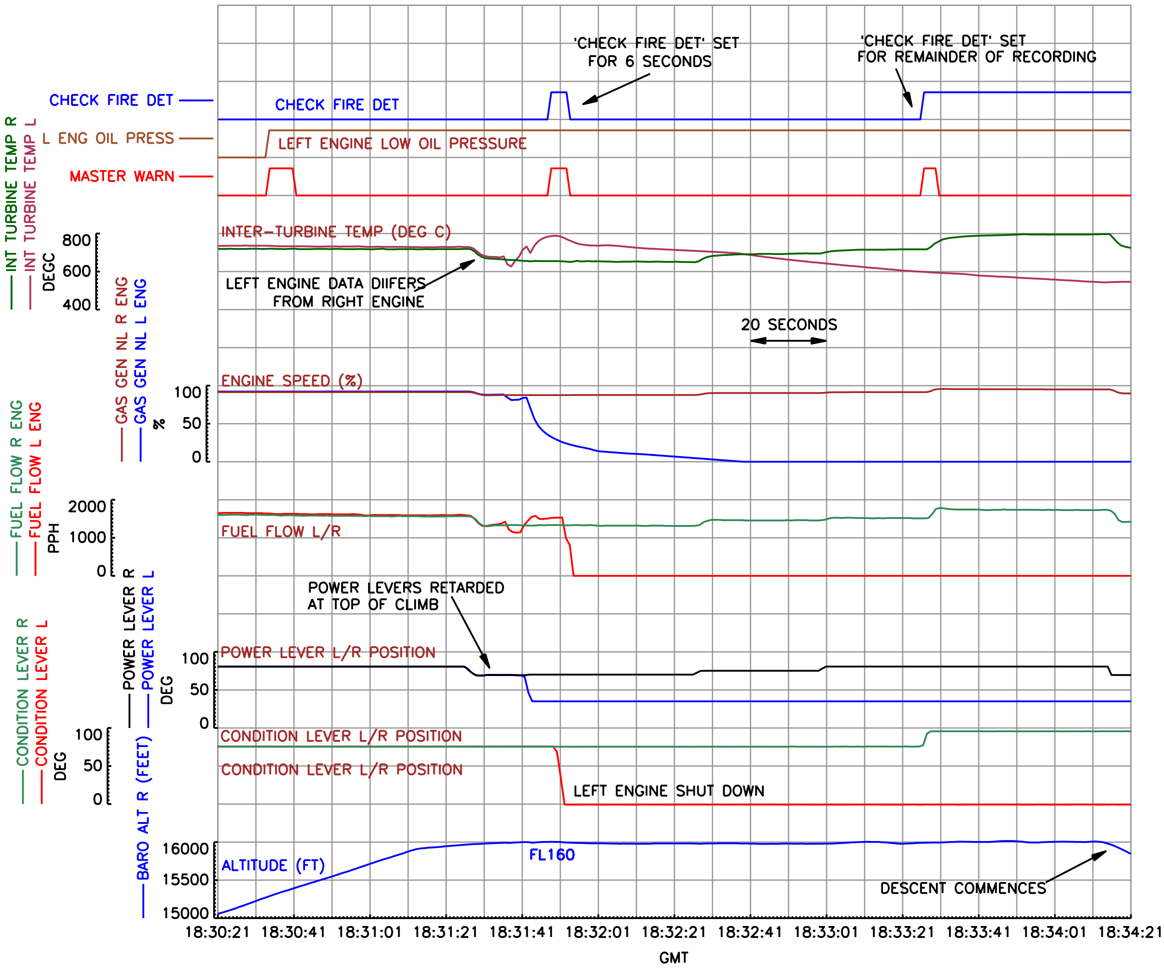

Figure 8

FDR parameters

Engine lubrication

The failure of the top bearing locating the driven gear of the engine oil pressure/scavenge pump assembly resulted in disengagement of this gear from the driving gear. Consequently, the driven gear's stack of scavenge pumps stopped. Since the pressure pump function continued, the RGB continued to receive oil. However, the RGB oil was not returned to the oil tank due to the lack of scavenge from that area. Hence, the oil tank progressively emptied and the RGB began to flood. Flooding in the RGB, as observed by the excessive volume drained before the engine strip, contributed to a low level in the oil tank, followed by overall starvation.

From detailed examination of the pressure and scavenge pump elements, it was concluded that contamination of the oil with titanium had occurred before complete engine failure. Since only the engine contains titanium components, it was considered possible that the oil pump assembly failure was the consequence of some form of failure, involving titanium, within the engine. It was subsequently deduced, however, that the presence of the blowdown system, to augment the scavenge pump performances, probably caused titanium products within the gas path to be directed into the oil system late in the failure sequence, after the scavenge pumps on the driven side of the pump assembly had ceased to rotate.

It was estimated that the pressure pump section in the engine continued to supply oil for approximately 17 seconds after the failure of the upper bearing of the driven scavenge pump stack. After this, an empty oil tank ensured that no more oil was delivered.

Final failure sequence

The loss of oil supply resulted in overheating and general deterioration of the No 4 bearing, leading to interference damage between the HP compressor impellor and casing. Loss of cooling and lubrication of the No 5 bearing would have led to the potential for local overheating and seizure. At the same time, rotating contact between the HP spool and the fixed structure in close proximity, permitted by forward movement of the spool, following deterioration of the No 4 bearing, would have created rapid frictional heating in the region of the No 5 bearing. Either of these last two mechanisms could have led to the internal fire which ultimately destroyed the No 5 bearing support web.

The recorded data indicated that low oil pressure in the left engine triggered a red MASTER WARNING. This occurred approximately 3 minutes after a turbomachinery chip warning (not displayed to the crew) had been created. The flow rate of oil to the RGB suggested that the oil tank depleted in approximately 17 seconds, after the driven scavenge pumps ceased to return oil to the tank. It, therefore, appeared most likely that initial failure of the key washer, releasing some ferrous material into the oil flow, occurred a little under 3 minutes before the failure of the upper bearing of the oil pump assembly.

Apart from the punctures in the combustor, the external casing of the engine remained intact. It appeared that the metal splatter, which impacted and passed through the combustor case and the insulation layer, was material released as a result of the rotating contact between the impellor and its casing. The same material was also responsible for creating the hole in one external fuel pipe.

Engine fire

It was concluded that fuel was liberated into a volume within the nacelle, from the holed external fuel pipe, and was exposed to the hot/burning centre of the engine carcase via the punctures in the combustor case. Much of the external heat damage to the engine is difficult to account for, other than as a result of an external fuel-fed fire. However, it is likely, from the EMU and FDR data and a study of the engine damage, that an internal fire had begun approximately 1 minute after the loss of oil pressure. Initially, burning at such a location is unlikely to have significantly altered conditions external to the engine casing or to have caused the fire warning to operate. Therefore, it is likely that an undetected internal fire persisted for a period before the combustor was penetrated and the fuel pipe became holed.

Following the fire warning, the fire suppression system was operated, both bottles being fired over a period. Although a flight crew member being carried in the cabin subsequently reported fire still being visible through gaps and louvres in the cowling, no further fire warning was reported.

Fire crew on the ground saw signs of fire beneath the cowling immediately after the aircraft landed. The nature of the titanium structure of the engine is such that the transfer of heat from within the core of the engine to visible areas on the outside casing of the unit would have been gradual. It is possible that, as a result of delayed conduction from the core of the engine, parts of the exterior casing glowed red and became visible in the darkness after the external fuel-fed fire ceased, or that a small amount of residual fuel from the engine fuel system continued to drain from the punctured fuel pipe, being re-ignited by the hot exterior of the engine casing. In addition, the elevated temperature of the exterior of the engine, once stationary on the ground, probably led to charring and smoke emission from insulation of cables and pipes on the exterior of the engine.

Safety action

On 21 December 2015, the engine manufacturer issued Alert Service Bulletin SB A35325. This requires in situ inspection of the No 4 bearing key washer and the removal from service of engines in which cracked washers are identified.

The manufacturer has used technical records to identify the service lives of key washers and, hence, priorities for inspection and maximum permitted running periods before inspections on particular engines are required to be carried out.

The inspection requires removal of a number of components from the engine, to gain access to the area of the key washer, and utilises an ultrasonic transducer to determine the presence or absence of cracking. In view of the complexity of the inspection process, the manufacturer has provided special training to operators. Where cracked washers have been identified, the corresponding engines have been removed from service.

In addition, the engine manual has been revised to instruct the replacement of the key washer upon access, and SB 35326 has been issued to instruct replacement of the key washer at engine shop visits, regardless of the reason for engine removal. Furthermore, the engine manufacturer introduced a new improved key washer in February 2016, per SB 35327.

Operations

The flight crew were presented with a loss of oil pressure in the left engine, which prompted them to initiate a return to Glasgow, their point of departure. There had been a brief fire warning while they were carrying out the QRH procedure for a loss of oil pressure but it then returned permanently and the crew elected to divert to the nearest suitable airfield, Belfast Aldergrove, as they carried out the QRH procedure for an engine fire.

Despite the engine being shut down and both fire extinguishers being discharged, the indications to the flight crew were that the fire remained for several minutes. The flight deck indications then cleared and from the cabin it also appeared that the fire had extinguished. However, shortly before landing, the flight crew received further reports from the cabin that there were, once again, signs of fire in the engine nacelle. This was communicated to the airport RFFS crews as being a fire in the cabin and they prepared themselves for the possibility that they may have to enter a burning aircraft.

Having landed safely, the aircraft was stopped on the runway. The flight crew were unable to speak to the RFFS crews direct and ATC relayed their request for the aircraft to be checked for signs of fire. Confirmation that there was a fire on the left side of the aircraft then prompted the crew to carry out an evacuation, during which there were some cuts and bruises but no major injuries.

The fire, which was visible in the engine nacelle, was quickly extinguished by the airport RFFS and, within a few minutes, the airport authorities had moved everyone to a place of safety, out of the rain.

Conclusions

While the aircraft was in the climb to its cruising altitude, fatigue cracking of the left engine's No 4 bearing key washer appears to have allowed a steel fragment to pass into the No 3/4 bearing cavity scavenge pump. This resulted in bearing damage, permitting disengagement of the drive to some of the scavenge pumps in the engine's oil pump assembly, while the pressure supply and four other scavenge pumps continued to function. The ultimate absence of oil in the engine's oil tank led to the total loss of lubrication and the rapid deterioration of dry bearings in the engine. This, in turn, caused engine shaft displacement and frictional rubs, creating internal titanium fires at a number of locations. The combustor case was penetrated, internal components were ejected and an external fire then developed.

The flight crew followed the QRH procedures for a loss of oil pressure and fire in the left engine and carried out a diversion to the nearest suitable airport. The fire extinguished after a few minutes but appeared to return shortly before the aircraft landed. The airport RFFS attended the aircraft when it stopped on the runway and observed signs of fire within the left engine nacelle. These were rapidly extinguished, while the passengers and crew evacuated from the aircraft.

In December 2015, the engine manufacturer issued an Alert Service Bulletin, SB A35325, requiring specialist internal inspection of engines to be carried out, in a time span dictated by the service life of the No 4 bearing key washer. In addition, the engine manual has been revised to instruct the replacement of the key washer upon access, and SB 35326 was issued in December 2015 to instruct replacement of the key washer at engine shop visits, regardless of the reason for engine removal. The engine manufacturer also introduced a new improved key washer in February 2016, as indicated in SB 35327.