ACCIDENT

Aircraft Type and Registration:	Hunting Percival P56 Provost T1, G-AWVF
No & Type of Engines:	1 Alvis Leonides 503/6A radial piston engine
Year of Manufacture:	1955
Date & Time (UTC):	8 July 2009 at 1334 hrs
Location:	1.3 nm east of Bishop Norton, Lincolnshire
Type of Flight:	Private
Persons on Board:	Crew - 1 Passengers - None
Injuries:	Crew - 1 (Fatal) Passengers - N/A
Nature of Damage:	Aircraft destroyed
Commander's Licence:	Airline Transport Pilot's Licence
Commander's Age:	74 years
Commander's Flying Experience:	13,750 hours (of which 150 were on type) Last 90 days - 11 hours Last 28 days - 2 hours
Information Source:	AAIB Field Investigation

Synopsis

While cruising at 2,500 ft the aircraft suffered a mechanical engine failure which led to an in-flight fire. The pilot was probably rendered unconscious by the smoke and fumes from the fire; the aircraft crashed into a field and the pilot was fatally injured. The engine failure was initiated by a fatigue crack of the No 6 piston gudgeon pin. The cause of the fatigue crack initiation could not be determined but it is likely that a high-load event, such as a partial or full hydraulic lock, initiated the crack in the pin. The presence of corrosion pits on the inner surface of the pin was probably a contributory factor and the aircraft's low utilisation rate during the previous 45 years probably contributed to the formation of corrosion. In addition to the initial CAA safety actions, three AAIB Safety Recommendations are made.

History of the flight

A pilot (not the pilot in this accident) had flown the aircraft from its base at Brimpton, Aldermaston to Old Buckenham Airfield, Norfolk, on 28 June 2009 and performed a flying display. The following day he flew it to RAF Waddington where it was to form part of a static display later in the week. The pilot, one of three pilots who flew the aircraft, described the performance of the aircraft and the engine during these flights as "normal". On 3 July 2009 the aircraft was refuelled to full tanks but other than removing and replacing the covers on the aircraft for static display purposes, no other work was carried out on the aircraft while it was at RAF Waddington.

On 8 July 2009 the aircraft was to be flown to RAF

Linton-on-Ouse to participate in another display. The pilot for this flight regularly flew the aircraft, and had last flown it on 21 June 2009. At around 1130 hrs, he was collected from Grantham railway station and taken to the aircraft, where the aircraft covers were removed and he stowed the covers and his personal kit bag in the aircraft. The pilot was then escorted to the briefing facilities at RAF Waddington where he was seen to check the NOTAMs, the meteorological conditions, and to book the flight out to RAF Linton-on-Ouse with airfield operations. The weather conditions were suitable for the planned flight, and the pilot was observed to be in good spirits. He was then taken back to the aircraft where he was seen to perform his pre-flight walk-around, which included turning the propeller through 15 blades in the direction of rotation, before he entered the cockpit.

Just after 1300 hrs the pilot started the aircraft. It seemed to an observer to be reluctant to start as it took about 10 starter engagements before the propeller made a complete revolution. Eventually the engine started with a cloud of white-grey smoke which the observer, who had seen this aircraft start before, considered normal. At 1311 hrs the pilot was given his taxi clearance. The aircraft appeared to be performing normally to people who watched the aircraft as it taxied out and at 1322 hrs the aircraft commenced its takeoff from Runway 02. The aircraft continued to the north, climbing initially to 2,000 ft, and the pilot was given a radio frequency change to receive a Basic service from Waddington Radar. At 1326 hrs the pilot requested, and was granted permission, to climb to 2,500 ft to remain clear of the Wickenby Aerodrome Traffic Zone. The aircraft was then allocated a Humberside transponder code, and the pilot changed radio frequency to Humberside Radar. At 1332 hrs Humberside Radar confirmed that G-AWVF was identified, and the pilot confirmed that the aircraft was at 2,500 ft.

At 1333 hrs ATC gave radar instructions to another aircraft, in the north of the Humberside area but the response was blocked by another aircraft transmitting. ATC repeated its radar instructions and again the reply was blocked. ATC asked the pilot to confirm he had received the instructions, and its third reply was uninterrupted. When two stations transmit simultaneously the resultant 'noise' is normally indecipherable but, in a controlled environment, an analysis of the 'noise' revealed that, at 1333.18 hrs the word "MAYDAY" was part of one of the transmissions.

At approximately 1335 hrs a person, driving his car along the A631, observed what he considered was an "old" aircraft trailing thick black smoke and descending rapidly towards the ground. The aircraft disappeared behind some trees, and shortly afterwards a cloud of black smoke appeared. The driver rang the emergency services and drove to the likely source of the smoke; on arrival he found that the aircraft was badly disrupted in a field, with several small fires around it. He ran to the aircraft to try and offer assistance, but as he got closer he realised that the cockpit area had been destroyed and so he looked around the area for survivors. He quickly located the body of the pilot, who had been thrown clear from the aircraft, but it was immediately obvious that the pilot had received fatal injuries.

There were many witnesses to the aircraft accident and all of them observed thick black smoke coming from the aircraft in the air. About half the witnesses saw flames, which they described as intense, coming from just behind the propeller, and a few witnesses observed objects dropping from the aircraft during the last 500 ft of its descent.

At 1334:48 hrs the Humberside Radar controller noticed that G-AWVF was no longer showing on radar and so he requested a radio check. He received no reply, and after having checked that the aircraft had not returned to RAF Waddington's frequency, he asked a nearby light aircraft to check the last known radar position for G-AWVF. The light aircraft quickly located the burning aircraft in a field, with people in attendance.

The air ambulance was on scene within 20 minutes of the accident, and paramedics confirmed that the pilot had received fatal injuries.

Investigation flight in a P56 Provost aircraft

The Royal Navy Historic Flight assisted the AAIB investigation by providing a flight in a P56 Provost aircraft in order to determine an approximate normal cruise speed and the stick-free response to a simulated engine failure. The aircraft was trimmed for level flight at 3,000 ft amsl with a normal cruise power setting of 0 boost and 2,150 propeller rpm, which gave an indicated airspeed of 120 kt. The control column was then released and the engine power reduced to idle. The nose of the aircraft slowly pitched down and the airspeed increased. At 1,000 ft amsl the aircraft had achieved a pitch attitude of around 35º nose-down and the ASI was indicating 160 kt.

Post-mortem examination

A post-mortem examination found evidence of soot in the airway of the pilot, which indicated that he had been breathing during exposure to smoke. Toxicology results showed the presence of cyanide in the pilot's blood at a significantly elevated level; cyanide is a common combustion product of some materials found in aircraft construction. A specialist aviation pathologist considered the level of cyanide meant that the pilot may have been unconscious, or otherwise incapacitated, prior to the aircraft hitting the ground. He judged that the forces involved in the accident were not survivable and that the pilot would have died instantaneously in the impact.

P56 Provost Pilot's Notes

The Pilot's Notes for the P56 Provost date back to when the aircraft was used as a training aircraft for the RAF. They state that, in the event of an in-flight engine fire which does not go out after turning off the fuel shutoff valve, the pilot should abandon the aircraft if height is sufficient. Parachutes were not carried in this aircraft at the time of the accident and, as the aircraft was on the civil register, they were not required. However, the CAA's CAP 632 ('*Operation of 'Permit to Fly' Ex-Military Aircraft on the UK Register*') recommends:

> *'Parachutes should be worn on all flights in ex-military aircraft.'*

Recorded radar data

Radar data was recorded for the accident flight. The aircraft was fitted with a transponder but this was not Mode C enabled so no height information was available. The radar returns were from Secondary Surveillance Radar (SSR) apart from the last two, which were primary returns.

Figure 1 shows the accident track which started at 1323:34 hrs at Waddington Airfield and ended at 1333:41 hrs, approximately 0.33 nm south of the accident site. Figure 2 shows a close-up of the radar track in the vicinity of the accident site.

The average groundspeed between each radar point was calculated and is presented in Figure 3 (note that these groundspeeds do not have any vertical speed component). This figure shows that the groundspeed during the majority of the flight was about 100 kt. Towards the end of the flight the groundspeed started to

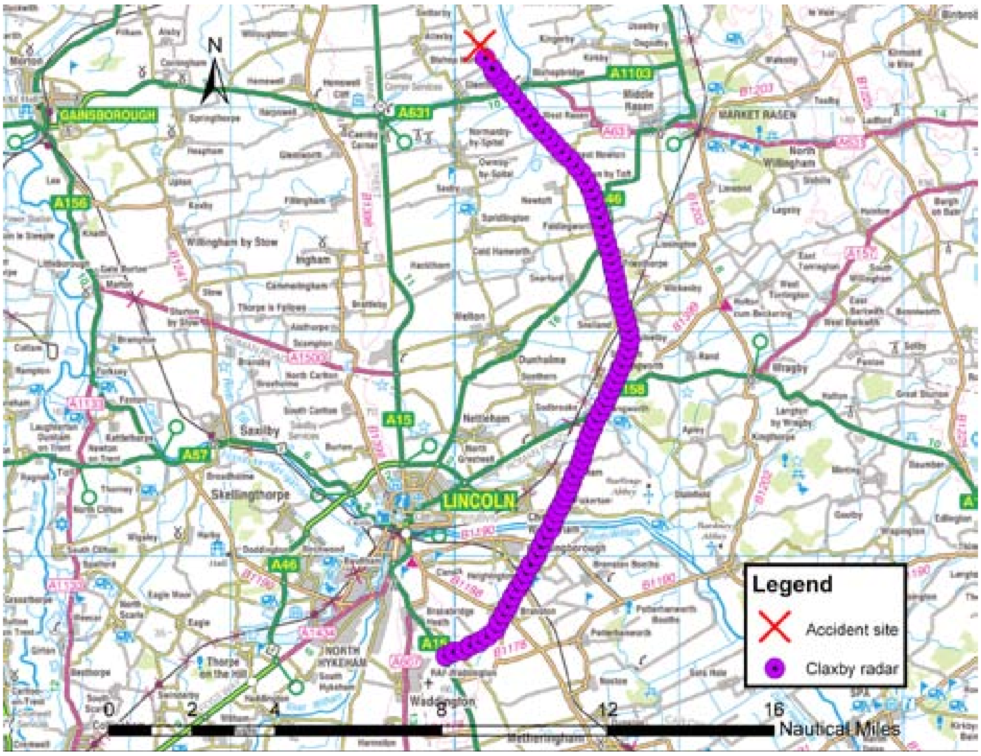

Figure 1

Radar track of G-AWVF and position of accident site

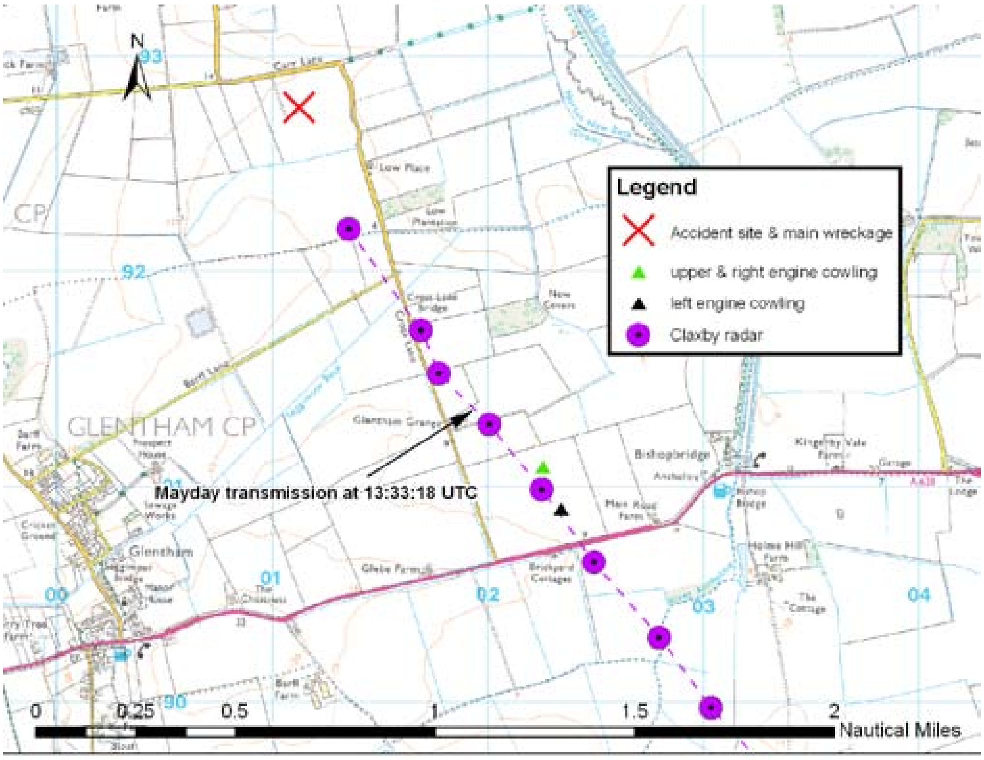

Figure 2

Radar track of G-AWVF approaching the accident site reduce. However, the reduced positional accuracy of the last two points (primary returns) compared to the rest (SSR) means that the calculated groundspeeds for these points are less reliable.

Aircraft information

The Hunting Percival P56 Provost T1, also known as a 'Piston Provost', is a single-engined two-seat military training aircraft with a fixed landing gear (Figure 4). It is powered by a 550 hp Alvis Leonides 503/6A 9-cylinder radial engine which, through a reduction gearbox, drives a three-bladed constant-speed propeller. The aircraft has conventional flying controls operated by push-pull rods and cables. It has a 24V electrical system and a pneumatic system which powers the flaps, wheel brakes and windscreen wipers.

G-AWVF (military registration XF877) was operated by the Royal Air Force (RAF) from 1955 to 1969 during which time it accumulated 3,735 flying hours. It then entered private use and had accumulated 4,100 hours at the time of the accident. The aircraft was operated under a CAA Permit to Fly and maintained by its owner under the supervision of a Licensed Aircraft Engineer.

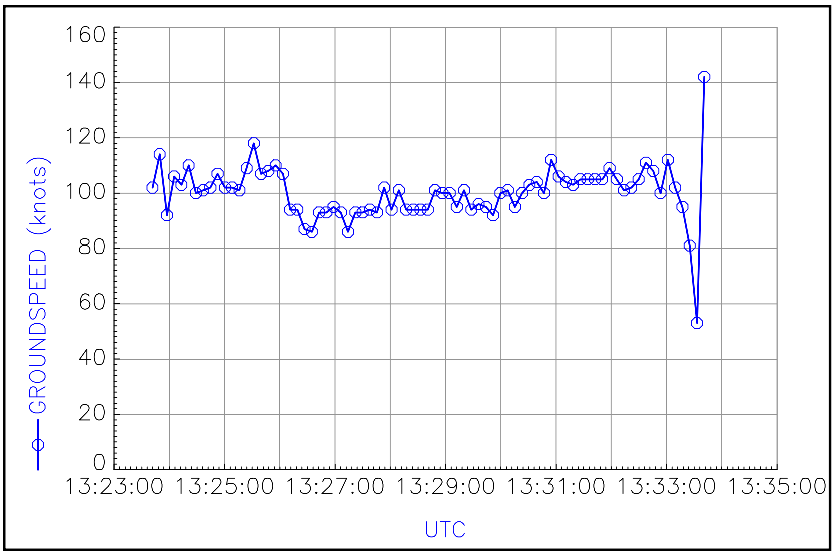

Figure 3

Accident flight calculated groundspeed from radar data

Figure 4

P56 Provost T1, G-AWVF
(photograph courtesy Brian Nicholas)

The owner of G-AWVF had been operating the aircraft for the previous 19 years, but had only taken ownership of it in April 2004. The owner last flew the aircraft in August 2007, but it continued to be flown by the accident pilot and one other pilot. On this aircraft the cartridge-type engine starter had been replaced by an electric starter.

Accident site examination

The aircraft had crashed in a field of tall crops about 1.3 nm east of Bishop Norton. From the initial impact point the aircraft had travelled 21 m in the direction of 340°(M) before coming to rest. The damage to the crops near the initial impact crater indicated a steep nose-down impact of approximately 35° to 40° with the wings nearly level. The aircraft's right wing had sheared near the root and its centre fuselage and cockpit area were almost completely destroyed by fire. The pilot's body had been thrown clear of the aircraft and was found 22 m beyond the main wreckage in the approximate direction of aircraft travel. The cockpit's sliding canopy was found 16.5 m north-west of the main wreckage (Figure 5).

A number of flight instruments and components from the instrument panel had been thrown clear of the post-impact fire, but exhibited evidence of sooting and high temperature exposure. The sliding canopy also exhibited evidence of exposure to high temperature, and sooting, but was surrounded by crops that were unburnt. A few large sections of broken transparency had become opaque and discoloured as a result of heat exposure but were surrounded by unburnt crops.

Both wing fuel tanks had ruptured, the separated engine was resting underneath the remains of the right wing fuel tank and the right side of the aircraft had been exposed to more fire than the left side. The paint scheme on the left wing upper surface and left side of the vertical tail was mostly untarnished by fire or heat; these parts of the aircraft were facing into the prevailing wind at the time of the accident. The three-bladed propeller exhibited chordwise scratches and leading edge nicks consistent with rotation at impact, but not with high power. The engine had suffered significant fire damage and its three lower cylinders (No 5, 6 and 7) had detached. The No 5 and 6 cylinders were located within the initial wreckage trail, while the No 7 cylinder was located about 40 m north-east of the impact site[1].

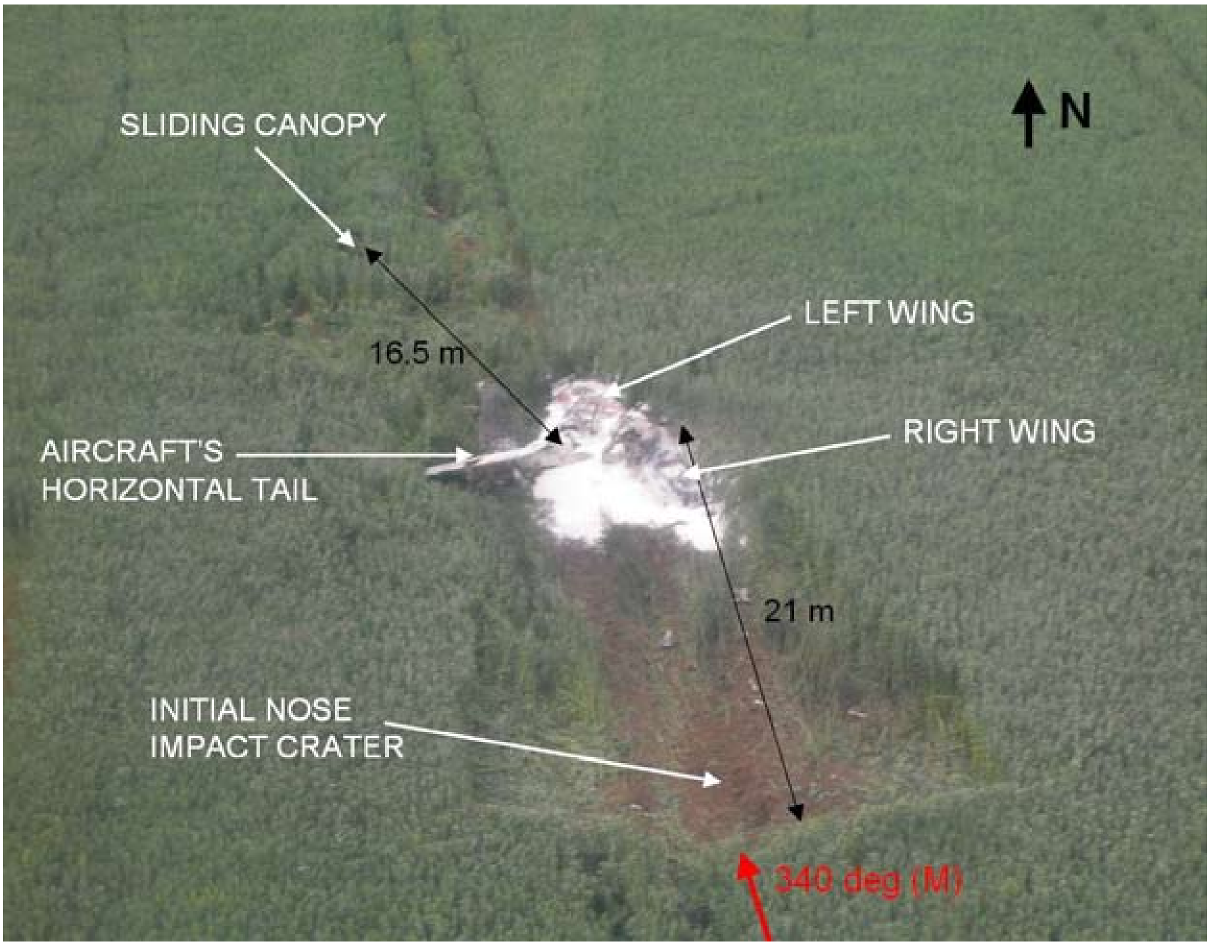

Figure 5

Accident site location – the main wreckage is surrounded by white fire-retardant foam that was applied by the fire service after the accident

Footnote

[1] The missing No 7 cylinder was found by farmers while harvesting the field in September 2009.

All major aircraft components were accounted for at the accident site, apart from the engine cowlings. The engine cowlings were found, one month after the accident, in a field 1.1 nm south-south-east of the accident site (Figure 2). The upper and right side cowlings were still attached to each other at the hinge. The left side cowling had detached at its hinge and was found 212 m south of the upper and right cowlings. The lower rear corner of the right cowling was burnt and sooted.

The aircraft wreckage was transported to the AAIB headquarters near Farnborough for detailed examination.

Detailed wreckage examination

Engine cowlings

The latches securing the engine cowlings to the aircraft had failed in overload. The right engine cowling was missing a small portion of its rear lower corner and this area was surrounded by black burn marks and blistered paint (Figure 6). On the internal surface of the right engine cowling, in the lower forward section, there were a number of puncture indentations (Figure 7). With the cowling installed these indentations would have been adjacent to the No 7 engine cylinder, and would have been aligned with the bolt ends protruding from the cylinder head's two rocker covers.

Fuel system

The aircraft contained two main fuel tanks, one inside each inboard wing section, which were connected to a 2.9 gallon collector fuel tank located centrally on the belly of the aircraft, aft of the engine firewall. A 'Saunders' shutoff valve was installed between each main fuel tank and the collector tank. These valves were wire-locked to the open position and were used solely for maintenance purposes. A third 'Saunders' shutoff valve was located between the collector tank and the fuel pipe passing through the engine firewall; this valve was controllable from the cockpit.

The left tank's shutoff valve was found in the wire-locked open position. The right tank's shutoff valve was badly burnt and had separated from the fuel lines, but it was also in the open position. The main

Figure 6

Right engine cowling external surface – burnt area on lower aft corner

Figure 7

Right engine cowling inner surface – same burnt area visible on lower aft corner, and indentations near forward edge pilot-controllable shutoff valve, which was also burnt and had separated from the fuel lines, was in an almost fully closed position.

The fuel collector tank and surrounding pipework were severely fire damaged and it was not possible to determine if they had been exposed to an in-flight fire before the post-impact fire.

Electrical system

The aircraft was equipped with a 24V electrical system. The battery cells had suffered fire damage and all the fuses and electrical wiring in the fuselage and engine bay were so severely burnt during the post-impact fire that a meaningful electrical failure analysis could not be carried out. SSR radar returns can only be received when an aircraft's transponder is powered; therefore, the last SSR radar return indicated that the aircraft still had some electrical power when it was within 0.75 nm of the accident site.

Ventilation system

The aircraft's ventilation system takes cold air from the engine air-intake and directs it via a series of ducts and pipes to two 'punkah louvres' on the instrument panel and two windscreen spray nozzles mounted below the windscreen (Figure 8). For the hot air supply, separate air inlet ducts, mounted on both sides of the engine, direct

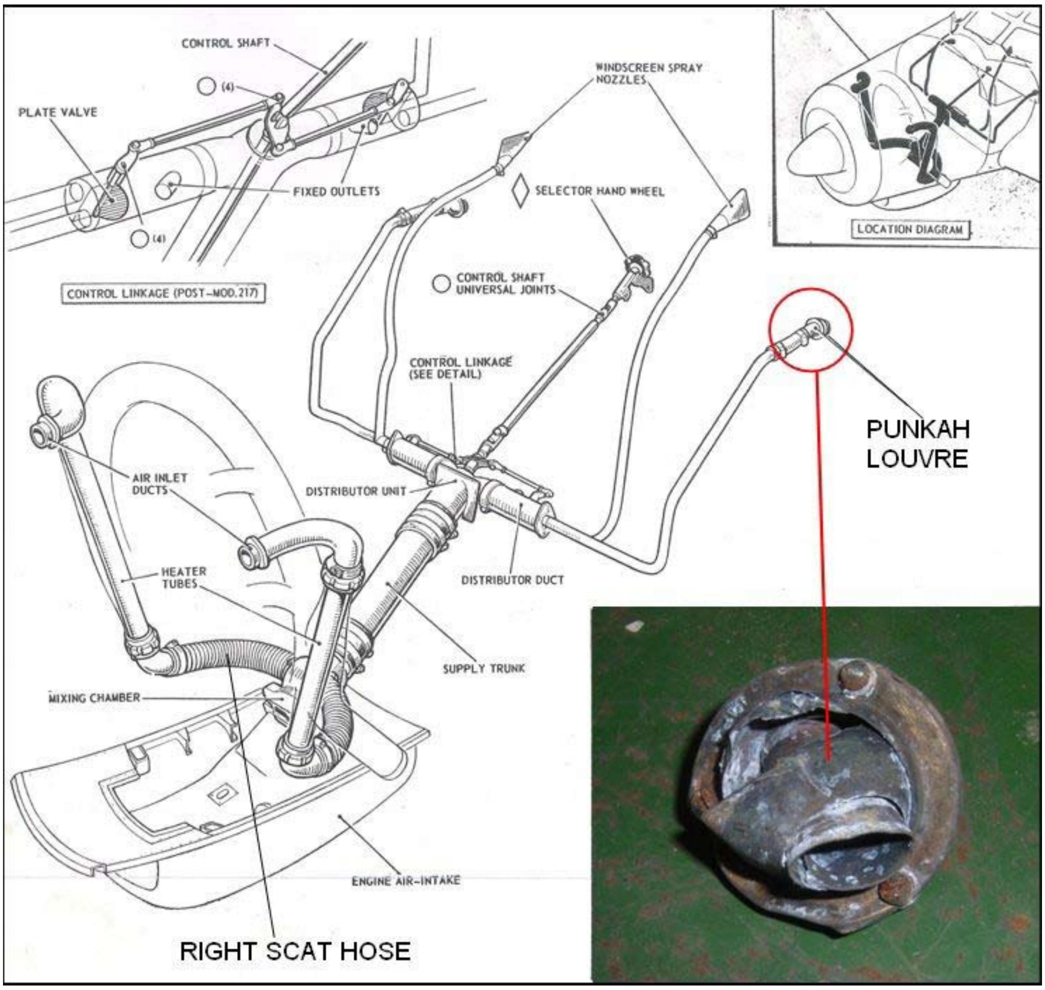

Figure 8

Ventilation system diagram showing location of right SCAT hose and punkah louvres.
The burnt punkah louvre shown in the photograph was either from the left or right side of the instrument panel.

air through heater tubes and SCAT hoses[2] to a mixing chamber where it is mixed with cold air and directed through the same pipework to the punkah louvres and windscreen spray nozzles.

The majority of the components of the ventilation system, including the SCAT hoses, had suffered from severe fire damage and it was not possible to determine if they had been exposed to an in-flight fire before the post-impact fire. However, one of the punkha louvres (shown in Figure 8) was found on the ground, well clear of the main wreckage and surrounded by unburnt crops. Despite this, it exhibited evidence of having been exposed to high temperature and possibly fire. The right SCAT hose, between the heater tube and mixing chamber, passed close to the aft lower corner of the right engine cowling, which had exhibited evidence of in-flight fire.

Pilot restraint system

The pilot restraint system on the aircraft consisted of a four-point harness, with the lap belts secured to the seat and the shoulder harness secured to a cable within an inertial reel attached to the rear cockpit structure. The harness buckle, with its four points still attached, and remains of the harness, were found severely burnt next to the pilot's body. Nearby was a small section of burnt seat material with a lap belt fitting attached. The pilot's shoulder harness inertial reel was still attached to the aircraft structure, and its cable end was attached to a small piece of burnt shoulder harness.

The canopy jettison handle was found in the wire-locked closed position.

Footnote

2 SCAT hose is a type of thin-walled flexible hose made of plastic reinforced with wire.

Engine examination

The Alvis Leonides 503/6A is a piston engine with nine cylinders mounted radially. The No 1 cylinder is located at the top ('12 o'clock') position, and the No 5 and No 6 cylinders are located at the bottom, either side of the 6 o'clock position. The No 6 cylinder contains the master rod (shown in Figure 9). This is the strongest connecting rod, and the other eight connecting rods, called 'articulating rods', are connected to the master rod. The crankshaft passes through the centre of the master rod which contains a plain bearing. The master rod and the eight articulating rods (the connecting rods) are connected to their respective pistons via a gudgeon pin (Figure 9). Each gudgeon pin is free to rotate within the bores of the piston bosses.

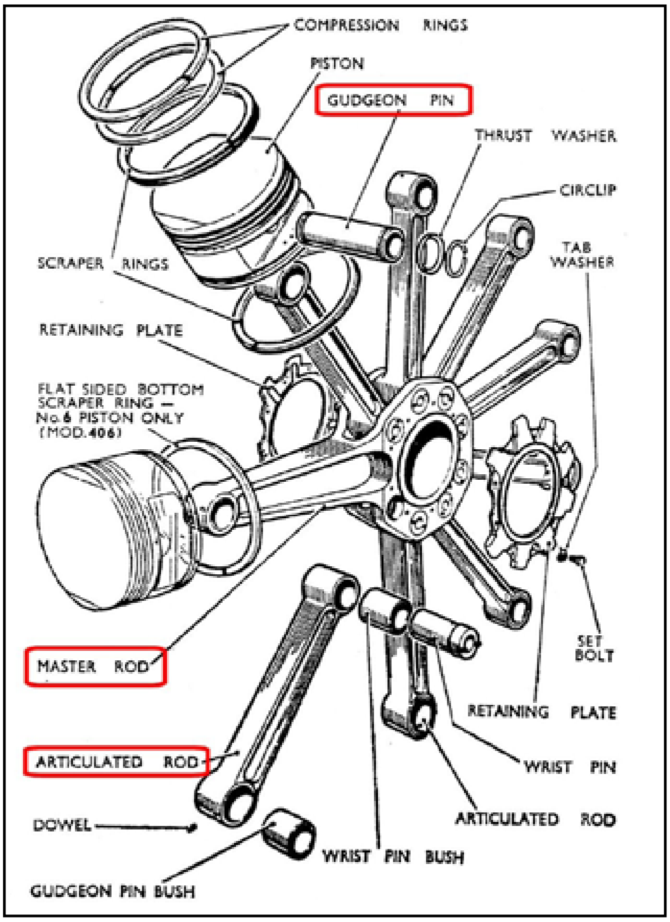

Figure 9

Connecting rod and piston arrangement in Alvis Leonides 503/6A radial engine

The engine had suffered from significant fire damage, and its No 5, 6 and 7 cylinders had detached (Figure 10). The cylinders had detached as a result of failure of some cylinder retaining bolts and the failure of engine casing material around the remaining cylinder retaining bolts. The master rod and all the articulating rods had failed near their roots. The section of master rod between the piston and root was missing. All the cylinders had damage of varying degrees to their skirt, consistent with impact from the connecting rods. The gudgeon pin from the No 6 piston, to which the master rod had been connected, had 'sheared' at its centre (Figure 11). The No 6 piston had suffered from multiple impact damage to its base and sidewalls, consistent with a flailing master rod. The No 5 and No 7 pistons were missing. Multiple sections of articulating rod material were also missing. The gudgeon pins from the remaining pistons (No 1, 2, 3, 4, 8, 9) were intact and still connected to sections of articulating rod of varying lengths. None of the pistons had seized in their cylinders, and although some articulating rod small end bearings were stiff, this could have been a consequence of the significant mud, debris and fire damage associated with the impact.

Figure 10

Front face of engine, positioned upside down, showing missing No 5, 6 and 7 cylinders (when the engine is installed, the No 1 cylinder sits at the '12 o'clock' position)

Figure 11

View inside No 6 cylinder showing damaged cylinder skirt, damaged piston and 'sheared' gudgeon pin

The engine was stripped and no other mechanical failures of significance were found. There was evidence that the crankshaft journal had been overheated, but it had not seized, and the crankshaft bearings were in satisfactory condition.

Metallurgical examination of engine components

The pistons and the remains of the master rod and articulating rods were examined by a metallurgist. The fracture surfaces of the master rod and of each of the articulating rod ends had been almost completely destroyed by post-failure mechanical damage (Figure 12). Areas which were not damaged exhibited dull, fibrous fractures and angled fracture surfaces which were characteristic of overload failure.

Figure 12
Remains of master rod and articulating rod ends

During the examination the sheared halves of the gudgeon pin from the No 6 piston were pushed inwards to their normal position (Figure 13). This revealed that between 5 and 20 mm of the pin was missing from its centre. The two portions of the pin (section A and section B) were removed from the piston and cleaned for more detailed examination and a close-up view of the two sections is shown in Figure 14. The fracture surface of section A was helical and had suffered from some post-failure mechanical damage. In the undamaged areas, the majority of the circumferential fracture surface was angled at 45° to the pin surface, which is characteristic of overload failure. However, the longitudinal fracture surface (annotated in Figure 14) was relatively flat and extended along a crack line to the end of the pin. This crack line also extended into the other half of the pin, section B.

The two sections of pin were opened along the crack line to permit examination with a Scanning Electron Microscope (SEM) and Figure 15 shows an SEM image of the longitudinal fracture surface of section A. There was clear evidence of beachmarks, which are associated with metal fatigue, and these indicated the origin of the fatigue crack. A higher magnification image of this area revealed striations, which are another characteristic of metal fatigue. SEM examination of the crack in section B also revealed beachmarks and striations. The beachmarks on the longitudinal fracture surface of section A were counted several times, on the sample and from photographs. The number of beachmarks observed was in the range of 30 to 35. Beachmarks relate to a major load cycle or a change in load cycle. The metallurgist indicated that for engine components, beachmarks usually relate to engine stop/start cycles, and therefore it was likely that at least 30 to 35 engine stop/starts had occurred during the life of the longitudinal fatigue crack.

A more detailed SEM examination of the fatigue crack origin revealed that it had initiated at a corrosion pit approximately 150 µm deep. There were a number of other corrosion pits on the inner surface of the pin in the vicinity of the fatigue crack origin; some of these are highlighted in Figure 15. Corrosion pits act as stress raisers and are a common initiation point for fatigue. The crack growth had not been caused by Stress Corrosion Cracking (SSC), as the striations were trans-granular, whereas SSC generates inter-granular failures.

The gudgeon pins from the remaining pistons (No 1, 2, 3, 4, 8 and 9) were removed, cleaned, and

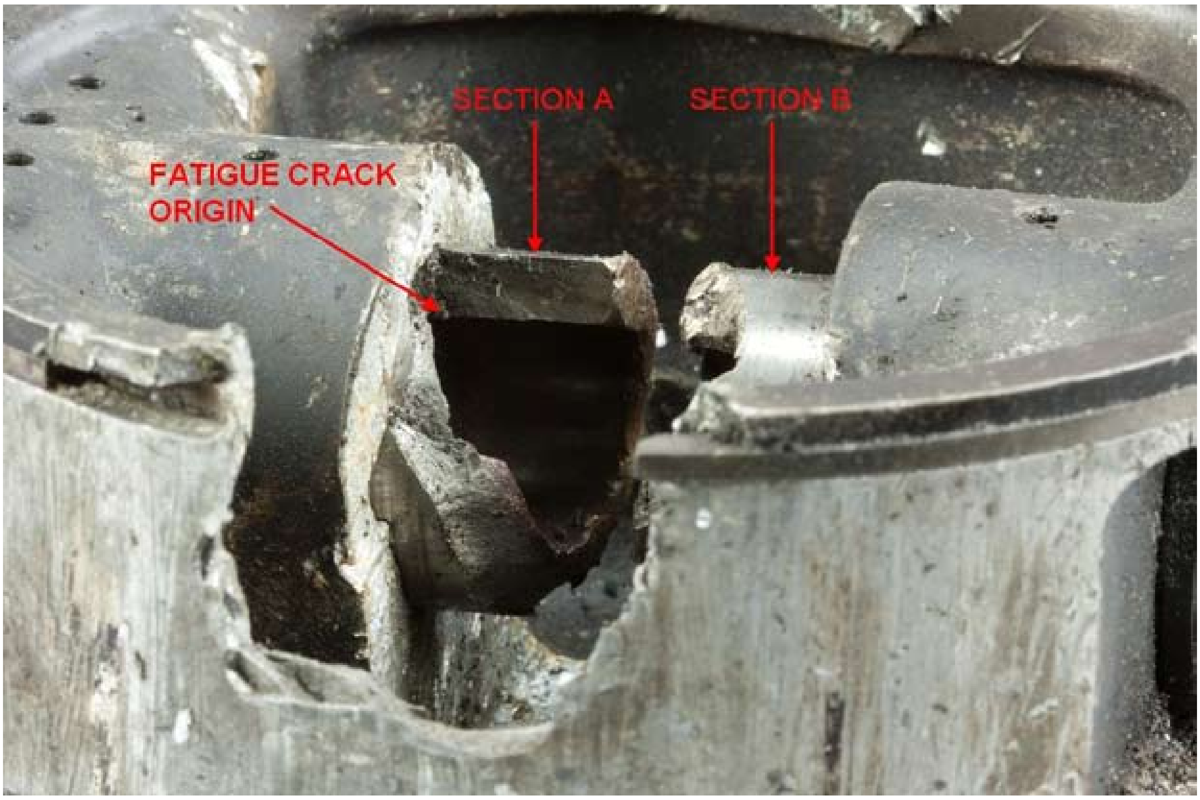

Figure 13

No 6 piston. Both portions of the failed gudgeon pin have been pushed back into their original seating position (compare to Figure 11 for their post-failure position)

Figure 14

Both portions of No 6 gudgeon pin, showing fatigue crack origin

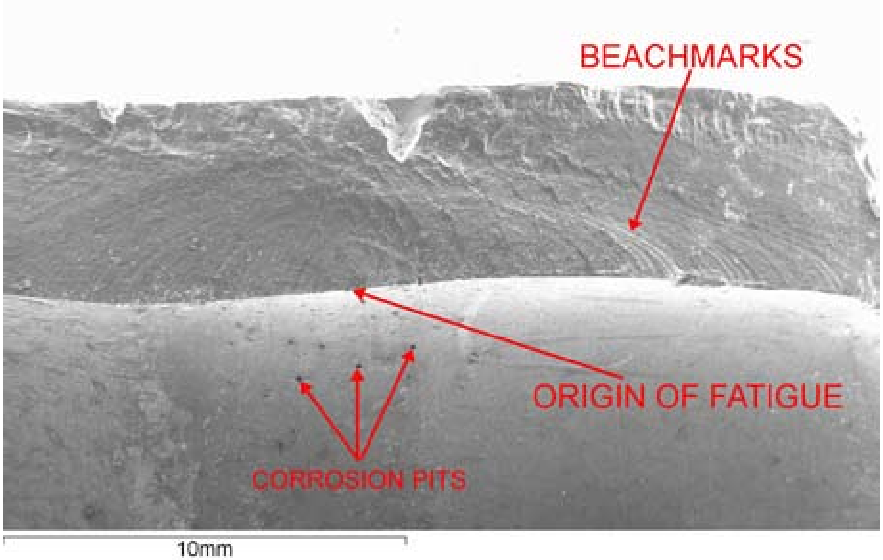

Figure 15

Scanning Electron Microscope (SEM) image of longitudinal fracture surface from section A, showing fatigue crack origin, beachmarks and corrosion pits

inspected with fluorescent dye penetrant to determine if any fatigue cracking was present. There were no indications of cracks on the external surfaces or the internal surfaces of the pins, although some dye was retained on the internal surfaces, which was indicative of general surface corrosion. The gudgeon pins were then sectioned longitudinally to permit a more detailed examination of their inner surfaces. All the pins exhibited some degree of internal surface corrosion, with pins No 4 and 8 having the most severe corrosion (see Figure 16 for a section of the No 8 pin). Pins No 1, 2, 3 and 9 showed a similar degree of corrosion. All the pins, except No 1, contained some corrosion pits. These pits were not visible with the naked eye, but became visible with at least x10 magnification. Surface roughness associated with the general corrosion could be felt by finger touch, but the corrosion pits could not be identified by touch.

Prior to removing the gudgeon pins from the pistons the metallurgist tried to measure the clearance between the pin and the piston bores. The manufacturer's tolerance for this clearance was between 0 and 0.015 mm for a new installation and up to 0.05 mm for a worn installation. Measuring this clearance did not prove possible due to the build-up of sludge, oil and debris – most of which would have been as a consequence of the post-impact fire and break-up. Some of the gudgeon pins were free to rotate within the piston bores but others were

Figure 16

No 8 gudgeon pin sectioned, showing corrosion on internal surface too stiff to rotate. However, this stiffness would not be abnormal at room temperature, as the assembly procedure calls for the piston to be heated prior to insertion of the pin. The pins were removed from the pistons and their diameter measured after cleaning with solvent in an ultrasonic bath. Apart from three pins, which had measured diameters at their mid-section of 28.03 mm, 28.04 mm and 28.04 mm, the remaining pins had diameters greater than the minimum 28.05 mm worn limit (at both ends and at their mid-sections). The piston bore diameters were also measured after cleaning, and then the pin-to-bore clearance was calculated. Apart from piston No 2, which had a calculated clearance of 0.14 mm, the remaining calculated clearances were all less than the 0.05 mm worn limit.

The metallurgist concluded in his report that fatigue, initiating from corrosion pitting on the internal surface of the No 6 gudgeon pin, was the cause of the pin failure. However, for the fatigue crack to propagate, the direction of the applied cyclical loads to the pin would have had to remain constant. The gudgeon pin is normally free to rotate within the piston bores, so some other factor had caused the pin to stop rotating in order to allow the fatigue crack to propagate.

Engine history

The engine logbook listed the engine's date of manufacture as 1 May 1964 but records obtained from a retired Alvis engineer revealed that the actual date of manufacture was 24 August 1954. These records also showed that between 1954 and 1964 the engine was overhauled three times and repaired once, with the last overhaul completed on 4 May 1964. The engine's total run time (TRT) at this time was 1,545 hours. The engine logbook stated that as of 10 April 1969 the engine had accrued 134 hours in RAF service, so these were probably the hours since the last overhaul in 1964.

The first logged hours under civilian use were recorded on 17 April 1969. In June 1972 the CAA decided that the engine hours under RAF service should be counted double towards the 'Time Between Overhauls' (TBO). Therefore, an additional 134 hours were added in the logbook. Between 4 May 1964 and 8 July 2009, the day of the accident, the engine was not overhauled. The last entry in the engine logbook was on 29 June 2009 which listed the logged time as 539.6 hours[3]. The subsequent flight was the accident flight which lasted about 12 minutes, so the engine logbook hours at the time of the accident would have been 539.8 hours. However, detailed examination of the logbook revealed an arithmetic error on 17 April 1984 whereby 100 hours were lost. So, the actual logged time at the time of the accident was 639.8 hours: the TBO for this engine was 800 hours and there was no calendar limit. The hours in the logbook and the TBO relate to engine flying hours. There is no requirement to log engine ground run time.

Examination of another Alvis Leonides engine

The owner of G-AWVF had bought a number of spare engine parts from the engine manufacturer when the company ceased production during the late 1980s. One of the items he purchased was an Alvis Leonides engine Mk 12701[4] that had been fitted to a twin-engine Pembroke. This engine had failed during a flight from Wildenrath, Germany, at some time during the 1970s. The aircraft returned safely to land so no details of the incident could be found. This engine was missing two cylinders, No 6 and No 7, and according to the owner of G-AWVF, these cylinders detached in flight and were never recovered. The internal damage

Footnote

[3] This figure includes the 134 hours under RAF service counted twice.

[4] The Mk 12701 is very similar to the 503/6A engine fitted to G-AWVF, which has a military designation of Mk 12601.

to this engine was very similar to the damage seen on G-AWVF's engine. The master rod and all the articulating rods had failed near their root. Without the No 6 cylinder available to examine, it was not possible to determine if the cause of failure had been the same as on G-AWVF.

Maintenance history

At the time of the accident the airframe had accumulated 4,100 flying hours, of which 3,735 hours were under RAF service between 1955 and 1969.

The aircraft was maintained in accordance with the CAA's Light Aircraft Maintenance Schedule (LAMS). The aircraft's last annual maintenance inspection for its permit renewal was completed on 14 August 2008. During this maintenance inspection a surveyor from the CAA carried out a survey of G-AWVF and no anomalies were noted in the Aircraft Survey Report. In May 2009 the owner had started carrying out some of the checks as part of the aircraft's annual inspection to renew the aircraft's permit before it expired on 13 August 2009.

In February 2005 the aircraft had suffered a propeller strike when the aircraft nosed over during taxi at Middle Wallop Airfield. The propeller was damaged and overhauled. In accordance with the instructions in the maintenance manual for propeller strikes, the engine's reduction gearbox was removed for inspection. No damage to the gearbox was found, but as a precautionary measure the gearbox was replaced with one from a spare engine which had accrued 308 hours since overhaul. While the gearbox was removed, a borescope inspection of the engine was carried out, with no anomalies noted.

A cylinder compression check was carried out on the engine on 6 May 2009. The compression readings of all the cylinders were between 75 and 79 psi which were considered 'good' by the Licensed Aircraft Engineer.

Aircraft utilisation history

Since leaving RAF service in 1969, the aircraft had logged 365 flying hours. This equates to an average flying rate of 9.1 hours per year, over a period of 40 years. In the year leading up to the accident the aircraft had logged 11 hours.

Between August 1977 and April 1979, a period of 20 months, there were no flights recorded in the airframe logbook. Between September 1984 and February 1988, a period of almost 4 years, there were no flights recorded in the logbook, although an un-dated note in the logbook during this period added 30 hours to the total time '*due unknown records*'. In both 1995 and 1996 the aircraft logged 4 hours, and in 1997 only 2.5 hours. The aircraft's monthly utilisation rate between January 2000 and the date of the accident is shown in Figure 17. Between June 2001 and July 2003 the aircraft did not fly for 23 months. However, an entry in the engine logbook for this period stated:

> *'Maintenance Statement: This is to confirm that this engine has been run monthly during long term storage.'*

The owner stated that he also squirted inhibiting oil into the cylinders via the spark plug holes.

From Figure 17 it can be seen that, in the last six years, the aircraft usually flew between 0.5 hours and 2 hours each month, but did not fly during the winter months. The last extended period of no flight was between 22 November 2008 and 15 March 2009. Between 15 March 2009 and the accident date, the aircraft carried out 17 flights. Seven of these flights were 10 minutes in duration, and three of these 10-minute flights included 5 minutes of aerobatics.

During the winter months between 22 November 2008 and 15 March 2009, the aircraft was stored in a hangar at a private airstrip in Bossington, Hampshire. This was close to where the accident pilot lived, and he was known to go to the airstrip to carry out engine ground runs during the winter months. The pilot's farming director recalled two or three occasions during the winter when he assisted in removing the aircraft from the hangar for an engine run and the farming director's foreman was also involved on three separate occasions in running up the aircraft, Neither of them was aware if the aircraft had flown after they had provided this assistance, so some of this assistance might have been provided in November or March when the aircraft had flown. It was, therefore, not possible to establish the number of occasions that the engine had been ground-run during the three months that it had not flown.

Engine manufacturer's recommended procedures for engine inhibition and storage

The '*Operation, Maintenance and Overhaul Handbook*', for Leonides 500 and 510 series engines, contains a chapter on '*Inhibition for Storage*' which recommends that for 'short term' storage of an engine that can be run, where 'short term' is defined as a storage period of less than one month, '*the engine should be run at least once in every seven days*.' The procedure involves a stepped increase in engine rpm, resulting in a final run at 2,600 rpm until an oil inlet temperature of approximately 75°C is obtained. The handbook states that if it is not practicable to run the engine then '*it must be inhibited and externally protected*.' For 'long

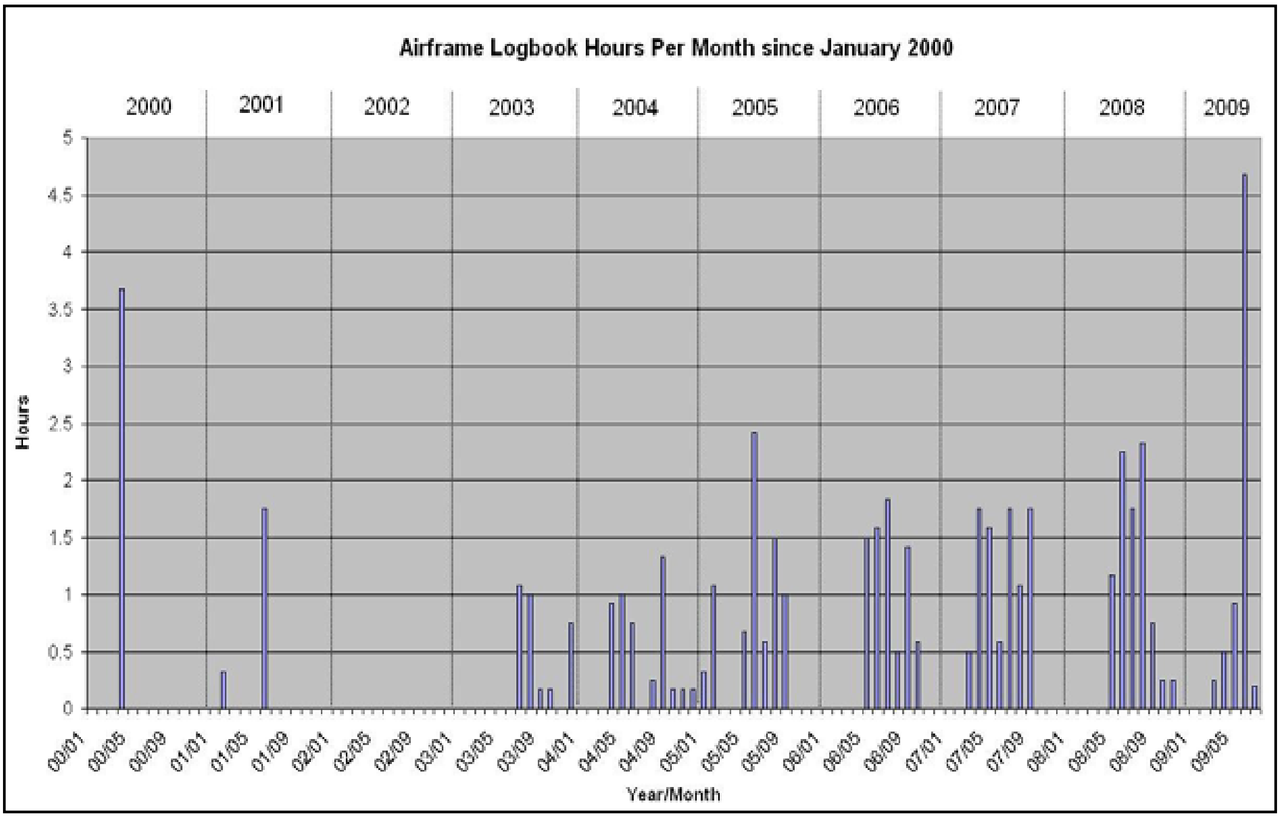

Figure 17

G-AWVF airframe logbook hours per month between January 2000 and July 2009 term' storage, defined as a period when the engine is expected to be out of service for one month or more, the handbook states that the engine '*should be fully inhibited as detailed in the following paragraphs*.' The ensuing procedure includes running the engine, draining all the oil and replacing it with storage oil, and then running the engine again. A detailed inhibiting procedure of each engine cylinder and its components is then described.

Hydraulic lock

Hydraulic lock is a phenomenon that can occur on piston engines that have downward-pointing cylinders, that is, cylinders orientated such that the piston is moving down during the compression stroke. All radial engines have some cylinders that are pointing downwards and are, therefore, susceptible to hydraulic lock. After a radial engine has been shut down for a period, oil may drain into the combustion chambers of the lower cylinders or accumulate in the lower intake pipes, ready to be drawn into the cylinders when the engine starts. As the piston approaches top dead centre (TDC) of the compression stroke (both valves are closed at this point), the oil, being incompressible, can stop the piston movement (Figure 18). If the crankshaft continues to rotate then damage to the engine will occur – this could result in a cylinder being blown out, a bent or fractured connecting rod, or damage to the gudgeon pin. This phenomenon is known as 'hydraulic lock'. A partial hydraulic lock can also occur when liquid is inside the combustion chamber, but is not sufficient to fill the space between the cylinder head and the piston when it is at TDC. In this situation, the air gap is still reduced and, therefore, the pressure rise within the cylinder can still be sufficient to stop the piston or to result in damage if the piston is forced through TDC during engine start. Damage resulting from a partial hydraulic lock can be more serious as it could go undetected during the engine start, and then result in failure at some later time in flight.

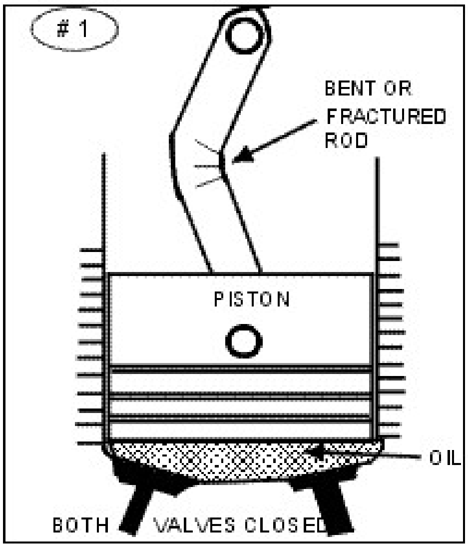

Figure 18

Diagram showing the possible effect of hydraulic lock on a piston connecting rod

To avoid hydraulic lock during engine start, the propeller should be turned through a few revolutions by hand in the direction of rotation (with the ignition switches off). If any excessive resistance is felt while pulling the propeller through a compression stroke, then liquid is present in one of the cylinders, and the propeller should not be pulled through any further.

The Provost T1 Pilot's Notes states:

> *'Unless the engine has been run during the preceding hour, check for hydraulic locking by having the propeller turned by hand through four revolutions.'*

The Pilot's Notes do not state what to do if hydraulic lock is encountered.

The RAF Ground Handling Notes for the Pembroke, which uses a similar Alvis Leonides engine to the Provost, states:

> *'All engines which have NOT been running during the 30 minutes preceeding the intended start, are to have the following 'hydraulic' check carried out:'*

After ensuring that the magneto switches are off the procedure states:

> *'With the right hand cupped about the lower descending propeller blade tip, advance across and forward of the propeller disc, pulling the propeller blade until the right hand releases naturally from the blade. Repeat this exercise until 12 blade tips have passed the lower vertical point. Any resistance to rotation of the propeller is to be reported to the propulsion trade manager. The resistance will indicate excess fluid in the lower cylinders and, in this event, the sparking plugs must be removed from the cylinders and the propeller turned through several revolutions to drain off the fluid.'*

With a three-bladed propeller, turning the propeller through '12 blades' ensures that the engine will have been turned through at least four complete revolutions[5]. The engine manufacturer's '*Operation, Maintenance and Overhaul Handbook*', for Leonides 500 and 510 series engines contains the following similar procedure:

> *'Anti-hydraulicing procedure. To prevent the possibility of a hydraulic lock occurring when an engine is started ensure that the ignition switches are OFF then turn the propeller through twelve blades. If undue resistance to movement is experienced during the above operation or after installation, after storage or when an installed engine has not been run for seven days or more, proceed with either of the two following procedures as applicable.'*

The two procedures which follow the above paragraph both involve removing the spark plugs from the No 4, 5 and 6 cylinders and turning the engine through several revolutions in order to expel the excess fluid.

The owner of G-AWVF, the accident pilot, and the third pilot who was permitted to fly the aircraft, employed different procedures to the aforementioned procedures when they encountered hydraulic lock. These included turning the propeller forward through at least 27 blades and, if any undue resistance was encountered, the propeller would be turned back in order to clear any hydraulic lock. The theory behind this procedure is that, by turning the propeller back, the intake and exhaust ports are opened and the fluid is allowed to drain into these ports. This procedure avoids the more time-consuming and work-intensive procedure of removing the spark plugs to drain the fluid.

Anecdotal evidence suggests that the use of this procedure may be widespread, but it is contrary to the advice from the engine manufacturer, and it has a potential problem. When the propeller is turned backwards, the piston which has encountered the hydraulic lock moves up (assuming it is a 'downward pointing' cylinder), and then the first valve to open is the intake valve. As the propeller continues to be

Footnote

[5] The engine has a 0.625 to 1 reduction gearbox, so four complete revolutions of the propeller actually equates to 6.4 revolutions of the engine.

rotated backwards the piston moves down and will help to force any liquid out through the intake port. As the propeller continues to rotate, the exhaust valve will open and some liquid might also drain into the exhaust port. Oil in the exhaust port is safe and will either drain out through drain holes in the exhaust, or result in smoke being produced during engine start. However, oil in the intake port is not safe, as it will not drain away and is likely to be sucked back into the cylinder during engine start, potentially causing damage as a consequence of hydraulic lock.

The US Air Force Powerplant Maintenance Manual (AFM 52-12, May 1953), in a section on hydraulic lock involving radial engines, states:

> *'Never attempt to clear the hydraulic lock by pulling the propeller through in the direction opposite to normal rotation, since this tends to inject the liquid from the cylinder into the intake pipe with the possibility of a complete or partial lock occurring on the subsequent start.'*

The owner of G-AWVF could not recall the last time he had encountered hydraulic lock, but when he had experienced it, he said he turned the propeller backwards and then forwards until it cleared. The third pilot who flew G-AWVF reported that he sometimes encountered undue resistance and that when he encountered this resistance he would "work it out" by turning the propeller backward and forward.

History of in-flight fires on Alvis Leonides series engines

Records obtained from a retired Alvis engineer listed the histories of 390 Provost aircraft, 59 Pembroke aircraft, 48 Sea Prince aircraft, 25 Prince aircraft, and 4 President aircraft, all of which were fitted with Alvis Leonides engines of similar types to the one fitted to the Provost. Out of the 390 Provost aircraft, one aircraft (WV423[6]) was listed as '*Engine failure. Fire destroyed South Cerney March 56*'. Another aircraft, WV507, was listed as '*Engine fire, crashlanded Crewe October 54*' and aircraft XF687 was listed as '*Fire in flt. Crashed on forced ldg. Ingoldsby July 58*'. Four additional Provost aircraft were listed as having crashed after the '*engine cut*'. Further details on these accidents could not be found. Out of the 59 Pembroke aircraft there were three aircraft which were listed as '*Engine fire*. *Damaged on landing.*'. No engine fires were listed for any of the Sea Prince, Prince or President aircraft.

Aircraft operating in the UK with Alvis Leonides series engines

Excluding G-AWVF, in January 2010 there were six remaining Provost aircraft on the UK G-register. Of these six aircraft only three have a valid Permit to Fly (G-AWPH, G-KAPW and G-MOOS). The other three aircraft are, or had been, in the process of being rebuilt or restored. There are two Pembroke aircraft on the G-register, one of which has a valid Permit to Fly. There are three Sea Prince aircraft on the G-register, none of which have a valid Permit to Fly – two are static display aircraft and one is being restored for flight. The last remaining aircraft on the G-register that has an Alvis Leonides engine is a Scottish Aviation Twin Pioneer, but its Certificate of Airworthiness has expired. In summary, there are currently four aircraft on the UK G-register with a valid Permit to Fly that have Alvis Leonides engines fitted (this accounts for five engines in total as there are two fitted to the Pembroke).

Footnote

[6] This is a military aircraft registration.

Anecdotal evidence suggests that there are two Provost aircraft operating in New Zealand and at least one in the USA.

Safety Action taken by the CAA

When the evidence of a fatigue failure of the No 6 gudgeon pin was found, the AAIB and the CAA discussed interim safety action while the investigation continued into the cause of the fatigue crack. The primary concern was to raise awareness of the findings to other operators of Alvis Leonides series engines. As a result, on 22 September 2009, the CAA published an 'Airworthiness Communication' (AIRCOM 2009/11) to '*Owners and Operators of Percival P56 Provost, Percival P50 Prince (and Sea Prince), Percival P66 Pembroke and Scottish Aviation Twin Pioneer aircraft.*' It highlighted the preliminary findings of the investigation and made the following two recommendations:

> *'3.1 Corrosion pitting may initiate on internal engine components for a number of reasons, but low utilisation operations can make components particularly susceptible to deterioration of this nature. It is therefore important that owners/operators of low utilisation engines in particular, take into account the manufacturer's recommendations for engine protection, including any applicable recommendations for storage and inhibiting.*
>
> *3.2 CAA will liase with AAIB as the investigation progresses and issue further information to owners/operators as appropriate. In the meantime, and in light of the apparent consequences of corrosion pitting in this particular case, owners/operators may wish to review the current calendar time since last overhaul and the maintenance history of engines fitted to their aircraft. This should also include any protection arrangements made for these engines during any storage period. Refer to the relevant engine Operation, Maintenance and Overhaul Handbook for the protective measures recommended by the manufacturer for both short and long term storage.'*

The CAA also plans to review its policy on parachute requirements for certain ex-military aircraft types. In the meantime, an AIRCOM will remind aircraft owners of the guidance in CAP 632 which recommends that parachutes should be worn in ex-military aircraft.

Analysis

Probable sequence of events

There were four separate pieces of evidence which showed that the aircraft had suffered from an in-flight fire prior to impact: (1) burnt pieces of wreckage at the accident site were surrounded by unburnt crops; (2) the right engine cowling, which had separated from the aircraft more than a mile south of the accident site, exhibited burn marks; (3) many witnesses reported seeing smoke and flames from the aircraft while it was in flight; and (4) the post-mortem found evidence that the pilot had inhaled smoke. The evidence also suggested that the fire had started in the engine bay and progressed aft into the cockpit.

The time between the fire becoming evident to the pilot and the engine cowlings detaching is not known. However, shortly after the engine cowlings detached, the pilot tried to declare a MAYDAY but his radio transmission was blocked by another transmission.

The main fuel shutoff valve was found in the near fully closed position, which indicated that the pilot probably tried to shut the fuel off the correct action to take following an engine fire. It was not possible to establish an accurate final flight profile from the radar data, but the data indicated that an approximately straight flight path was maintained following the "MAYDAY" transmission and then the aircraft initially slowed, possibly as a consequence of a power reduction, before accelerating just as radar contact was lost. The post-mortem evidence indicated that the pilot would have probably lost consciousness prior to impact, and the ensuing 35° to 40° nose-down impact was consistent with the dive angle obtained during an investigation flight when power was reduced to idle and the control column was released.

The damage to the engine, consisting of a failure of the master rod and all the articulating rods, indicated that a serious mechanical engine failure had occurred in flight. It is probable that the ground impact would have caused some damage to a rotating engine, but it is unlikely that it would have caused the failure of all connecting rods. The indentations on the inside of the right engine cowling were in line with the No 7 cylinder head, indicating that the cylinder head had struck the cowling or the cowling had struck the cylinder head. The No 7 cylinder had separated from the engine and had been thrown 40 m clear of the impact site, which suggested that it may have already been partially detached from the engine prior to impact (cylinders No 5 and 6 were close to the impact site). The engine cowling latches had failed in overload, so the overall evidence indicated that the right cowling probably began to detach as a result of it being struck by the No 7 cylinder, which had been blown out as a result of the mechanical engine failure.

The No 6 gudgeon pin was found to have failed due to a fatigue crack which had been propagating over the previous 30 to 35 engine stop/start cycles. Once this pin failed a catastrophic mechanical engine failure would have ensued. Based on an examination of all the evidence the following probable sequence of events was constructed:

1. The No 6 piston gudgeon pin failed in overload after a fatigue crack reached a critical length.
2. The master rod, no longer retained at the piston end, started to flail, damaging the piston and cylinder skirt.
3. The loss of rigidity of the master rod resulted in excessive loading on the articulating rods, causing them to fail.
4. The master rod impacted into the No 7 cylinder, causing the cylinder partially to separate from the engine and strike the right engine cowling.
5. The No 7 cylinder separation resulted in disconnection of the cylinder's inlet and exhaust pipes.
6. A mixture of fuel and air was released from the disconnected inlet pipe and ignited (possibly due to its proximity to the hot exhaust pipe).
7. The burning fuel travelled aft towards the firewall and burnt the aft lower corner of the right engine cowling.
8. The force of the airstream eventually caused the right engine cowling to detach completely and take the upper and left cowlings with it.

9. The fire in the engine bay probably burnt through the right SCAT hose that forms part of the ventilation system, permitting the fire to enter the cockpit via the punkha louvres. It is also possible that other entry points through the firewall were compromised, permitting the fire to enter the cockpit.

10. It is probable that the pilot lost consciousness due to the build-up of toxic fumes, and released the control stick.

11. The aircraft entered a steep dive due to the loss of engine power and the control stick being released, and then hit the ground.

Probable cause of gudgeon pin fatigue crack

The gudgeon pin had failed due to fatigue, so the investigation considered what might have caused the fatigue crack to initiate. The origin of the fatigue crack was located at a corrosion pit and corrosion pits act as stress raisers which reduce the fatigue life of a component. The longitudinal fatigue crack had propagated along the 'bottom' of the pin, which is the likely direction for such a crack to propagate. The gudgeon pin is a hollow tube that experiences compressive loads perpendicular to its longitudinal axis. Therefore, the inner surfaces at the top and bottom positions would experience cyclic tensile stress during operation, and are therefore the most likely areas to experience fatigue. However, for the fatigue crack to propagate, the direction of the applied cyclical loads would have had to remain constant, which meant that the gudgeon pin would have needed to stop rotating within its piston bores.

The clearance between the pin and bores is small (less than 0.05 mm), so it is possible that, over time, a build-up of debris inside the bore had constrained the pin's rotation. Some of the pistons examined had gudgeon pins that were more difficult to rotate than others as a result of a build-up of debris, but some of this debris could have been introduced during the impact and fire. The clearance between the pins and bores had not been checked since 1964, so it cannot be ruled out that a build-up of debris was a factor in constraining the pin. However, anecdotal evidence from engineers who have experience of dismantling historic radial engines, revealed that although 'fully floating' gudgeon pins may be designed to rotate, in practice many (up to 30% in any given engine) do not, despite there being no faults apparent (ie clearances are within limits, no damage, no excessive sludge or corrosion, and the pin slides and rotates freely). It is thought that, perhaps, the pin finds its own 'niche' due to tiny imperfections on its surface and once it stops rotating for a few cycles, microscopic build-ups reinforce this tendency. In normal circumstances, the fact that the pin has stopped rotating does not appear to result in any adverse effects.

An important factor that helped to initiate the fatigue crack was the presence of corrosion pits on the inner surface of the gudgeon pin. There was corrosion on the inner surface of the failed gudgeon pin and on most of the other gudgeon pins. Corrosion is generally caused by the presence of moisture. Frequent use of an engine usually results in any moisture build-up evaporating during operation, which helps to prevent corrosion from setting in. However, G-AWVF's history reveals long periods of inactivity, which probably resulted in the build-up of corrosion inside the gudgeon pins. During one long period of inactivity, there was a note in the logbook indicating that the engine had been run monthly. However, the engine manufacturer recommended that if the engine was not operated within a seven-day period, then it should be inhibited. It further recommended that an engine be inhibited if it was unlikely to be used for a period of more than one month. There is no evidence from the engine logbooks to indicate that the engine had ever been inhibited.

The presence of corrosion pits on the inner surface of the gudgeon pin would have made it more susceptible to a fatigue crack. It is possible that the presence of these pits alone, combined with normal cyclical loads, caused the crack to initiate. However, it is more likely that a high-load event, such as a partial or full hydraulic lock, caused the crack to initiate and the corrosion pit helped to site it. In discussing this investigation with a number of engineers experienced on working on historic piston engines, the comment was made that gudgeon pin failures for reasons other than hydraulic lock are extremely rare. Some engineers had seen gudgeon pins with a similar or worse degree of corrosion than on the pins found on G-AWVF, and these had not failed or suffered cracks.

If a high load or overload event triggered the fatigue crack, then it is likely to have occurred some 30 to 35 stop/start cycles prior the accident and therefore no earlier than June 2008. The aircraft suffered from a propeller ground strike in February 2005 and therefore it is unlikely, by the stop/start cycles, that this event triggered the onset of the fatigue crack. However, a partial or full hydraulic lock event during start-up was a possibility. The pilots of G-AWVF had not been employing the engine manufacturer's recommended practice of removing the spark plugs to clear a suspected hydraulic lock and their practice of turning the propeller back to clear the lock could have caused oil to be re-introduced into the cylinder during start, and cause hydraulic lock damage. It is also possible that, in turning the propeller forwards, against a high resistance caused by fluid in the compression chamber, a sufficiently high load was applied to the gudgeon pin to cause the fatigue crack to initiate.

The engine had been in service for 45 years without an overhaul so there had not been an opportunity to check for corrosion or the build-up of debris within the piston bores. The TBO was 800 hours without a calendar time limit, and the original engine designers would probably not have envisaged an engine being used for 45 years without exceeding 800 hours. The piston engines built by Lycoming and Teledyne Continental were also originally manufactured with an 'hours-based' TBO and no calendar limit. However, both manufacturers later introduced a recommended 12-year calendar limit between overhauls. Introducing a similar calendar limit for the Alvis Leonides series engines would reduce the likelihood of engine failures caused by factors associated with a lack of use. Therefore, in addition to the safety actions (noted earlier) by the CAA, the following three Safety Recommendations are made:

Safety Recommendation 2010-029

It is recommended that the Civil Aviation Authority consider implementing calendar time limits between overhauls for Alvis Leonides series engines, and other historic aircraft engines that do not have manufacturer-recommended calendar limits.

It could not be conclusively determined if an overload event, such as hydraulic lock, had initiated the gudgeon pin fatigue crack, or if the presence of corrosion pits with normal cyclical loads had initiated the fatigue crack. However, it is more likely that hydraulic lock was a factor. In order to reduce the likelihood of future engine failures caused by hydraulic-lock-induced damage, the CAA should publicise to operators of radial engines the correct technique for clearing hydraulic lock. Therefore:

Safety Recommendation 2010-030

It is recommended that the Civil Aviation Authority notify operators of piston radial engines of the correct technique for clearing a hydraulic lock.

In order to reduce the likelihood of future Alvis Leonides series engine failures due to gudgeon pin corrosion pitting, the CAA should consider introducing a gudgeon pin inspection. However, it is difficult to detect corrosion pits of the small magnitude seen in the G-AWVF gudgeon pins without sectioning the pins and examining them with an SEM. Therefore, a simpler inspection of the pins, examining for cracks and corrosion, may be sufficient. Therefore:

Safety Recommendation 2010-031

It is recommended that the Civil Aviation Authority consider introducing a requirement to inspect the gudgeon pins on Alvis Leonides series engines.

Conclusions

The accident was caused by an in-flight engine fire that probably rendered the pilot unconscious. The fire was caused by a catastrophic mechanical engine failure which was initiated by a fatigue crack of the No 6 piston gudgeon pin. The exact cause of the fatigue crack initiation could not be determined but it is likely that a high-load event, such as a partial or full hydraulic lock, initiated the crack in the pin. The presence of corrosion pits on the inner surface of the pin, which would act as stress raisers, was probably a contributory factor, and the aircraft's low utilisation rate during the previous 45 years probably contributed to the formation of corrosion.