De Havilland DH98 Mosquito T3, G-ASKH

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Aircraft Type and Registration: De Havilland DH98 Mosquito T3, G-ASKH

No & Type of Engines: Rolls Royce Merlins: left; Mk 25, right; Mk 502

Year of Manufacture: 1945

Date & Time (UTC): 21 July 1996 at 1201 hrs

Location: Near Barton Airfield, Manchester

Type of Flight: Air Display

Persons on Board: Crew - 1 - Passengers - 1

Injuries: Crew - Fatal - Passengers - Fatal

Nature of Damage: Aircraft destroyed

Commander's Licence: Airline Transport Pilot's Licence

Commander's Age: 50 years

Commander's Flying Experience: 10,395 hours (of which 72 were on type)

Last 90 days - 118 hours

Last 28 days - 74 hours

Information Source: AAIB Field Investigation

History of flight

On 17 July the aircraft took on 275 gallons of Avgas at RAF Valley before returning to its base at Hawarden Airfield. It did not fly again until the day of the accident. It was defuelled to approximately 160 gallons on 19 July to bring the weight down to a level appropriate to display flying.

The aircraft left Hawarden at 1130 hrs on 21 July and flew to Barton Airfield where, after a short period holding off, the pilot started his display routine at 1156 hrs. The main display axis was along Runway 09/27. The routine consisted of a series of non-aerobatic manoeuvres such as climbs, descents, medium turns, level flight at 220 to 240 kt along the display axis not below 100 feet agl and 'wingovers'; the latter is a manoeuvre which involves the aircraft reversing its course by climbing and rolling to the left or right. The weather was fine, the surface wind was generally from the south at 9 kt and the temperature was 26°C; the wind at 2,000 feet was 240°/10 kt. The display was nearing its conclusion with a fly past along the display axis from east to west followed by a
steep climb into a 'wingover' to the right during which control of the aircraft was lost. The aircraft was then observed to complete a number of uncontrolled manoeuvres before control appeared to have been regained, but at too low a height to prevent impact with the ground.

Accident site details

The aircraft crashed into a small, dense wood approximately one mile west of the airfield. There had been an impact fireball, with burning wreckage being scattered throughout the wood and into a potato field beyond. The wreckage trail extended approximately 80 metres from the point of impact.

The wood consisted predominantly of oak and birch trees, with dense undergrowth, growing on a peat bog. The main impact area had become water-logged and unstable. The aircraft had come down through the trees at an angle of approximately 40°, with both propellers severing substantial branches. The impact point of both engines could be discerned in the ground, although the engines themselves had travelled a further 10 metres, tunnelling through the peat to become completely buried. The left propeller had become detached early in the impact sequence and was found buried aft of the engine. The right propeller was found in undergrowth some 10 metres to the right and forward of the right engine. The blades from both propellers were found to have sustained similar amounts of damage, thus providing a tentative indication of nominally symmetrical engine power at impact. The wooden airframe was highly fragmented, with much of the fuselage structure being consumed by a post-impact fire. Some of the fuel cells, located in the inboard and outboard wing sections, and which had been released on impact, had also been badly fire affected. The debris found in the potato field included some cockpit items, the cockpit canopy structure and the radiator shutters located on the lower surfaces of the inboard leading edge wing sections.

The primary flying control operating cables were lying in the centre of the main wreckage area and had retained their basic cruciform layout, although there was considerable disruption in the cockpit area. Many of the fittings had remained attached to substantial sections of structure, and it was possible to verify the pre-impact integrity of much of the flying controls before the wreckage was removed from the site.

Following an on-site examination the wreckage was recovered to the AAIB Farnborough. The recovery entailed cutting a clearing in the wood to allow space for recovery vehicles. A mechanical excavator was used to dig around the main wreckage area, each scoopful of earth being sifted for items of wreckage.

Video analysis

The best evidence of the event was obtained from analysis of several video recordings obtained from members of the public. The display proceeded normally with steep turns and wingovers to the left and right being completed without evidence of any difficulty. The bank angle used during the steep turns was estimated to be 60° and the wingovers reaching approximately 90°. On several of the fly pasts the speed of the aircraft was assessed by measuring the movement of the aircraft against background objects frame by frame. These were not exact measurements but the results showed that the aircraft ground speeds were within the range of 220 to 240 kt. The speed during the final fly past was similarly assessed and, by repeating the process with several of the recordings, it was possible to say with a high degree of confidence that the groundspeed on this occasion was close to 240 kt. With the lighter crosswind at the time there would have been little difference between airspeed and groundspeed. Without adequate background reference it was not possible to estimate the height and speed of the aircraft at the apex of the wingovers. The other pilot who shared the display flying on
the Mosquito suggested that the airspeed would be 140 kt or more at the apex. Eye witnesses to the accident estimated the height to be about 1,500 feet at the apex of the final wingover.

The video soundtrack of one of the recordings of the final flypast was subjected to a spectral analysis, which gave an RPM of 2,660, averaged for the two engines. This accords with typical engine RPM used for display flying of 2,600. The boost setting is assumed to have been selected to the usual value of around +7 psi.

On one recording, the rotation of the propellers had been slowed by the strobe effect which resulted from the propeller blade passing frequency being a harmonic of the camera shutter speed. Calculations made on a frame by frame basis suggested that the left propeller was operating generally 20 to 40 RPM lower than the right. This is considered to be of no particular significance as there is no automatic propeller synchronisation system on the aircraft.

The final part of the display was examined in greater detail. The aircraft flew from right to left along the display line at about 240 kt and entered a straight climb. During the initial climb the RPM of both propellers reduced slightly, probably as a function of reducing airspeed. The aircraft rolled to the right and the bank angle increased to about 90°. Shortly before the aircraft reached the apex of the 'wingover', the speed of the left propeller appeared to slow relative to the right and continued to slow until, at the apex, it appeared to stop completely. The roll continued until reaching an estimated 100° to 110°. The aircraft yawed to the left and rapidly lost airspeed; the nose then pitched down, relative to the lateral axis and the aircraft began to fall. The bank angle reduced and the aircraft nose pitched down violently. The aircraft then entered what appeared to be a spin to the left from which it recovered briefly before entering a spin to the right. Shortly before impact the aircraft appeared to recover from the spin in a steep nose down attitude but this was followed by a violent yaw to the right from which it had insufficient height to recover.

The apparent slowing of the left propeller indicated only a change in RPM. However, the subsequent behaviour of the aircraft, namely the left yaw and the autorotative manoeuvre at low airspeed, was strongly indicative of an asymmetric condition caused by a larger reduction of power from the left engine. It is thus probable that the observed RPM change was indeed a reduction. The fact that the right-hand propeller continued to rotate at the same speed was considered significant in that it suggested that the pilot was not making any adjustments to the engine controls at the time. Similarly, boost lever movement would initially result in an RPM excursion; this would be detected by the propeller control unit which would cause the blade pitch to alter such that the RPM returned to the selected value. It was therefore concluded that unless the pilot inexplicably reduced the power on the left engine, the observed propeller RPM change was symptomatic of a power loss.

On another video recording, a puff of smoke, with an accompanying 'bang' was apparent when the nose of the aircraft was pointing at the ground following the initial loss of control. It is believed that this puff of smoke came from the left engine although the evidence was not conclusive. This event may have been due to a rapid throttle (ie boost lever) closure by the pilot as part of the recovery procedure, 'bangs' or 'crackles' being a characteristic engine response to such action. It is noteworthy that no smoke was visible from the left engine at the time of the observed propeller RPM reduction prior to the loss of control. This suggested that the cause of the propeller RPM reduction was not due to an excessively rich mixture.
Most of the recordings showed the yaw to the right during the descent, as noted earlier. This could have been caused by a restoration of power on the left engine, and could explain the indications of symmetrical power at impact.

**Pilot's flying experience**

The pilot started flying in 1968 and qualified for a Private Pilot's Licence; in 1978 he gained an Airline Transport Pilots Licence. His main experience was on transport aircraft although he had flown about 529 hours on light aircraft. His first recorded flight in the Mosquito was in 1991. He flew it for 16 hours in 1993, 20 hours in 1994 and 27 hours in 1995. His first flight in 1996 was a display practice on 7 June. On 8 June he flew to Cranfield where he did 2 displays. His next flight, the last before the accident flight was on 17 July. His total logged flying in the Mosquito, in 1996, was 4:25 hours.

**Medical and pathology**

There was no evidence of any pre-existing medical condition which could have contributed to the accident. The impact forces were such that no safety equipment could have been expected to have prevented a fatal outcome.

**History of the aircraft**

This aircraft had the military serial number RR299 and was built as an unarmed, dual control trainer at Leavesden in 1945. It served in the Middle East until 1949, when it returned to the United Kingdom. It then served with a variety of RAF units, this service being interspersed with periods in storage. The aircraft was retired from the RAF in 1963 and was acquired by Hawker Siddeley Aviation (now British Aerospace) at Chester. The first Permit to Fly was issued on 9 September 1963. The aircraft continued to be based and maintained at Chester and typically flew around 50 hours per year.

**Powerplant description**

The left engine was a Rolls Royce Merlin Mark 25, with a Merlin Mark 502, which differed only in installational details from the Merlin 25, being fitted in the right-hand position. The engines were liquid cooled, 12 cylinder units, equipped with single stage, two-speed superchargers. The high-speed mode had been disabled, mainly because its use was not necessary at the low altitudes at which this aircraft was operated, but also in the interest of avoiding high boost settings which could accelerate both airframe and engine wear.

The carburettors were SU AVT40, twin-choke, updraught units, which were attached to the supercharger intakes. Each carburettor has two float chambers, with a needle valve in each chamber controlling the fuel delivery. Each needle valve is in turn controlled by a pressure sensitive capsule, i.e., an evacuated bellows assembly. The needle valve in one chamber responds to changes in atmospheric pressure. The needle valve in the other responds to changes in boost pressure (which is dependant on the throttle butterfly position controlling the flow of air into the supercharger), as selected by the pilot operating the boost lever in the cockpit. The dimensional changes of the capsules result in needle valve movement such that they alter the flow of fuel, thereby maintaining the correct fuel/air ratio.
The carburettors were supplied with fuel by means of engine-driven fuel pumps. Unlike many Merlin installations, there was no separate pressure regulating valve between the pumps and carburettors, the regulating function being performed within the pumps themselves.

The fuel tanks on this aircraft are arranged into inboard (or main supply) and outboard wing groups. Fuselage tanks were also fitted at one time, but these had been removed. Fuel from the inboard groups is fed to a gallery, or manifold, in the fuselage, and thence to the engines via a fuel valve on each engine firewall. The outboard tanks are connected directly to the fuel valves, by-passing the central gallery. Fuel tank selection is by means of two selectors, left and right, in the cockpit, each one being selectable to 'outer tanks', 'main supply' (ie inboard tanks) and 'off'. A cable loop links the chain and sprocket assemblies mounted on the backs of both the valves and the selector handles.

An additional feature of engine operation was an automatic boost control system. This consists of a separate housing containing another pressure sensitive capsule, and is connected to the throttle butterflies via a mechanical differential linkage. The system is designed to maintain the boost at the value set by the pilot. In simple terms, the capsule detects any change in boost pressure, the resulting movement operating a spool valve. This ports pneumatic pressure to a piston, the output arm of which moves the butterflies, via the differential linkage, such that the boost setting is restored.

The engines drove three-bladed, variable pitch Hamilton Standard propellers via reduction gears. RPM control was by means of propeller control units (PCUs) which use engine oil pressure to operate the blade pitch change mechanism within the hubs.

**Carburettor problems: historical aspects**

Early on in the Second World War, it was found that Merlin powered RAF aircraft were disadvantaged when taking evasive action due to a tendency for the engine(s) to cut under negative g conditions. Essentially, this was a two-stage phenomenon. Initially, the onset of negative g resulted in the fuel moving to the top of the float chambers, thus starving the jet well (ie the entrance to the needle valve assembly) and causing a 'weak cut'. This was followed by a 'rich cut' as fuel, under pump pressure, flooded into the chamber through the fully open float valve, the floats having adopted their lowest position.

The SU company, in conjunction with the Royal Aircraft Establishment (RAE), developed a modification which led to the 'RAE Anti g Carburettor'. Both carburettors in G-ASKH were found to be of this type. The salient features of the float chamber are shown in the sketch at Figure 1, and it can be seen that the principal element of the modification is the stand pipe or shroud tube assembly. The fuel off-take to the jet well is via the tops of the tubes, which remain immersed in fuel regardless of whether the g forces are positive or negative. Whilst this addressed the problem of the 'weak cut', it did nothing to solve the subsequent 'rich cut'. An initial remedy was the incorporation of a restrictor in the fuel line to the carburettor, which limited the fuel flow to a value approximating to the engine demand at maximum power. However, the final solution was the addition of a pintle on the float valve stem, - item G in Figure 1. This is shaped like a small nailhead, and, whilst it has no effect in normal flight conditions, it imposes an increasing restriction on the fuel flow as it approaches the valve orifice. The maximum restriction occurs with the floats in the lowest position, which is set by the adjustable stop 'H' in Figure 1. A Rolls Royce instruction manual of the time contains requirements for bench testing the carburettors, using a fuel flow rig, in which the minimum fuel flow with the floats in the fully down position should be set up at 330-350 pints/hour for each float chamber. These instructions are reproduced in an RAFAir Publication (AP), but neither
document explains the consequences of incorrect adjustment. The sketches at Figure 3 (i) and (ii) show the valve operation in more detail.

The diameter of the pintle is slightly less than that of the valve orifice, with the result that in the event that the adjustable stop 'H' is set too high, the pintle can enter the float valve orifice, leaving only a small annular area for the fuel to pass through. In such a condition, it will be appreciated that the inlet fuel pressure is now acting on the lower face of the pintle, thus giving rise to a force which opposes the natural float buoyancy.

NB. None of the foregoing applies to engines equipped with Bendix injection carburettors.

Recent aircraft history

The aircraft was maintained by British Aerospace, with the scheduled inspections in general following the original military schedule. Any airframe component replacement or rectification, scheduled or otherwise, was also carried out by BAe. However, engine and associated component overhaul and servicing activity was generally sub-contracted, although engine and associated components were usually removed and replaced by BAe. Much of the servicing and overhaul of the engines and carburettors was conducted by an approved company based in the Channel Islands.

In addition, BAe had an informal (ie non-contractual) relationship with the RAF's Battle of Britain Memorial Flight (BBMF) based at RAF Coningsby, who have extensive experience of operating and maintaining Merlin powered aircraft, and which allowed the pooling of knowledge and experience. BBMF allowed BAe use of their equipment and facilities, and performed limited powerplant maintenance tasks.

i) The left engine

The left engine (Serial Number 104573) was last overhauled, by the Channel Islands company in 1986 and, after seeing service in another aircraft, it was installed on G-ASKH in November 1993. In April 1994, the left engine suffered rough running, together with a red 'low fuel pressure' light. The symptoms could be reproduced (according to the technical log), by reducing below 1 g with a slight control column push. This problem was eventually traced to an incorrectly wired fuel gauge, leading to the selection of a nearly empty fuel tank, and consequent fuel starvation. By 14 July 1996 (the last log book entry before the accident), this engine had achieved 296 flying hours out of an overhaul life, set by Rolls Royce, of 500 hours.

The carburettor on the left engine at the time of the accident had the serial number 61345, and was initially on the engine at the time of its installation in November 1993. At that time it was noted that it was subject, by serial number, of a Notice to Operators issued in 1992 by the same Channel Islands organisation that had overhauled the engines, and who had also overhauled a batch of carburettors. The Notice to Operators noted that a sealant material, which had been used in certain parts of the carburettors instead of the usual gaskets, constituted a potential risk of causing a fuel blockage. Accordingly, this carburettor was removed from the engine and a spare installed. Before the April 1994 rough running incident was traced to an incorrectly wired fuel gauge, the replacement carburettor was suspected, with the result that it was removed for inspection. The checking of carburettors in accordance with the Notice to Operators required the use of specialised equipment, namely a needle projection test rig, which BAe did not possess. The available documentation suggests that in early May 1994, BAe took the suspect carburettor, together with the one removed in November 1993, to the BBMF at Coningsby, who had the necessary rig. Both carburettors were
checked, with the unit bearing the serial number 61345 being re-installed on the left engine on 11 May 1994.

The Notice to Operators did not require the carburettors to be flow-checked. In any case, BBMF did not have a flow rig and worked any of the BBMF's carburettors which required the use of such a rig would have been subcontracted to the Channel Islands company.

The detailed history of the unit could not be established. An entry in the engine log book noted that the carburettor was removed for 'rig calibration' and subsequently re-installed in August 1987. Although the carburettor serial number was not recorded, the absence of any other log book entry concerning carburettor removal suggests that it was the same unit (i.e. serial number 61345) as that found at installation on GASKH in November 1993.

On 30 June 1996, three weeks and approximately six flying hours before the accident, the left engine was recorded in the technical log as suffering from 'rough running at zero g'. This occurred towards the end of a flying display at Lille, in France, as the pilot (who was not the pilot on the day of the accident) applied forward control column movement in order to level the aircraft following a steep climb. The engine did not immediately recover following resumption of 1 g flight, and the RPM excursions suggested to the pilot that there might be a propeller control problem. Accordingly, he closed both throttles before shutting down the left engine and feathering the propeller. The aircraft then landed eventfully on the remaining engine. Despite exhaustive checks and ground runs, no fault was found with the left engine, and the aircraft was eventually cleared for a flight back to Hawarden. On arrival over the airfield, the pilot put the aircraft through a series of manoeuvres, which included the application of reduced g, in an attempt to reproduce the rough running symptoms; however, both engines ran normally throughout. On the ground, additional checks, including the use of the needle projection rig (borrowed from BBMF) which applied pneumatic pressure to the carburettor, in order to check the functions of both pressure sensitive capsules and their associated needle valves. Again, no fault was found, although this would not have checked the carburettor's performance under reduced g.

It was apparent that there was an perception among pilots who had flown the Mosquito, that Merlin engines were likely to suffer a momentary cut under reduced or negative g conditions, with the result that such events, when experienced, were not entered in the technical log.

i) The right engine

The right-hand engine (Serial Number 305607) had been re-installed on the aircraft, following an overhaul by the Channel Islands company, in June 1990. In September 1990 there was a record of the right-hand engine suffering a power loss; this was rectified by replacing the engine driven fuel pump. The right engine carburettor, serial number 82258, was last overhauled, again by the Channel Islands company, in March 1990. The records indicated a flow check had been carried out at the time, although the actual values were not recorded. It was subsequently inspected in accordance with the Channel Islands company's Notice to Operators on 11 January 1993. This work was done by BAe personnel using BBMF's test equipment.

Detailed examination of wreckage

i) Airframe general
A detailed examination of the wreckage did not reveal any evidence of a pre-impact failure or disconnect in the flying control system. It was established that the flaps were retracted at impact, and the electrically operated radiator shutters in the inboard wing leading edges were in the 'closed' condition. (The shutters create significant drag forces in their open positions). Also, there was no evidence of a structural failure. Only a few cockpit instruments were recovered in identifiable condition, and contributed little to the investigation. One cockpit item of interest was the throttle pedal, which contained the broken-off stubs of the engine RPM and boost levers. Whilst no reliance could be placed on their actual positions, it was considered noteworthy that both pairs of levers had remained together, suggesting that the engines were not being handled separately at the time of impact.

ii) Fuel system

The impact fireball had consumed most of the fuel, although some inboard fuel cells had escaped the ground fire as a result of being buried. However, they had ruptured in the impact, with the fuel being lost in the peat. Thus no meaningful fuel sample was available from the wreckage.

The right engine fuel tank selector handle backing plate bore an impact mark, made by the handle itself, at the 'main supply' position, i.e., the inboard tank group. There was no similar witness mark visible on the left tank selector that could have indicated its position, although both should have been selected to 'mainsupply'. The ports on the firewall-mounted fuel valves were found in the 'off' and 'outboard' positions on the left and right sides respectively. However, it was considered that these positions were not necessarily representative of their pre-impact condition, and most probably resulted from one cable in each loop breaking before the other during the impact, such that tension in the surviving cable lengths rotated the sprockets that were attached to the valves.

The aircraft had been equipped with two fuel filters, each mounted upstream of the firewall-mounted fuel valves. Neither filter was recovered. Also, considerable lengths of fuel line were not accounted for, due to the fragmented nature of the wreckage.

iii) Power plant

It was not considered necessary to strip the right engine as there was no evidence of any malfunction. The left engine and both propellers were taken for strip-examination at the BBMF.

The propeller pitch change mechanism in the hubs showed no evidence of a pre-impact failure. Blade angle change is effected by the action of a piston moving within the dome, under the action of oil pressure ported from the propeller control unit. Piston movement causes rotation of a bevel gear, which mates with segment gears attached to the blade roots. In both propeller assemblies, the bevel gears were found jammed at a position approximately 10° away from the fine pitch stops. This suggested both engines were delivering a degree of power at impact, although it was not possible to quantify this. However, it was considered significant that both units were found at similar pitch angles, as it reinforced the indications of symmetrical power at impact. The left propeller control unit was not recovered.

Examination of the left engine revealed that there had been no pre-impact mechanical failure of any of the components. There was no evidence of lubrication failure or operation at excessively high temperatures, such as might occur due to coolant loss, and the supercharger and magneto drive gear-trains were all intact. It was also possible to account for all but one of the fuel pump drive components, the remaining item, a gear wheel, having been lost via a hole in the gear case. The
general condition of the engine was good, and this included such components as the sparkplugs and flame traps. The fuel pump was not capable of being tested, but a strip inspection revealed no evidence of pre-impact failure, and a diaphragm, which performed the pressure regulating function, was intact.

The high tension (HT) harness and both magnetos were examined in the BBMF electrical bay. Both magnetos (Rotax type NSE 12/9C) had sustained substantial impact damage to the extent that they could not be bench tested. It was noted that both magnetos were fitted with slightly higher resistance coils than those specified in the relevant manual, which may have resulted in slightly reduced output energy. There was a small bulge in the coil from the right magneto, and there was a crack in the condenser. However, there was no evidence of HT tracking that could have been indicative of an ignition coil breakdown. The only visible defect noted on the left magneto was that a low tension lead was bearing on a bolt head such that the cable insulation was partly worn through. There was thus a risk of an electrical short which would have caused the magneto to produce no output; however this situation had not yet arisen.

The HT leads are packed into conduits in a Merlin installation, and each harness consists of the lead and conduit assembly. A length of flexible steel braid protects each lead over the portion between the conduit and spark plug. An insulation check showed that all the leads were shorted together, despite the lack of significant damage sustained by the conduits in the accident. The leads were extracted from the conduits and tested individually. Breakdown still occurred at a very low voltage however, and it was noted that the lengths of each lead that had been enclosed within the flexible steel braids were crazed and cracked. However, it was evident that the conduits were full of water as a result of being buried in the peat bog, and it likely that the poor insulation properties were largely caused by moisture ingress. After drying out overnight, the leads were re-tested and were found to have markedly improved. It was concluded that despite the foregoing observations, the engine power loss was probably not caused by an ignition problem. A complete ignition failure would have required both magnetos to fail within the duration of the accident flight, and probably would have resulted in additional symptoms, such as backfiring.

The automatic boost control capsule was removed from its assembly, and was found to have failed in that the output shaft could be pushed against spring pressure, but not pulled; ie it was no longer 'double acting'. The capsule itself was not visible, but was sealed in an outer brass capsule. It was clear that the pressure sensitive capsule had failed so that it had expanded to fill the length of the outer capsule. In an attempt to discover the effects such a failure would have on engine operation, the unit was installed on a Lancaster engine, which was then ground-run, and the engine parameters compared with those obtained with an intact capsule. The results indicated that the defective capsule caused a boosting increase, and was therefore not likely to have caused the engine to lose power. The unit from the right engine was subsequently examined, and found to be in a similar condition. It was thus concluded that both capsules failed as a result of the impact forces.

Another defect that was observed in the left-hand automatic boost control capsule was a loose union between the capsule output shaft and the spool valve which ported pressure to the pneumatic automatic boost control output piston. The union was in the form of a small universal joint, and this had worn to the extent that there was approximately 1 mm of axial free play, which amounted to almost 15% of the total valve travel. Rolls Royce stated that although the wear exceeded overhaul limits, they did not believe it would have made any contribution to the engine problem.

iv) Carburettors
The carburettor from the left engine was initially stripped at BBMF, with no obvious abnormalities being found. Both carburettors were then taken to an overhaul organisation with limited experience of this type of component, and were subsequently examined by an engineer who was involved in carburettor development work during the Second World War. Disassembly of the carburettors involved removal of the throttle butterfly and associated housing, and separating the upper and lower float chamber castings. In both carburettors the upper castings contained the float height adjustable stops and the needle valve housings, see Figure 4. Gaskets of 0.060" thickness sealed the joints between the upper and lower castings.

It was noted that the shroud tubes on the left carburettor had played outwards so that they intermittently fouled the floats, although the lack of any wear pattern on the floats suggested that this damage was caused during disassembly. However, it was also noted that the circular hole in the base of the tubes was ovalised such that when it was reassembled with its seals (which in fact were in good condition) onto the needle valve housings, gaps were visible. One shroud also bore the marks of what could have been pliers jaws. With the seals thus only partially effective, there would have been a risk of some air entrainment during negative conditions. Other observations included confirmation that the aneroid capsules of both carburettors were undamaged, as were the accelerator pumps. It was noted however, that on the left carburettor, considerable wear had occurred in the bushings in which the altitude compensation needle was located. The shroud tubes of the right-hand carburettor were different in detail from those of the left unit, and were perhaps from a different manufacturer. All the floats appeared to be in good condition: those from the right-hand float chamber of the left carburettor were weighed and were found to be less than 3% above the specified weight, indicating minimal fuel absorption, and in consequence, satisfactory buoyancy.

The carburettors had suffered impact damage such that only the right-hand float chamber of each carburettor could be checked for float level and flow rate. This was accomplished on a suitable test rig. The available maintenance manuals specified that with a fuel inlet pressure of about 8 psi applied to the carburettor, the float mechanism should shut the fuel off at a level 0.35" - 0.45" below the casting joint face. The fuel level in the chamber of the right carburettor was found to be within these limits, although the corresponding value for the left carburettor was approximately 0.20". However, there was a tendency for the fuel level to continue to rise if the inlet fuel pressure was increased slightly. Both carburettors failed to control at 10 psi, with fuel flooding over the top of the casting. This was likely to be due to pitted grooves found on the conical face of the float valves where they had been in contact with the valve seat. (See the photograph at Figure 4.) The available maintenance publication indicated that the valve face should only show 'a light indication of the seating position, without any ridge ....'

Fuel level adjustment is accomplished by means of an eccentric pin which is used to attach the float valve link to the float pivot (see Figures 3 and 4). After loosening a pinch bolt, the pin can be rotated so that, for a fixed float position, the valve moves up or down from a mean position. It will be appreciated that as the pin is rotated, the valve link could either be vertical, leaning towards the floats, or away from the floats (ie towards the float chamber wall). Extracts from two photocopied maintenance documents that were included with the aircraft documentation contained instructions on fuel level adjustment. One, which had 'Extracts from Rolls Royce Overhaul Manual... TSD 293' handwritten on the first page, stated that: '...the eccentrics must be adjusted so that the needle connecting rod pivot pins are towards the float chamber wall'. The other document comprised selected pages from the Maintenance Manual for Merlin Single Stage Engines, and contained the statement: 'When making the adjustment the eccentric pin must be kept towards the float. The reasons for the requirement for the direction on the eccentric were not given in either document. Although the actual direction of the eccentric was probably of little consequence, the contradictory
nature of the manuals is obvious. In all four float chambers, the eccentric adjusters were such that the valve links were inclined towards the chamber walls, rather than towards the floats.

The heights of the floats above the casting joint faces, and therefore the proximity of the top of the floats to the chamber roofs, will depend on the setting of the fuel level eccentric adjustment. The tips of the floats in the left carburettor were only 0.10" below the roof (allowing for the 0.060" thickness of the gasket), due to the high fuel level. This may have accounted for the areas of the chamber roof which had been crudely machined with milling cutters, apparently to provide additional clearance. If this were the case, it would demonstrate a lack of understanding by the perpetrator on the purpose of the eccentric adjusters. It was not established when or where this was done.

The most serious problem with the carburettors concerned the adjustable stops (H in Figure 1) which set the lowest float height, which in turn controlled the fuel flow under negative g conditions. These stops (which were found wire-locked in position), should have been set during the flow check following overhaul. The operator would not have adjusted the float stops because, without installing the carburettor in the fuel flow test rig, there would be no way of knowing the effect of any adjustments made on the flow rates. It was found that the stops were inoperative in that they were adjusted out to the point where they did not contact the top of the float valve link, see the diagram at Figure 2. As a result, the floats' lowest positions were simply when they contacted the float chamber floor. This caused the float valve pintles to enter the valve orifices, thereby severely restricting fuel flow. The sketches at Figure 3 (iii) give the relevant dimensions.

The corresponding dimensions for the left float valves of each carburettor could not be measured due to the disruption that had occurred to the float chamber lids. However, similar lengths of the adjusters were exposed, indicating that they similarly had not been contacting the valve links. It is believed that the original gasket material (between the float chamber and lid castings) may have been considerably thinner than that found during disassembly. It will be appreciated that replacing the gasket with a thicker item clearly increases the gap between the stop and valve link, which therefore necessitates adjustment of the stop when the carburettor is flow checked. However, this dimensional change would not have explained the extent of the maladjustment of the float stop in the right-hand carburettor. It was noted that the maintenance instructions contained no requirement to re-check the flow rates following gasket replacement or disturbance.

The flow rates through the float valves with the floats at their fully depressed positions were measured, using the test requirement of 8 psi inlet fuel pressure, as specified in the available manuals. The values obtained were 35 and 158 pints/hour respectively for the left and right carburettors, compared with the specified 330-350 pints/hour. Also measured were the times from empty float chambers, with the floats therefore fully down, to the point where fuel started to flow into the tops of the shroud tubes. These were found to be approximately 60 seconds and 12 seconds respectively for the left and right carburettors. The large difference between the two was attributed to the fact that the left carburettor's valve pintle was further into the orifice than that of the right, thereby creating a smaller annular area for the fuel to flow through. Thus in the event of negative g conditions resulting in a severely reduced fuel flow through the float valves, the left carburettor's float chamber could be slow to refill, compared to the right, once positive g conditions were restored. It was therefore concluded that no restricted flow check had been carried out on either carburettor at overhaul.

**Condition of other carburettors**
During the early 1990s the Channel Islands company held the contract for the overhaul of BBMF carburettors. More recently the BBMF submitted many of their carburettors, under a change of contract, to another maintenance organisation for examination. Of the first 6 to be tested most were well below the restricted flow requirement of 330 to 350 pints per hour per chamber and ridges were apparent on the conical faces of the float valves. In addition, a number of carburettors from privately owned aircraft were found to be in a similar condition.

**Summary and discussion**

The investigation established that the accident resulted from a loss of control of the aircraft associated with a temporary loss of power from the left engine. The nature of the accident site, plus the high degree of fragmentation of the wreckage meant that some potentially useful items, such as the fuel filters and the left engine propeller control unit, were not recovered. Thus, although the possibility of fuel line or fuel filter blockage could not be ruled out, such an event would more probably manifest itself at higher fuel flows, such as during takeoff or climb to altitude. A PCU malfunction may have caused the observed RPM excursion of the left-hand propeller close to the apex of the final wingover, but it is unlikely this would have resulted in an immediate power reduction to the observed extent indicated by the left yaw.

The left engine ignition harness was found to be below the specified insulation requirements; however, this was most probably due to the effects of moisture ingress as a result of being buried in the peat bog. In any event, an HT failure is likely to be progressive, accompanied by a series of backfires, and is more likely to occur at a high boost setting. The available evidence did not suggest any failure within either of the left-hand engine's magnetos, both of which would have had to have failed after the aircraft took off from Hawarden, in order to produce an engine failure.

It was not possible to exclude fuel starvation due to the left outboard tank being selected, although this would have meant an asymmetric fuel selection, as the evidence suggested that the right engine was selected to the inboard (main supply) tanks. Similarly, the possibility of a tank fuel outlet becoming exposed whilst manoeuvring, thus entraining air into the fuel system, also could not be excluded.

A worn universal joint that connected the capsule output shaft and spool valve was found in the automatic boost control assembly. The engine manufacturer considered that this had no bearing on the engine problem. However, small boost variations around the selected value would have resulted in correspondingly small capsule movements that would not have been transmitted to the spool valve. There was therefore a possibility that this free play may have contributed to a minor difficulty in synchronising left and right propeller RPM as was apparent on the video recording.

The investigation of the carburettors revealed that neither unit met the specified fuel flow requirements under negative g conditions, as the adjustable stops that controlled the float height (which in turn controlled the float valve) were not even contacting the valve links. As noted earlier, these stops should have been set at overhaul, and not touched by the operator. As a result, it was found that the fuel flows for the one float valve of each carburettor that was capable of being tested were reduced to approximately 10% and 50% of the required values for the left and right units respectively. Assuming both float valves of each carburettor were in similar states, it is probable that with either or both floats in their fully depressed positions, the reduced fuel flow would not sustain the left engine at moderate power settings. It is rather more difficult however, to relate the as-found condition of the carburettors to the likely effects on the engines during the wingover manoeuvre that preceded the accident. The display sequence was similar to countless others,
although the display line was perhaps shorter than most, with an attendant possibility of steeper manoeuvres at either end.

In deference to the age of the aircraft, the display pilots never intentionally applied negative g, although reduced positive g (ie less than 1 g) would have occurred to varying degrees. Apart from g loadings experienced on the aircraft centreline, each carburettor might be subjected to greater or lesser accelerations due to engine vibration, turbulence, sideslip, and rolling motion about the aircraft longitudinal axis. For example, the left carburettor could experience reduced or negative g if a roll to the left were initiated, or a roll to the right arrested, while the right carburettor would see positive g. The movement of the fuel within the float chambers ('slosh'), and in consequence the float behaviour, therefore is a function of complex dynamic conditions. In the event that the combined dynamics of the aircraft and float chamber fuel masses caused the floats to be forced towards their fully depressed conditions, then it is likely that the ensuing restricted fuel flow could cause a loss of engine power, as the residual fuel in the chamber would last only a few seconds. Although it could not be concluded that this caused a power loss, it was considered that the as-found adjustment states of the carburettors were capable of producing it under certain conditions. The fact that the restriction of flow in the left carburettor was more severe than the right (based upon the results of bench testing one chamber from each carburettor), might indicate a greater susceptibility of the left engine to cut. Nevertheless, the number of variables involved in creating a restricted flow condition also suggested that actual occurrence could be of an unpredictable nature. This might explain why the symptoms could not be reproduced following the Lille incident, when the pilot deliberately put the aircraft through a series of reduced g manoeuvres.

The Merlin's reputation for cutting under negative g conditions had endured since the beginning of the Second World War. Curiously, the fact that a successful carburettor modification had been developed (and incorporated on the subject aircraft) to remedy the problem had largely been forgotten.

With the benefit of hindsight it is appreciated that gasket thickness can have a critical effect on the dimensional relationship between the float valve pintle and the associated valve orifice. Accordingly, it would be advisable to recheck the restricted flow rate through the carburettor following disturbance or replacement of the gasket. No such requirement was contained within the maintenance manuals which were examined.

**Future action**

Rolls-Royce has operated a long-standing policy that support should be provided to Merlin and Griffon engines operated by:

- The Battle of Britain Memorial Flight (Hurricanes, Spitfires & Lancaster)
- British Aerospace (Mosquito)
- Rolls-Royce (Spitfire - until 1992 and resumed in 1996)
- Royal Navy Historic Flight (Firefly and, other than with Merlin and Griffon engines, Sea Hawk and Swordfish)

Rolls-Royce is the obvious organisation to remain the centre of excellence for these historic engines.
Safety recommendations

In view of the investigation finding that the carburettor flows did not comply with the negative g flow requirements, it is recommended that:

97-23 Rolls-Royce communicates with all known operators of Merlin engines and organisations involved in their maintenance to advise them of the requirements specified in the maintenance manual for setting up and adjusting carburettors. The essential requirement for the use of a flow rig should be emphasised.

97-24 Rolls-Royce should advise known Merlin operators and maintenance organisations of the continuing availability of technical advice and interpretation on the Merlin engine manuals.