De Havilland DH98 Mosquito T3, G-ASKH

AAIB Bulletin No: 6/97 Ref: EW/C96/7/9Category: 1.1

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 Valleybefore returning to its base at Hawarden Airfield. It did notfly again until the day of the accident. It was defuelled toapproximately 160 gallons on 19 July to bring the weight downto a level appropriate to display flying.

The aircraft left Hawarden at 1130 hrs on 21 July and flew toBarton Airfield where, after a short period holding off, the pilotstarted his display routine at 1156 hrs. The main display axiswas along Runway 09/27. The routine consisted of a series ofnon-aerobatic manoeuvres such as climbs, descents, medium turns,level flight at 220 to 240 kt along the display axis not below100 feet agl and 'wingovers'; the latter is a manoeuvre whichinvolves the aircraft reversing its course by climbing and rollingto the left or right. The weather was fine, the surface windwas 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 nearingits conclusion with a fly past along the display axis from eastto west followed by a steep climb into a 'wingover' to the rightduring which control of the aircraft was lost. The aircraft wasthen observed to complete a number of uncontrolled manoeuvresbefore control appeared to have been regained, but at too lowa height to prevent impact with the ground.

Accident site details

The aircraft crashed into a small, dense wood approximately onemile west of the airfield. There had been an impact fireball,with burning wreckage being scattered throughout the wood andinto a potato field beyond. The wreckage trail extended approximately80 metres from the point of impact.

The wood consisted predominantly of oak and birch trees, withdense undergrowth, growing on a peat bog. The main impact areahad become water-logged and unstable. The aircraft had come downthrough the trees at an angle of approximately 40°, withboth propellers severing substantial branches. The impact pointsof both engines could be discerned in the ground, although theengines themselves had travelled a further 10 metres, tunnellingthrough the peat to become completely buried. The left propellerhad become detached early in the impact sequence and was foundburied aft of the engine. The right propeller was found in undergrowthsome 10 metres to the right and forward of the right engine.The blades from both propellers were found to have sustained similaramounts of damage, thus providing a tentative indication of nominallysymmetrical engine power at impact. The wooden airframe was highlyfragmented, with much of the fuselage structure being consumedby a post-impact fire. Some of the fuel cells, located in theinboard and outboard wing sections, and which had been releasedon impact, had also been badly fire affected. The debris foundin the potato field included some cockpit items, the cockpit canopystructure and the radiator shutters located on the lower surfacesof the inboard leading edge wing sections.

The primary flying control operating cables were lying in thecentre of the main wreckage area and had retained their basiccruciform layout, although there was considerable disruption inthe cockpit area. Many of the fittings had remained attachedto substantial sections of structure, and it was possible to verifythe pre-impact integrity of much of the flying controls beforethe wreckage was removed from the site.

Following an on-site examination the wreckage was recovered tothe AAIB Farnborough. The recovery entailed cutting a clearingin the wood to allow space for recovery vehicles. A mechanicalexcavator was used to dig around the main wreckage area, eachscoopful of earth being sifted for items of wreckage.

Video analysis

The best evidence of the event was obtained from analysis of severalvideo recordings obtained from members of the public. The displayproceeded normally with steep turns and wingovers to the leftand right being completed without evidence of any difficulty. The bank angle used during the steep turns was estimated to be60° and the wingovers reaching approximately 90°. Onseveral of the fly pasts the speed of the aircraft was assessedby measuring the movement of the aircraft against background objectsframe by frame. These were not exact measurements but the resultsshowed that the aircraft groundspeeds were within the range of220 to 240 kt. The speed during the final fly past was similarlyassessed and, by repeating the process with several of the recordings,it was possible to say with a high degree of confidence that thegroundspeed on this occasion was close to 240 kt. With the lightcrosswind at the time there would have been little differencebetween airspeed and groundspeed. Without adequate backgroundreference it was not possible to estimate the height and speedof the aircraft at the apex of the wingovers. The other pilotwho shared the display flying on the Mosquito suggested that theairspeed would be 140 kt or more at the apex. Eye witnesses tothe accident estimated the height to be about 1,500 feet at theapex 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 of2,660, averaged for the two engines. This accords with typicalengine RPM used for display flying of 2,600. The boost settingis assumed to have been selected to the usual value of around+7 psi.

On one recording, the rotation of the propellers had been slowedby the strobe effect which resulted from the propeller blade passingfrequency being a harmonic of the camera shutter speed. Calculationsmade on a frame by frame basis suggested that the left propellerwas operating generally 20 to 40 RPM lower than the right. Thisis considered to be of no particular significance as there isno 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 atabout 240 kt and entered a straight climb. During the initialclimb the RPM of both propellers reduced slightly, probably asa function of reducing airspeed. The aircraft rolled to the rightand the bank angle increased to about 90°. Shortly beforethe aircraft reached the apex of the 'wingover', the speed ofthe left propeller appeared to slow relative to the right andcontinued 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; thenose then pitched down, relative to the lateral axis and the aircraftbegan to fall. The bank angle reduced and the aircraft beganto yaw to the left. There was little or no forward speed as thewings levelled and the aircraft nose pitched down violently.The aircraft then entered what appeared to be a spin to the leftfrom which it recovered briefly before entering a spin to theright. Shortly before impact the aircraft appeared to recoverfrom the spin in a steep nose down attitude but this was followedby a violent yaw to the right from which it had insufficient heightto recover.

The apparent slowing of the left propeller indicated only a changein RPM. However, the subsequent behaviour of the aircraft, namelythe left yaw and the autorotative manoeuvre at low airspeed, wasstrongly indicative of an asymmetric condition caused by a largereduction of power from the left engine. It is thus probablethat the observed RPM change was indeed a reduction. The factthat the right-hand propeller continued to rotate at the samespeed was considered significant in that it suggested that thepilot was not making any adjustments to the engine controls atthe time. Similarly, boost lever movement would initially resultin an RPM excursion; this would be detected by the propeller controlunit which would cause the blade pitch to alter such that theRPM returned to the selected value. It was therefore concludedthat unless the pilot inexplicably reduced the power on the leftengine, the observed propeller RPM change was symptomatic of apower loss.

On another video recording, a puff of smoke, with an accompanying'bang' was apparent when the nose of the aircraft was pointingat the ground following the initial loss of control. It is believedthat this puff of smoke came from the left engine although theevidence was not conclusive. This event may have been due torapid throttle (ie boost lever) closure by the pilot as part ofthe recovery procedure, 'bangs' or 'crackles' being a characteristicengine response to such action. It is noteworthy that no smokewas visible from the left engine at the time of the observed propellerRPM reduction prior to the loss of control. This suggested thatthe cause of the propeller RPM reduction wasnot due to an excessively rich mixture.

Most of the recordings showed the yaw to the right during thedescent, as noted earlier. This could have been caused by a restorationof power on the left engine, and could explain the indicationsof symmetrical power at impact.

Pilot's flying experience

The pilot started flying in 1968 and qualified for a Private Pilot'sLicence; in 1978 he gained an Airline Transport Pilots Licence. His main experience was on transport aircraft although he hadflown about 529 hours on light aircraft. His first recorded flightin the Mosquito was in 1991. He flew it for 16 hours in1993, 20 hours in 1994 and 27 hours in 1995. His first flightin 1996 was a display practice on 7 June. On 8 June he flew toCranfield where he did 2 displays. His next flight, the lastbefore the accident flight was on 17 July. His total logged flyingin the Mosquito, in 1996, was 4:25 hours.

Medical and pathology

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

History of the aircraft

This aircraft had the military serial number RR299 and was builtas an unarmed, dual control trainer at Leavesden in 1945. Itserved in the Middle East until 1949, when it returned to theUnited Kingdom. It then served with a variety of RAF units, thisservice being interspersed with periods in storage. The aircraftwas retired from the RAF in 1963 and was acquired by Hawker SiddeleyAviation (now British Aerospace) at Chester. The first Permitto Fly was issued on 9 September 1963. The aircraft continuedto be based and maintained at Chester and typically flew around50 hours per year.

Powerplant description

The left engine was a Rolls Royce Merlin Mark 25, with a MerlinMark 502, which differed only in installational details from theMerlin 25, being fitted in the right-hand position. The engineswere 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 altitudesat which this aircraft was operated, but also in the interestof avoiding high boost settings which could accelerate both airframeand engine wear.

The carburettors were SU AVT40, twin-choke, updraught units, whichwere attached to the supercharger intakes. Each carburettor hastwo float chambers, with a needle valve in each chamber controllingthe fuel delivery. Each needle valve is in turn controlled bya pressure sensitive capsule, ie an evacuated bellows assembly. The needle valve in one chamber responds to changes in atmosphericpressure. The needle valve in the other responds to changes inboost pressure (which is dependant on the throttle butterfly positioncontrolling the flow of air into the supercharger), as selectedby the pilot operated boost lever in the cockpit. The dimensionalchanges of the capsules result in needle valve movement such thatthey alter the flow of fuel, thereby maintaining the correct fuel/airratio.

The carburettors were supplied with fuel by means of engine-drivenfuel pumps. Unlike many Merlin installations, there was no separatepressure 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 (ormain supply) and outboard wing groups. Fuselage tanks were alsofitted at one time, but these had been removed. Fuel from theinboard 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 meansof two selectors, left and right, in the cockpit, each one beingselectable to 'outer tanks', 'main supply' (*ie* inboardtanks) and 'off'. A cable loop links chain and sprocket assembliesmounted on the backs of both the valves and the selector handles.

An additional feature of engine operation was an automatic boostcontrol system. This consists of a separate housing containinganother pressure sensitive capsule, and is connected to the throttlebutterflies via a mechanical differential linkage. The systemis 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 pneumaticpressure 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 Standardpropellers via reduction gears. RPM control was by means of propellercontrol units (PCUs) which use engine oil pressure to operatethe blade pitch change mechanism within the hubs.

Carburettor problems: historical aspects

Early on in the Second World War, it was found that Merlin poweredRAF aircraft were disadvantaged when taking evasive action dueto a tendency for the engine(s) to cut under negative g conditions. Essentially, this was a two-stage phenomenon. Initially, theonset of negative g resulted in the fuel moving to the top ofthe float chambers, thus starving the jet well (*ie* theentrance 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, thefloats 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. Thesalient features of the float chamber are shown in the sketchat Figure 1, and it can be seen that the principal element ofthe modification is the stand pipe or shroud tube assembly. Thefuel off-take to the jet well is via the tops of the tubes, whichremain immersed in fuel regardless of whether the g forces arepositive 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 thefuel line to the carburettor, which limited the fuel flow to avalue approximating to the engine demand at maximum power. Howeverthe final solution was the addition of a pintle on the float valvestem, - 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 approachesthe valve orifice. The maximum restriction occurs with the floatsin the lowest position, which is set by the adjustable stop 'H'in Figure 1. A Rolls Royce instruction manual of the time containsrequirements for bench testing the carburettors, using a fuelflow rig, in which the minimum fuel flow with the floats in thefully down position should be set up at 330-350 pints/hour foreach float chamber. These instructions are reproduced in an RAFAir Publication (AP), but neither document explains the consequencesof 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 valveorifice, with the result that in the event that the adjustablestop 'H' is set too high, the pintle can enter the float valveorifice, leaving only a small annular area for the fuel to passthrough. In such a condition, it will be appreciated that theinlet 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 equippedwith Bendix injection carburettors.

Recent aircraft history

The aircraft was maintained by British Aerospace, with the scheduledinspections in general following the original military schedule. Any airframe component replacement or rectification, scheduledor otherwise, was also carried out by BAe. However, engine andassociated component overhaul and servicing activity was generallysub-contracted, although engine and associated components wereusually removed and replaced by BAe. Much of the servicing andoverhaul of the engines and carburettors was conducted by an approvedcompany based in the Channel Islands.

In addition, BAe had an informal (ie non-contractural) relationshipwith the RAF's Battle of Britain Memorial Flight (BBMF) basedat RAF Coningsby, who have extensive experience of operating andmaintaining Merlin powered aircraft, and which allowed the poolingof knowledge and experience. BBMF allowed BAe use of their equipmentand facilities, and performed limited powerplant maintenance tasks.

i) The left engine

The left engine (Serial Number 104573) was last overhauled, bythe Channel Islands company in 1986 and, after seeing servicein another aircraft, it was installed on G-ASKH in November 1993. In April 1994, the left engine suffered rough running, togetherwith a red 'low fuel pressure' light. The symptoms could be reproduced(according to the technical log), by reducing below 1 g with aslight control column push. This problem was eventually tracedto an incorrectly wired fuel gauge, leading to the selection ofa nearly empty fuel tank, and consequent fuel starvation. By14 July 1996 (the last log book entry before the accident), thisengine 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 accidenthad the serial number 61345, and was initially on the engine atthe time of its installation in November 1993. At that time itwas noted that it was subject, by serial number, of a Notice toOperators issued in 1992 by the same Channel Islands organisationthat had overhauled the engines, and who had also overhauled abatch of carburettors. The Notice to Operators noted that a sealantmaterial, which had been used in certain parts of the carburettorsinstead of the usual gaskets, constituted a potential risk ofcausing a fuel blockage. Accordingly, this carburettor was removedfrom the engine and a spare installed. Before the April 1994rough running incident was traced to an incorrectly wired fuelgauge, the replacement carburettor was suspected, with the resultthat it was removed for inspection. The checking of carburettorsin accordance with the Notice to Operators required the use ofspecialised equipment, namely a needle projection test rig, whichBAe did not possess. The available documentation suggests thatin early May 1994, BAe took the suspect carburettor, togetherwith the one removed in November 1993, to the BBMF at Coningsby,who had the necessary rig. Both carburettors were checked, withthe unit bearing the serial number 61345 being re-installed onthe left engine on 11 May 1994.

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

The detailed history of the unit could not be established. Anentry in the engine log book noted that the carburettor was removedfor 'rig calibration' and subsequently re-installed in August1987. Although the carburettor serial number was not recorded,the absence of any other log book entry concerning carburettorremoval suggests that it was the same unit (*ie* serial number61345) as that found at installation on GASKH in November1993.

On 30 June 1996, three weeks and approximately six flying hoursbefore the accident, the left engine was recorded in the technicallog as suffering from 'rough running at zero g'. This occurredtowards the end of a flying display at Lille, in France, as thepilot (who was not the pilot on the day of the accident) appliedforward control column movement in order to level the aircraftfollowing a steep climb. The engine did not immediately recoverfollowing resumption of 1 g flight, and the RPM excursions suggestedto the pilot that there might be a propeller control problem. Accordingly, he closed both throttles before shutting down theleft engine and feathering the propeller. The aircraft then landeduneventfully on the remaining engine. Despite exhaustive checksand ground runs, no fault was found with the left engine, andthe aircraft was eventually cleared for a flight back to Hawarden. On arrival over the airfield, the pilot put the aircraft througha series of manoeuvres, which included the application of reducedg, in an attempt to reproduce the rough running symptoms; however,both engines ran normally throughout. On the ground, additionalchecks, including the use of the needle projection rig (borrowedfrom BBMF) which applied pneumatic pressure to the carburettor,in order to check the functions of both pressure sensitive capsulesand their associated needle valves. Again, no fault was found,although this would not have checked the carburettor's performanceunder reduced g.

It was apparent that there was an perception among pilots whohad flown the Mosquito, that Merlin engines were likely to suffera momentary cut under reduced or negative g conditions, with theresult that such events, when experienced, were not entered inthe technical log.

i) The right engine

The right-hand engine (Serial Number 305607) had been re-installedon the aircraft, following an overhaul by the Channel Islandscompany, in June 1990. In September 1990 there was a record ofthe right-hand engine suffering a power loss; this was rectifiedby replacing the engine driven fuel pump. The right engine carburettor,serial number 82258, was last overhauled, again by the ChannelIslands company, in March 1990. The records indicated a flowcheck had been carried out at the time, although the actual valueswere not recorded. It was subsequently inspected in accordancewith the Channel Islands company's Notice to Operators on 11 January1993. 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 evidenceof a pre-impact failure or disconnect in the flying control system. It was established that the flaps were retracted at impact, andthe electrically operated radiator shutters in the inboard wingleading edges were in the 'closed' condition. (The shutters cancreate significant drag forces in their open positions). Also,there was no evidence of a structural failure. Only a few cockpitinstruments were recovered in identifiable condition, and contributedlittle to the investigation. One cockpit item of interest wasthe throttle pedestal, which contained the broken-off stubs ofthe engine RPM and boost levers. Whilst no reliance could beplaced on their actual positions, it was considered noteworthythat both pairs of levers had remained together, suggesting thatthe engines were not being handled separately at the time of impact.

ii) Fuel system

The impact fireball had consumed most of the fuel, although someinboard fuel cells had escaped the ground fire as a result ofbeing buried. However, they had ruptured in the impact, withthe fuel being lost in the peat. Thus no meaningful fuel samplewas available from the wreckage.

The right engine fuel tank selector handle backing plate borean impact mark, made by the handle itself, at the 'main supply'position, ie the inboard tank group. There was no similar witnessmark visible on the left tank selector that could have indicatedits position, although both should have been selected to 'mainsupply'. The ports on the firewall-mounted fuel valves were foundin the 'off' and 'outboard' positions on the left and right sidesrespectively. However, it was considered that these positionswere not necessarily representative of their pre-impact condition,and most probably resulted from one cable in each loop breakingbefore the other during the impact, such that tension in the survivingcable lengths rotated the sprockets that were attached to thevalves.

The aircraft had been equipped with two fuel filters, each mountedupstream of the firewall-mounted fuel valves. Neither filterwas recovered. Also, considerable lengths of fuel line were notaccounted for, due to the fragmented nature of the wreckage.

iii) Power plant

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

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

Examination of the left engine revealed that there had been nopre-impact mechanical failure of any of the components. Therewas no evidence of lubrication failure or operation at excessivetemperatures, such as might occur due to coolant loss, and thesupercharger and magneto drive gear-trains were all intact. Itwas also possible to account for all but one of the fuel pumpdrive components, the remaining item, a gear wheel, having beenlost via a hole in the gear case. The general condition of theengine was good, and this included such components as the sparkplugs and flame traps. The fuel pump was not capable of beingtested, but a strip inspection revealed no evidence of pre-impactfailure, and a diaphragm, which performed the pressure regulatingfunction, was intact.

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

The HT leads are packed into conduits in a Merlin installation,and each harness consists of the lead and conduit assembly. Alength of flexible steel braid protects each lead over the portionbetween the conduit and spark plug. An insulation check showedthat all the leads were shorted together, despite the lack ofsignificant 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 itwas noted that the lengths of each lead that had been enclosedwithin the flexible steel braids were crazed and cracked. However,it was evident that the conduits were full of water as a resultof being buried in the peat bog, and it likely that the poor insulationproperties were largely caused by moisture ingress. After dryingout overnight, the leads were re-tested and were found to havemarkedly improved. It was concluded that despite the foregoingobservations, the engine power loss was probably not caused byan ignition problem. A complete ignition failure would have requiredboth magnetos to fail within the duration of the accident flight,and probably would have resulted in additional symptoms, suchas backfiring.

The automatic boost control capsule was removed from its assembly,and was found to have failed in that the output shaft could bepushed against spring pressure, but not pulled; ie it was no longer'double acting'. The capsule itself was not visible, but wassealed in an outer brass capsule. It was clear that the pressuresensitive capsule had failed so that it had expanded to fill thelength of the outer capsule. In an attempt to discover the effectssuch a failure would have on engine operation, the unit was installedon a Lancaster engine, which was then ground-run, and the engineparameters compared with those obtained with an intact capsule. The results indicated that the defective capsule caused a boost*increase*, and was therefore not likely to have caused theengine to lose power. The unit from the right engine was subsequentlyexamined, and found to be in a similar condition. It was thusconcluded that both capsules failed as a result of the impactforces.

Another defect that was observed in the left-hand automatic boostcontrol capsule was a loose union between the capsule output shaftand the spool valve which ported pressure to the pneumatic automaticboost control output piston. The union was in the form of a smalluniversal joint, and this had worn to the extent that there wasapproximately 1 mm of axial free play, which amounted to almost15% of the total valve travel. Rolls Royce stated that althoughthe wear exceeded overhaul limits, they did not believe it wouldhave made any contribution to the engine problem.

iv) Carburettors

The carburettor from the left engine was initially stripped atBBMF, with no obvious abnormalities being found. Both carburettorswere then taken to an overhaul organisation with limited experienceof this type of component, and were subsequently examined by anengineer who was involved in carburettor development work duringthe Second World War. Disassembly of the carburettors involvedremoval of the throttle butterfly and associated housing, andseparating the upper and lower float chamber castings. In bothcarburettors the upper castings contained the float height adjustablestops and the needle valve housings, see Figure 4. Gaskets of0.060" thickness sealed the joins between the upper and lowercastings.

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

The carburettors had suffered impact damage such that only theright-hand float chamber of each carburettor could be checkedfor float level and flow rate. This was accomplished on a suitabletest rig. The available maintenance manuals specified that witha 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 ofthe right carburettor was found to be within these limits, althoughthe corresponding value for the left carburettor was approximately0.20". However there was a tendency for the fuel level tocontinue to rise if the inlet fuel pressure was increased slightly. Both carburettors failed to control at 10 psi, with fuel floodingover the top of the casting. This was likely to be due to pittedgrooves found on the conical face of the float valves where theyhad been in contact with the valve seat. (See the photographat Figure 4.) The available maintenance publication indicatedthat the valve face should only show 'a light indication of theseating position, without any ridge ....'

Fuel level adjustment is accomplished by means of an eccentricpin which is used to attach the float valve link to the floatpivot (see Figures 3 and 4). After loosening a pinch bolt, thepin can be rotated so that, for a fixed float position, the valvemoves up or down from a mean position. It will be appreciatedthat as the pin is rotated, the valve link could either be vertical,leaning towards the floats, or away from the floats (ie towardsthe float chamber wall). Extracts from two photocopied maintenancedocuments that were included with the aircraft documentation containedinstructions on fuel level adjustment. One, which had 'Extractsfrom Rolls Royce Overhaul Manual.... TSD 293' handwritten on thefirst page, stated that: '...the eccentrics must be adjustedso that the needle connecting rod pivot pins are towards the floatchamber outer wall'. The other document comprised selected pagesfrom the Maintenance Manual for Merlin Single Stage Engines, andcontained the statement: 'When making the adjustment the eccentricon the pin must be kept towards the float'. The reasons for therequirement for the direction on the eccentric were not givenin either document. Although the actual direction of the eccentricwas probably of little consequence, the contradictory nature ofthe manuals is obvious. In all four float chambers, the eccentricadusters were such that the valve links were inclined towardsthe chamber walls, rather than towards the floats.

The heights of the floats above the casting joint faces, and thereforethe proximity of the top of the floats to the chamber roofs, willdepend 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 thegasket), due to the high fuel level. This may have accountedfor the areas of the chamber roof which had been crudely machinedwith milling cutters, apparently to provide additional clearance. If this were the case, it would demonstrate a lack of understandingby 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 adjustablestops (H in Figure 1) which set the lowest float height, whichin turn controlled the fuel flow under negative g conditions. These stops (which were found wire-locked in position), shouldhave been set during the flow check following overhaul. The operatorwould not have adjusted the float stops because, without installingthe carburettor in the fuel flow test rig, there would be no wayof knowing the effect of any adjustments made on the flow rates. It was found that the stops were inoperative in that they wereadjusted out to the point where they did not contact the top ofthe float valve link,- see the diagram at Figure 2. As a result,the floats' lowest positions were simply when they contacted thefloat chamber floor. This caused the float valve pintles to enterthe valve orifices, thereby severely restricting fuel flow. Thesketches at Figure 3 (iii) give the relevant dimensions.

The corresponding dimensions for the left float valves ofeach carburettor could not be measured due to the disruption thathad occurred to the float chamber lids. However, similar lengthsof the adjusters were exposed, indicating that they similarlyhad not been contacting the valve links. It is believed thatthe original gasket material (between the float chamber and lidcastings) may have been considerably thinner than that found duringdisassembly. It will be appreciated that replacing the gasketwith a thicker item clearly increases the gap between the stopand valve link, which therefore necessitates adjustment of thestop when the carburettor is flow checked. However, this dimensionalchange would not have explained the extent of the maladjustmentof the float stop in the right-hand carburettor. It was notedthat the maintenance instructions contained no requirement tore-check the flow rates following gasket replacement or disturbance.

The flow rates through the float valves with the floats at theirfully depressed positions were measured, using the test requirementof 8 psi inlet fuel pressure, as specified in the available manuals. The values obtained were 35 and 158 pints/hour respectively forthe left and right carburettors, compared with the specified 330-350pints/hour. Also measured were the times from empty float chambers,with the floats therefore fully down, to the point where fuelstarted to flow into the tops of the shroud tubes. These werefound to be approximately 60 seconds and 12 seconds respectivelyfor the left and right carburettors. The large difference betweenthe two was attributed to the fact that the left carburettor'svalve 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 severelyreduced fuel flow through the float valves, the left carburettor'sfloat chamber could be slow to refill, compared to the right,once positive g conditions were restored. It was therefore concludedthat no restricted flow check had been carried out on either carburettorat overhaul.

Condition of other carburettors

During the early 1990s the Channel Islands company held the contractfor the overhaul of BBMF carburettors. More recently the BBMFsubmitted many of their carburettors, under a change of contract,to another maintenance organisation for examination. Of the first6 to be tested most were well below the restricted flow requirementof 330 to 350 pints per hour per chamber and ridges were apparenton the conical faces of the float valves. In addition, a numberof carburettors from privately owned aircraft were found to bein a similar condition.

Summary and discussion

The investigation established that the accident resulted froma loss of control of the aircraft associated with a temporaryloss of power from the left engine. The nature of the accidentsite, plus the high degree of fragmentation of the wreckage meantthat some potentially useful items, such as the fuel filters andthe left engine propeller control unit, were not recovered. Thus,although the possibility of fuel line or fuel filter blockagecould not be ruled out, such an event would more probably manifestitself at higher fuel flows, such as during takeoff or climb toaltitude. A PCU malfunction may have caused the observed RPMexcursion of the left-hand propeller close to the apex of thefinal wingover, but it is unlikely this would have resulted inan immediate power reduction to the observed extent indicatedby the left yaw.

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

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

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

The investigation of the carburettors revealed that neither unitmet the specified fuel flow requirements under negative g conditions,as the adjustable stops that controlled the float height (whichin turn controlled the float valve) were not even contacting thevalve links. As noted earlier, these stops should have been setat overhaul, and not touched by the operator. As a result, itwas found that the fuel flows for the one float valve of eachcarburettor that was capable of being tested were reduced to approximately10% and 50% of the required values for the left and right unitsrespectively. Assuming both float valves of each carburettorwere in similar states, it is probable that with either or bothfloats in their fully depressed positions, the reduced fuel flowwould not sustain the left engine at moderate power settings. It is rather more difficult however, to relate the as-found conditionof the carburettors to the likely effects on the engines duringthe wingover manoeuvre that preceded the accident. The displaysequence was similar to countless others, although the displayline was perhaps shorter than most, with an attendant possibilityof steeper manoeuvres at either end.

In deference to the age of the aircraft, the display pilots neverintentionally applied negative g, although reduced positive g(ie less than 1 g) would have occurred to varying degrees. Apartfrom g loadings experienced on the aircraft centreline, each carburettormight be subjected to greater or lesser accelerations due to enginevibration, turbulence, sideslip, and rolling motion about theaircraft longitudinal axis. For example, the left carburettorcould experience reduced or negative g if a roll to the left wereinitiated, or a roll to the right arrested, while the right carburettorwould see positive g. The movement of the fuel within the floatchambers ('slosh'), and in consequence the float behaviour, thereforeis a function of complex dynamic conditions. In the event thatthe combined dynamics of the aircraft and float chamber fuel masscaused the floats to be forced towards their fully depressed conditions,then it is likely that the ensuing restricted fuel flow couldcause a loss of engine power, as the residual fuel in the chamberwould last only a few seconds. Although it could not be concludedthat this caused a power loss, it was considered that the as-foundadjustment states of the carburettors were capable of producingit under certain conditions. The fact that the restriction offlow in the left carburettor was more severe than the right (basedupon the results of bench testing one chamber from each carburettor),might indicate a greater susceptibility of the left engine tocut. Nevertheless, the number of variables involved in creatinga restricted flow condition also suggested that actual occurrencecould be of an unpredictable nature. This might explain why thesymptoms could not be reproduced following the Lille incident,when the pilot deliberately put the aircraft through a seriesof reduced g manoeuvres.

The Merlin's reputation for cutting under negative g conditionshad 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 problemhad largely been forgotten.

With the benefit of hindsight it is appreciated that gasket thicknesscan have a critical effect on the dimensional relationship betweenthe float valve pintle and the associated valve orifice. Accordinglyit would be advisable to recheck the restricted flow rate throughthe carburettor following disturbance or replacement of the gasket. No such requirement was contained within the maintenance manualswhich were examined.

Future action

Rolls-Royce has operated a long-standing policy that support shouldbe 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 Merlinand Griffon engines, Sea Hawk and Swordfish)

Rolls-Royce is the obvious organisation to remain the centre ofexcellence for these historic engines.

Safety recommendations

In view of the investigation finding that the carburettor flowsdid not comply with the negative g flow requirements, it is recommendedthat:

97-23 Rolls-Royce communicates with all known operatorsof Merlin engines and organisations involved in their maintenanceto advise them of the requirements specified in the maintenancemanual for setting up and adjusting carburettors. The essentialrequirement for the use of a flow rig should be emphasised.

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