

**INCIDENT**

<b>Aircraft Type and Registration:</b>	Boeing 747-436, G-BNLG
<b>No &amp; Type of Engines:</b>	4 Rolls-Royce RB211-524G turbofan engines
<b>Year of Manufacture:</b>	1989
<b>Date &amp; Time (UTC):</b>	20 February 2005
<b>Location:</b>	En route from Los Angeles International Airport to London (Heathrow) International Airport
<b>Type of Flight:</b>	Public Transport (Passenger)
<b>Persons on Board:</b>	Crew - 18                      Passengers - 352
<b>Injuries:</b>	Crew - None                      Passengers - None
<b>Nature of Damage:</b>	Major damage to No 2 engine
<b>Commander's Licence:</b>	Airline Transport Pilot's Licence
<b>Commander's Age:</b>	48 years
<b>Commander's Flying Experience:</b>	12,680 hours (of which 1,855 were on type) Last 90 days - 212 hours Last 28 days - 75 hours
<b>Information Source:</b>	AAIB Field Investigation

**Synopsis**

Immediately after the aircraft took off on a night flight from Los Angeles to London, a banging sound was heard and passengers and ATC reported seeing flames from the No 2 engine. The symptoms and resultant turbine over-temperature were consistent with an engine surge; the crew completed the appropriate checklist, which led to the engine being shut down. After assessing the situation, and in accordance with approved policy, the commander decided to continue the flight as planned rather than jettison fuel and return to Los Angeles. Having reached the east coast of the USA with no indications of further abnormality and with adequate predicted arrival fuel, the crew decided to continue to the UK. The winds and available flight levels were subsequently less favourable

than anticipated and, nearing the UK, the crew decided to divert to Manchester in order to maintain the required arrival fuel reserve.

In the latter stages of the flight the crew encountered difficulties in balancing the fuel quantities in the four main tanks. They became concerned that the contents of one tank might be unusable and declared an emergency in accordance with the operator's procedures. The aircraft landed with low contents in both outboard main tanks, although the total fuel quantity was in excess of the planned reserve. The fuel system, in the configuration selected, should have continued to feed the operating engines until all tanks emptied.

The investigation determined that the engine surge had been due to excessive wear to the high-pressure compressor casing and, with the standard of fuel controller software installed, this resulted in turbine over-temperature damage. There was no evidence of fuel system malfunction and it was possible to maintain fuel tank quantities in balance by the selective use of fuel pumps. The evidence suggested that the operator should ensure that flight crews are provided with relevant instruction on 3-engined fuel handling during initial and recurrent training, and that the regulators should review the policy on flight continuation for public transport aircraft operations, following an in-flight shutdown of an engine, in order to provide clear guidance to the operators. Eight recommendations are made, six of which relate to flight data recorders.

### History of the flight

Following a 48 hour period of rest, the crew reported for duty on 20 February 2005 to operate a flight from Los Angeles International Airport to London (Heathrow) International Airport. The flight crew consisted of three pilots: the commander and two first officers (designated 'primary' and 'heavy'), who had all operated an inbound flight two days previously. For the outbound flight they decided to load an additional 4 tonnes (4,000 kg) of fuel due to the forecast weather and possible air traffic flow restrictions into London; this resulted in a total ramp fuel of 119 tonnes. There were no known relevant deficiencies with the aircraft. All three pilots were on the flight deck for the initial part of the flight.

The 'primary' first officer was the handling pilot in the right seat. The takeoff, at 0524 hrs, was from Runway 24L using reduced power and Flap 20; the 'heavy' first officer was seated on the jump seat. It was raining and the surface wind was from 180° at 10 kt. The takeoff appeared normal until, just after the landing gear

had been selected up, at approximately 100 ft agl, there was an audible and continuous "BUMP, BUMP, BUMP" sound from the left side of the aircraft. The handling pilot was aware of a slight yaw to the left, which was easy to control. All three flight crew members saw a reduction in the indicated No 2 EPR and an increase in the associated EGT. The EGT rise continued above the normal limits and the exceedance and corresponding digital display were annunciated in red.

At the same time ATC transmitted that flames could be seen down the left side of the aircraft. The crew agreed that it was a surge on No 2 engine and that the commander, who was the non-handling pilot, should carry out the appropriate recall actions. The commander was the only member of the flight crew who had previously experienced an airborne engine surge. With the correct engine identified, he completed the memory items from the quick reference handbook (QRH) procedure for '*ENGINE LIMIT/SURGE/STALL*', retarding the No 2 thrust lever until the abnormal conditions ceased; this occurred at the idle position. By now, G-BNLG was climbing through approximately 1,500 ft and the crew declared a 'PAN' to ATC, who cleared the flight to continue the climb to 5,000 ft amsl. The crew also requested radar vectors to remain within the local area whilst they evaluated the situation. Once the aircraft was in the clean configuration, the commander passed the QRH to the first officer on the jump seat for him to confirm and read the checklist for '*ENGINE LIMIT/SURGE/STALL*'. Continuous ignition was selected 'ON' and the crew confirmed that the engine indications appeared normal. The commander then gently advanced the No 2 engine thrust lever and this resulted in an almost immediate audible surge noise. A subsequent attempt at a higher airspeed had the same effect. The crew discussed the situation and agreed that the best course of action was

to shut down the No 2 engine. This was actioned by the commander in accordance with the QRH.

The crew then agreed that the 'heavy' first officer would go to the cabin to look out of the left side of the aircraft for signs of damage and to brief the Cabin Services Director (CSD), while the commander and the 'primary' first officer would review their options. The CSD was advised of the situation and asked to stand-by for further instructions. No damage could be seen by looking out of the aircraft, but it was dark and there was no effective illumination of the relevant area. Several passengers informed the 'heavy' first officer that they had seen flames and one passenger, who was a pilot, stated that he thought that it had been an engine surge. The 'heavy' first officer returned to the cockpit and briefed the commander accordingly. By then, the commander and 'primary' first officer had reviewed the situation. The 'Eng Out' option had been selected on the Flight Management Computer (FMC) and the crew had consulted the aircraft and company manuals. Additionally, the commander had spoken with the operator's base at Heathrow by radio and had been advised that it would be preferable to continue the fight but that the course of action was the commander's decision.

The subsequent decision to continue the fight was taken by the commander, in consultation with the other fight crew members, after consideration of the following factors:

1. The 'Eng Out' fuel prediction indicated a landing at final destination with approximately 7 tonnes, compared to the required minimum reserve of 4.5 tonnes. (4.5 tonnes represents the fuel required for 30 minutes holding at 1,500 ft, in the clean configuration.)

2. An additional engine failure was considered and, with regard to the aircraft performance, it was deemed safe to continue.
3. The initial routing was across the continental USA where there were numerous suitable diversion airfields.
4. The present situation would not justify an overweight landing, and the time to jettison fuel (approximately 70 tonnes) down to below maximum landing weight would be about 40 minutes.
5. The No 2 engine was shut down and the windmilling parameters were normal; the aircraft appeared to be in a safe condition for continued flight.
6. The company policy was to continue to destination as long as the aircraft was in a safe condition.
7. The manufacturer's QRH procedure for *ENGINE LIMIT/SURGE/STALL* did not require the crew to consider landing at the nearest suitable airfield.

The commander's decision was to continue the fight, but the crew would monitor the situation carefully. Accordingly, he advised ATC that the 'PAN' situation was cancelled and that they would continue the fight.

For the subsequent fight across the USA, the aircraft flew at FL 270 at a Mach No of 0.75. At that level and with the predicted winds entered into the FMC, the landing fuel at Heathrow was forecast to be about 10 tonnes. For the first 2 hours of the fight, the 'heavy' first officer rested in the crew bunk. When he returned, the commander took some rest before returning to the cockpit in order to make the final decision of whether to continue before

the aircraft commenced the North Atlantic crossing. For the crossing, the crew had requested FL320 but ATC could only clear the aircraft at FL350 or FL290 due to opposite direction traffic. Aircraft performance precluded FL350 and, when FL290 was entered into the FMC the landing fuel at London Heathrow was indicated to be between 7 and 7.5 tonnes. The crew had agreed to plan on a minimum landing fuel of 6.5 tonnes at Heathrow.

During the Atlantic crossing, the crew continued to monitor the fuel situation. It was noted that the fuel appeared evenly distributed until the total fuel decreased below 55 tonnes. Thereafter, with the normal fuel feed being 'Tank to Engine', No 2 Tank contents remained constant until balanced by the crew. This was achieved by selective use of the Override/Jettison pumps in No 2 Tank.

As G-BNLG approached Ireland, the total fuel indicated was about 12 tonnes, which was evenly balanced between the four main fuel tanks. By now, the aircraft was at FL350 and, due to a stronger than forecast headwind, the FMC now predicted a landing fuel at London of 6.5 tonnes. The crew discussed the situation and decided to divert to Manchester; they advised ATC accordingly. Reprogramming the FMC resulted in a predicted landing fuel at Manchester of approximately 7 tonnes.

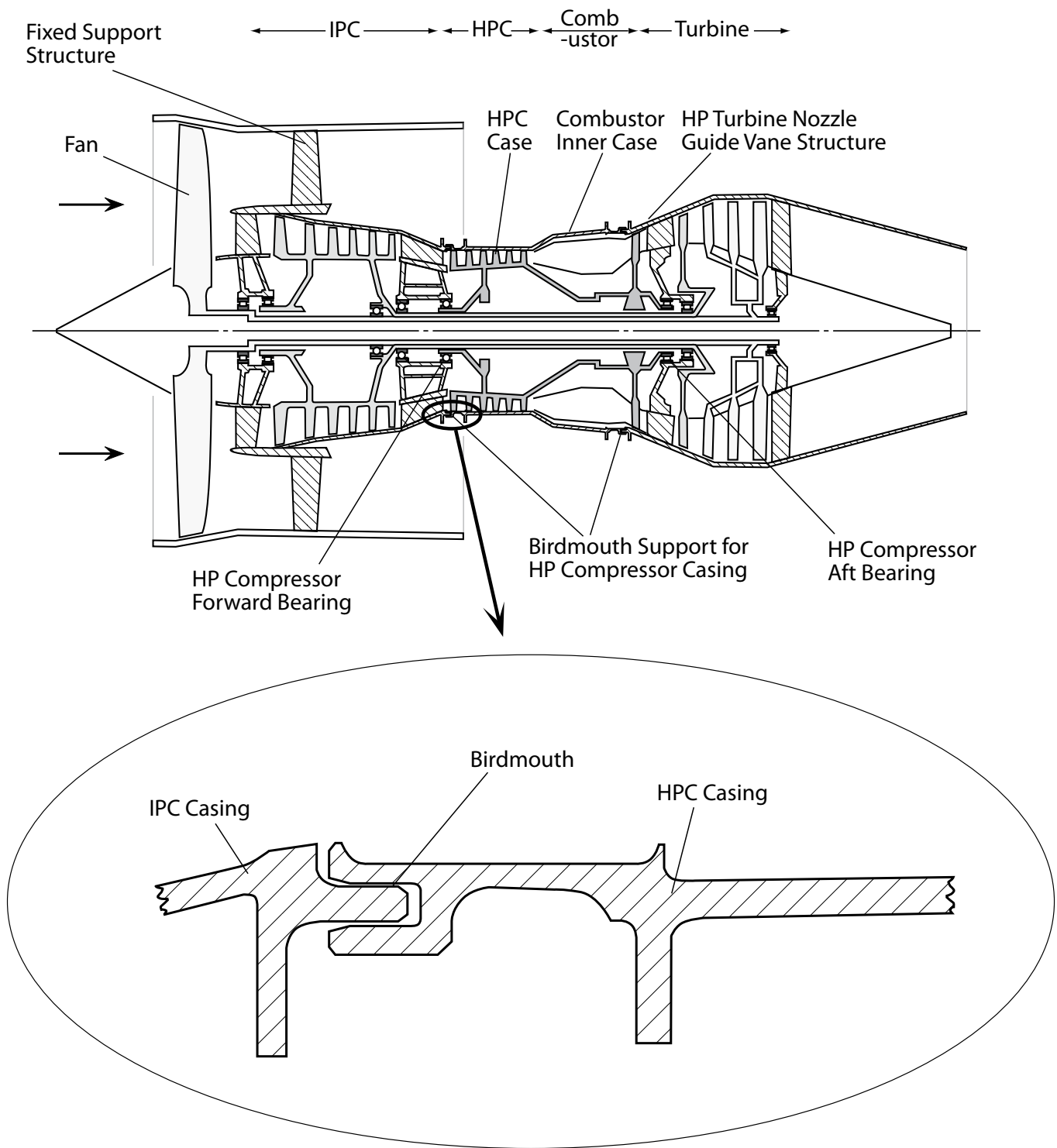
During the descent towards Manchester, the crew became concerned that fuel did not appear to be feeding from No 2 tank, even with selective switching of the main pumps within the fuel system. With the possibility that this fuel might be unusable, which would result in the aircraft landing with less than the final reserve fuel, the commander declared a 'PAN' call to ATC. G-BNLG was cleared direct to a position 10 nm on the extended centre line for Runway 06R. Around this time, the 'FUEL

QTY LOW' caution message illuminated on the Engine Indication and Crew Alerting System (EICAS) and No 4 tank indicated a quantity of 0.9 tonnes. The appropriate QRH procedure was completed, which resulted in all main fuel pumps being switched on and all cross feed valves being open. In this configuration all operative engines will be fed with fuel. The commander, concerned that the useable fuel at landing would be below the minimum reserve fuel of 4.5 tonnes, declared a 'MAYDAY' to ATC, in accordance with the operator's procedures, and assumed the role of handling pilot for the subsequent uneventful manual landing. After landing, the auxiliary power unit (APU) was started and the aircraft taxied to its allocated stand, accompanied by the AFRS. Data from the flight data recorder (FDR) indicated that the fuel on landing was approximately 5.8 tonnes.

### **Aircraft Description**

#### *Engine*

The aircraft was powered by four RB211 engines (models 524G2 and 524G2-T); a 3-spool turbofan engine with a rated maximum sea-level static thrust of around 58,000 lb. Airflow through the engine passes in turn through a fan, an intermediate pressure compressor (IPC) and a high pressure compressor (HPC), each driven by a corresponding turbine assembly (Figure 1). The HPC is a conventional axial compressor with 6 rotor stages, each followed by a ring of fixed stator blades attached to the HPC casing. The HPC casing is bolted to the engine's combustor section inner case and the combined HPC-combustor inner case is supported between the IPC support structure and the HP nozzle guide vanes structure, in each case via a circumferential socket-spigot arrangement, known as a 'birdmouth'. The HPC spool is supported on a forward ball bearing mounted to the IPC support structure and a rear roller bearing mounted to the HP-IP turbine module casing.



- IPC - Intermediate Pressure Compressor
- HPC - High Pressure Compressor

**Figure 1**  
Engine HP Compressor Support Arrangement

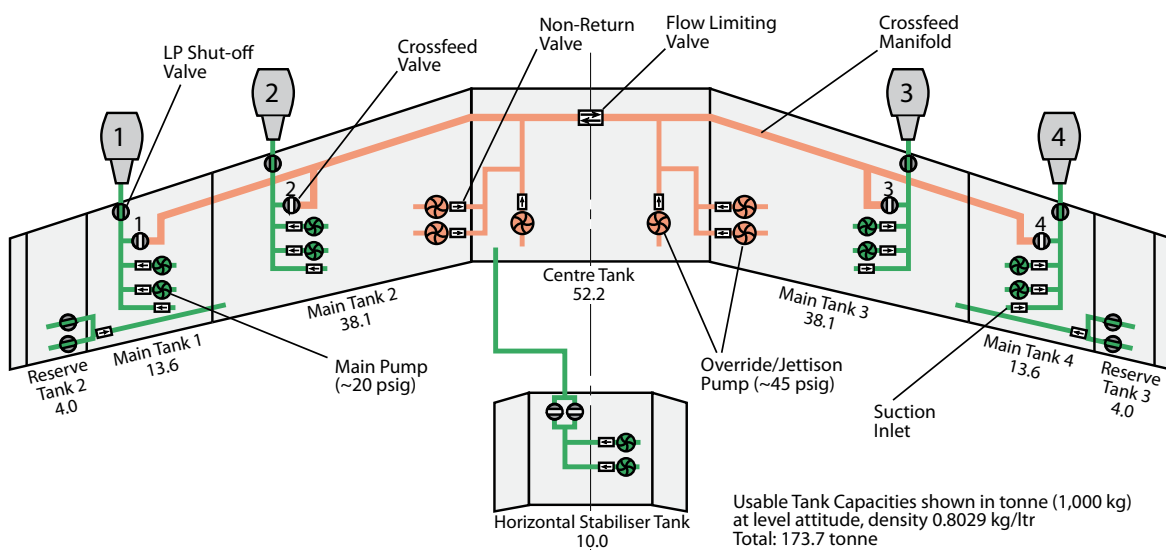
The fuel system on each engine was controlled by a Full Authority Fuel Controller (FAFC) which is an electronic computerised unit. The software installed on G-BNLG’s No 2 engine FAFC was to Issue 15. Issue 16 software was available and being embodied on the BA feet at each workshop visit; it had not yet been incorporated on this particular unit. At the time of this event the operator’s feet was approximately 80% embodied with Issue 16 software.

*Aircraft fuel system arrangement*

The B747-400 has two main fuel tanks and a reserve tank in each wing, plus a wing centre section tank (referred to as the ‘centre wing tank’) and a horizontal stabiliser tank (Figure 2). Fuel volumes and density are sensed by a fuel quantity indication system (FQIS) using capacitance probes in the tanks. Indications of the fuel quantities, in tonnes in individual tanks and for the whole aircraft, are displayed on a fuel system synoptic diagram on a crew-selectable page of the EICAS. The total fuel on board is always displayed on the EICAS. The tanks are also fitted with a magnetic dip-stick system to allow ground calibration of fuel quantities.

Fuel can be fed from each main tank via two main pumps, operating in parallel, or from a suction inlet in the tank. This feed can be directed to the respective engine, via a low pressure shut-off valve, and/or into a crossfeed manifold, via a crossfeed valve. In addition, each inboard main tank (Nos 2 & 3), with almost three times the capacity of each outboard main tank (Nos 1 & 4), has two override/jettison pumps, feeding into the crossfeed manifold. In order to prevent excessive fuel depletion in a jettison situation these pumps are arranged with standpipe inlets which uncover when the fuel quantity in a tank reduces to around 3.2 tonnes, causing pumping to cease. The centre tank also has two override/jettison pumps, feeding into the crossfeed manifold. The crossfeed manifold incorporates a flow-limiting valve intended to prevent unwanted crossfeed between the left and right sides of the aircraft due to normal variation in pump output pressure.

In order to induce fuel usage from an inboard tank in preference to the adjacent outboard tank when crossfeeding, a considerably higher pump output pressure in the inboard tank is required. This overcomes the



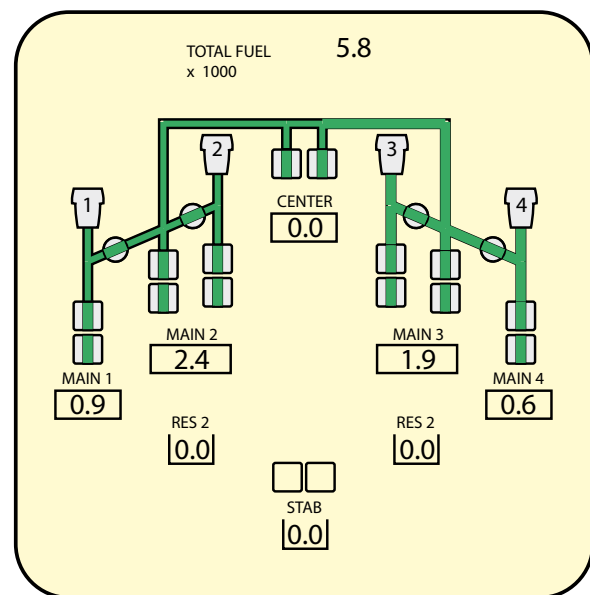
**Figure 2**  
B747-400 Engine Fuel Feed System Schematic

difference in static head between the tanks occasioned by the wing dihedral. A higher pressure is also required for such crossfeeding, because of the longer flow path and the consequent higher pipeline pressure loss when doing so. Pump outlet pressure at typical flow rates is approximately 20 psig for the main pumps and 45 psig for the override/jettison pumps. Thus the override/jettison pumps will automatically deliver the fuel feed in a situation where main pumps and override/jettison pumps are outputting to a common point.

The pumps and crossfeed valves can be controlled using push-button selector switches on an overhead fuel system panel on the flight deck. Lights in the switches illuminate to indicate a low pump outlet pressure situation or a crossfeed valve that fails to achieve the selected position. The EICAS fuel system synoptic diagram includes coloured lines signifying fuel flows (Figure 3); these are based on measured pressures, valve positions and system logic and are thus predicted, rather than sensed, flows. The flow indications are intended as secondary, rather than primary, information for the crew.

#### *Fuel System Operation and Limitations*

The control of fuel usage is largely automatic, once the system has been set before takeoff by selecting all pumps ON and all crossfeed valves OPEN. The system causes the horizontal stabiliser tank, the centre tank and the reserve tanks to empty in turn, and then for fuel to be fed from the inboard main tanks, using the override/jettison pumps to overpower the main pumps in the outboard main tanks. When the fuel quantity in an inboard main tank becomes approximately equal to that in the adjacent outboard main tank, the crew is provided with an EICAS message 'FUEL TANK/ENG'; this occurs at a total fuel load of around 55 tonnes (13.75 tonnes/tank). At this point the crew



Green line indicates predicted flow.

Fuel quantities shown are approximately those present at G-BNLG's landing.

**Figure 3**

#### Flight Deck Fuel Feed System Synoptic Display

is required to select manually Crossfeed Valves 1 and 4 Closed and Tank 2 and 3 override/jettison pumps Off, effectively causing each engine to be supplied from its respective tank.

The design intention is that no further crew action is required except in response to EICAS messages indicating the abnormal conditions of fuel tank imbalance or low fuel quantity. Imbalance is not subject to Flight Manual limitations but should generate EICAS messages to alert the crew, as follows:

1. 'FUEL IMBALANCE 1-4':  
There is a fuel imbalance of 1,360 kg between main tanks 1 and 4.
2. 'FUEL IMBALANCE 2-3':  
There is a fuel imbalance of 2,700 kg between main tanks 2 and 3.

### 3. 'FUEL IMBALANCE':

This message is effective only after the 'FUEL TANK/ENG' condition and indicates that there is an imbalance of 2,700 kg between inboard main tanks (2 and 3) and outboard main tanks (1 and 4).

Some differences were noted between the Operations Manual issued by the manufacturer and that issued by the operator, relating to fuel balancing. The operator's manual expanded on the information in the manufacturer's manual providing practical advice on fuel balancing. However, the operator's manual required the use of the override/jettison pumps to correct any imbalance between main tanks; if this was not possible, the main pumps in the low quantity tank should be switched off. The manufacturer made no reference to the override/jettison pumps and required that the main pumps in the low tank be switched off in the event of an imbalance between main tanks. The rationale behind the manufacturer's procedures was that the balancing procedure was the same, regardless of whether the fuel quantities had decreased below the override/jettison pump standpipe level or not.

In the event that the fuel quantity in any main tank reduces to 0.9 tonnes an EICAS 'FUEL QTY LOW' message is given. The operator's QRH procedure for this condition required the crew, having considered the possibility of an engine fuel leak, to select manually all crossfeed valves OPEN and all main pumps ON. In this configuration all the operating engines should continue to be fed, even if one or more main tanks is emptied, until all four main tanks empty. The procedure also specified that the crew should plan to land at the nearest suitable airfield and avoid high nose-up attitudes and/or excessive longitudinal acceleration.

### *Auxiliary power unit*

The aircraft was fitted with an APU in the rear fuselage. The APU can be used in flight to supply pneumatic and electrical power but cannot normally be started in flight. Fuel for the APU is fed from No 2 main fuel tank.

### **Aircraft Examination**

#### *Engine*

Strip examination of G-BNLG's No 2 engine (Serial No 13367), by an engine overhaul agency, revealed significant wear of the rotor blade tips of several stages of the HPC and of the mating static abradable liner of the compressor casing. Significant fretting wear of the female part of the HPC casing forward birdmouth was evident, with a maximum gap of 0.240 inch present compared to a limit of 0.208 inch. It was concluded that this had allowed sufficient radial displacement of the front end of the casing to cause the blade and liner contact damage. A number of blades and vanes from both the IP and HP compressors had suffered damage consistent with blade contact with adjacent vanes as a result of engine surging. A Service Bulletin (SB72-D574) that modified the geometry of the casing and added a wear-resistant coating to the birdmouth had been issued. The Service Bulletin recommended accomplishment of the modification when the engine was next disassembled for refurbishment or overhaul and the operator was modifying its feet accordingly.

The IP turbine was found to have suffered severe over-temperature damage, with substantial portions of both stator and rotor blades burnt away. This damage was consistent with the effects of over-fuelling. The downstream LP turbine section had also suffered overheat and debris damage and it was found necessary to replace all the turbine blades and nozzle guide vanes for all three turbine stages. Records indicated that the



engine had accumulated 24,539 operating hours and 3,703 cycles since new; it had not been overhauled or repaired during its life.

### *Fuel system*

Aircraft documentation indicated that G-BNLG departed Los Angeles with 119 tonnes of fuel and arrived on stand at Manchester with 4.9 tonnes, all in the main tanks. The FDR recorded a total of 5.8 tonnes on landing. The operator's engineering staff reported that, after a short period of APU ground running at Manchester, the EICAS system indicated the following fuel quantities in the main tanks:

Tank No	Fuel Quality - tonnes
1	0.5
2	2.1
3	2.0
4	0.1
Total	4.7

A series of ground checks carried out on the fuel system at Manchester showed that all pumps functioned and that no anomalies had been registered by the aircraft's Central Maintenance Computer, neither had any non-normal indications been presented to the crew on the EICAS display during flight. G-BNLG was then refuelled and, with the No 2 engine inoperative, flown to London (Heathrow) by a crew qualified to conduct planned 3-engine ferry flights. The commander of the ferry crew reported that no fuel system anomalies were detected and that crossfeeding checks during the flight showed that it was possible to feed any of the operating engines from any of the main tanks. However, he commented that, in order to get fuel to feed from an inboard main tank in preference to an outboard main tank while both were crossfeeding, it was necessary to take the 'aggressive' action of selecting both main pumps in the outboard tank 'OFF'.

Further ground checks at Heathrow revealed no anomalies. These checks consisted of dip-stick measurements of the outboard main tank contents, Aircraft Maintenance Manual fuel system checks, rig tests of the Tank 2 main pumps and testing of crossfeed operation with three engines running and the aircraft configured to simulate conditions during the incident flight. No reports of relevant fuel system anomalies have occurred during subsequent months of in-service operation.

### **Engine Surge**

#### *Cause of Engine Surge*

It was clear from the evidence that the initial No 2 engine problem had been a surge, an abnormal condition where the air flow through a gas turbine engine becomes unstable and momentarily reverses. The cause is generally the rapid spread of a rotor blade stall condition in part of one of the engine's compressors. Blade stall occurs if the angle of incidence of the local air flow within the compressor relative to a rotor blade becomes excessive and the normal smooth flow over the blade breaks down. The angle of incidence is the resultant of the rotational speed of the blades and the flow velocity through the engine. Thus anomalies that significantly affect the flow rate at a given compressor pressure ratio can result in a stall. The stall condition can extend over a number of blades, and/or a number of compressor stages, causing a reduction in air flow, in pressure rise and in efficiency that, if sufficiently severe, can lead to a surge.

The engine is designed such that a margin from compressor stall is maintained for all steady-state and transient situations but this is reduced, and can be eliminated, if compressor rotor blade tip clearances become excessive. Information from the engine manufacturer indicated that the normal steady-state tip clearance of the HPC rotor blades was in the order of 0.020 in. In transient conditions the clearance alters due

to the combined effects of varying centrifugal loading on the compressor rotor, differential thermal expansion of the compressor rotor and casing and deflections due to thermally induced loading. Because of these effects the engine will have a reduced surge margin approximately 50 seconds after take-off power is set.

The flow reversal associated with a surge can commonly occur on a low-frequency cyclical basis, up to 7 times per second. The symptoms can include a loud bang, or series of bangs, audible to the passengers and crew, flames at the engine inlet and exhaust and sudden loss of engine thrust. This may be followed by an engine rundown or by a restoration of stable flow through the engine, possibly with areas of compressor stall still present. Compressor damage can be caused during the surge and may assist its continuation.

#### *HPC Birdmouth wear surge*

Rotor blade tip clearance can be affected by wear of the HPC casing birdmouth feature. Excessive wear allows the forward end of the HPC casing to displace radially downwards, thereby increasing blade tip clearances over the lower half of the compressor and causing the rotor blades to contact the liner over the upper part and erode, further increasing the lower clearances. Experience has shown that where this has led to a compressor stall and engine surge the HPC tip clearance has increased to around 0.020-0.040 inch, with the engine typically having accumulated in the order of 3,500 cycles. Commonly, where the clearances have become excessive, a stall will occur when power is increased in reverse thrust. Information suggested that this may have been used as an indicator that repair was required. Two previous cases of RB211 in flight shut downs (IFSDs) due to surge resulting from HPC birdmouth wear had been reported, on RB211-524G-T and 524H-T type engines.

#### *Engine over-fuelling*

The software installed in G-BNLG's No 2 engine FAFC was at Issue 15. A Rolls Royce Service Bulletin (SB) No RB.211-73-D435, issued on 6 July 2001, amended the software to Issue 16, with the stated objective of 'upgrading the software standard and maintaining reliability'.

The reason for the change was to rectify problems that had been experienced with Issue 15. One had resulted from a change of logic introduced at Issue 14 (and included in Issue 15) in order to address a control problem found in cases of fracture of the burner pressure (P30) sensing line. Fuel flow was computed as a function of P30 and fracture of the P30 line originally caused the fuel flow to decrease and the engine to flame-out. In order to prevent this, a P30 pipe break logic was introduced at Issue 14 whereby, in the event of an anomalous P30 decrease, the FAFC used a synthesised P30 based on HP rotor speed N3. However, service experience showed that this logic could be erroneously activated during a surge and locked-in stall event, leading to over-temperature damage to the turbine blades and vanes.

The justification evidence for the SB included:

*"The following events have been reported in service: (a) During Take-off rotation engine surged and locked in stall due to HP compressor damage. The stall triggered the FAFC P30 pipe break logic and increased fuel flow leading to high TGT [turbine gas temperature] and turbine damage."*

The Issue 16 software aimed to overcome this and other problems. Compliance with the SB was specified as: "RECOMMENDED (1B). Rolls-Royce recommends that this Service Bulletin be accomplished on an

expedited basis.” The operator noted that modification of their feet, on this basis, would take between 4 and 5 years. At the time of the incident approximately 80% of the feet had been modified; the remainder of the feet has been modified subsequently.

### **Possible consequences of an engine failure**

#### *Engine surge effects*

During the investigation, detailed information on the possible adverse structural and systems consequences on the aircraft and engines of an engine surge was sought from the aircraft and engine manufacturers. Their experience indicated that a surge that did not self-recover was likely to cause damage to the engine. This could include contact damage between compressor rotor and stator blades due to forward displacement of the rotor, leading to bent or cracked blades, detachment of parts of the compressor liner and possibly overload damage to engine bearings or bearing mounting structure. With some standards of fuel control system, turbine over-temperature damage could also occur.

Testing had shown that the loads on the engine due to a surge were relatively low compared to the design case of detachment of a fan blade; significant damage to the engine structure or its mounts would not be expected. The experience gave no indications that engine rotor blade rubbing had caused a fire hazard or that there had been a significantly increased overall probability of an engine internal fire or an engine bay fire following a surge. Neither were there signs, for aircraft configured similarly to the B747, that the operation of other engines had been affected, either from the surging engine or because of intake flow distortion caused by the surge or by the resultant aircraft yaw.

Clearly a surge would result in a loss of thrust and in thrust asymmetry. However, the engine manufacturer,

in conjunction with the CAA, had conducted a risk assessment, which had also considered the risk of the same event occurring at the same time, on the same aircraft in more than one engine. The conclusion reached was that an engine surge is not hazardous. Following any subsequent shutdown of the engine, the output of bleed air, electrical and hydraulic power from the engine would be affected in certain flight conditions. In order to meet certification requirements for multi-engined public transport aircraft, the loss of an engine at the most adverse point is a design case that is catered for by redundancy. The B747 has an appreciable level of systems redundancy and no evidence was found to suggest that the aircraft systems would be affected by the loss of an engine. The principal effects on the aircraft would be in terms of performance penalties, with altitude capability reduced by around 5,000-8,000 ft and fuel consumption increased by around 8% at normal cruise speed.

#### *Effects of extended continued flight*

Detailed information on the possible adverse consequences of a long period of flight with a damaged engine that had been shutdown was sought during the investigation. The engine manufacturer noted that engine certification regulations generally did not require a prolonged windmilling to be demonstrated and this was the case for the RB211-524. However, the qualification testing for the type had included 3 hours of engine windmilling operation, related to the 180 minutes Extended Twin Operations (ETOPS) clearance, with no bearing damage expected. In accordance with this, the manufacturer's Maintenance Manual permits an engine to be ferried, whilst windmilling, with no restriction except with relation to FAFC low temperature limits. In response to operator inquiries about the effects of windmilling after the loss of engine oil, the manufacturer had issued a Notice To Operators (NTO) 421 on 25 July 1991. This concluded that:

*'windmilling the engine for lengthy periods without engine oil does no harm to the bearings within that engine. In engine terms therefore, a flight may continue after in-flight shut down for oil loss. Should an Operator nevertheless wish a flight to return or divert in such circumstances, this remains an airline decision based upon commercial/operational considerations.'*

While these observations relate to an undamaged engine, the manufacturer did not foresee further major damage resulting from windmilling an engine with damage similar to that sustained by G-BNLG's No 2 engine for a period of 12 hours or more.

The possibility of engine seizure was considered, although this is reportedly a rare occurrence. The aircraft manufacturer noted that seizure at full power had been a B747 design case and that, in the unlikely event that windmilling caused additional engine damage that led to a seizure, no hazardous effects would be expected. A seized engine would be easily identifiable by the flight crew; the relevant QRH procedure, 'Severe Engine Damage', requires a landing at the nearest suitable airfield.

Similarly, it was considered that the vibrational stresses associated with a windmilling engine that had been damaged would be relatively low compared to those generated in other design cases, such as high power operation with an IPC rotor blade detached. The engine manufacturer did not anticipate hazardous effects from prolonged windmilling of an engine that had been damaged during a surge event and then shutdown.

As a 4-engined aircraft the B747 is designed and certificated to tolerate the loss of a second engine following an initial IFSD, without losing essential

systems or necessary performance capabilities. The likely effects on systems would include the need to shed non-essential electrical loads, such as galleys, and to limit bleed air supplies in order to maintain adequate performance from the operating engines. There would also be a loss of the auto-land capability with two engines inoperative on one side of the aircraft. Aircraft performance implications would include a substantial further loss of altitude capability, but it is intended that route planning after the first IFSD would cater for this eventuality. The probability of the loss of a third engine, during the diversion that would subsequently follow the second engine loss, is considered below.

#### *Loss of engine power*

Modern public-transport aircraft design has included target maximum rates for engine failure and IFSD in order to achieve an acceptably low risk of a potentially catastrophic loss of aircraft propulsion. For design and certification a risk level of "Extremely Improbable", or  $1 \times 10^{-9}$  per flight hour, is generally used.

Assessments have been particularly focused on ETOPS and on the allowable flight time of the planned route from the destination or a suitable diversion airfield. In this case the intention is, following the loss of an engine, to maintain an acceptable risk of failure of the second engine from an unrelated cause during the diversion. Probability calculations allow for variation in IFSD rates with the level of engine power set (lower rate than average for cruise power and higher for maximum continuous power). The current internationally accepted guideline in order to maintain 180 minutes ETOPS status is in the order of 0.02 IFSDs per 1,000 engine flight hours.

Similar assessments have been extended to 3-engined and 4-engined aircraft. A particular case for a 4-engined aircraft is where, after an initial engine failure and IFSD,

the fight is continued until a second engine failure, at which point a diversion and landing is carried out. For comparison, information from the aircraft manufacturer indicated that the average IFSD rates required to achieve an Extremely Improbable risk level for catastrophic loss of propulsion were as follows. These were based for the purpose of the assessment on a planned flight time of 20 hours and a maximum diversion time of 10 hours:

Number of Engines	Action After Initial IFSD	IFSD Rate -ISFDs/1,000 Engine Hours
4	Diversion	0.11
4	Continuation until 2nd IFSD then diversion	0.09

Information from the engine manufacturers indicated that the average IFSD rate achieved in revenue service with the type of engines fitted to G-BNLG for the 12 months up to June 2005 had been 0.0073/1,000 engine flight hours.

### Operational Policy

#### *Flight Continuation*

The aircraft manufacturer did not provide guidance as to the acceptable period of continued flight following an IFSD. The crew was subject to the operator's written policy for flight continuation which was that, once certain considerations have been satisfied, the fight should continue to destination or to an operator-served destination as close as possible to it. This policy had been approved by the UK CAA. The following factors were to be reviewed before making the decision to continue:

1. *The circumstances leading to the engine failure should be carefully considered to ensure that the aircraft is in a safe condition for extended onward flight.*
2. *The possibility of a second engine failure should be considered. This would require evaluation of performance considerations, diversion requirements and range and endurance on two engines.*

The USA Federal Aviation Regulations (FAR Part 121.565) requires a landing at the nearest suitable airport following an engine failure or IFSD, except for an aircraft with three or more engines. In this case, the commander 'may proceed to an airport he selects if he decides that this is as safe as landing at the nearest suitable airport', having considered a number of factors. These included the nature of the malfunction and possible mechanical difficulties, fuel requirements, weather, terrain and familiarity with the chosen airport. The commander is required to keep ATC informed and the operator is required to inform subsequently their airworthiness authority of the event.

As part of this investigation a review was also made of other UK and overseas operating companies to determine the guidance given to their crews in the event of an engine failure on a 4-engined aircraft. One operator required that the aircraft land at the nearest suitable airport. Another had no policy and left it as a commander's decision. One operator required the aircraft to return to the airfield of departure if the engine failure occurred prior to reaching cruise altitude and the conditions at that airfield were suitable; otherwise, the commander could continue to an airfield of his selection. Three other operators had policies similar to that of G-BNLG's operator. All of the continuation policies emphasised that any continuation was dependent on the aircraft being in '*a safe condition for flight*'.

### *Three-engine operations and fuel management*

Following the incident involving G-BNLG, the operator issued Operational Safety Notice (OSN) 06/05 on 23 February 2005 on the subject of 'Three Engine Operations and Fuel Management'. This OSN acknowledged the differences in fuel management following an IFSD and provided guidance to crews. Thereafter, the operator issued a Flight Crew Notice (FCN) 20/05 on 7 June 2005, which introduced the use of the three-engine ferry procedure of anticipating a fuel imbalance. However, on 5 September 2005, after further discussion with the airframe manufacturer, the operator withdrew this FCN and instructed all crews to follow the manufacturer's standard fuel handling procedures.

### **Other incidents**

Since April 2001 this operator has recorded 15 incidents with the B747 where an engine has been shutdown and the flight continued. Over the same period, two incidents involving an IFSD each resulted in a diversion. One of these involved a fuel leak and the other involved an engine reverser unlocked indication.

The engine manufacturer provided statistics showing that, from 1989 to May 2005, there had been 389 surge events from all causes for the RB211 524G2 and 524G2-T engines. The worldwide fleet size was 603 with a total engine operating time of  $26.4 \times 10^6$  hours. Of the 389 surge events, 57 resulted in an abandoned takeoff and 65 resulted in an IFSD; of these 54 were subsequently removed due to damage. The manufacturer considered that prolonged windmilling may have caused additional damage in two of the cases, both LP compressor fan blade failures, but in both cases a diversion had been carried out due to significant vibration.

### **Flight Recorders**

#### *General*

The aircraft was equipped with a 25 hour duration flight data recorder (FDR) and a thirty minute cockpit voice recorder (CVR). The CVR did not assist in this investigation as the approach and landing phases had both been overwritten prior to electrical power being isolated from the CVR. The aircraft was also equipped with a data management unit (DMU<sup>1</sup>) which recorded additional flight data on to an optical quick access recorder (OQAR<sup>2</sup>).

Following the replay of the FDR, it was found that just over three hours of data had not been recorded by the FDR, which included the first hour and fourteen minutes of the incident flight. The QAR data was successfully replayed and provided data for the entire flight.

The FDR did not record individual fuel tank quantities; however it did record the total fuel quantity. Individual fuel tank quantities were provided by the QAR data, as was the sequence of events during the take-off phase, when FDR data was not recovered.

#### *Data recorded during the flight*

The aircraft took off at 0524 hrs with a total fuel quantity of 119.2 tonnes. Nine seconds after takeoff, at 296 ft radio height, the No 2 engine N1 shaft speed reduced from 102%, coincident with an increase in the EGT. Four seconds later the position of the No 2 engine throttle reduced. However, the EGT continued

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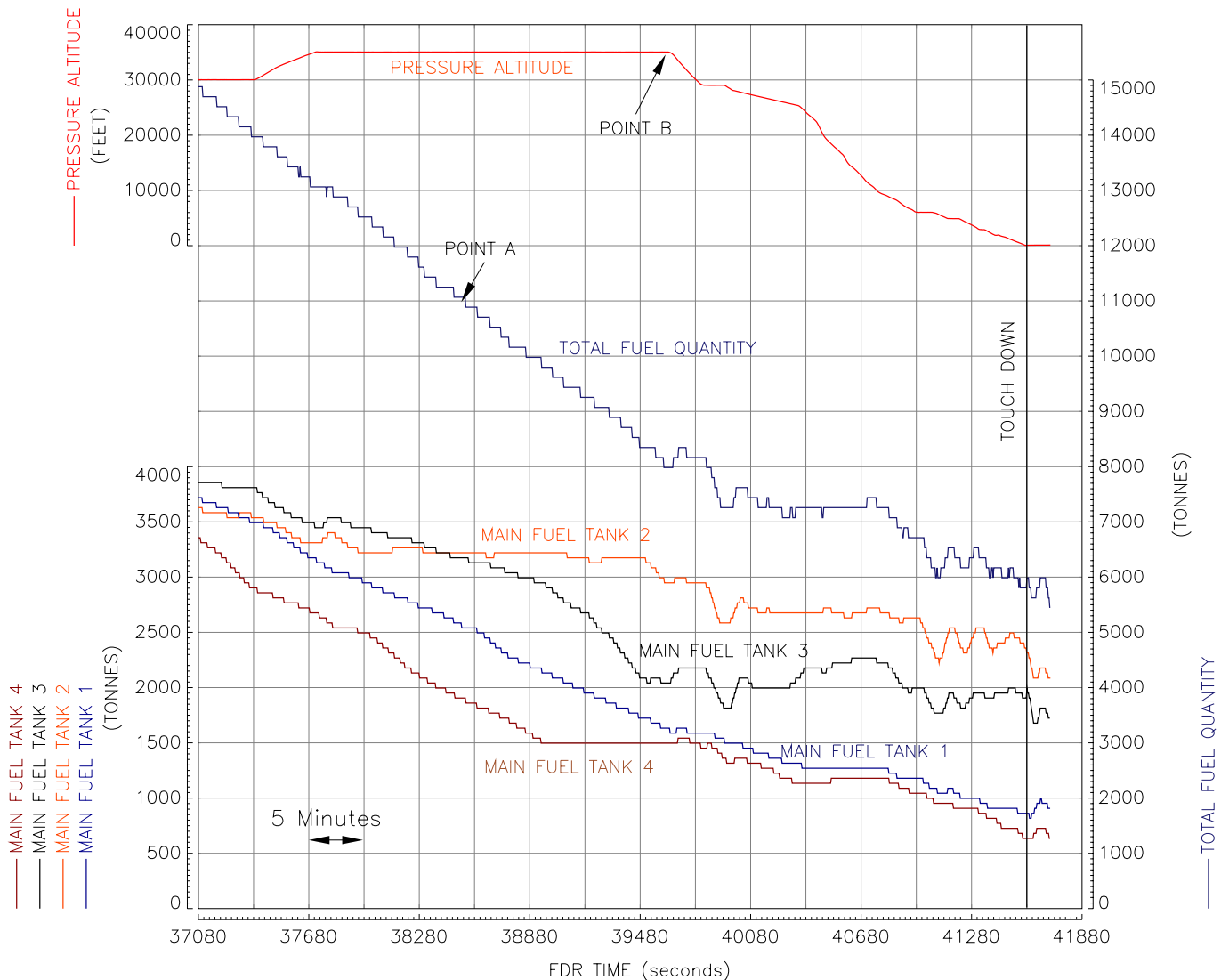
#### **Footnotes**

<sup>1</sup> Teledyne Controls DMU. The DMU was a non-mandatory acquisition unit that was programmed by the operator. One of its functions was to record flight data onto a quick access recorder for the purpose of supporting a flight data monitoring (FDM) program.

<sup>2</sup> Penny and Giles Aerospace QAR. A non-crash protected recorder that utilised a removable magneto-optical disk for the purpose of recording data.

to increase until it peaked at 1,172° C. As the throttle reached the idle thrust position, the N1 shaft speed decayed to approximately 35% and the EGT then reduced. The aircraft continued the climb to 5,000 ft. Over the next two minutes the No 2 throttle position increased and subsequently reduced for two short durations; the No 2 engine was then shutdown at 0529 hrs. At 0541 hrs the aircraft commenced a climb to FL 270, which it reached at 0606 hrs with a total fuel quantity of 106.7 tonnes.

The main tank fuel quantities prior to the top of descent until the landing are depicted in Figure 4. At 1513 hrs (Figure 4, point A) whilst at FL350, the total fuel quantity was 11 tonnes. The stabiliser, and both reserve fuel tank quantities were at zero with the centre tank at 0.2 tonnes and the main fuel tank quantities for No 1 to No 4 tanks were: 2.6 tonnes, 3.2 tonnes, 3.1 tonnes and 1.9 tonnes respectively. At 1532 hrs (Figure 4, point B), with a total fuel quantity of 8.1 tonnes, a descent to FL290 was initiated; this altitude was maintained until 1537 hrs when the final descent was commenced.



**Figure 4**  
 Salient FDR Parameters  
 (Incident to G-BLNG on 20 February 2005)

Touchdown occurred at 1604 hrs when the total fuel quantity was 5.8 tonnes. The fuel distribution across the No 1 to No 4 main fuel tanks was: 0.9 tonnes, 2.4 tonnes, 1.9 tonnes and 0.6 tonnes respectively. The FDR stopped recording at 1617 hrs when the aircraft was shutdown.

### **FDR data recovery**

#### *Recording overview*

The data was recorded onto eight tracks of a magnetic tape. Each track was no less than three hours and eight minutes in duration, ensuring a minimum of 25 hours was recorded. The tracks were written sequentially; at the end of writing one track the FDR would automatically change direction of the tape and write data onto the next track. Odd numbered tracks, 1, 3, 5 and 7, were written to in one direction and even tracks, 0, 2, 4 and 6, the other.

The FDR utilised four heads, two erase and two for recording and replaying data. The heads were paired; one erase and one record and replay. One pair recorded odd and the other even numbered tracks. The erase head is physically positioned upstream of the record and replay head; during the recording process the track to be recorded on was erased prior to new data being recorded on it. Tracks should never have been erased simultaneously in normal operation.

#### *Workshop test findings*

The FDR was initially taken for testing to a Honeywell approved repair agent. The FDR was disassembled and the incident tape was retained by the AAIB. A test tape was installed and preliminary tests confirmed that the FDR was capable of writing data to all tracks.

The FDR was then taken to the operator's avionics repair facility. The operator had two test rigs, a

Honeywell Acceptance Test Unit<sup>1</sup> (ATU) and a Honeywell FDR functional tester. The ATU provided a predominantly automated test of the unit, whereas the functional tester relied upon a predominantly manually operated test of the unit. The operator confirmed that the ATU was the preferred means of performing initial tests on an unserviceable unit and that it was also the preferred system when carrying out the final release to service test. The operator advised that the functional tester had been used rarely since the introduction of the ATU, which had been in use since about 1995. The component maintenance manual (CMM) also provided details of two alternative methods of testing that used automatic test equipment.

The FDR was first tested using the ATU which reported no faults with the unit. The FDR was then connected to the functional tester and the unit was configured to record test data onto tracks 4 through 7. When the tracks were replayed, data was recovered from all tracks, except for track 6, which had no data recorded on it. Additional tests were performed confirming that when data was being written to track 7 the data on track 6 was being simultaneously erased.

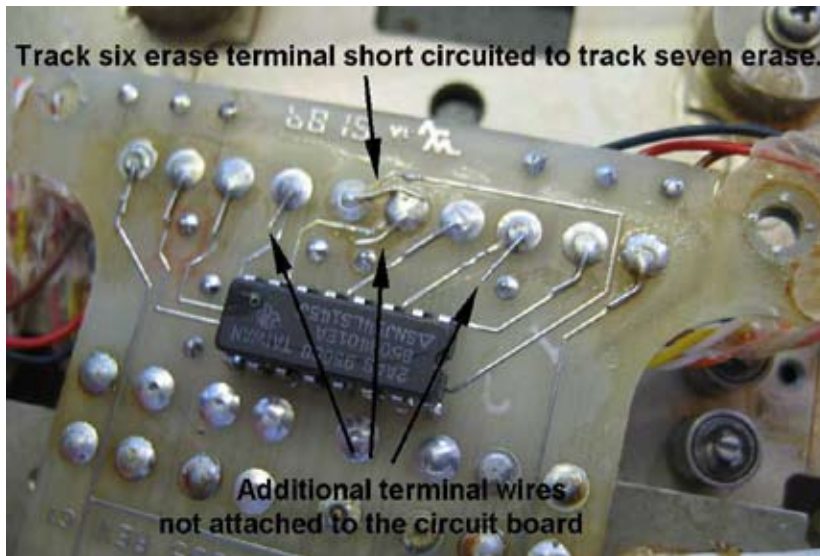
The fault was traced to the distribution board. The distribution board forms part of the crash protected tape transport assembly. Part of its function is to provide an interconnecting point between the four heads and the FDR's circuitry that was external to the crash protected assembly. A short circuit, between terminals E48 and E49, was found on the underside of the distribution board (see Figure 5). The short circuit was made by a terminal attachment wire, from terminal number E48, becoming

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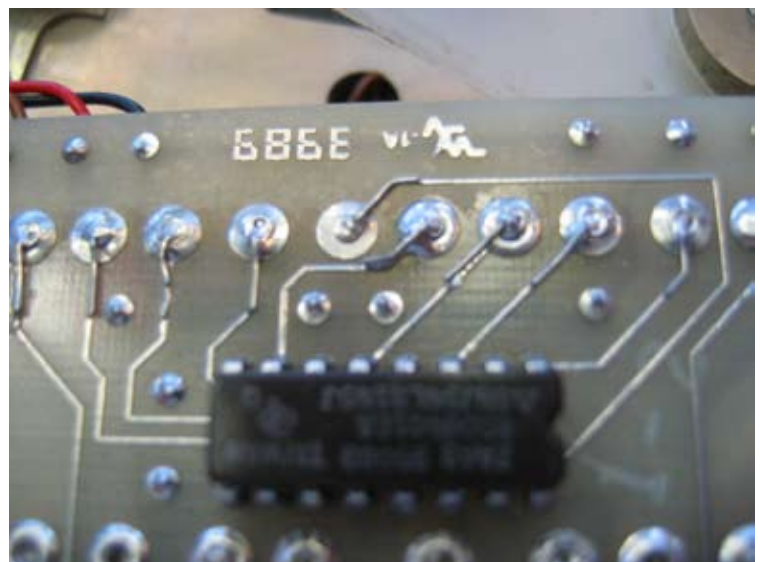
#### **Footnote**

<sup>1</sup> Honeywell ATU: A PC-based system that performed tests under software control that enabled FDR's to be released to service. ATU part number 964-0434-042, utilising test software part number 998-1513-513.





**Figure 5 (left)**  
Faulty distribution board



**Figure 6 (right)**  
Correctly configured distribution board

detached from its correct position and becoming soldered to the adjacent terminal, E49. It was also noted that other attachment wires were in close proximity to adjacent circuitry. Figure 6 shows the attachment wires in the correct positions.

The result of the short circuit was that when track 7 had been recording, data previously recorded on track 6 would have been erased.

#### *Workshop history*

The workshop history of the unit was checked and it was found that all four heads had been replaced in

September 2002. The operator's annual FDR replay records were inspected and it was found that the erasure fault had not been present prior to the replacement of the heads. Therefore it is considered most likely to have been introduced as a result of this maintenance work. The short circuit was not detectable until the board had been physically removed from the transport assembly. The operator advised that the board would not typically be removed when the heads were replaced as access to the solder terminals was adequate. The history also indicated that after the heads had been changed the unit had been to the workshop on three further occasions and released to service prior to the incident.

### *Built In Test Equipment (BITE)*

When it was initially discovered that data was missing from the FDR, the aircraft technical records were checked to see if an FDR fault had been reported prior to, or during, the incident flight. No report had been made. The aircraft's Central Maintenance Computer records were checked and it had not received a fault message from the FDR systems BITE. During the workshop tests, the BITE did not indicate the presence of the fault.

### *FDR annual readouts*

The operator, in accordance with the regulation, had performed annual readouts of the FDR. The last readout had been performed in January 2005. The operator had also retained two additional readouts, from April 2004 and August 2002. The data from August 2002 was inspected. No data was missing, although, data was found to be missing from the April 2004 and January 2005 readouts. The duration was consistent with the loss of one track in both readouts.

### *Subsequent FDR faults*

Following the discovery of the short circuit fault, the operator carried out a review of its FDR annual readouts. The review identified an FDR of the same type which had data missing that was consistent with the loss of one track. The operator advised that the FDR passed the ATU tests but failed the functional tester release to service test. The FDR was disassembled at the operator's avionics repair facility and a short circuit on the underside of the distribution board was found between terminals E47 and E49. The result of the short circuit was that when track 6 had been recording, data previously recorded on track 5 would have been erased.

### *Operators FDR testing procedures*

Following the discovery of the short circuit fault, the operator's avionics repair facility introduced a change to its testing procedures for the series 980-4100 model of FDR. The change required that a recording test be performed, using the functional tester, that would identify a failure in the erase function.

### **Analysis**

#### *Initial crew actions*

The abnormal engine behaviour indicated to the crew shortly after takeoff and reported by ATC and passengers was symptomatic of an engine surge. The crew dealt with the situation by prioritising control of the aircraft, declaring an emergency and remaining close to the airfield while evaluating the situation. The check of engine behaviour on advancing the thrust lever and the subsequent IFSD were in accordance with the QRH.

#### *Engine failure*

It was clear from the evidence found during the investigation that the initial No 2 engine problem had been a surge. The degree of wear found to the front of the HPC casing birdmouth locating ring allowed radial displacement of the front of the HPC casing that would have increased the HPC rotor blade tip clearance and thus eroded the normal compressor stall margin. The further increase in clearance, that was a consequence of the loading and thermal effects when engine power was advanced, was predicted to peak around 50 seconds after setting take-off power. The surge that occurred just after G-BNLG took off was consistent with the effects of a compressor stall induced by the increase in HPC tip clearance from these combined effects.

This was the third case globally of an IFSD due to 'Birdmouth Wear Surge' and the first experienced

by this operator. Birdmouth wear only affects some variants of the RB211 engine. While such a surge should not directly cause a hazard, the associated sudden loss of thrust and possible major engine damage made it an undesirable event, particularly since the engine manufacturer indicated that there was a propensity for the surge to occur close to the aircraft take-off point. However, the risk assessment carried out by the engine manufacturer, in conjunction with the CAA, prior to the publication of the Service Bulletin, had concluded that an engine surge is not hazardous. The modification action to rectify this problem, recommended by the engine manufacturer, had not yet been taken on this unit because neither the engine nor the module had visited an engine overhaul facility since new.

#### *Engine fuel control*

The major turbine damage sustained by the No 2 engine due to over-fuelling during the surge was a likely consequence of the FAFC behaviour when operating with the Issue 15 software used with this engine. The problem could be prevented by upgrading to Issue 16, and this had been recommended by the engine manufacturer “on an expedited basis.” At the time of the incident approximately 80% of the operator’s feet had been modified, but this particular unit had not. This modification has now been incorporated across the entire RB211-524G/H-T feet.

#### *Flight continuation*

Once the engine had been shutdown, the crew had to decide between the options of continuing to the original destination or diverting to a suitable alternate airfield, which could include the departure airfield. In the absence of any indications of damage, other than possibly to the shutdown engine, the commander assessed that an immediate, overweight landing was not required.

A decision to return to Los Angeles would have required approximately 70 tonnes of fuel to be jettisoned to reduce the aircraft’s weight to below the normal maximum landing weight. As this would have taken around 40 minutes the commander decided to continue the flight and monitor the situation, as numerous suitable diversion airfields would be available near the route. The crew confirmed that the aircraft had sufficient fuel and performance to continue the flight safely, even considering the possibility of a further engine failure. They judged that the engine had not suffered damage likely to cause a seizure or other further significant damage. In addition, the manufacturer’s QRH procedure for ENGINE LIMIT/SURGE/STALL did not require the crew to consider landing at the nearest suitable airfield.

In the continuing absence of indications of other abnormalities, the final decision to continue to their destination was in accordance with the operator’s policy of continuing the flight provided the indications suggested that “the aircraft is in a safe condition for extended onward flight”.

Systems operation should not be affected significantly following an IFSD; the level of redundancy would be reduced but the aircraft was designed and certificated to tolerate the loss of a second engine without losing essential systems. Previous experiences of the effects of engine surge suggest that it was likely that damage would be confined to the affected engine. Furthermore, the manufacturers did not foresee any problems with the extended windmilling of a damaged engine and previous cases had not resulted in significant additional damage.

A consideration, in relation to an extended continuation after an IFSD, would be the possibility of further engine failures. An indication of the relative risk for a 4-engined

aircraft of continuation, compared to a diversion, was given by an assessment of the average IFSD rate required to achieve an equivalent Extremely Improbable risk of subsequent potentially catastrophic loss of propulsion in the two cases. This indicated a marginally higher rate for the continuation, but the calculated IFSD rate in both cases exceeded the rate that had recently been experienced in-service for G-BNLG's engine type. The crew's evaluation of the planned route showed that the further aircraft performance degradation resulting from a second engine loss would not be critical.

Thus, no evidence was found to show that the fight continuation posed a significant increase in risk, and the investigation established that the aircraft landed with more than the required minimum fuel reserves. However, there were indications of deficiencies in the training regarding fuel management provided to the flight crew. The three qualified pilots were not confident that all the fuel was available and their difficulties with fuel management indicated that their knowledge of the fuel system with three engines operating was insufficient. The fuel balancing procedures used by the operator, while suitable for normal operations, was a factor in the diversion involving G-BNLG. Following the incident, the operator provided guidance to crews that was more extensive, whilst progressing discussions with the airframe manufacturer. This has resulted in the operator reverting to the fuel handling procedures recommended by the manufacturer.

The operator's continuation policy had been approved by the CAA and was similar to that used by other overseas airlines operating 4-engined aircraft. The investigation noted, however, that there was a variation in operators' policies varying from "land at the nearest suitable airfield" to no policy at all. With the introduction of public transport flights of up to 16 hours duration it is

considered that clear guidance should be provided to operators on the possible consequences of continued operation following an IFSD, particularly when this occurs early in the fight. It is therefore recommended that the CAA and the FAA, in conjunction with other relevant agencies, should review the policy on fight continuation for public transport aircraft operations, following an in-flight shutdown of an engine, in order to provide clear guidance to the operators.

### **Aircraft fuel management**

There had not been any malfunction of G-BNLG's fuel system. Following the point at which the main fuel tank contents had equalised, a balanced distribution between the tanks had been achieved over most of the subsequent fight by periodic use of the override/jettison pumps in Tank 2, in accordance with the operator's procedures. These pumps, with their higher output pressure, would override the main pumps in the outboard tanks and induce preferential engine feed from the inboard tank.

This facility was lost when fuel levels decreased below the inlet level for the override/jettison pumps and this was the point at which the distribution problems began. Thereafter, it would have been possible to induce preferential engine feed from an inboard tank by keeping both its main pumps running and shutting off both main pumps in the adjacent outboard tank, as shown during testing after the incident. However, the effectiveness of this procedure would not be readily apparent during descent, because of relatively low fuel consumption. Shutting off only one pump in the outboard tank was insufficient and an engine would tend to continue to feed from the outboard tank in this configuration.

Although the fuel system was fully described in the aircraft manuals, the operator's fuel balancing procedures were different from that of the manufacturer.

The crew had been using the override/jettison pumps to maintain fuel balance but these became ineffective towards the end of the flight. Thereafter, there was a reluctance to turn both main pumps off in a tank and a lack of confidence that this would be effective. There was increasing concern that they would not be able to keep the main tanks balanced and that some of the fuel might be unavailable.

A better understanding of the fuel system should have reassured the crew that fuel should have been available to all engines even with one tank empty. Nevertheless, the awareness of the apparent problem came at a time when the crew had made the decision to divert, had started the descent to Manchester and was therefore busy. If the crew had been in the habit of utilising the manufacturer's procedures for balancing fuel by only using the main pumps, it is possible that they would have become more confident with the procedure. Although the problem had not previously been encountered by other company pilots, the potential difficulties might have been foreseen by the operator. After the incident, the operator reverted to the manufacturer's fuel handling procedures.

The operator has a training programme for pilots who are qualified to carry out planned 3-engined ferry flights, the emphasis of which rightly concentrates on the takeoff. Additionally, all flight crews are subject to regular simulator evaluation of 3-engine handling. However, this later training is necessarily limited in time and crews are not normally subject to an extended period of 3-engine flight with the associated fuel balancing requirements. It is therefore recommended that the operator include relevant instruction on 3-engined fuel handling during initial and recurrent training.

## Safety Recommendations

The following recommendations are made:

### Safety Recommendation 2006-018

It is recommended that the Civil Aviation Authority and the Federal Aviation Administration, in conjunction with other relevant agencies, should review the policy on flight continuation for public transport aircraft operations, following an in-flight shutdown of an engine, in order to provide clear guidance to the operators.

### Safety Recommendation 2006-019

It is recommended that British Airways include relevant instruction on 3-engined fuel handling during initial and recurrent training.

### Response to Safety Recommendation 2006-019

*British Airways has accepted this recommendation and has taken the following action:*

*The revised fuel management procedures have been incorporated into the relevant manuals and training courses. All Boeing 747-400 flight crew have received additional engine-out fuel management training as part of their regular simulator training. Three-engine fuel management, including low fuel quantity procedures, have been added to the recurrent training cycle.*

## Recommendations relating to the FDR

Reliable FDRs are an essential component of effective accident investigation and in order to address the anomalies found with the model of flight recorder fitted to G-BNLG the following recommendations are made:

**Safety Recommendation 2006-022**

It is recommended that the Federal Aviation Administration should require that Honeywell modify the appropriate Return to Service test procedures, to ensure the detection of a fault which prevents a series 980-4100 model of fight recorder from retaining the appropriate minimum duration of recorded data proscribed by regulation.

**Safety Recommendation 2006-023**

It is recommended that the Federal Aviation Administration should require that Honeywell modify the design and operation of its automated equipment used for testing the series 980-4100 model of fight data recorder, to ensure the detection of a fault which prevents such a model of fight recorder from retaining the appropriate minimum duration of recorded data proscribed by regulation.

**Safety Recommendation 2006-024**

It is recommended that the Federal Aviation Administration should require that Honeywell alert all users of Acceptance Test Unit part number 964-0434-042, utilising test software part number 998-1513-513, to make them aware that the equipment will not detect a short circuit fault between one or more tracks on the distribution board of the series 980-4100 model of fight data recorder.

**Safety Recommendation 2006-025**

It is recommended that the Federal Aviation Administration should require Honeywell to amend the Maintenance Manual for the series 980-4100 model of fight data recorder to include a specific inspection of the underside of the distribution board for the presence of short circuits and detached wiring following the replacement of components.

**Safety Recommendation 2006-026**

It is recommended that the United Kingdom Civil Aviation Authority should require that operators of United Kingdom registered aircraft, installed with the series 980-4100 model of fight data recorder, review the annual fight recorder readout records for those aircraft in order to determine compliance with the applicable requirements for duration of recording.

In order to ensure the detection of failures within any mandatory fight recorder installation, which prevent the minimum required duration of recording being retained, the following safety recommendation is made:

**Safety Recommendation 2006-027**

It is recommended that the Federal Aviation Administration, European Aviation Safety Agency and the United Kingdom Civil Aviation Authority should require that, as part of any fight recorder readout procedure mandated by regulation, an assessment is conducted to ensure that the quantity and quality of all data recovered from the FDR is correct for the data rate of the system and the recorder part number concerned.