SAFE WITH THREE?

A 747 flight of nearly 11 hours with an engine shut down has touched off an international debate and a call for clear guidance for airlines.

BY MARK LACAGNINA

Picture yourself in command of a four-engine aircraft embarking on a transcontinental, transoceanic flight. Persistent surging necessitates the shutdown of one engine soon after departure. Consultation with crewmembers, company and charts gives a green light for continuing the flight. Nevertheless, the decision — and the responsibility for the decision — rest squarely on your shoulders. Do you forge ahead, or turn back, dump fuel and land?

This decision was faced last year by the commander of a Boeing 747-400 bound from Los Angeles to London. He decided to continue the flight toward the destination, but stronger-than-expected headwinds over the North Atlantic and a projected fuel reserve below the flight crew's comfort level prompted a diversion to an alternate airport. The crew's declaration of an emergency when a fuel-management problem developed during the final stage of the flight only muddied the not-so-pretty picture.

Soon after the aircraft landed safely in Manchester, England, the airline was slapped with a proposed civil penalty by the U.S. Federal Aviation Administration (FAA), which claims that the aircraft was in an unairworthy condition when the flight was continued in U.S. airspace. A recent report on the incident by the U.K. Air Accidents Investigation Branch (AAIB), on the other hand, said that the aircraft was in "safe condition for extended onward flight" and that the commander's decision to continue the flight was based on airline policy that had been approved by the U.K. Civil Aviation Authority (CAA).[1]

However, AAIB found during the investigation that policies for continued flight of a four-engine aircraft after an in-flight engine shutdown vary among airlines and has called on FAA and the CAA to work with other agencies to develop clear guidance for airlines.

As the debate inspired by this flight continues to swirl around the world, a clear understanding of what happened during that flight is essential.

'Bump, Bump, Bump'

The AAIB report said that the incident began at 0524 coordinated universal time (UTC; 2224 local time) on Feb. 20, 2005, when the aircraft took off from Los Angeles International Airport with 18 crewmembers and 352 passengers for a scheduled British Airways flight to London Heathrow Airport.

The augmented flight crew had been off duty for 48 hours after conducting the inbound flight to Los Angeles. The commander, 48, had 12,680 flight hours, including 1,855 flight hours in type.

The flight crew had decided to have an additional four tonnes (4,000 kg [8,818 lb])

of fuel loaded aboard the aircraft because of forecast weather conditions and possible traffic flow restrictions in London. Total fuel load was 119 tonnes (262,350 lb).

The first officer was the pilot flying. The standby first officer occupied the jump seat for the departure from Runway 24L. The airplane was about 100 ft above ground level and the landing gear was being retracted when the crew heard "an audible and continuous 'bump, bump, bump' sound from the left side of the aircraft," the report said. The first officer corrected a slight left yaw, and the crew observed that the no. 2 — left inboard — engine's exhaust gas temperature was increasing and its engine pressure ratio was decreasing.

A tower controller told the crew that flames were visible on the left side of the airplane.

The crew agreed that surges (compressor stalls) were occurring in the no. 2 engine. The commander, the only crewmember who had previously experienced an engine surge in flight, conducted the memory items from the quick reference handbook (QRH) "Engine Limit/Surge/Stall" checklist. The surges abated when he moved the throttle to the idle position.

Surge Symptoms

Surge is defined by the report as "an abnormal condition where the airflow through a gas turbine engine becomes unstable and momentarily reverses." The cause typically is stalling of compressor rotor blades.

"Blade stall occurs if the angle of incidence of the local airflow within the compressor relative to a rotor blade becomes excessive and the normal smooth flow over the blade breaks down," the report said. "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 spread and affect other compressor blades and other compressor sections, resulting in airflow disruption and surge.

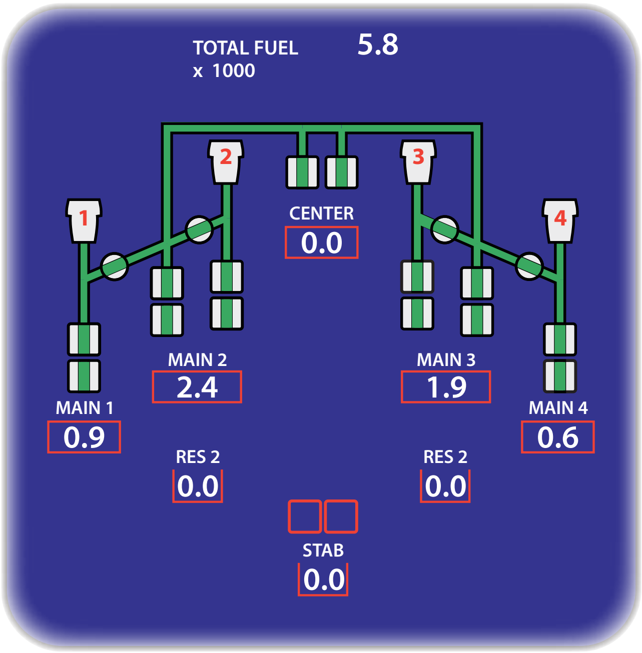
"The flow reversal associated with a surge can commonly occur on a low-frequency cyclical basis up to seven times per second," the report said. "The symptoms can include a loud bang or series of bangs audible to the passengers and crew, flames at the engine inlet and exhaust, and sudden loss of engine thrust."

The report said that jet engines often "self-recover" from a surge, but a "locked-in" compressor stall results in persistent surging.

Decision Time

The airplane was climbing through 1,500 ft when the

Copyright © Chris Sorensen Photography



Fuel quantities shown on this EICAS display are approximately what the crew would have seen after landing.

U.K. Air Accidents Investigation Branch

flight crew declared an urgent condition — pan-pan — with air traffic control (ATC) and requested radar vectors to remain in the area while they analyzed the situation. They completed the checklist, and engine indications appeared normal. However, when the commander slowly advanced the throttle for the no. 2 engine, the crew heard a surge.

The commander advanced the throttle again at a higher altitude, and the crew again heard a surge. "The crew discussed the situation and agreed that the best course of action was to shut down the no. 2 engine," the report said.

The crew shut down the engine at 0529 UTC. The cabin services director was briefed on the situation and told to stand by for further instructions. The standby first officer went to the cabin and looked out a window to check for damage. "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," the report said.

The commander and first officer reviewed company manuals and aircraft manuals, and radioed the airline's base at Heathrow. "The commander was advised that it would be preferable to continue the flight but that the course of action was the commander's decision," the report said.

The report said that the flight crew also considered the following factors:

- "The [flight management computer (FMC)] indicated a landing at final destination with approximately seven tonnes [15,432 lb of fuel], compared to the required minimum reserve of 4.5 tonnes [9,921 lb], which represents the fuel required for 30 minutes holding at 1,500 ft in the clean configuration;
- "An additional engine failure was considered, and, with regard to aircraft performance, it was deemed safe to continue;
- "The initial routing was across the continental USA, where there were numerous suitable diversion airfields;
- "The present situation would not justify an overweight landing, and the time to jettison fuel (approximately 70 tonnes [154,324 lb]) down to below maximum landing weight would be about 40 minutes;
- "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; [and,]
- "The manufacturer's QRH for 'Engine Limit/Surge/Stall' did not require the crew to consider landing at the nearest suitable airfield."

The commander decided to continue the flight and monitor the situation.

What If?

Because of adequate redundancy, the aircraft's systems would not be affected by long-range flight with one engine out, according to the report. "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 percent at normal cruise speed," the report said.

The possibility of damage to the no. 2 engine from prolonged windmilling was studied during the investigation. The engine — a Rolls-Royce RB211-524, which also is used on the 767-300 — had undergone 180 minutes of windmilling, with no bearing damage, during tests for ETOPS (extended-range twin-engine operations) approval. Moreover, Rolls-Royce issued a notice in 1991 advising operators that "windmilling the engine for lengthy periods without engine oil does no harm to the bearings within that engine … therefore, a flight may continue after in-flight shutdown for oil loss." The company told investigators that no further major damage would be expected from windmilling for 12 hours or more an engine with damage similar to that in the incident engine.

What if another engine failed or had to be shut down by the crew?

"As a four-engine aircraft, the B747 is designed and certificated to tolerate the loss of a second engine following an initial IFSD [in-flight shutdown], without losing essential systems or necessary performance capabilities," the report said. "The likely effects on systems would include the need to shed nonessential electrical loads, such as galleys, and to limit bleed air supplies in order to maintain adequate performance from the operating engines. … Aircraft performance implications would include a substantial further loss of altitude capability."

Rolls-Royce told investigators that the IFSD rate for RB211-524 engines in the 12 months preceding the incident was 0.0073 per 1,000 engine flight hours — or about one IFSD per 137,000 engine flight hours.

"Previous experiences of the effects of engine surge suggest that it was likely that damage would be confined to the affected engine," the report said. "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."

Across the Pond

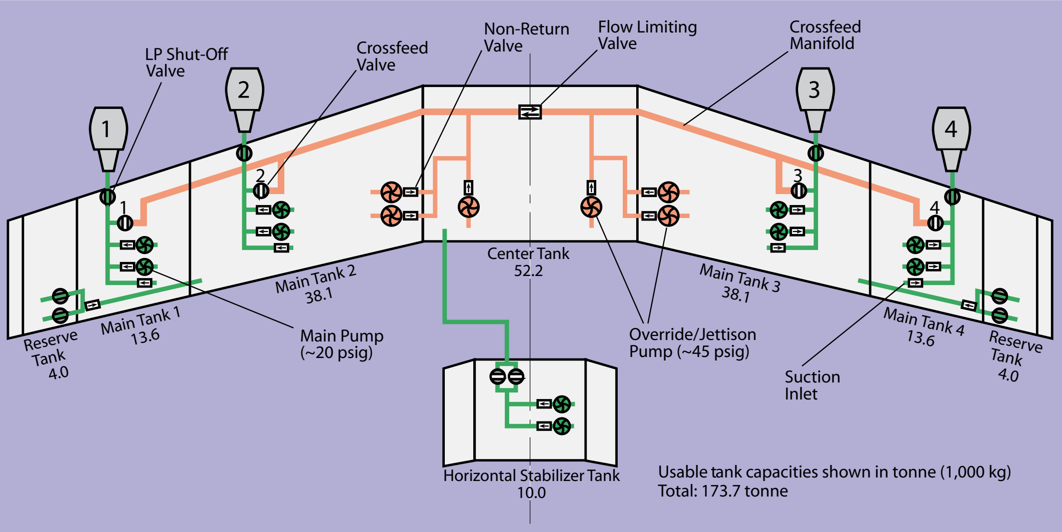
After deciding to continue the flight, the flight crew canceled the urgent condition and obtained clearance from ATC to climb to Flight Level (FL) 270, approximately 27,000 ft, where cruise was established at 0.75 Mach.

The commander rested in the crew bunk before returning to the flight deck as the aircraft neared the North Atlantic. The crew had agreed to plan for a landing at Heathrow with no less than 6.5 tonnes (14,330 lb) of fuel remaining and had requested FL 320 for the overwater segment of the flight. ATC told the crew, however, that because of opposite-direction traffic, FL 320 was not available but that either FL 350 or FL 290 was available. The crew chose FL 290 because the FMC indicated that 7.0 to 7.5 tonnes (15,432 to 16,535 lb) of fuel would remain on landing at Heathrow.

Based on the indication of adequate fuel reserve on arrival, plus the absence of any further abnormalities during the trip across the United States, the crew decided to continue the flight to London while closely monitoring the fuel supply.

The fuel system in a 747-400 comprises two main tanks and a reserve tank in each wing, a wing center-section tank and a horizontal stabilizer tank (Figure 1). In each main tank are two "main" pumps that operate in parallel and supply fuel to the respective engine and/or the crossfeed manifold. The inboard main tanks, which hold almost three times more fuel than the outboard main tanks, also have two override/jettison pumps that provide

B747-400 Fuel System



Usable tank capacities shown in tonne (1,000 kg)
Total: 173.7 tonne

psig= Pounds per square inch gauge

Source: U.K. Air Accidents Investigation Branch

Figure 1

more than double the flow rate of the main pumps and supply fuel only to the crossfeed manifold.

In normal operation, all the pumps are activated and all crossfeed valves are opened before takeoff. During flight, the horizontal stabilizer tank is emptied first, followed by the wing center-section tank and the reserve tanks. Fuel in the inboard main tanks then is cross-fed to the engines until fuel quantity in the inboards matches the quantity in the outboard main tanks; total fuel quantity at this point typically is 55 tonnes (121,254 lb). An engine indicating and crew alerting system (EICAS) message then prompts the crew to discontinue crossfeeding by deactivating the override/jettison pumps and closing the crossfeed valves in the outboard main tanks. Each main tank now feeds fuel only to its respective engine, and no further crew action is required for fuel management unless a fuel imbalance or a low-fuel condition occurs.

Because the no. 2 engine was inoperative, a fuel imbalance did occur after the crew discontinued crossfeeding. The fuel quantity in the left inboard main tank, which normally would have been supplying fuel to the no. 2 engine, did not decrease as rapidly as the fuel quantities in the other main tanks. The crew, following the procedure in the airline's operations manual, periodically activated the override/jettison pumps in the left inboard main tank to balance the fuel in the main tanks.

Strong Winds

At an unspecified point during the overwater flight, the crew had conducted a climb to FL 350. They found, however, that the headwind was stronger than forecast at that flight level. As the aircraft neared Ireland, the EICAS indicated 12 tonnes (26,455 lb) of fuel aboard, and the FMC indicated that the aircraft would have 6.5 tonnes of fuel remaining on landing at Heathrow.

Checking alternate airports, the crew noted an FMC indication that the aircraft would have seven tonnes of fuel remaining if it were landed at Manchester Airport, which is about 140 nm (260 km) northwest of London. The crew decided to divert to Manchester.

While conducting the descent, the crew noticed that the fuel quantity in the left inboard tank no longer was decreasing, even when the override/jettison pumps were activated. Concerned that the fuel in that tank might not be usable, the crew declared an urgency and were cleared by ATC to fly directly to a position 10 nm on the extended centerline of Manchester's Runway 06R.

Inbound to Manchester, the EICAS generated a low fuel warning. The crew conducted the QRH procedure, activating all main fuel pumps and opening all crossfeed valves, and declared an emergency. The commander took control and landed the aircraft at 1604 UTC without further incident. The EICAS showed 5.8 tonnes (12,787 lb) of fuel remaining in the tanks.

The report said that the crew's concern that fuel would not be available from the left inboard main tank indicated that their knowledge of the fuel system and their training on fuel management were deficient. The fuel quantity in that tank had stopped decreasing when the standpipe inlets for the override/jettison pumps were unported. This is a fuel-system feature designed to prevent fuel quantity in either inboard main tank from being reduced below about 3.2 tonnes (7,055 lb) when the override/jettison pumps are used to jettison fuel.

According to the airline's fuel-balancing procedure, the main pumps in the tanks with the lowest fuel quantity should be deactivated if use of the override/jettison pumps fails to balance the fuel. The report said that the crew apparently had been reluctant to deactivate the main pumps. It noted that the airline's fuel-balancing procedure differed from the aircraft manufacturer's recommended procedure, which calls only for deactivation of the main pumps in the tanks with the lowest fuel levels.

"If the crew had been in the habit of utilizing 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," the report said. "After the incident, the operator reverted to the manufacturer's fuel-handling procedures."

Based on these findings, AAIB recommended that the airline include "relevant instruction on three-engined fuel handling during initial and recurrent training." Among actions taken in response to the recommendation, British Airways revised fuel-management procedures in relevant manuals and training courses, provided additional engine-out fuel-management training to all 747-400 flight crews and added three-engine fuel-management and low-fuel procedures to its recurrent training programs.

Case Displacement

The report said that the surges in the no. 2 engine likely had resulted from a series of events that began when excessive wear of a compressor section casing joint, called a birdmouth, caused a slight downward displacement of the forward end of the high-pressure compressor case. The displacement increased the clearance between the rotor blades and case liner in the lower half of the compressor. The clearance further was increased by erosion of the rotor blades from contact with the case liner in the upper half of the compressor.

The surges caused further damage resulting from contact between blades and guide vanes in both the high-pressure and intermediate-pressure compressors. This damage, in turn, exacerbated the surging.

Two previous incidents of engine surges and shutdowns resulting from birdmouth wear had led to the issuance of a Rolls-Royce service bulletin, SB 72-D574, that called for modifying the geometry of the casing and applying a wear-resistant coating to the birdmouth during routine disassembly of RB211 engines. The incident engine, which had accumulated 24,539 operating hours and 3,703 cycles, had not been disassembled and, thus, had not been modified according to the bulletin.

The surges in the incident engine also had led, indirectly, to overtemperature damage to the turbine sections. The software controlling operation of the full-authority fuel controller (FAFC) included logic that increased fuel flow to prevent flameout if a burner pressure sensing line fractured. "However, service experience showed that this logic could be erroneously activated during a surge and locked-in stall event, leading to [over-fueling] and overtemperature damage to the turbine blades and vanes."

Rolls-Royce SB RB.211-73-D435 in July 2001 introduced revised FAFC software designed to prevent this problem. At the time of the incident, British Airways had installed the revised software in 80 percent of the affected engines in its fleet. The software had not yet been installed in the incident aircraft.

Guidance Varies

During the investigation, AAIB surveyed the policies of several public transport aircraft operators regarding continued flight of a four-engine aircraft following an IFSD. The report said that British Airways provided the following guidance to its flight crews:

- "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; [and,]
- "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."

Three operators provided similar guidance, but the guidance provided by others varied. "One operator required that the aircraft land at the nearest suitable airport. Another had no policy and left it as a commander's decision," the report said. "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."

Based on these findings, AAIB recommended that CAA and FAA, "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."

Current FAA guidance is contained in U.S. Federal Aviation Regulations Part 121.565, which says that after one engine on a three- or four-engine airplane in airline service fails or is shut down, the pilot-in-command (PIC) may continue the flight to "an airport that he selects" if he decides that this is as safe as landing at the nearest suitable airport. The regulation says that the PIC must base his decision on the following:

- "The nature of the malfunction and the possible mechanical difficulties that may occur if flight is continued;
- "The altitude, weight and usable fuel at the time of engine stoppage;
- "The weather conditions en route and at possible landing points;
- "The air traffic congestion;
- "The kind of terrain; [and,]
- "His familiarity with the airport to be used."

Opinions Vary

The incident investigation supported the commander's decision to continue the flight. "No evidence was found to show that the flight continuation posed a significant increase in risk," the report said. "And the investigation established that the aircraft landed with more than the required minimum fuel reserves."

In its complaint proposing a civil penalty of US$25,000, however, FAA said that British Airways "operated an aircraft in the United States in an unairworthy condition" and "failed to comply with its operations specifications." In response, the airline requested a hearing. The case had not been resolved at press time.●

Note

1. U.K. Air Accidents Investigation Branch (AAIB) report no. EW/C2005/02/04. *AAIB Bulletin* 6/2006.