All Engines-out Landing Due to Fuel Exhaustion, Air Transat, Airbus A330-243 marks C-GITS, Lajes, Azores, Portugal, 24 August 2001

Micro-summary: **Following an undetected fuel leak, this A330-243 had to dead-stick to a successful landing.**

Event Date: **2001-08-24 at 0613 UTC**

Investigative Body: **Aviation Accidents Prevention and Investigation Department, Portugal, with extensive cooperation by Canada TSB**

Investigative Body's Web Site: **http://www.gpiaa.gov.pt/**

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Government of Portugal

MINISTÉRIO DAS OBRAS PÚBLICAS, TRANSPORTES E COMUNICAÇÕES

GABINETE DE PREVENÇÃO E INVESTIGAÇÃO DE ACIDENTES COM AERONAVES

Aviation Accidents Prevention and Investigation Department

Accident Investigation Final Report

All Engines-out Landing Due to Fuel Exhaustion

Air Transat
Airbus A330-243 marks C-GITS
Lajes, Azores, Portugal
24 August 2001

22 / ACCID /GPIAA / 2001

GPIAA
Homologo nos termos
do n.º 3 do art.º 26.º, do
D.L. 318/99, de 11/8

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Occurrence Summary

On August 24, 2001, Air Transat Flight TSC236, an Airbus 330-243 aircraft, was on a scheduled flight from Toronto Lester B Pearson Airport, Ontario (CYYZ), Canada to Lisbon Airport (LPPT), Portugal with 13 crew and 293 passengers on board. At 05:33, the aircraft was at 4244N/2305W when the crew noted a fuel imbalance.

At 05:45, the crew initiated a diversion from the flight-planned route for a landing at the Lajes Airport (LPLA), Terceira Island in the Azores. At 05:48, the crew advised Santa Maria Oceanic Control that the flight was diverting due to a fuel shortage.

At 06:13, the crew notified air traffic control that the right engine (Rolls-Royce RB211 Trent 772B) had flamed out. At 06:26, when the aircraft was about 65 nautical miles from the Lajes airport and at an altitude of about FL 345, the crew reported that the left engine had also flamed out and that a ditching at sea was possible.

Assisted by radar vectors from Lajes air traffic control, the crew carried out an engines-out, visual approach, at night and in good visual weather conditions.

The aircraft landed on runway 33 at the Lajes Airport at 06:45. After the aircraft came to a stop, small fires started in the area of the left main-gear wheels, but these fires were immediately extinguished by the crash rescue response vehicles that were in position for the landing.

The Captain ordered an emergency evacuation; 16 passengers and 2 cabin-crew members received injuries during the emergency evacuation.

The aircraft suffered structural damage to the fuselage and to the main landing gear.

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1.0 Factual Information

1.1 History

1.1.1 History of the Flight

On August 24, 2001, Air Transat Flight TSC236, an Airbus 330-243 aircraft, was on a scheduled flight from Toronto Lester B Pearson Airport, Ontario (CYYZ), Canada to Lisbon Airport (LPPT), Portugal with 13 crew and 293 passengers on board. The Captain was carrying out the pilot flying (PF) duties for this flight. TSC236 was planned to depart CYYZ at 00:10 UTC[1], with 47.9 metric tons of fuel[2], which included a 5.5 tons over and above the fuel required by regulations for the planned flight; the actual take-off time was at 00:52 with a reported 46.9 tons of fuel on board. According to the crew, the flight progressed normally until after crossing 30º West and at 05:03 when they observed unusual engine oil indications on the Number 2 (right) engine (Rolls-Royce RB211 Trent 772B)[3]. The ENGINE Electronic Centralized Aircraft Monitoring System (ECAM) page was manually selected by the crew, and the oil indications were communicated by high-frequency (HF) radio to the dispatcher at the company's Maintenance Control Centre (MCC)[4] at Mirabel Quebec, Canada.

At approximately 05:33, an advisory ADV message was displayed on the Engine/Warning Display (EW/D). The crew noticed the ADV and deselected the ENGINE ECAM page. This action resulted in the Fuel ECAM page being displayed and the crew becoming aware of a fuel imbalance between the left and right inner-wing tanks. To correct the imbalance, the crew selected the cross feed valve OPEN and the right-wing fuel pumps OFF in order to feed the right engine from the left-wing tanks.

At 05:45, the fuel on board had reduced to below the minimum required fuel on board to reach Lisbon, and the crew initiated the diversion to Lajes Airport (LPLA) on Terceira Island in the Azores. By 05:48, the crew advised Santa Maria Oceanic air traffic control[5] that the flight was diverting due to a fuel shortage; the fuel on board had reduced to 7.0 tons. In attempts to resolve the sudden and unexplained reduction in the fuel quantity readings, the crew asked the cabin crew to visually check the wings and engines for a possible fuel leak: the visual check did not reveal any evidence of a fuel leak.

At 05:54, in reaction to the continued abnormally high rate of reduction in the fuel-on-board quantity reading, the crew selected the right-wing fuel pumps to ON and the left-wing pumps to OFF. These selections established cross feed of the fuel in the right wing tanks to both engines. According to the crew, the cross feed from the right tank was established to use up the fuel from the right wing and to counter the possibility that the fuel loss was the result of a leak in the right wing tanks.

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[1] All times are Coordinated Universal Time unless otherwise noted.

[2] All fuel quantities are in metric tons, unless otherwise noted.

[3] Analysis of the DFDR data indicates that a higher-than-normal rate of reduction in aircraft gross weight started at 04:38, the time that the fuel leak started.

[4] Air Transat's MCC is manned by the company's dispatcher and maintenance manager.

[5] The cabin preparations for the possible ditching and eventual engines-out landing are detailed in section "1.15 Passenger Safety and Survival" of the report.

The crew then contacted MCC on HF, advising the dispatcher of the inexplicable low fuel quantity readings. At this time, fuel on board was 4.8 tons, or 12 tons below the planned quantity. The crew reported that they could not determine what the problem was, that the fuel indication was continuing to reduce, and that the apparent fuel leak was happening in the right-wing inner tanks. At 05:59, during the dialog with MCC, the crew reported that the fuel quantity had further reduced to 1.0 tons in the right tanks and 3.2 tons in the left tanks. MCC asked whether the fuel loss might be a leak in the left engine. In reaction to this suggestion, the Captain momentarily re-selected cross feed from the left tanks. The crew stated that all fuel pumps were selected ON when the fuel remaining was 1.1 tons.

At 06:13, when the aircraft was at FL390 and 150 miles from Lajes, the right engine flamed out. The crew notified Santa Maria control that the engine had flamed out and that the flight was descending. At 06:15, the crew reported to air traffic control that the fuel on board had reduced to 600 kilograms. At 06:23, the First Officer declared a "Mayday" with Santa Maria Oceanic Control, and at 06:26, when the aircraft was 65 nautical miles from the Lajes airport and at an altitude of about FL 345, the left engine flamed out. The ALL ENG FLAME OUT procedure was completed by the crew and an engines-out descent profile was flown towards Lajes.

At 06:31, the flight was transferred to Lajes Approach Control. Assisted by radar vectors and flashing of the runway lights, the aircraft arrived about 8 miles off the approach end of runway 33 at approximately 13 000 feet on a track of about 270°. The Captain advised Lajes that he was conducting a left 360-degree turn in order to lose altitude. During the turn, the aircraft was configured with leading-edge slats out and landing gear down for the landing. S-turns were conducted on final to lose additional altitude.

Figure 1 - Aircraft After Landing

At 06:45, the aircraft crossed the threshold of runway 33 at about 200 knots, touched down hard 1 030 feet down the runway, and bounced back into the air. The second touchdown was at 2 800 feet from the approach end of the runway, and maximum braking was applied. The aircraft came to a stop 7 600 feet from the approach end of the 10 000-foot runway. After the aircraft came to a stop, small fires started in the area of the left main-gear wheels, but these fires were immediately extinguished by the crash rescue response vehicles that were in position for the landing[6]. The Captain ordered an emergency evacuation. Fourteen passengers and two cabin-crew members received minor injuries, and two persons received serious injuries during the emergency evacuation. The aircraft suffered structural damage to the fuselage and to the main landing gear.

[6] The response of crash file rescue services to this emergency landing are detailed in section "1.14 Crash Fire Rescue and Survival" of the report.

1.1.2 Passenger Cabin Events

All activities in the passenger cabin were proceeding normally until approximately 05:45 when the FD entered the cockpit to brief the Captain on the special passenger services that would be required when the flight arrived at Lisbon. At this time, the flight crew was occupied with the fuel imbalance problem and in setting up for the diversion to Lajes. The Captain advised the FD that the flight was diverting due to a fuel shortage and would be landing on Terceira Island in the Azores. She was told to come back for an update on the situation in about 15 minutes. Based on this information, the FD returned to the passenger cabin, informed the flight attendants of the diversion, and directed them to pick up the remaining snack trays and to secure the galley equipment.

About five minutes later, when the cabin was secured, the FD returned to the cockpit for further instructions. The Captain informed the FD that there was a possible fuel leak. He then directed the FD to conduct a visual check of the engines and wings for evidence of a fuel leak, in particular for vapor or cloud condensation forming beneath, below and behind the wing and the engine.

The FD returned to the cabin and briefed the R2 flight attendant on the situation and what signs to look for. The FD went door L3 to assess the left-hand side wing and the other flight attendant assessed the right side of the aircraft from the area of door R3. Because the lights were on in the cabin and because it was nighttime it was difficult to see outside the aircraft. So, the FD briefed the L3 flight attendant on what to look for, returned to her station, and turned off the cabin lights. No signs of a fuel leak were evident.

At 06:01, the FD returned to the cockpit to inform the Captain of the results of the inspection. The Captain then informed the FD that the flight would be landing in about 40 minutes and to prepare the cabin. The FD inquired whether the briefing should be for a landing or for a ditching. The Captain stated that it should be for a ditching. The FD returned to the cabin and briefed the flight attendants on the situation, instructing them to get their life jackets and position themselves for the passenger briefing.

At 06:13, the FD returned to the cockpit to get further instructions from the Captain. The Captain informed the FD that he did not have any time to brief the passengers and directed the FD to do all the remaining cabin announcements. The FD used the Emergency Action Plan checklist to brief the passengers on the action plan for a ditching, which included instructions on donning of life jackets and demonstration of the brace position.

Just as the cabin announcements were being completed and as a result of the flame out of the second engine at 06:26, the normal cabin lighting began fluctuating and the public address system became intermittent. The FD was able use the public address system to command the cabin crewmembers to be seated. The normal lighting then failed and the emergency lighting came on.

Approximately five minutes after the power failure, the oxygen masks deployed in the passenger cabin as the result of the loss of cabin pressurisation.

Most passengers did not have difficulty in putting on their oxygen masks. However, some of the flight attendants in the following positions reported that there were problems with oxygen flow for some masks in their areas of responsibility: L-3, R-3, and R-2.

It was also reported that the oxygen container door at position R2 did not open automatically, and that the R2 flight attendant had to use a manual release tool to open the container door.

The First Officer subsequently made a public address announcement that the flight would be landing on or near the runway in 5 to 7 minutes and to prepare for a land evacuation. Just prior to the landing the First Officer issued a “Brace, Brace, Brace” command. The flight attendant shouted the prescribed brace commands to the passengers.

Immediately after the landing, the passengers began cheering and clapping. Concerned those follow-on instructions from the flight deck would not be heard, the flight attendants shouted to the passengers to be quiet; the passengers complied. About 10 to 20 seconds after the aircraft came to a stop, the Captain made the “EASY VICTOR” evacuation command.

The evacuation was attempted using all emergency exits and evacuation slides. All doors and slides functioned normally, except for exit L3, which only opened approximately 20 to 25 centimetres. The passengers in the area of L3 were redirected to other exit doors.

The only other problems noted with the evacuation from the cabin were the following:

- Some passengers were reluctant to leave the aircraft and had to be aggressively encouraged to do so;
- Many passengers attempted to leave with carry-on baggage; and
- One paraplegic passenger located in row 1 in the forward cabin and an elderly man in row 39 in the aft-cabin, who could not walk without his cane, had to be physically assisted to reach the exit and to get onto the escape slide.

The evacuation reportedly was completed in approximately 90 seconds. Following the evacuation, the passengers were marshalled away from the aircraft.

1.1.3 Summary of Related Engine Maintenance Events

On 15 August 2001, during a routine inspection of the Air Transat Airbus 330-243, Serial Number 271 aircraft, metal chips were found on the master chip detector in the oil system of the right (No #2) engine (Rolls-Royce RB211 Trent 772B, # 41075). On 17 August 2001 there was a second incidence of metal particles in the oil system, and because the origin of the metal could not be identified, Air Transat decided to replace the engine. Air Transat's spare engine was not available; consequently, a Rolls-Royce loaned engine, previously positioned at the Air Transat facilities, was used.

The engine change, which commenced at midnight on 17 August 2001, proceeded normally up to the point when it was discovered that the rear hydraulic pump (P/N: 974800), taken from the removed engine, could not be fitted onto the replacement engine due to an interference with the high pressure fuel pump inlet tube (P/N: FK12446) already on the engine.

A search through the Airbus Illustrated Parts Catalogue (IPC) revealed the existence of a Service Bulletin (SB) RB.211-29-C625. It was then realized that the loaned engine, last certified by Hong Kong Aero Engine Services Limited, was in a pre-SB configuration, and the engine being replaced was in a post-SB configuration. The technician leading the engine change could not access the SB’s from the available computer terminals, and accepted advice from the maintenance-engineering department that only the rear, fuel tube from the engine being replaced needed to be used. According to the technicians, a clearance between the fuel and the adjacent hydraulic tube was obtained.

Upon completion of the engine replacement, inspections were conducted by both the lead technician and another technician and no discrepancies were noted. The engine was successfully ground run and the aircraft was released for flight with a post-SB RB.211-29-C664, hydraulic pump (P/N: 974800), a post-SB C625 fuel tube (P/N: FK30383), and a pre-SB C625 hydraulic line (P/N: LJ51006).

An examination of the aircraft following the occurrence determined that both engines stopped due to fuel exhaustion, which was precipitated by a rupture of the high-pressure fuel pump inlet fuel tube on the right engine, which failed as a result of hard contact with the hydraulic line. The engine had accumulated 67.5 flight hours since the engine installation.

1.2 Injuries to Persons

	Crew	Passengers	Others	Total
Fatal	-	-	-	0
Serious	-	2	-	2
Minor/None	13	291	-	304
Total	13	293	-	306

All the injuries to the passengers were as the result of the evacuation from the aircraft. Although most injuries were of a very minor nature, two passengers required hospitalization for treatment of their injuries.

1.3 Damage to Aircraft

The aircraft first contacted the runway at 1 050 feet from threshold and then bounced for 1 650 feet prior to the second and last touch down. The touchdowns were sufficiently hard to cause some skin wrinkles on each side of the fuselage just above the main wings trailing edges.

Figure 2 - Left-main Boogie

Due to the engines-out condition, the landing was conducted without the brake anti-skid and normal breaking systems. Because the emergency brake accumulator only provides for a limited amount of brake applications, full braking was applied and retained at the second touch down, resulting in the main wheels locking up. The tires quickly abraded and deflated at a point between about 300 and 450 feet beyond the second and final touch down. The segments of the main wheels contacting the pavement were worn down to the bearing journals, the left, rear, inboard wheel detached from the axle. Both left and right brake anti-torque links attachment horns on the bottom segments of the main oleos also contacted the pavement; the horns were abraded to the point that some of the links separated from the oleo resulting in the rotation of at least one brake carrier.

Shedding of brake and wheel components during the landing run also resulted in a combination of punctures and impact damage to the airframe and left engine nacelle.

1.4 Other Damage

Some minor damage, consisting of scoring and scuffing, was caused to the runway surface due the skidding of the wheels and the contact of the brake/oleo components. Immobilization of the aircraft on the runway resulted in closure of the airport for a 4-day period and caused substantial disturbance to the traffic of island inhabitants as well as movement of goods. Moving of the aircraft off the runway was delayed due to problems encountered during the initial salvage attempts, and delays encountered in obtaining the required replacement undercarriage parts and adequate lifting equipment.

1.5 Personnel Information

1.5.1 Flight Crew

	Captain	First Officer
Age	48	28
Pilot Licence	ATPL	ATPL
Medical Expiry Date	1 January 2002	1 June 2002
Total Flying Hours	16 800	4 800
Hours on Type	796	386
Hours Last 90 Days	160	158
Hours on Type Last 90 Days	160	158
Hours on Duty Prior to Landing	13	8
Hours Off Duty Prior to Work Period	62	25

1.5.1.1 Captain Information

The Captain held a Canadian Airline Transport Pilot Licence – Aeroplane (AA112310), endorsed for single and multi-engine land and seaplanes, with individual type aircraft ratings on B73A, B73B, CS12, CV58, DC3, DC4, DC6, E120, EA33, FA27, HS25, HS74, and L1011 aircraft. His licence was endorsed with a Group 1 Instrument Rating valid until 1 November 2001.

The Captain started working for the company as a First Officer on the L1011 on 11 March 1996, and he was upgraded to Captain on L1011 on 15 December 1997. On 23 March 2000, he began his conversion to the A330. From 23 March 2000 to 7 April 2000, he completed the Video and Computer Based Instruction course and 3D trainer portions of the A330 training in Mirabel, Quebec, Canada, under the supervision of an Air Transat instructor. The flight simulator portion of the initial A330 training was conducted by Airbus instructors at the Airbus Industries Training Center in Toulouse, France from 12 April 2000 to 8 May 2000. All training was done in accordance with the Airbus A330 training program.

The Captain passed his initial Pilot Proficiency Check as an A330 Captain on 11 May 2000, and his final Route Check was performed on 22 June 2000. Company training records indicated that he had successfully completed all required recurrent training. No shortcomings in performance were recorded on his file. The Captain successfully completed his most recent check ride on 29April 2001.

1.5.1.2 First Officer Information

The First Officer held a Canadian Airline Transport Pilot Licence – Aeroplane (AA731791), endorsed for single and multi engine land and seaplanes, with individual type aircraft ratings on BA31, EA33, L101, and LR35 aircraft. His licence was endorsed with a Group 1 Instrument Rating valid until 1 January 2003.

The First Officer started working for the company on 11 November 1998 as a First Officer on the L1011 aircraft. His initial training on the A330 was done in Airbus training facility in Miami, Florida, United States of America, in accordance with the Airbus A330 training program under the supervision of Air Transat instructors. He completed his A330 training in November 2000.

The First Officer passed his initial Pilot Proficiency Check as an A330 First Officer on 22 November 2000, and his final Route Check was done on 23 December 2000. Company training records indicated that he had successfully completed all required training. No shortcomings in performance were recorded on his file. The First Officer successfully completed his most recent check ride on 15 May 2001.

1.5.2 Cabin Crew

The cabin crew consisted of a Flight Director (FD)[7], an Assistant Flight Director (AFD), and nine flight attendants. The FD also carried out the responsibilities for cabin safety position L1, and the AFD, cabin safety position L4. The other flight attendants were assigned to positions L1A, L2, L3, L4, L4A, R1, R2, R3, R4, and R4A. This manning level was in accordance with the flight attendant requirements specified Canadian Aviation Regulation subpart 705.104.

The Flight Director had been employed as a flight attendant with the company since 1992, and was qualified on the A330 in November 1998. Seven of the ten flight attendants had at least eight years of experience with the company, two had six years, and one had three years experience; all of the flight attendants had 30 or more months of experience on the A330.

Company training records indicate that all cabin crewmembers had received the initial and recurrent training required for their positions.

1.5.3 Technical Personnel

1.5.3.1 Engine Controller

At Air Transat, each engine model is assigned to an Engine Controller, who liaises with the manufacturer to obtain additional expertise as needed. The controller's responsibility centres on the off-wing maintenance of the engine. Air Transat's Trent Engine Controller was assigned to this position because of his previous experience with Rolls-Royce engines. He did not hold an Aircraft Maintenance Engineer licence, nor was he required to.

[7] Flight Director is the lead flight attendant in charge of the passenger-cabin crew.

The Trent Engine Controller worked Monday to Friday, and was on call during the weekend that the engine was being replaced.

1.5.3.2 Maintenance Technicians

The engine change was carried out by different crews of four to six technicians. Each crew had at least one A330-rated technician, and the crews worked normal 8-hours shifts. The technicians normally worked a sequence of 4 days on then 3 days off. Some worked an extra day with over-time compensation.

The crews were lead by a lead technician holding an AME licence endorsed on the A330 aircraft. He had been selected to supervise the engine change because of his previous experience with three A330 engine changes within the last year. The lead technician normally worked day shift Monday to Friday. On Friday, 17 August 2001, he was called at home around 19:00 hours and asked to lead an engine change the next day. He reported to work on Saturday at 06:30 and worked until 19:00 hours. He was back to work the next morning at 06:30 hours and left upon completion of the engine change at 17:30 hours.

1.5.4 In-house Rolls-Royce Representative

A provision of the aircraft leasing agreement was that the aircraft lessor, International Lease Finance Corporation, would position a Rolls-Royce representative with Air Transat. The representative functioned mainly as a facilitator, assisting the operator and providing a direct communication link with the engine manufacturer. The representative could offer advice, but was not part of, nor responsible for decision-making.

1.6 Aircraft Information

Manufacturer	Airbus Industries
Type and Model	A330-243
Year of Manufacture	1999
Serial Number	271
Type Approval	A-205
Certificate of Airworthiness (Flight Permit)	03 May 1999
Total Airframe Time	10 433 hours
Total Cycles	2 390
Engine Type (number of)	Rolls-Royce RB211 Trent 772B (2)
Maximum Allowable Take-off Weight	230 000 kilograms
Recommended Fuel Type(s)	JET A-1, JET A JET B, JP 4, JP 5, JP 8
Fuel Type Used	JET A-1

The lease status of the aircraft had no bearing on the control of the aircraft. The operation and maintenance of the aircraft was the responsibility of the air operator.

The aircraft was registered to Air Transat AT, Inc. on 28 April 1999 and had a valid Certificate of Airworthiness issued on the same date. The aircraft was configured with 362 passenger seats.

1.6.1 Weight & Balance

The following information was derived from operational records. The documentation indicated that the aircraft was planned to be within the certified weight and centre of gravity limits for take-off.

Maximum Operational Take-off Weight	214 682 kilograms
Maximum Zero-fuel Weight	167 345 kilograms
Actual Zero-fuel Weight	152 988 kilograms
Fuel On Board at Take-off	47 400 kilograms
Actual Operational Take-off Weight	200 388 kilograms
Center of Gravity	
Index	134 inches
% MAC	30.7

The actual fuel on board at take-off as calculated from the DFDR data was 46 900 kg.

1.6.2 Right Engine Information

Manufacturer	Rolls Royce
Model	RB211 Trent 772 - 60
Part Number	Trent 772 B
Serial Number	41055
Time Since New	3062.7 hours
Time Since Last Shop Visit	67.5 hours
Total Cycles Since New	2047
Cycles Since Shop Visit	14

1.6.2.1 Right Engine History

The right engine, serial number 41055, underwent a post-lease shop visit[8] at Hong Kong Aero Engine Services Limited (HAESL), which is a Rolls-Royce-approved facility; and, on 31 July 2000, the engine was certified to772 & 772B rating.

Correspondence between HAESL and Rolls-Royce indicated that the plan was to embody SB.RB.211-29-C625, modifying the engine dressing of the engine (41055). However, this modification was not done due to a parts shortage. Upon completion of the shop visit, the engine was test-run without the hydraulic pumps installed, which is an accepted practice.

Following the HAESL shop visit, the engine was shipped to, and stored at the Air Canada facilities in Toronto at the end of July 2000. On 1 August 2001, in response to a request from Air Transat that a spare engine be made available at its facilities in Mirabel, Quebec, the engine was sent to Air Transat. Included in the documentation forwarded with the engine from HAESL were the Rework Summary Sheet, the Carry-Forward Items List and the Engine Log Book.

[8] The term "shop visit" is used in the aviation industry to describe any off-wing maintenance activity that takes place in a recognized engine overhaul facility, where either the engine is separated into modules for the purpose of refurbishment, or where modifications resulting in configuration change are embodied.

As requested by Rolls-Royce, the engine was stored in a restricted area to ensure its integrity in the event that it urgently was required by another airline, because this was the only available spare loaned engine in North America. Access to the engine required notifying the in-house Rolls-Royce representative. Because the engine had to remain available to other user's world wide, it was kept in an "as received" status.

1.6.2.2 Rework Summary Sheet

The Rework Summary Sheet recorded several modifications that were embodied during the post-lease shop visit. It also detailed modifications found embodied, but not documented by the last operator. The Rework summary sheet only addressed the SB's for which some action had taken place during the shop visit. The Rework Summary Sheet did not contain any reference to SB.29-C625, showing that it had not been embodied during the shop visit.

There was no requirement on the part of HAESL to comply with an Airbus recommendation that SB's be embodied at the earliest opportunity, nor a requirement for HAESL to advise potential users of the engine about any SB's that had not been embodied. *In fact, it's a requirement for the airline who installs the core engine to check its configuration and receipt and ensure that it complies with the manufacturers specifications.*[9]

1.6.2.3 Carry-forward Items

Typically, owner-operated and leased engines are forwarded without some accessories, such as starter and hydraulic pumps. These accessories are often referred to as a Quick Engine Change (QEC) kit. The Carry-Forward Items list indicated that 60 additional components would be required when the engine was installed on an aircraft. The list provided pertinent component information, such as the Air Transportation Association (ATA) number, the part number, the part name or description, and the quantity required.

The 60 components on the list included 13 major parts, with the remaining components required for their installation. Items 58 and 61 on the carry-forward item list attached to the loaned engine showed that both front and rear hydraulic pumps required for the installation were of the Part Number 974976-type, a post-modification-model hydraulic pump. Because the engine dressing was not changed during the last shop visit at HAESL, the engine was in the pre-mod configuration, which required a hydraulic pump of part number 848354 or 971844 or 972630.

1.6.2.4 Engine Log Book

Regulations require that technical records be maintained on major aircraft components, such as engines. The technical record that accompanied engine (41055) received from HAESL was the Engine Log Book, which contained a record of all maintenance performed on the engine, including the SB's embodied. The Engine Log Book, which is the primary document for the engine, accurately reflected the configuration of the engine.

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[9] *Note from Bureau d´Enquêtes et d´Analyses pour la Sécurité de l´Aviation Civile (BEA) – Ministére de l´Equipement , des Transports, de l´Aménagement du Territoire, du Tourisme et de la Mer- REPUBLIQUE FRANÇAISE*

1.6.3 Engine Fuel Tube Rupture

The initial inspection of the right engine following the occurrence uncovered the presence of an L-shaped crack on the inlet fuel tube wall (Part No FK30383). The crack was approximately 3.0 inches (80mm) long, and was spread to a width of about 1/8 inches (2.5mm). In addition, the hydraulic outlet tube (pressure) for the rear hydraulic pump was found to be in hard contact with the fuel tube. The cracking on the fuel tube extended to both sides of a mechanically worn (chafed) area where the tubes came into contact. It was evident that the interference and chafing occurred due to the mismatched installation of the post-mod fuel tube (P/N: FK30383) and pre-mod hydraulic tube (P/N: LJ51006). Based on the DFDR data, it was determined that the fuel leak rate through this cracked reached a maximum of about 13.0 metric tons per hour.

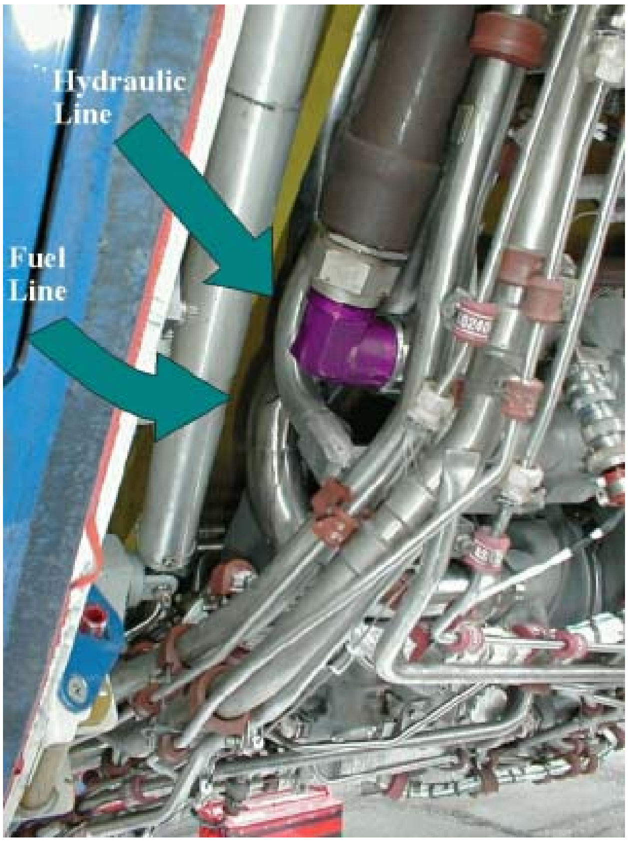

Figure 3 - Right Engine Pipe Contact

The hydraulic and fuel tubes were sent to the Rolls-Royce Laboratory in Derby, England for further analysis under the supervision of the United Kingdom Air Accidents Investigation Branch. The analysis resulted in two reports: MFR 41281 covered the examination of the fuel tube, and MFR 41283 covered the examination of the hydraulic tube.


Figure 4 Fuel Pipe Crack & Scratches

Both reports concluded that the fuel and hydraulic tubes fully matched the drawing characteristics for material, form and shape. The fuel tube wall section was measured and showed that the wear had reduced the wall thickness by 0.005 inches, and that the hard contact had resulted in a dent measuring 0.044 inches deep. The examination concluded that the fuel tube fractured in high cycle fatigue at multiple initiation sites in the bore and the outside diameter, due to a combination of vibratory stresses being superimposed on the tube deformation. Also noted were some scratches and deep scores around the chafed location on both tubes. Report MFR 41281 stated that these marks are believed to have been made at the time of installation of the engine because this was the only time the post-SB fuel line and pre-SB hydraulic lines were mounted adjacent to one another. The report concluded that the scratches and scores were directionally aligned and that they could have been caused from repeated contact from a blunt instrument, such as a screwdriver being inserted between the tubes in order to force a clearance between them. There were no cracks initiated from the score or scratch marks.

1.6.4 Oil parameters

During the flight, the crew called MCC to check on the differing oil parameters that they were observing between the engines, which were as follows:

	Engine No 1	**Engine No 2**
Oil temperature	110°C	65°C
Oil pressure	80 psi	150 psi
Oil quantity	17 litres	14 litres

Rolls-Royce conducted a technical review of the oil parameters. Technical Report Number FSG44035 in part determined that, because the position of the leak was downstream of the fuel/oil heat exchanger, the high fuel-flow through the heat exchanger would have cooled the oil resulting in the oil parameters shown. A characteristic of the Mobil Jet oil II used for engine lubrication is that the viscosity increases rapidly when the temperature decreases. The higher viscosity resulted in an increase in oil pump outlet pressure, and in a low flow rate of oil back to the reservoir. Because the oil quantity is measured at the reservoir, a lower quantity of oil would have resulted.

Post occurrence verification of the oil reservoir sight gauge showed the oil level to be 1.5 litres below the full line. Assuming that the oil reservoir was full at departure, the oil used was less than the normal oil consumption after 5 hours of operation.

1.6.5 Fuel System

1.6.5.1 Fuel System Description

The main tanks of the A330-200 fuel system are located in the wings and in the Trimmable Horizontal Stabilizer (THS). There is also a main center fuel tank. A crossfeed valve is fitted to connect the left and right hand fuel tanks to either engine.

Each wing has an inner and an outer tank. Each inner tank is divided into two parts; the division is fitted with a split valve that is normally open. Each inner tank feeds its respective engine by two main fuel pumps. Each engine has a low-pressure valve that is installed to cut off fuel to the engine. Each inner tank also has a standby pump that can also feed the engine; this pump operates automatically if there is a failure of one of the main pumps.

Two transfer valves allow the fuel from the outer tanks to transfer to the adjacent inner tanks. As soon as the inner tank quantity drops below 3 500 kg, and the trim tank is empty, the outer tank transfer valves open to cycle the inner tank content between 3 500 and 4 000 kg. The outer to inner tank transfer is indicated by a green transfer symbol on the ECAM Fuel page, and by an "OUTR TK XFR" message, in green, on the ECAM Memo page. When the transfer is complete, an "OUTR TK XFRD" message is displayed in green on the ECAM Memo page.

A trim tank is located in the THS. The trim tank transfer system is a fully automatic mode system that controls the center of gravity of the aircraft. When the aircraft is in cruise, the primary Fuel Control and Management Computer (FCMC) calculates the C of G and compares the result to a target value that depends on the aircraft actual weight. From this calculation, the FCMC optimizes the C of G by deciding to transfer fuel to or from the trim tank. There is normally only one aft transfer at the beginning of the flight. During the flight, there is a series of small forward transfers. If the actual C of G is different from the target C of G by more than 0.5% and the aircraft is above Flight Level 255, an appropriate transfer occurs. If an inner tank quantity drops below 4 000 kg, forward transfer also occurs to maintain the fuel in the inner tanks between 4 000 kg and 5 000 kg until the trim tank is empty. If during a forward transfer the inner tanks are out of balance by more than 500 kg, the transfer is automatically stopped on the heaviest side until the fuel balance is achieved. A final forward transfer occurs when the time to destination is less than 35 minutes, when either set of wing tanks is below 4.0 tons, or when the aircraft descends through FL245. When fuel is being transferred, a “TRIM TANK XFR” message appears on the ECAM Memo screen; when the trim tank is empty, a “TRIM TANK XFRD” message appears on the ECAM Memo portion of the E/WD screen.

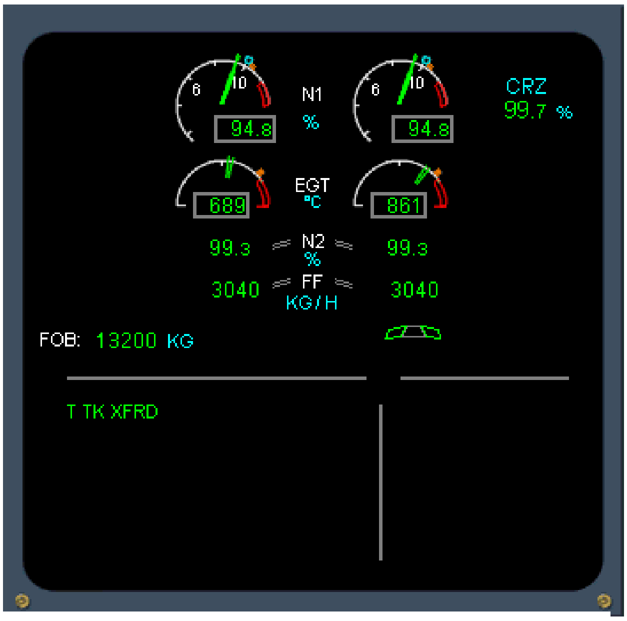

Figure 5 - E/WD & Trim Tank Transferred Memo

The Fuel ECAM page displays the following:

- Layout of the fuel tanks,
- Fuel tank quantities,
- Fuel used by each engine, and the total fuel used,
- Fuel on Board quantity
- The status of the eight fuel pumps,
- The low-pressure valves, crossfeed valve, and the trim tank isolation and inlet valves positions, and
- Anomalies to the system in amber colour.

The fuel panels, located on the overhead panel, incorporate selectors and switches to control the fuel pumps, crossfeed valve, inner tank split valves, trim tank isolation valve, center tank valve, and outer tank to inner tanks transfer valves.

The fuel system incorporates a fuel/oil heat exchanger that uses fuel flowing to the engine to cool engine oil and to pre-heat the fuel.

A crossfeed valve is fitted in the fuel system to connect or isolate the left and right engine feeds. The valve position is controlled by a push-button switch. The primary purpose of the crossfeed switch is to provide a capability to correct fuel imbalance situations, in particular to allow both engines to be fed from either the right-hand or left-hand wing tanks. In normal operation, the switch lights are out, and the crossfeed valve is in the CLOSED position[10]. To connect the left and right hand sides of the fuel system, the pilot pushes the WING X FEED switch to open the crossfeed valve: the ON light illuminates "white" to indicate that the valve is opening; and, the OPEN light illuminates "green" when the valve is fully open. With the crossfeed valve selected to the AUTO position, the valve automatically opens in the emergency electrical configuration.

1.6.5.2 Fuel System Operation on the Occurrence Flight

The refuelling slip indicates that 47 258 litres of Jet A1 fuel were added to the aircraft prior to the flight.

The fuel quantities indicated in the table on the right are those that were contained in the Flight Release form for the planned flight from Toronto (CYYZ) to Lisbon (LLPT).	Fuel to Destination	34 682	kilograms
	En-route Fuel Reserve	1 734	kilograms
	Alternate Fuel	2 621	kilograms
	Stand-off Fuel	2 800	kilograms
	Additional Fuel	0	kilograms
	Minimum Brake Release Fuel	41 837	kilograms
	Extra Contingency Fuel	5 500	kilograms
	Total Brake Release Fuel	47 337	kilograms
	Taxi Fuel	600	kilograms
	Ramp Fuel	47 937	kilograms

The planned fuel load included a 1 734 kg en-route 5% fuel reserve. An additional 5 500 kg of fuel was put on board for cost-saving tankering and to accommodate for possible re-routing or altitude restrictions while on the North Atlantic Track System. According to the company operations manual, the minimum, planned reserve fuel at destination was required to be 5 421 kg.

The following tables depict the fuel on board in metric tons: the Post-flight Report table was based on data that was extracted from the on board computers after the flight; and, the Flight Log table is based on information on the Flight Log maintained by the crew during the flight.

Post-flight Report		
Waypoint	**Time**	**Fuel on Board**
Take-off	00:52	46.9
ABENE	01:42	39.1
ABYHZ	02:17	35.8
ABBANCS	03:11	31.3
4550N	03:22	30.1
4540N	04:08	26.2
4430N	04:57	21.6

Flight Log			
Waypoint	**Minimum Fuel On Board**	**Fuel on Board**	**Variance**
CYYZ	40.1		
ENE	32.2	39.2	+ 7.0
YHZ	28.9	35.8	+ 6.9
BANCS	24.1	31.2	+ 7.1
45N050W	23.1	30.1	+ 7.0
45N040W	19.0	26.2	+ 7.2
44N030W	14.9	21.7	+ 6.8

[10] In some parts of the manufacturer's documentation, the CLOSED position is sometimes referred to as the AUTO position.[The valve (cross feed) automatically opens in emergency configuration]

The only fuel quantity recorded on the DFDR was the quantity in the trim tank. The following table represents, for each fuel-related event, the aircraft position and the trim tank fuel (TTF) as recorded on the DFDR, as well as the fuel on board (FOB) and leak rate (Leak/R tons per hour) as calculated by subtracting the zero fuel weight from gross weight recorded on the DFDR.

Event	Time	Position	TTF	FOB	Leak/R
Position Report	04:08	4500N4006W	3.9	26.2	0
Fuel Leak Starts	04:38	4430N3355W	3.5	23.7	0.5
Forward transfer of trim tank fuel starts	04:56	4403N3018W	3.5	21.8	3.8
Forward transfer of trim tank fuel stops	04:58	4359N3008W	3.2	21.4	4.6
Forward transfer of the remaining trim tank fuel begins	05:11	4334N2719W	3.1	18.7	9.7
Trim tank forward transfer complete.	05:30	4251N2339W	0.0	13.2	13.2
Fuel Imbalance "ADV" on the E/WD	05:33	4244N2305W	0.0	12.3	13.7
Fuel Crossfeed from Left tank starts	05:36	4237N2235W	0.0	11.4	13.8
Fuel Crossfeed from Right tank starts	05:54	4131N2142W	0.0	5.9	13.5
FUEL R WING TK LO LVL (less than 1640 kg for 60 seconds) displayed on E/WD	05:58	4115N2216W	0.0	4.7	13.0
Fuel Crossfeed from Left tank starts	05:59	4111N2225W	0.0	4.4	12.9
FUEL L WING TK LO LVL (less than 1640 kg for 60 seconds) displayed on E/WD	06:08	4033N2341W	0.0	1.8	12.5
Right (#2) Engine Flame-out	06:13	4010N2427W	0.0	0.7	0.0
Fuel Trim Tank pump selected FWD	06:21	3941N2524W	0.0	0.2	0.0
Left (#1) Engine Flame-out	06:26	3923N2556W	0.0	0.0	0.0

1.6.5.3 Fuel System Examination

Following the occurrence, an examination of the fuel system components was conducted. A review of the Fuel Panel in the cockpit revealed that the six fuel pump switches were depressed, indicating that the pumps were selected ON. To complete the testing, all the pump switches were selected to the OFF position. When power was applied to the aircraft, the fuel quantity displays indicated the following: the Trim Tank indicated 40 kg of fuel; and, the remaining tanks indicated 0 kg. Each fuel pump was then selected ON, and verified as functioning by hearing sound and by observing the pump low pressure indication the ECAM. The operation of the crossfeed and low-pressure valves was verified by observing the indications on ECAM. The Fuel Control and Monitoring System report indicated that there were no failures during the flight. The on-ground test system did not reveal any system failures. In summary, all components of the fuel system were verified as functioning properly.

1.6.6 Electronic Centralized Aircraft Monitoring

1.6.6.1 Electronic Centralized Aircraft Monitoring System Description

The A330 is equipped with an Electronic Centralized Aircraft Monitoring (ECAM) system that monitors the aircraft systems. If something abnormal is detected, ECAM alerts the pilots and, for most abnormals, provides an electronic procedure to help handle the abnormality. The ECAM is made up of two displays: the Engine Warning Display (E/WD), and the System Display (SD). These ECAM displays provide normal and abnormal system information to the pilots.

Colour coding is used on the ECAM screens for clarity, to aid identification of system parameters and system status, and to indicate the importance of the failure/indication, as follows:

- Green is used to indicate that an item or system is operating normally;
- White is used for titles and remarks to guide the flight crew as it executes procedures;
- Blue is used to indicate actions to be carried out by the crew;
- Amber is reserved for abnormal indications of failures leading to a loss of system redundancy or system degradation, and for system failures having no direct consequence on flight safety. An amber caution requires crew awareness and monitoring, but does not require immediate action by the crew; and,
- Red is reserved for serious parameter exceedance and warnings that require immediate crew action.

The E/WD is divided into two main parts. The upper area is used for the main engine parameters, Fuel On Board (FOB), fuel flow and Slat/Flap position. Under normal conditions, the lower part of the E/WD is used to display MEMO's. If failures occur, Warning/Caution alerts and messages are displayed in place of the memos, and the required crew action items (procedure) by the abnormal situation are depicted in blue.

The SD is used to display particular system information. Normally, the CRUISE page is displayed for the majority of the time that the aircraft is airborne; the FOB quantity is displayed on the upper ECAM page. The SD can also be used to display synoptic diagrams of the aircraft systems, either manually selected by the crew, or automatically displayed for the ECAM system when a system anomaly is detected. The SD displays other permanent flight data such as gross weight and C of G.

Under normal conditions, the ECAM system provides the pilots with the information that they "Need to Know" for the particular phase of flight. For example, if a system parameter drifts out of normal range, the ECAM system generates a white ADVISORY (ADV) on the memo portion of the E/WD, and will advise the crew of this condition by automatically displaying the relevant system page on the SD. The affected parameter on the SD will pulse in green, because it is approaching, but still within limits. If, at the time that the ADV is generated, another system page is already manually selected and displayed on the SD, the relevant systems page called by the advisory is not displayed; however, a pulsing white ADV notice is displayed in the Memo area of the E/WD. Although immediate pilot action may not be required by all ADVISORY messages, crew monitoring of the system is required.

When a failure occurs, leading to a loss of redundancy or loss of a system that does not affect the safety of the flight, the ECAM system informs the crew by displaying an amber failure message on the E/WD, and displays the relevant system page on the SD. The affected parameter on the SD will be displayed in amber. A related FAULT light may be illuminated as well.

When a more serious fault occurs, the ECAM system alerts the crew aurally by a single chime, and visually by an amber MASTER CAUTION light. The ECAM system informs the crew by displaying an amber failure message on the E/WD, the crew action items (procedure) required for the abnormal situation, and the relevant system synoptic page on the SD. The affected system on the SD will be displayed in amber.

For ECAM Caution messages, the first action required by the crew is to ensure that the aircraft is on a safe flight path. Although the flight crew needs to be aware of the configuration or failure, immediate action is not required. Depending on the fault, a related FAULT light may be illuminated as well.

When there is a serious failure that requires immediate action, the ECAM system alerts the crew with a continuous repetitive chime and a flashing red MASTER WARNING light. The ECAM system informs the crew by displaying a red failure message on the E/WD, the crew action items (procedure) required for the abnormal situation, and the relevant system synoptic page on the SD. The affected system on the SD will be displayed in red.

For ECAM Warning messages, the first action required by the crew is to ensure that the aircraft is on a safe flight path, and that the required crew actions depicted on the warning/message portion of the E/WD are completed in a timely manner.

1.6.6.2 ECAM Indications during the Occurrence Flight

The information contained in this section was derived from the DFDR, PFR, and crew testimony.

According to the crew, all aircraft systems functioned normally, up to when the aircraft passed 040W at 04:08. No anomalies were noted on the DFDR for this portion of the flight. Of particular note is that at this point in the flight, the right engine oil quantity was stable at approximately 16.0 quarts (18.2 litres[11]). Oil pressure and temperature are not recorded on the DFDR.

At 04:38, the DFDR recorded an increased rate of reduction in the fuel quantity. Analysis of this DFDR data determined that this anomaly was the start of the fuel leak in the right (#2) engine, low-pressure fuel line. The increased rate of reduction in fuel quantity would have been indicated in lower-than-anticipated FOB quantity figure on the E/WD.

At 04:44, the DFDR recorded a decrease in oil quantity on the right engine; however, because the oil parameters were within operating limits an ECAM message was not generated.

At 04:56, the DFDR recorded the commencement of a two-minute forward transfer of fuel from the trim tank to the main wing tanks. Total transfer was about 0.3 tons. During this transfer, a green TRIM TANK XFR ECAM message would have been displayed in the memo section of the E/WD. The occurrence crew did not recall seeing this message.

According to the crew, at 04:58, shortly after the aircraft crossed 030W, a routine check of the aircraft instrument indications was commenced. It was at this time that the crew noticed that the oil quantity on the right engine was markedly lower than the quantity on the left engine. At 05:04, the crew selected the ENGINE status page on the SD to verify other engine readings.

[11] Oil quantity is recorded on the DFDR in imperial quarts; whereas, oil quantity is displayed in the cockpit in litres.

At 05:11, the DFDR recorded the commencement of a 19-minute forward transfer of the remaining 3.2 tons of fuel in the trim tank commenced. During this transfer, a green ECAM message TRIM TANK XFR would have been displayed.

AT 05:21, the crew notified the company operations centre that, although at the beginning of the flight the right engine had 18.5 litres of oil, the oil quantity was now only 14.5 litres, the oil temperature was 65 degrees Celsius, and the oil pressure was 150 pounds per square inch (psi); these readings were significantly different from the readings on the left engine, which were 18.2 litres, 110 degrees Celsius, and 80 psi. MCC advised the crew that the problem would be analysed and that the flight would be contacted with the results[12]. The readings were within the parameters specified in the Engine Oil Consumption Airbus A330 chart.

At 05:30, the trim tank forward fuel transfer was completed and a TRIM TANK XFRD message would have appeared in the memo section of the E/WD; this message would remain displayed for the duration of the flight. The complete forward transfer of the trim tank fuel is not scheduled to occur until 35 minutes from the destination airport, until the wing tanks are below 4.0 tons, or until the aircraft descends below FL 245.

At 05:33, a pulsing, white ECAM advisory ADV message was generated and displayed in the memo area of the E/WD, indicating a 3 000 kg fuel imbalance between the right and left wing tanks. Under normal conditions, this ECAM advisory brings up the FUEL system page on the SD. However, the manual selection of ENGINE systems page by the crew inhibited the display of the fuel page. A 3 000 kg fuel imbalance is an abnormal condition that does not result in a display of the corrective action required to correct the imbalance. To ascertain the required corrective action, the crew must view the fuel page, diagnose the pulsing fuel quantity indications, and then refer to the appropriate page in the Quick Reference Handbook (QRH).

At 05:34, the crew deselected the ENGINE page, and the FUEL page was displayed in the SD.

At 05:36, having noted the fuel imbalance, the crew opened the crossfeed valve and turned off the right-wing fuel pumps, establishing a crossfeed from the left wing tank to the right engine. An amber FUEL R WING PUMPS LO PR message[13] would have appeared on the left side of the message area of the E/WD and a green WING X FEED memo would have appeared on the right side. Shortly afterward, the crew also noted that the remaining fuel on board was significantly below the planned quantity. Fuel losses or leaks themselves cannot be identified as such by the ECAM system; consequently, a specific ECAM warning is not generated for these conditions, although related system messages would be generated as normal parameters were approached or exceeded.

At 05:52, the caution message ENG 2 FUEL FILTER CLOG appeared on the E/WD. This message indicated an abnormal (and sometimes temporary) pressure loss across the fuel filter of the right engine. This type of message does not require action by the crew; it is only generated for crew awareness and monitoring, if necessary.

[12] Prior to MCC re-contacting the flight on the unusual oil readings, the fuel loss problem occurred and communications on this problem took precedence.

[13] Amber messages are accompanied by an amber CAUTION and a single chime caution.

At 05:54, the crew established crossfeed from the right-wing tank to the left engine by selecting the right-wing pumps ON and the left-wing fuel pumps OFF. A FUEL L WING PUMPS LO PR message appeared on the left portion of the E/WD message screen and the WING X FEED memo would have continued to appear on the right portion.

At 05:58, the FUEL R WING TK LO LVL message appeared, indicating less than 1 640 kg of fuel remaining in the right inner tank for more than 60 seconds.

At 06:08, the FUEL L+R WING TK LO LVL message appeared, indicating that inner tanks on both wings were now below 1 640 kg for more than 60 seconds.

At 06:13, the ENG 2 STALL and ENG 2 FAIL messages were displayed indicating that the right engine had flamed-out. The RPM decay resulted in the ENG 2 STALL message; the ENG 2 FAIL message indicated that core speed had decelerated to below idle with the master switch ‘on’ and the fire pushbutton ‘in’ (not pushed).

At 06:21, the FUEL TRIM TK PUMP LO PR message was displayed indicating that the trim tank transfer pump switch had been selected to FWD and no fuel remained in the trim tank.

At 06:26, the ENG 1 STALL and ENG 1 FAIL messages were generated as the left engine flamed-out. As the associated generator decelerated, the aircraft would have automatically reverted to the emergency electrical configuration, with power supplied by the automatic extension of the ram air turbine. The EMER ELEC CONFIG warning may have been inhibited by the ENG ALL ENG FLAMEOUT warning; neither warning was recorded on the Post Flight Report.

1.6.7 Flight Management Guidance Computer

The A330 aircraft is equipped with a Flight Management Guidance Computer (FMGC). The flight management part of the computer performs four main functions: navigation, flight planning, prediction and optimization of performance, and management of displays. Predictions are displayed on the Multi-purpose Control Display Unit (MCDU). When making fuel remaining predictions for an aircraft in flight, the FMGC, in part, takes into account the fuel currently on board, flight plan, planned vertical profiles, predicted times, and fuel flow to operating engines. The estimated fuel on-board at destination (EFOB) prediction would not take into account fuel being lost as the result of a fuel leak.

On the occurrence flight following the annunciation of the fuel imbalance advisory, the crew, on a number of occasions, referred to the predicted fuel remaining on board at destination figures presented on the MCDU to make decisions. By not taking into account the fuel leak rate, the FMGC would have predicted fuel reserve quantities significantly above what would actually occur, and the EFOB at destination would have been constantly decreasing. The FMGC would have displayed minus quantity when a diversion was a priority.

1.6.8 Electrical Systems

The A330 aircraft electrical system is normally powered by two engine driven generators. The aircraft also has three 24-volt batteries. The aircraft's electrical network can also be supplied by the APU generator. These three generators are all identical and any one of them can supply the entire aircraft electrical needs. As a backup, there is a hydraulically driven emergency electrical generator, which is powered by the green hydraulic system.

In the event of a severe electrical failure and a lack of hydraulic power to actuate the emergency generator, a Ram Air Turbine (RAT) can be automatically or manually deployed to provide the hydraulic pressure to power the emergency generator. During the RAT extension, the electrical system is powered from the batteries.

On the occurrence flight, as a consequence of the double-engine failure, the aircraft lost both engine-driven generators and hydraulic pressure, and the RAT was deployed. This deployment resulted in the aircraft electrical system being supplied by the emergency generator. This configuration resulted in the loss, in part, of the following electrical services: Flight Guidance Management Computer, Multipurpose Control and Display Unit, HF 1 radio, Cockpit Voice Recorder, Flight Data Recorder, Auto-pilot 2, Flight Control Data Concentrator 1, flaps, pitch trim, rudder trim, Navigation Display 1, Auto Break/Anti Skid, Distance Measuring Equipment, and standby altimeter lighting.

In preparation for landing, in accordance with the ENG ALL ENGINE FLAME OUT, the crew selected the LAND RECOVERY push button and selected FLAP 1, which extended the slats. At slats extension, the emergency generator was inhibited and the electrical supply automatically transferred to the batteries. The approximate flight time on batteries is 30 minutes.

1.6.9 Flight Controls

The Airbus A330 is a new generation aircraft that utilizes fly-by-wire technology, in that the flight control surfaces are electrically controlled and hydraulically activated. Some surfaces, like the stabilizer and the rudder, can be mechanically controlled. Three independent hydraulic systems are used to power all the flight control surfaces.

Five flight control computers process pilot and autopilot inputs according to normal, alternate or direct flight control laws: three Flight Control Primary Computers (FCPC) and two Flight Control Secondary Computers (FCSC). Two Flight Control Data Concentrators acquire the data from the FCPCs and FCSCs and send the data to the Electronic Instrument System (EIS) and Central Maintenance Computer (CMC).

On the occurrence flight, the flameout of both engines resulted in the loss of the BLUE and YELLOW hydraulic systems. The GREEN hydraulic system continued to be powered by the RAT. Loss of the BLUE and YELLOW systems results in the following inoperative systems: Flight control protection (degradation), stabilizer, auto-pilot 1 and 2, most spoilers, alternate brakes, yaw damper 2, nose wheel steering, and reversers. The HYD B + Y SYS LO PR procedure states that pitch authority will be reduced, and suggests that the flare for landing must be started earlier and that more stick deflection might be needed to achieve the flare. The reversion to emergency electrical power also resulted in the loss of pitch and rudder electric trim.

1.6.10 Emergency Exit L3

When the evacuation was ordered, the flight attendant seated at L3 position attempted to open door L3; however, the door handle did not rotate all the way up, and the door only opened approximately 20 to 25 centimetres. It also was reported that the power-assist did not appear to work.

The L3 flight attendant reported that, prior to departure, door L3 had been armed and that the indicator at the door indicated that the door was properly armed. The indicator at the FD's panel also indicated that the door was armed. Following the evacuation, the L-3 attendant examined the door and the slide appeared to be partially attached to the exit door. A photo taken of the door from outside the aircraft showed the L3 door partially opened and the escape slide slightly askew and apparently connected to both the floor and the door.

Sometime after the landing, fire-rescue crews, in attempting to eliminate the hazard of the escape slide inflating within the cabin, used a pry-tool to release the slide and open the door. Reportedly, when the door was opened, the slide fell out the door and only inflated partially.

Figure 6 - Door L3 Jammed

By the time that investigators arrived to examine door L3, the door had been closed and all eight slides had been moved and stored in four aircraft luggage containers.

Inspection of the L3 exit did not reveal any damage to the door or frame, other than minor scratches and minor damage to the plastic panel in the area where the pry bar was used. When operated by investigators, the door opened and closed without any restriction and no mechanical distortion or malfunction was found either with the arming system or with the locking/unlocking of the girt bar. An examination of the power-assist unit indicated that it had been activated.

The slide is packed in a decorative cover called a "bustle". The assembly is attached to the door by a rail on each side. Forming part of the slide system is a "girt bar" to which the slide is attached. In the un-armed position, the girt bar is locked to the bottom of the door. When the arming lever is moved to the armed position, the bar is mechanically unlocked from the door and locked to the door sill, securing the upper portion of the slide to the aircraft and preparing the slide for activation when the door is opened in the emergency mode.

The containers containing the slides were shipped back to Canada. When the containers arrived, the L3 slide was identified by checking serial number against aircraft logs. The L3 slide was forwarded for examination to the Aircraft Evacuation Systems Division of the Goodrich Corporation, the manufacturer, located in Phoenix, Arizona, United States of America. The examination was carried out under the supervision of an investigator from National Transportation Safety Board (NTSB) Survival Factors Group.

When the shipping container was received at the Goodrich facility, it contained the slide/raft, its girt bar, and the packboard with the decorative cover. However, the crate did not contain the two release rails, rail adapters, rail release pins, or girt panel sleeve. An additional search did not locate the missing items or identify specifically the ones installed at the L3 location.

The NTSB, Survival Factors Group Report, dated 19 November 2001, detailed the condition of the slide. Specifically, the inflation bottle gauge reading of “0" and the detached firing line were consistent with the firing of the inflation valve; and, an “L” shaped tear, measuring 7 by 19 inches, of the fabric was the reason for incomplete inflation of the slide. The other abrasion marks on the slide attachments were probably caused by the attempts by the fire-fighters to open the door and to release the chute.

Conclusive finding as to the cause of the door jam could not be made, primarily because of the missing components. Notwithstanding, interviews and photos confirm that the slide had not released completely from the door, and that the bustle rails/rail adapters may have jammed.

There have been at least two, previously documented cases where the slide rails have jammed preventing opening of the door in the emergency mode. Studies of these previous occurrences by Goodrich indicated that the jamming might have been caused by incomplete installation of a pin forming part of the assembly. On 30 July 2001, to mitigate risks of improper installation, Goodrich published Service Bulletin Number 25-306, introducing a rework of the rail-associated components. Goodrich recommended compliance with the SB at the next scheduled unit maintenance. In conjunction with the Goodrich SB, Airbus issued SB’s A330-25-3126 and A340-25-4152 (for the A330 and A340 respectively) dated 07 August 2001. Airbus also recommends compliance, but with no time frame specified. At the time of the accident (two weeks later), the Airbus non-mandatory bulletins had not been yet received by Air Transat.

In 17 October 2001, France’s aviation regulator, Direction Générale de l’Aviation Civile (DGAC), upgraded compliance with these SB’s by issuing Airworthiness Directive (AD) numbers AD 2001-465 (B) R1, for the A330; and, AD 2001-464 (B) R1 for the A340, both dated 17 October 2001. Compliance with these AD’s was required no later than 13 October 2004. AD 2001-465 (B) R1 applies to the occurrence aircraft.

1.6.11 Cabin Pressurization System

According to the aircraft manuals, the oxygen masks will deploy when the cabin altitude exceeds 14 000 feet, –500/+0 feet.

Due to the lack of recorded aircraft and ground-based data, it could not be precisely determined at what aircraft altitude the cabin altitude exceeded 14 000 feet, or the maximum cabin altitude reached during the engines-out descent. However, based on an analysis of the theoretical cabin leak rate and of the aircraft average descent rate following the loss of the second engine, it was assessed that the cabin altitude would have reached 13 500 feet as the aircraft descended through about 17 000 feet. Based on these calculations, the passengers would have been exposed to a maximum cabin altitude above 13 500 for about 1 minute. [15]

1.6.12 Passenger Cabin Oxygen System

1.6.12.1 Oxygen System Components

The passenger oxygen system components are contained in oxygen container assemblies installed overhead the passenger cabin seats. Each container has a door with a latch that is released electrically when the cabin altitude exceeds 14.000 feet. When the door opens, the masks drop. Within the compartment there is a chemical oxygen generator canister and oxygen masks. The canister is activated when a release pin is withdrawn from the assembly as the result of the oxygen mask lanyards being pulled. Each canister also has an EXPENDED COLOR INDICATOR witness patch that is normally coloured a bright yellow/orange. The patch is designed to turn a dirty brown colour if it is exposed to heat, such as when the oxygen generator is activated. Each oxygen mask is connected to the canister by a transparent plastic supply hose, which has a flow indicator in the portion of the supply hose close to the oxygen generator. When oxygen flows through the hose, a green-coloured flow valve becomes visible in the flow indicator. The oxygen compartment doors are to be drop-tested on every aircraft 4C check, which is required every 24 000 hours or 5 years. The aircraft was not required to undergo a “4C check” because the aircraft time and calendar limits had not been reached since the aircraft was put into service by Air Transat.

Following the occurrence, all of the oxygen facilities in the passenger cabin were examined.

A general inspection of the passenger cabin determined that the following five oxygen container doors were still in the closed position: 10D, 35B, 36F, 42B, and 45D.

The general examination of the oxygen generators throughout the cabin determined the following:

- Patches for all the generators that had the retaining pins pulled from the activation squibs were brown in colour indicating that the generators had been activated; and
- The patches for all the generators that had the retaining pins still in place were bright yellow/orange in colour indicating that the generators had not been activated.

1.6.12.2 Oxygen System Requirements

The applicable design standard for passenger oxygen systems is Federal Aviation Regulation (FAR) 25.1447 or (JAR) 25.1447, which requires that the number of masks exceed the number of seats by 10 percent, evenly distributed throughout the cabin.

The occurrence aircraft was configured with 362 passenger seats. Each outboard row of seats was serviced by an oxygen container containing three oxygen masks: rows 1, 2, 3, and 41 through 46 had two seats in each outboard row; and rows 4 through 40 had three seats per outboard row. Each centre row of seats was serviced by two containers, each containing two masks: all centre rows had three seats. The flight attendant location at Door 2R was serviced by one container containing 2 masks. Based on the passenger-seat and oxygen-container configurations, there would have been approximately 65 more masks than seats.

[15] Appendix A details the calculation of cabin pressures.

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1.6.12.3 Oxygen Container Examination

Following the occurrence, power was applied to the aircraft, and a drop-down test of the five oxygen container doors that had not dropped was conducted; none of them opened. A current test of the actuators revealed that electrical power was reaching the release mechanisms.

A TSB Engineering Branch examination of the Nellcor Puritan Bennett oxygen containers[16] was conducted to determine the reasons why the doors failed to open. The findings of this examination were as follows:

- An external visual inspection revealed that there were no indications of defects, damage, or other problems.
- The door latches actuated and doors opened immediately when power was applied.
- Each door and hinge was examined and found to operate smoothly and continuously with no binding.
- All the masks, tubes, lanyards, etc were neatly packed. They did not overlap the edge of the door or hinge, and did not cause an extra load on the latch assembly.
- There were no burrs on the latch post or its receptacle, nor on the test button or its receptacle that may have been impeding opening.
- Tactile examination of the door frame and hinge did not find any evidence of dirt or sticky residue that may have been impeding opening.
- The latches were tested manually using a manual release tool, and found to operate readily without bind or restriction.

The oxygen containers were subsequently examined by the manufacturer of the units. This examination also did not find any anomalies to explain why the doors failed to open.

The following summarizes the row-location of the oxygen panel doors that failed to open, the number of seats in the row-location, the number of masks servicing the seats, the number of masks that failed to open, and the number of passengers seated in the row-location:

Row-Location	Seats	Masks	Failed Masks	Seats Occupied	Shortage
Position 2R	2	2	2	1	1
Row 10 Centre	3	2 + 2	2	2	0
Row 35 Left	3	3	3	3	3
Row 36 Centre	3	2 + 2	2	3	1
Row 42 Left	2	3	3	2	2
Row 45 Centre	3	2 + 2	2	3	1

A review of the Transport Canada and the Federal Aviation Authority Service Difficult Reporting (SDR) system confirmed a number of previous similar instances where there have been problems with emergency mask deployment involving a wide range of different models of aircraft.

[16] P/N AF5L32-25 S/N 90631; P/N AF5R32-25 S/N 90637; P/N AF5R32-25 S/N 90658; P/N AF5L33-25 S/N 91049; and P/N AF5L34-24 S/N 00112

The reasons given for these failures, in part, included doors failing to open due to an electrical fault or for no apparent technical reason.

The number (14) of masks that failed for undetermined reason was within the 10 percent boundary assumed by the design standard.

1.6.12.4 Oxygen Flow to Passenger Masks

The general examination of the oxygen generators throughout the cabin determined the following:

- Oxygen masks were deployed from all open oxygen containers;
- Patches for all the generators that had the retaining pins pulled from the activation squibs were brown in colour indicating that the generators had been activated; and
- The patches for all the generators that had the retaining pins still in place were bright yellow/orange in colour indicating that the generators had not been activated.

These indications are consistent with an assessment that these passenger masks functioned as designed.

1.6.12.5 Oxygen Flow to L3 Masks

A detailed check of the oxygen components was conducted at flight attendant position L-3. The flight attendant at this location had reported that she could not breathe when she donned the mask. She attempted to confirm the presence of oxygen flow by pinching the bottom of the mask and observing the mask bag for signs of inflation; however, the mask bag did not inflate. She did not check the indicator in the flow line.

An examination of oxygen components at this position revealed the following:

- The retaining pin was pulled from the activation squib and the canister patch was brown in colour, indicating that the generator had been activated.
- Both masks at this location were found deployed, but the mask bags were still in a folded position, indicating that oxygen had not flowed to the masks.

Although the oxygen masks from position L3 were to be transported back to Canada for further investigation, they were never located and therefore could not be examined to confirm the functioning of the oxygen system at position L3.

1.6.12.6 Oxygen Flow to R3 Masks

An inspection of the oxygen components at position R-3 was conducted to determine why the oxygen had not flowed to the masks at this location. The following were observed:

- The retaining pin for the activation squib was not in the ignition assembly;
- The witness patch indicated that the generator canister had not been activated; and
- The generator had not been activated because the activation squib was being held in position by a maintenance retaining pin connected to a bright yellow flag with the following markings:
    - UNIT IS NOT READY FOR USE WHILE THIS FLAG IS INSTALLED, and

- WARNING - MUST OPEN DOOR THEN REMOVE RING AND THIS FLAG FROM THIS GENERATOR PRIOR TO PLACING THIS UNIT IN SERVICE

This oxygen unit had been installed at the time the aircraft was manufactured.

1.7 Meteorological Information

The weather information in the flight planning package for the flight included, in part, the weather for the departure point, Toronto CYYZ and Lisbon LPPT, as well as the destination alternate LPFR, and en-route airports, including Lajes, Terceira LPLA.

For the cruise portion of the flight, the aircraft was operating at FL 390, clear of cloud, in dark, night-time conditions.

The actual weather reported for the Lajes airport was as follows:

- At 05:55, approximately 50 minutes before the landing, wind 350° true at 13 knots, visibility unlimited, few clouds at 2 400 feet, few clouds at 5 000 feet, temperature 19 degrees Celsius, dew point 12 degrees, altimeter setting 30.07 inches, sky 2 tenths covered, and remarks – centre runway wind 340° at 9 knots.
- At 06:50, just after the landing, wind 350° true at 13 knots, visibility unlimited, few clouds at 2 500 feet, and few clouds at 5 000 feet, temperature 19 degrees Celsius, dew point 12 degrees, altimeter setting 30.07 inches, sky 2 tenths covered and remarks – centre runway wind 340° at 8 knots.

The crew had visual contact with ground-based lights in the direction of Terceira Island when the aircraft was descending through flight level 370 and at 120 nautical miles north-east of Lajes.

1.8 Aids to Navigation

The A-330 is equipped with a navigation system that is divided into three main groups of components. The Air Data and Inertial Reference System include Air Data Inertial Reference Units, Global Positioning System, and stand-by instruments. The radio-navigation group includes radio navigation aids, radio altimeters, and Digital Distance and Radio Magnetic Indicator. The navigation system group includes Ground Proximity Warning System, ATC transponders, and weather radar.

All navigation system components reportedly were functioning properly up to the time that the second engine flamed out. After this event, the aircraft electrical system reverted to the electrical emergency configuration. For the approach, the only on-board navigation components available to the crew were the very high frequency omni-directional range (VOR), automatic directional finder (ADF), and the instrument landing system (ILS). The crew used the LM VOR site for directional guidance to Lajes.

1.9 Communications

1.9.1 Communications Equipment

During the portion of the flight subsequent to the initial recognition of engine reading anomalies, the flight crew used the aircraft's HF radio to communicate with Santa Maria air traffic control and the company MCC; the very high frequency (VHF) radio was used to communicate with Lajes Approach Control. No anomalies were reported regarding the operation of these radios.

1.9.2 Cockpit Communications Activity

The CVR recording was examined to determine the level of communications, both internal to the cockpit and external with ground-based entities, to determine the amount of time the crew were occupied with these communications, as well as the effect of this occupation on the decision-making by the crew[17]. The CVR recording spanned 28 minutes and 24 seconds of the flight, starting at 05:59:17 partway during the crew's first HF notification to MCC regarding the indications of a loss of fuel on board the aircraft, and ending at 06:27:41, shortly after the flameout of the second engine when electrical power was switched to EMERGENCY.

Very little data exists from the time that the crew first reacted to the discrepancy in the engine oil parameters at 05:04, up to the time that the CVR recording started. What is known is that the First Officer was in HF communications with company dispatch on four occasions for up to 10 minutes total time.

During CVR recording, the crew was occupied speaking or listening for 22 minutes and 20 seconds, or 79% of the time[18], as follows:

- With MCC – 2 minutes 42 seconds;
- With ATC – 9 minutes and 58 seconds; and
- Inter-crew communication – 9 minutes and 40 seconds.

1.10 Air Traffic Control and Airport Services

1.10.1 Air Traffic Control Units

Santa Maria Oceanic Control is responsible for air traffic control in an area bounded on the west (40°W) by New York Oceanic Flight Information Region (FIR), on the north (45°N) by Gander and Shanwick FIRs, on the south by Sal and Canarias FIRs, and on the east by Canarias, Lisboa and Madrid FIRs. Control relies on flight plans, position reports, track predictions, and HF communications. Santa Maria Oceanic Control does not have radar. The occurrence flight was in communications with Santa Maria Oceanic Control from approximately 04:10 until 06:31 when control of the aircraft was passed to Lajes Approach Control.

Santa Maria Approach control is responsible for air traffic control in the area around the Azores islands (approximately 240 wide by 540 miles long) between 1 000 feet and FL 285. Control relies on flight plans, position reports, track predictions, and VHF communications. Although Santa Maria Approach was involved in passing situation information to Lajes, it was not involved in the direct control of the aircraft.

Lajes Approach Control is a military terminal area control facility that is responsible for controlling air traffic arriving and departing Lajes. The control area is bounded by a 45 nm arc commencing from the 270° clockwise to 150°, and then from 150°/45nm to 270°/45nm point; and between 700 feet above mean sea level (msl) to FL155. Control relies on flight plans, position

[17] Appendix B details an overview of the cockpit communications activity level.

[18] These times are based solely on utterance times, and do not include the entire time occupied with communicating. Specifically, times not included are the following: the periods before speaking, planning the communication; waiting time between communications where a response is expected; and, the periods following the communication, recognizing and analyzing the meaning of the communication.

reports, track predictions, radar, and VHF communications. Lajes Approach provided control for the flight from 06:31 until the aircraft landed. Radar data is not recorded.

Lajes Tower is a military facility that is responsible for air traffic control within its 5nm zone. Control relies on flight plans, aircraft position reports, radar information from Lajes Approach, and VHF communications. Although Lajes Tower was not directly involved in controlling the aircraft, it did provide landing clearance and did coordinate the response of airfield facilities.

1.10.2 Aerodrome Information

The Lajes (LPLA) airport on Terceira Island, Azores is operated by the Portuguese Air Force. LPLA is located at 38°46´N/027°06´W and has one runway, RWY 33/15, which is 10 866 feet long by 200 feet wide. The airport elevation is 180 feet above msl[19].

Runway 33 is equipped with Sequenced Flashing (SF) High Intensity Runway Lights (HIRL), Standard High Intensity Cat I (ALSF-1), and a Precision Approach Path Indicator (PAPI). Runway 33 is served by the LM very high frequency omni-directional range (VOR) site, the TRM terminal area control area navigation (TACAN)[20] site, and the OZ instrument landing system (ILS). Lajes Airport has a "Fire 9" rescue and fire fighting capability.

LPLA was one of the designated ETOPS alternates for the flight from Toronto to Lisbon.

The only operational LPLA Notices To Airmen (NOTAMS) in effect, and applicable to arriving aircraft at the time of the occurrence landing were as follows:

- LPLA M8793/01 24AUG1151-24AUG1211 : : GPS NON-PRECISION APCH NOT AVBL; and
- LPLA M8794/01 25AUG1147-25AUG1207 : : GPS NON-PRECISION APCH NOT AVBL

1.10.3 Lajes Approach and Tower Control Services

At 06:31, Air Transat 236 checked in on Lajes Approach Control frequency and declared a MAYDAY; at this time, the aircraft was descending through FL273 and at 33 miles northeast from Lajes. On a number of occasions, the crew requested that the all runway lights be flashed to aid in the visual acquisition of the runway; each time the approach controller relayed the request to the tower controller, and the approach controller responded to the flight that the lights were being flashed.

At 06:36, when the aircraft was passing through approximately FL220 and 14 miles from the airport, the crew confirmed the runway in sight. The crew also requested confirmation that the Crash Fire Rescue (CFR) vehicles were standing by, and prepared for an aircraft evacuation; this transmission was acknowledged by the controller.

AT 06:43, the tower controller advised the approach controller that the flight was cleared to land.

[19] Appendix A contains the Terceira airport and approach charts.

[20] The TRM TACAN is a military navigation system that incorporates distance-measuring equipment that can be used by civilian operators.

At 06:45, just after landing, the crew requested that fire crews go to the area of the tires, and at 06:46, advised that an evacuation was in progress.

At 06:46, the tower controller suspended runway operations due to the disabled aircraft.

1.11 Flight Recorders

1.11.1 Recorders General

The aircraft was equipped with an Allied Signal Model 6022 solid state Cockpit Voice Recorder (CVR), part number 980-6022-001 and serial number S/N 0327, and an Allied Signal Model 4700 Digital Flight Data Recorder (DFDR), part number 980-4700-003 and serial number 5636. The two recorders were sent to the Bureau d'Enquêtes et d'Analyses pour la Sécurité de l'Aviation Civile (BEA) in France for read out and analysis.

1.11.2 Solid State Cockpit Voice Recorder

The CVR was capable of providing two hours of recorded sounds and conversations. The CVR was not damaged in the accident, and the examination determined that the CVR functioned properly. There were no problems recovering the recorded information.

The recording was in two segments:

- The first, 26-minute segment, airborne segment started at 05:59:17 when the aircraft was at 41°09'39" N / 022°27'02" W, about 258 nm north of Lajes; and the recording ended at 06:26:37 when the aircraft electrical system reverted to emergency electrical configuration with the aircraft at 39°21'16" N /026°00'35" W and about 65 nm north-east of Lajes.
- The second, approximately 95-minute segment, contained recordings created during ground operations at Lajes as the result of ground power being applied to the aircraft following the occurrence landing.

The A-330 aircraft recorders are powered from the AC2 electrical bus. The recorders have a protection system that is designed to automatically stop recordings on the ground 5 minutes after the aircraft electrical system is energized if both engines are shut down. Three circuit breakers protecting the recording system are located in the avionics compartment below the cockpit: one for the DFDR, one for the SSCVR, and one for the protection system.

Following the occurrence landing, there was a requirement to power up the aircraft to offload passenger baggage and belongings. Prior to applying power to the aircraft, the crew contacted the company and was advised to pull two circuit breakers. The First Officer went in the avionics compartment and had difficulty locating the CVR and FDR circuit breakers, because he could not find them in the locations provided by the company. Two circuit breakers were pulled, one for the CVR and one for the FDR. The investigation could not determine positively which circuit breakers were pulled. Notwithstanding, based on the facts that the protection system did not work as designed and that the CVR was overwritten, it is concluded that the CVR circuit breaker pulled was the one for the protection circuit and not the power supply circuit breaker.

The First Officer was not familiar with the layout of the circuit breaker panel in the avionics bay, nor was he knowledgeable about the location and number of circuit breakers associated with the recorders.

1.11.3 Digital Flight Data Recorder

The DFDR recorded about 450 parameters. The DFDR was not damaged in the accident, and the examination determined that the DFDR functioned properly. There were no problems downloading the 27 hours of data from the memory. The record stopped at 06:26:37 UTC just after the left engine flamed out and the aircraft electrical system reverted to emergency electrical configuration. At this time, the aircraft was at 39°21'16" N /026°00'35" W, about 62 nm north-east of Lajes, and in descent through 34 264 feet.

1.11.4 Digital Access Recorder

The aircraft was equipped with a digital access recorder (DAR), P/N 2248000-61, S/N 00548. Following the occurrence, the optical cartridge (S/N 009) installed in the DAR was sent to the Flight Recorder Playback Centre of the National Research Council (NRC) of Canada for data retrieval. The NRC examination determined that the cartridge was properly formatted and had a root directory; however, the cartridge did not have any recorded data.

To determine the reason for the lack of data, the airline was requested to provide the cartridges previously installed on the aircraft DAR. These cartridges (S/N 5, 14, and 3) were in the airline's queue for download/analysis and had not yet been analyzed. The cartridges were examined by Flight Recorder Playback Centre, with the following results:

Cartridge Number	Removed Date	Aircraft Hours	Data Date	Base	Comments
004	31-Jul-01	10131.1	31-Jul-01	Mirabel	Good data
005	07-Aug-01	10226.0		Mirabel	Unreadable
014	14-Aug-01	10322.3		Mirabel	Unreadable
003	21-Aug-01	10399.0		Mirabel	Blank
009	25-Aug-01			Azores	Blank
Unreadable = Root directory (disk structure) corrupted Blank = No data written onto cartridge after installation					

The analysis of these cartridges concluded that the DAR failed on or immediately after 31 July 2001. It was also concluded that Air Transat was unaware of the failure of the DAR.

1.11.5 Recorders Power Source

Because the recorders are both powered from the same AC2 bus, and did not have an independent power supply, the recorders did not record events after the aircraft electrical system reverted to emergency electrical configuration. Effectively, the last 19 minutes of the engines-out approach and landing were not recorded, a situation that deprived investigators of data and hampered the investigation into this critical portion of the flight.

A similar situation occurred during the Transportation Safety Board (TSB) of Canada's investigation into the Swissair Flight 111 in-flight fire and loss-of-control accident that occurred off the coast of Nova Scotia, Canada, on 2 September 1998. On 9 March 1999, TSB issued the following recorder, power-supply related recommendations based on its determination that "A lack of recorded voice and other aural information can inhibit safety investigations and delay or prevent the identification of safety deficiencies":

> As of 01 January 2005, for all aircraft equipped with CVR's having a recording capacity of at least two hours, a dedicated independent power supply be required to be installed adjacent or integral to the CVR, to power the CVR and the cockpit area microphone for a period of 10 minutes whenever normal aircraft power sources to the CVR are interrupted.
>
> **A99-03**
>
> Aircraft required to have two flight recorders be required to have those recorders powered from separate generator buses.
>
> **A99-04**

In its response to TSB Recommendation A99-04, Transport Canada stated that it supported this TSB recommendation with the provision that the U.S. and Canadian requirements are harmonized. The Federal Aviation Administration of the United States of America (FAA) response to a similar recommendation from the NTSB, indicated that the FAA would be introducing a Notice of Proposed Rulemaking to amend Technical Standard Order (TSO) 123 (a) to address the requirement for a 10 minute independent power supply for CVR's. This TSO is based on a standard developed by the European Organisation for Civil Aviation Equipment (EUROCAE), of which Transport Canada is a participating member. Transport Canada will monitor the progress of this standard and, when appropriate, consider introducing the requirement into Canadian legislation.

In its response to TSB Recommendation A99-03, Transport Canada stated that Canadian Aviation Regulations subsections 551.01 and 605.33, as well as Airworthiness Manual 551.00, already require the use of separate busses. Furthermore, the Transport Canada requirement is harmonized with the EUROCAE-ED-56A.

1.12 Wreckage and Impact Information

The aircraft landed on the hard surface runway 33 at Lajes. The aircraft structure remained intact. Minor components of the main landing gear wheel assembly were scattered along the runway.

1.13 Medical Information

Crash Fire Rescue (CFR) reported that 82 persons were examined for medical conditions after the evacuation, and that 18 of these persons had injuries: 5 were treated in the USAF clinic; and 13 were sent to the Portuguese Air base clinic. The two seriously injured persons were subsequently sent for treatment at the hospital in the city of Angra on Terceira Island.

1.14 Crash Fire Rescue Services

At 06:15, Lajes Base Operations notified the CFR unit that an emergency was in progress involving the Air Transat Flight 236, an Airbus 330 aircraft with 306 persons on board, and that the aircraft would be landing on runway 33. All immediate-reaction CFR units were in position at 06:19.

Following the aircraft landing at 06:45, CFR reported that there was fire visible coming from the main wheels, and responded to put out the fire. At 06:46, CFR reported that the evacuation was in progress and that some signs of fire still existed in the left main wheels. By 06:54, all fires were extinguished; the areas around the main wheels continued to be monitored due to the fire hazard associated with the damaged wheels and hot brakes.

In total, 11 CFR vehicles and 23 persons responded to the emergency landing: 2 command vehicles, 1 rescue vehicle, 4 crash trucks, 1 structural pumper, 2 support vehicles, and 1 foam trailer. In addition, 4 ambulances and 23 medical staff responded to the occurrence.

1.15 Passenger Safety and Survivals

1.15.1 Cabin Emergency Preparation

The FD's briefing to the passengers on the action plan for a ditching included instructions on donning of life jackets and demonstration of the brace position. The briefing was given in English and French.

Many of passengers did not react appropriately to the briefing. On being advised that a number of Portuguese passengers were having difficulty in understanding the briefing, the FD had another flight attendant repeat the briefing in Portuguese. A number of passengers also required the physical assistance of the flight attendants to find and don their life vests. According to the cabin crew, the passengers, although obviously stressed by the situation, were cooperative and responsive to these instructions.

Canadian Aviation Regulations (CAR's), subsection 705.43, requires that the air operator ensure that passengers are given safety briefings in English and French. This subsection, in part, also states that where the safety briefing is insufficient for a passenger because of comprehension limitations, the passenger shall be given an individual safety briefing that is appropriate to the passenger's needs. Notwithstanding, this subsection of the CAR's does not specifically require that briefings be given in languages other than the official Canadian languages of English and French.

Although the company also does not have a specific policy or standard on providing passenger safety briefings in other than in English of French, it has been normal practice for passenger service reasons to have flight attendants on board capable of providing such service in other languages based on the destinations and clientele being served. In addition, the company uses appropriate language subtitles in its preflight safety videos; Portuguese subtitles were used for this flight.

1.15.2 Passenger Life Jackets

The passenger life jackets are stored in pouches beneath the passenger seats. The jackets are packed into sealed plastic bags with the waist straps tightly folded and bound by a plastic band.

The life jackets have an inspection cycle of two years. Each bag contains an inspection tag that indicates a “REINSPECTION DATE” for the vest, and an additional, red colour sticker affixed to the outside of the bag indicates the “DUE TO BE CHANGED” date.

Most of the life jackets on board the aircraft had been packed in 1998 and had a “REINSPECTION DATE” of OCT 2002. One of the inspection tags had an overhaul inspection date of 16 DEC 98, and another, 21 JAN 99.

The passenger life jackets found on the aircraft after the occurrence were of two types: a single-strap type similar to the one described on the passenger safety card and the cabin safety demonstration video; and, a two-strap version.

While donning the vests, some of the passengers had difficulty in finding the bound waist straps. The reported donning problems were associated with the single-strap jackets.

The Cabin Attendant Operations Manual specifies that the occurrence aircraft was equipped with only the single-strap type of life jacket. On the occurrence flight, the pre-flight passenger safety briefing and the demonstration of the donning of the life jackets during the preparation for the anticipated ditching were based on the single-strap type life jacket.

There is no CAR’s specifying that there should only be one type of life jacket on an aircraft. However, CAR’s subpart 705.43 (1) requires that the air operator ensure that passengers are given a safety briefing in accordance with the Commercial Air Service Standards, and CAR’s Subpart 705.44 requires that the air operator provide each passenger, at the passenger's seat, with a safety features card containing, in pictographic form, the information required by the Commercial Air Service Standards (CASS).

CASS subpart 725.43 requires that the standard passenger safety briefing consist of an oral briefing provided by a crew member or by audio or audio-visual means in both official languages which includes the location, and use of life preservers, including how to remove from stowage/packaging and a demonstration of their location, method of donning and inflation, and when to inflate life preservers.

CASS subpart 725.44 (vii) requires that the safety features card contain the location of life preservers and correct procedures for removal from stowage/packaging; donning and use of the life jacket for adult, child and infant users including when to inflate; and that the safety information provided by the card be accurate for the aeroplane type and configuration in which it is carried and in respect of the equipment carried.

The Emergency Equipment Section of the Air Transat Cabin Attendant Operations Manual states that all life jackets on board must be of the same type, and states that, during the pre-flight check, flight attendants must verify the presence of a life jacket at each seat. Although this section of the manual also refers to the fact all life jackets on board are to be of the same type, verifying that the type of life jacket during the pre-flight check is not a flight attendant responsibility. According to the flight attendants on the occurrence flight, the presence of lifejackets at each seat was verified before the passengers boarded the aircraft.

The installation and verification of the status of life jackets is a maintenance function. All life jackets are verified on installation and at every “C” check of the aircraft for compliance in regards to the “re-inspect due date” to ensure that each vest has sufficient time remaining until the next “C” check. The aircraft had not undergone a “C” check since it was acquired by Air Transat.

1.16 Tests and Research

1.16.1 Examination Reports

The following test and examinations were performed in support of the investigation:

- Rolls-Royce Document Number MFR41281, Report N° DNS 81874, dated 4 October 2001, "Air Transat (TSC) Trent 772, Engine Number 41055, LP Fuel Tube Failure Investigation"
- Rolls-Royce Document Number DHP117761, Report N° MFR 41283, dated 23 October 2001,"Air Transat (TSC) Trent 772, Engine Number 41055, Rear Hydraulic Pump Outlet Tube Failure Investigation"
- Rolls-Royce Document Number DHP117772, Report N° MFR 41281, dated 5 July 2002,"Air Transat (TSC) Trent 772, Engine Number 41055, Rear Hydraulic Pump Outlet Tube Failure Investigation"
- Rolls-Royce Document Number DNS85146, Report N° FSG44035, dated 30 May 2002, "RB2211 Trent 700 – Estimate of Effect of LP Fuel Leakage on Engine Oil System Parameters"
- NTSB Survival Group Factual Report on Airbus A330 L3 Slide, dated 5 February 2002
- B/E Aerospace, Engineering Report on Oxygen Modules, Doc 3500-02-08, dated 20 January 2002.
- Transportation Safety Board of Canada, Laboratory Project LP002/02, dated 19 August 2002, "Testing of Passenger Emergency Oxygen Units"
- Airbus, Fuel System Analysis, Doc LP011/01, dated 27 May 2002.

1.16.2 Hydraulic Line Installation Tests

A test installation was carried out after the occurrence on the installed right engine using a new post-mod fuel tube (FK30383) and the pre-mod hydraulic line installed on the engine. The hydraulic line was easily aligned and screwed onto the hydraulic pump fitting by hand. However, as the "B" nut was further tightened, the hydraulic tube was drawn into contact with the fuel tube. A clearance of about 0.025 inches between the hydraulic and fuel tubes subsequently was achieved by manually bowing the hydraulic flex line away from the fuel tube while applying torque to the nut.

During similar test done at Rolls-Royce, carried out in the presence of the AAIB, a degree of difficulty was encountered when connecting the hydraulic line. It was also noted that, after the line was torqued, only a small amount of push on the line was required to move it back and make contact with the fuel tube.

It is well known that a flex tube will tend to expand radially, shorten in length, and straighten once pressurised. Considering the hydraulic system working pressure of 3,000 psi and the pump pulsation, it is feasible that any clearance present at installation on the occurrence aircraft would have vanished once the line was pressurized.

1.17 Organizational and Management Information

1.17.1 Company Certificates

Air Transat A. T. Inc is authorized by the Minister of Transport of Canada to provide the types of services specified in its Air Operator Certificate (AOC), number 6767[21]. Pertinent to the occurrence flight, Part I of the AOC, in part, authorizes non-scheduled and scheduled international operations between Canada and points abroad, and between points abroad using its Airbus 330 aircraft.

A condition for a Canadian company to acquire and maintain an AOC is that the company must have an appropriate Operations Manual, which includes a Transport Canada approved flight crew training program.

Air Transat carries out its maintenance internally under the authority of its Approved Maintenance Organization (AMO) Certificate number 32-87 issued by Transport Canada. The Air Transat AMO Certificate is valid for a large spectrum of maintenance work applicable to the various aircraft types that it maintains. Air Transat is authorized to maintain its fleet of Lockheed 1011, Boeing 757, Airbus A310 and A330 aircraft.

Subpart 706 of the Canadian Aviation Regulations provides the requirements for the maintenance of the air operator's aircraft. In accordance with Section 706.08 of the Canadian Aviation Regulations, the company has a Maintenance Control Manual (MCM). The MCM specifies the maintenance organization and the maintenance control system required to maintain the air operator's aircraft in conformity with regulations.

1.17.2 Extended Range Twin-engine Operations

Under Part IV of the AOC, Operations Specification Number 61[22], Air Transat was authorized to fly its aircraft, at the airspeed and for the time period referred to in Section 3 of its operations specification, on routes that did not contain a point farther from an adequate aerodrome than the distance that could be flown in 60 minutes at the one-engine-inoperative cruise speed.

This operations specification was valid if the air operator complied with the requirements of the *Safety Criteria for Approval of Extended Range Twin-engine Operations (ETOPS) Manual*[23]. Specifically, Section 3 authorized Air Transat conduct ETOPS operations with A330 aircraft on routes that did not contain points that were farther than 150 minutes at an A330 speed of 427 knots true air speed from an adequate aerodrome. Records indicate that the occurrence flight was conducted in accordance with the AOC and Operations Specification 61 in force at the time of the occurrence.

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[21] AOC 6727 in force on the day of the occurrence was approved on 10 October 1996.

[22] Operations Specification 61 in force on the day of the occurrence was approved on 15 June 2001.

[23] TP 6327, *Safety Criteria for Approval of Extended Range Twin-engine Operations (ETOPS) Manual*, dated 1996 Edition, is published by Transport Canada Safety and Security under the authority of the Director general, Civil aviation by the Director, Commercial and Business Aviation in coordination with the Director, Airworthiness.

Chapter 4 of Transport Canada publication TP 6327 E specifies the standards and necessary guidance that must be contained in the maintenance program to qualify for ETOPS. The Air Transat MCM, containing the maintenance procedures for it's A330 aircraft involved in ETOPS, was approved by Transport Canada. The MCM specifies the qualification required for maintenance personnel involved on ETOPS aircraft. This ETOPS qualification is provided as an element in the company's training that provides its technicians with a technical maintenance rating on the A330. Other than a requirement to maintain an ETOPS reliability program, which includes reporting to Transport Canada, there are no additional maintenance actions or record keeping required, other than maintaining compliance with the provisions in the company's MCM.

Section 6.13 of the company Operations Manual provides direction as to the conduct of ETOPS flights. Section 6.13. H) specifies the following conditions that would mandate an en-route diversion to an ETOPS alternate airport:

- Engine failure;
- Multiple system failures that would make it impossible for safe flight continuation to destination;
- When a LAND ASAP message is displayed on the ECAM; and
- When an immediate landing is indicated in an emergency or abnormal procedure checklist.

Section 6.13 H) also specifies that some failures, such as a fuel leak, depressurization, or higher-than-normal fuel consumption, may warrant a diversion.

1.17.3 Flight Crew Training

The approved Air Transat Training Manual meets the requirement for the Operations Manual to have a Transport Canada-approved flight crew-training program. This manual includes A330 initial ground training, specialized ground training, cockpit procedures training, fixed-base simulator training, full-flight simulator training, line indoctrination, line check, and line duties. All the training is based on the A-330 Flight Crew Operating Manual, Volumes 1, 2, 3, and 4, and the A-330 Flight Crew Training Manual.

1.17.4 Air Transat Maintenance Organizations

1.17.4.1 Engineering

The Air Transat Engineering Department is responsible for the reliability program and ensures that repairs and/or modifications to aircraft are carried out in accordance with company- or manufacturer-approved procedures. The department also reviews all Airworthiness Directives, Service Bulletins, and technical correspondence with manufacturers, and directs maintenance actions to be taken in response to these documents.

1.17.4.2 Engine Control

At Air Transat, each engine model is assigned to an Engine Controller, who liaises with the manufacturer to obtain additional expertise as needed. The controller's responsibility centres on the off-wing maintenance of the engine.

1.17.4.3 Quality Assurance

In accordance with the MCM, the company has a quality assurance program. The Director Quality Assurance Director oversees the adequacy of the overall maintenance program through a number of methods including Quality Control.

1.17.4.4 Quality Control

The quality of maintenance carried out is monitored by the Quality Control (QC) manager and delegated inspectors who are all licensed AME's. The accuracy and quality of work is insured by two methods: the first is by physical inspection of work done on aircraft; and, the second is through the review of logbooks and documentation for accuracy, completeness and validity of certification.

There was no QC person on site during the time that the engine was replaced, nor there was a requirement for one specified in the MCM. At the time of the occurrence, QC staff worked Monday to Friday.

Designated supervisors do the day-to-day quality control of work being done. In addition, following the completion of major maintenance tasks, independent inspections are carried out.

1.17.4.5 Maintenance Control Centre

The Maintenance Control Centre (MCC) is located in the company's System Organization Operations Centre (SOOC), which operates 24/7 and coordinates all airline operations. The MCC is manned by two aircraft technicians, who analyse anomalies reported by the flight crew and coordinate maintenance resources where and when required. The MCC technicians keep the SOOC informed of time of completion for ongoing maintenance. If requested, and, if time is available, the technicians can also provide technical support to maintenance crews.

During the engine change, both AME's on duty at MCC were endorsed on the A330.

1.18 Maintenance and Technical Factors

1.18.1 Illustrated Parts Catalogue

An Illustrated Parts Catalogue (IPC) is a document that is intended for use in identifying, provisioning, requisitioning, storing and issuing line replacement aircraft parts and units. An IPC is a companion to the Maintenance Manual and includes all parts for which a maintenance practice has been provided.

There are two IPCs that can be referenced by technicians when performing maintenance on the Trent-772 engine dressing: the Airbus A330 IPC, which forms part of the ADRES (Airbus Documentation Retrieval System); and, the Rolls-Royce Engine Illustrated Parts Catalogue (EIPC).

The Airbus A330 IPC, also referred to as ADRES (Airbus Documentation Retrieval System), is presented on a series of CD-ROMs. It specifies the configuration status of each aircraft by serial number. It lists both the current aircraft parts applicability and includes a note informing the reader of the embodied SB.

Concerning the engine dressing and the hydraulic pump modification, Airbus published its own SB's (A330-29-3068). Although the Airbus IPC referenced the applicable Rolls-Royce SB's, a direct hyperlink to the Rolls-Royce SB's is not a design feature of the Airbus IPC.

The Rolls-Royce EIPC for the Trent 772B engine series is available on a single CD-ROM. The CD-ROM also contains relevant SB's, which are accessible through a number of different methods, one of which is via hyperlinks from the IPC portion of the CD-ROM.

The Airbus IPC, Rolls-Royce IPC and associated SB's are available on the company computer network. These documents are also available on standalone PC's and CD's at the MCC station and in the Air Transat Technical library. Additionally, a paper copy of each SB is held in the Air Transat Technical Library, under controlled access, in order to preserve its integrity. Technicians rarely, if ever, access either the library's hard copy or the standalone CD's; maintenance management more commonly uses them.

Neither the Airbus IPC, nor Rolls-Royce EIPC was referenced at the time of engine receipt, nor during review by engineering prior to the engine installation. The Airbus IPC was referenced by the lead technician during the engine installation.

1.18.2 Scope of Service Bulletins

Air Transport Association (ATA) Specification 100 specifies that Service Bulletins (SB's) shall be the only document used by manufacturers to notify operators of recommendations and modifications to their products. Although many other publications and methods of correspondence are available to airframe, engine and components manufacturers to forward miscellaneous information on their products, only the SB is to be used for actions that require a record of accomplishment. SB's are published for a number of reasons, one of which is to present a product improvement, and they can be triggered by the discovery of an in service failure, an unforeseen wear pattern, or several other causes. SB's are published with a required level[24] of compliance, either "Optional", "Recommended" or "Mandatory".

If the SB has an airworthiness implication, the bulletin may be forwarded with a mandatory compliance date. In such cases, the regulatory authorities of the country of manufacture will normally generate an Airworthiness Directive (AD) on the related matter to mandate the embodiment of the SB. Non-compliance with an AD results in the invalidation of the aircraft Certificate of Airworthiness.

A specific requirement of ATA 100 is that once issued, an SB may be revised, but cannot be cancelled. Since aeronautical products tend to stay in service for several decades, over the years, an aircraft or an engine may well cumulate over a thousand SB's. Operators must have access to a library of all SB's applicable to the aircraft, engines and appliances that they maintain.

SB's carried out or embodied must be documented in the pertinent log book (airframe, engine and or appliance). SB's determined to be unrelated to a given airframe, engine or component, and those not embodied are not documented.

[24] Although an SB may be designated as "Mandatory" by the manufacturer, the embodiment of the SB only becomes mandatory if the civil aviation authority issues an airworthiness directive directing the embodiment of the SB.

In cases, when an airframe manufacturer-controlled system interacts with an engine system, both manufacturers will publish their own separate SB. In such cases, embodiment of the SB would normally be found in both the airframe log under the airframe manufacturer's designation and in the engine log under the engine manufacturer's designation. When a modification associated with an SB is embodied during production, the annotation provided in log book by Airbus will be the modification number with a brief description of the modification; the description does not reference the SB number.

Rolls-Royce SB's for the RB211-700 and 800 series are listed together in a 75-page index. At the time of the occurrence, there were a total of 908 Service Bulletins published, of which 545 concerned the 700 series. Out of those 545 SB's, a total of 295 were relevant to the condition of the engine. Review of the loaned engine logbook showed that out of the remaining 250 SB's, 167 had been carried out or embodied. These were documented on 10 different pages throughout the engine logbook.

1.18.3 SB's Addressing the Hydraulic Pump and Engine Dressing

On 21 April 1999, in reaction to several cases of hydraulic fluid leakage at the hydraulic pump or attached hydraulic lines, Airbus published an optional SB (Service bulletin A330-29-3068) offering a modified hydraulic pump. The SB offered three physically similar and interchangeable models bearing Part Numbers #974800, #974976 or #66198. Part #974800 was used by Airbus for embodiment of the SB at the time of manufacture, while the other two models of pump were available for modification and/or replacement by operators.

Because the pump was mounted on the engine, Rolls Royce, on 15 January 1999, issued the following two SB's: Optional Rolls-Royce SB RB.211-29-C664, detailing the replacement of the hydraulic pump; and SB RB.211-29-C625, detailing modifications to the engine dressing to accommodate the widened pump housing and the resulting interference with the adjacent fuel line. Modification of the dressing consisted of the replacement of the three fuel tubes and two hydraulic tubes for the front and rear hydraulic pumps.

SB RB.211-29-C664 clearly outlines the requirement that SB RB.211-29-C625 be fitted prior to or concurrently with its embodiment. SB RB.211-29-C625 stated that it was essential that the tubes be fitted as a set.

For aircraft manufactured after the introduction of the SB's, the embodiments are documented by Airbus in the airframe log as modification numbers 43680S14635 and 46553S14262.

The Airbus SB's only applied to 27 A330 airframes equipped with Rolls-Royce engines and included one of the three A330 aircraft operated by Air Transat. On that aircraft (SN: 111), both SB's had been embodied by the previous operator.

The two Rolls-Royce SB's were introduced into new engine production at engine serial number 41071; therefore, these SB's were not incorporated at the time of manufacture of the loaned engine (41055), nor during the last shop visit due to the unavailability of parts.

Jmv

1.18.4 Methods of Reviewing Service Bulletins

As with other mandatory maintenance requirements, such as for the AD's, the common method used by maintainers to determine the current status of an aircraft is to compare the pertinent airframe, engine or component logbooks against the list published by the manufacturer. There is no requirement to re-examine the content of the SB's that are recorded as being embodied.

Because of the airworthiness implications, Transport Canada audits the lists of pertinent AD's and mandatory SB's, as well as the completeness of their embodiment. Recommended or optional SB's are not given the same level of attention by the operator, nor are they audited by Transport Canada.

The most thorough method of confirming SB parity between an engine being removed and the one replacing it, is to mirror each engine log book against one another. In addition, the SB main index list would have to be scrutinized for every unmatched SB to assess the possibility of concurrent requirements. This method would have required the comparison of 167 SB's in the case of the replacement engine.

An alternative method, suggested after the accident by the engine manufacturer as a quicker means of establishing SB parity, is that the operator should accept the airworthiness status of the parts installed on the engine and the correctness of the SB's listed as being embodied in the engine log book. Using this method, it only would be necessary to check the major components that were to be installed against the EIPC to check for any associated SB. This method, in the case of the loaned engine, would have reduced the number of SB's to be checked for applicability to 13.

If and when an SB is found to apply, it would have to be reviewed for other part number applicability and for any concurrent requirements.

1.18.5 Company Review of Non-mandatory SB's

SB's having an optional or recommended compliance are not reviewed by maintenance supervisors at Air Transat. The Air Transat Engineering Section leads these reviews with senior management. Although maintenance crews may become aware of specific SB's, the crews are not part of the embodiment decision-making process.

Neither SB RB.211-29-C664 (pump), nor SB RB.211-29-C625 (dressing), went through the reviewing process at Air Transat, specifically because all the Air Transat A330 aircraft, including serial 271 involved in the event, were post-SB mod status when acquired. This situation also meant that the maintenance management at Air Transat had not been exposed to these pre-SB aircraft or to the associated SB's.

1.18.6 Receipt and Inventory of Engines

Subpart 571.13 of Canadian Aviation Regulations requires that no person shall install a part on an aeronautical product unless the part is inspected and its accompanying documentation verified in accordance with a procedure that ensures that the part conforms to its type design, as is indicated by the maintenance release.

In this regard, the Air Transat MCM contains a procedure that requires incoming parts and materials be subjected to a receiving inspection in order to verify that the subject items are acceptable for use on company aircraft. In order to verify acceptability of items, the receiving inspector's responsibilities include ensuring that:

- The delivered goods match the items on the respective purchase order with regard to part number specification and quantity;
- The B757, A310 and A330 components critical to ETOP's meet the requirements for ETOP's capability;
- The visual inspection ensure that the received goods have not suffered damage in transit; and
- The paperwork accompanying the goods provides data substantiating that airworthiness requirements have been met by the supplier.

As per CARs 571.08 (1) (a), the above requirements do not apply for serviceable, used parts that are removed from an aircraft and are immediately installed on another aircraft.

When the engine RB211 Trent 772-60 SN 41055 arrived at Air Transat's facility, the engine controller compared the status of the engine to the Rework Summary Sheet and the Carry Forward Items List. He was satisfied that the components on the carry-forward item list were available either in stock, or off any engine that might require replacement.

The review of the documentation and receiving inspection of the engine did not detect that the engine condition was in the pre-mod (SB RB.211-29-C625) configuration.

1.18.7 Engine Change Planning

Although CAR's do not specifically refer to a maintenance planning function, they do require that aircraft be maintained and repaired in accordance with the manufacturer's recommendation, the CAR's, and the requirements of the Air Transat MCM.

Maintenance falls into two major categories: scheduled routine maintenance; and unscheduled defect rectification. Although advance planning and allocation of logistic and personnel resources is possible for scheduled maintenance, it is not the case for rectification of unanticipated defects.

The presence of metal particles on the original No. 2 engine on 17 August 2001 required an unscheduled engine change. Various options for the engine replacement were considered, including outside contracting. Notwithstanding, after confirming the availability of experienced Air Transat technicians, it was decided, late Friday afternoon, that the work could be done using in-house resources, with the work starting at midnight the same day.

To support the work required for the engine change, work-card package No: 710000-05-01, revision 06, was extracted from the Airbus ADRES. The package contained all applicable references to the Maintenance Manual. As per the maintenance procedure outlined in the MCM, the installation of the carried-forward items was to be documented on additional work sheets.

These sheets were to be completed during the course of the engine change. Because the pre-mod configuration of the engine had not been identified, no work sheets were issued to address the applicable SB's.

1.18.8 Right Engine Replacement

Subpart 571.02 of CAR's requires that a person who performs maintenance or elementary work on an aeronautical product shall use the most recent methods, techniques, practices, parts, materials, tools, equipment and test apparatuses, as follows:

- Those that are specified for the aeronautical product in the most recent maintenance manual or instructions for continued airworthiness developed by the manufacturer of that aeronautical product;
- Those that are equivalent to those specified by the manufacturer of that aeronautical product in the most recent maintenance manual; or,
- Those instructions for continued airworthiness, or in accordance with recognized industry practices at the time the maintenance or elementary work is performed.

Subpart 571.13 of CARs requires the inspection of a part to be installed and verification of the accompanying documentation to that the part to ensure that it conforms to its type design, as is indicated by the maintenance release. Subpart 571.08 (1) (a) states that these requirements do not apply for used parts which are removed serviceable from an aircraft and which are immediately installed on another aircraft. Notwithstanding, Subpart 571.08 applies to components of identical part number; the IPC must be referenced in every other case.

The engine change started around midnight on Friday, 17 August 2001, with the removal of accessories from the engine being removed. It was assessed that the work could be completed by Sunday, noon to meet the commitment of the aircraft for the scheduled flight and commitment of the hangar space for another use. On Saturday morning, at 06:30, 18 August 2001, the lead technician met with the night crew for a shift hand-over briefing.

Some delays were incurred around midday due to the late arrival of a leased jacking pad. The Rolls-Royce representative visited the hangar during the day to keep updated on the progress of the engine change. At the end of the day, the lead technician handed over the hanging of the replacement engine to the night shift. Even though the work had progressed at a somewhat slower pace than planned, no remarkable difficulties were encountered.

The lead technician returned to work early on Sunday morning. Shortly after commencing his shift, he was advised that the rear hydraulic pump could not be fitted due to interference with the high-pressure fuel pump inlet tube. A search through the Airbus IPC revealed the existence of SB29-C625 and of pre- and post-SB configurations. At this time, the lead technician realized that the replacement engine was in a pre-SB configuration, while the removed engine was post-SB. The lead technician attempted to access the SB from Rolls-Royce EIPC CD installed on the network using three different computer stations. All attempts resulted in access being denied, as a result of a computer network malfunction.

The lead technician then contacted the MCC, who in turn paged the Air Transat Trent Engine Controller for advice. While waiting for the Trent Engine Controller to return the call, the MCC technician attempted to access the Rolls-Royce EIPC and the SB's through the computer network, but was also denied access. While MCC had its own stand-alone maintenance EIPC CD's, including the SB's, they were not used.

The use of the EIPC CDs was not considered by the lead technician because he was not aware of this capability in the MCC. The use of the CDs by the MCC technicians was not considered because their role in providing technical assistance to maintenance crews was to locate resources and not to provide technical assistance in searching for technical references."

When the Trent Engine Controller called back, he readily recalled the rationale for the pump modification as being excess vibration. He also recalled that the modified pump interfered with the fuel lines, and that these would need to be replaced. He further advised the lead technician to confirm that, when the pump and lines were installed, adequate clearances existed between lines and components. The lead technician queried the possibilities of using a pre-mod pump to save time, because the work was already running late. Based on his knowledge that all Air Transat aircraft were of post-mod status, as were all other Roll Royce powered A330's flown in Canada by other operators, the Engine Controller informed the lead technician that such a pump was not available on short notice. Both agreed that there was no choice other than to replace the fuel tubes. In discussing the estimated time required to complete the transfer of the tubes, the controller suggested that the time outlined in the SB should be used. At this time, the controller was told, in passing, that the crew had not been able to access the SB. While the difficulty in accessing the SB initially was a concern, the discussion quickly reverted to the time required to complete the work, without further discussion of the SB. The controller was advised that he would be kept informed of the situation.

Both segments of the post-SB fuel tube assembly (P/N's: FK30382 & FK30383) were taken from the removed engine and installed on the replacement engine. The different shape and routing of the new fuel line overcame the earlier difficulties encountered in installing the hydraulic pump. The pre-SB hydraulic tube LJ51006, received with the loaned engine, was retained. The installing technician recalled that, during the installation of the hydraulic line when trying to achieve the required separation between the fuel and hydraulic line, the hydraulic line had a tendency to spring back. Notwithstanding, according to the technician who did the installation, clearance between components was easily obtained by positioning and holding the hydraulic tube, while applying torque to the “B“ nut. He also stated that a tool was not used to force the separation between the fuel and hydraulic tubes. There was no additional installation difficulties reported.

The Rolls-Royce representative telephoned MCC during the engine installation on Sunday to inquire about the work progress and to offer help if required. He was informed that the pre-mod status of the loaned (right) engine did not permit installation of the hydraulic pump and was informed that the fuel tube was being changed over from the removed engine to the loaned (right) engine to allow the pump installation. The Rolls-Royce representative was unaware of the engine dressing SB modification status of the loaned engine and of the status of the Air Transat engine fleet. The Rolls-Royce representative was not specifically told of the difficulties in accessing the SB's nor was he specifically asked to consult his documentation. His offer to attend on-site if required was not taken up.

The installation of the post-mod hydraulic pump, the pre-mod hydraulic tube and the post-mod fuel tube assembly resulted in a mismatch between the fuel and hydraulic tubes.

When the engine change was completed, the lead technician arranged for an independent inspection.

1.18.9 Pressure Line Installation

The hydraulic line connecting the pump to the pylon is about 11 feet long. Both ends of the line are rigid; the middle section is flexible to assist in dampening hydraulic pump pulsations. The line routing includes a 90-degree bend near the hydraulic pump connector.

During the installation of the line on the occurrence engine, pulling to position the line away from the fuel tube would have resulted in some rotation of the hydraulic tube flange under the "B" nut. Torquing of the "B" nut would have provided force on the flanges to counteract the tendency for the flange to rotate back to its normal position. Pressurizing the hydraulic line would result in a force to straighten the line, which would result in force to rotate the flange to a position that would eliminate the separation between the fuel and hydraulic lines.

The standards and procedures for installing hydraulic lines built with a middle, flexible portion are not specified in the training manuals, such as "Maintenance and Repair of Aerospace Vehicles" and "Basic Science for Aerospace vehicles" published by "Northrop Institute of Technology". The issue also is not addressed in widely known technical aviation reference manuals, such as the "Fletcher Standard Aircraft Worker Manual", the FAA "AC 43.13-1B/2A", or CAA Information and Procedure Leaflet 5-5. All these manuals treat rigid tubing and flexible hoses as different issues. The illustration provided in these manuals for flexible hoses indicates that a slight bow is desirable to allow for shortening when pressurized.

A visit to a government-sponsored regional aerospace training school in Canada also revealed that, although training covers the installation of both rigid and flexible lines, training is not given on the installation of mixed-construction lines similar the hydraulic line on the Trent engine. The criteria for training programs and practical tests do not comment on the risks of using torque as a means of positioning such lines during component installation.

Tubes constructed of both rigid and flexible sections are used throughout the aviation industry. They are used extensively in many airframe and engine combinations for a variety of hydraulic fluid, oil, or fuel system applications.

1.18.10 Documentation of Work Done

Air Transat MCM section 1.4.3 outlines that the rectification of defects must be appropriately entered in the log. Consequently, the switching of the tubes from the removed engine to the loaned (right) engine should have been recorded in both, the removed and installed engine logs. A review of the log book ,after the accident, showed that entries for all expected components changed over to the installed right engine had been properly made, signed and countersigned by the supervisor; however, the recording of the unexpected replacement of the fuel tubes was not documented.

1.18.11 Quality Control

Following completion of the engine change, the lead technician inspected all the work done and the tasks documented on the work cards and additional work sheets. The inspection was to ensure that the work was complete, within tolerances and secured. His inspection did not uncover any anomaly with the engine installation.

Another inspection called “the independent inspection” was done by a qualified technician, who had not been involved with the work being inspected. The independent inspection was done to ensure that engine controls are properly connected and secured. This scope of this inspection was not intended to include the fuel or hydraulic system components.

Following these inspections, the engine was ground run, without problems, and was released for flight.

The company MCM specifies a requirement for a quality control inspection of the documentation after an engine installation; however, company manuals do not specify a time frame for this inspection. There was no QC representative on site on the weekend of the engine installation. The company plan was to do the document verification when preparing the removed engine for shipment for repair. As of the occurrence date, 24 August 2001, the engine change documentation had not yet been reviewed by the quality control staff.

1.19 Aircraft Operational and Operational Factors

1.19.1 Cockpit Management

The captain of an aircraft has overall responsibility for the safe operation of the flight. In a two-man cockpit, one pilot is designated as Pilot Flying (PF) with the other pilot being Pilot Non Flying (PNF).

Regardless of the allocated duties, the crew must work as a team, and this requirement is a basic part of Crew Resource Management (CRM) training. A basic element of CRM is that, whenever possible, the situation must be fully understood and agreed to by the crew before any corrective action is taken. In accordance with the instructions detailed in Air Transat A330 Flight Crew Operating Manual (FCOM) 3, the Abnormal and Emergency procedures represent the actions applicable after a failure, to ensure adequate safety and to ease the further conduct of the flight. They are applied following the “READ and DO” principle.

1.19.2 Fuel System Abnormal Procedures

The integrity of any abnormal procedure relies on the premise that only the correct procedure should be used for a given situation, and that the procedure should be completed in its entirety. On the A330, most procedures are displayed on the ECAM, and as each procedure item is properly completed, the item is removed from the display screen. Crews are taught to trust that the ECAM system will alert them of significant events that could have an effect on safety, and that completing the prescribed procedure will best ensure safety of flight. Neither the FUEL IMBALANCE procedure, nor the FUEL LEAK procedure, is displayed on the ECAM.

1.19.2.1 Fuel Imbalance

A FUEL IMBALANCE is an abnormal condition that results in an ADV. According to the FCOM, an ADV does not require an immediate action, and only requires crew monitoring of the system. The Fuel ADV does not result in a display of the corrective action required to correct the imbalance. Consequently, the crew is required to refer to the appropriate page in the Quick Reference Handbook (QRH) to complete the procedure items.

The FUEL IMBALANCE procedure is specifically designed to specify the actions required to mitigate imbalance, by cross-feeding fuel from the wing tank that has the higher quantity, and when the balance has been corrected, to return the fuel system to normal configuration.

The procedure also contains a CAUTION note that, if a fuel leak is suspected, the crew should instead refer to the FUEL LEAK procedures.

FUEL IMBALANCE

CAUTION
Do not apply this procedure if fuel leak is suspected . Refer to FUEL LEAK procedure.

- WING X FEED .... ON

■ **If the WING X FEED valve is open :**

● **On the lighter side :**
- (ALL) FUEL PUMPS (STBY then NORM) .... OFF

● **When fuel balanced :**
- PUMPS (NORM then STBY) .... ON
- WING X FEED .... AUTO

■ **If the WING X FEED valve is failed closed :**
- OUTER TK XFR .... ON
- BANK ANGLE ..... 3 DEG WING DOWN ON LIGHTER SIDE
Fuel transfer only occurs if bank angle is at or above 2 to 3 deg.
Modulate the fuel imbalance through the bank angle.
- RUDDER TRIM .... USE
Use rudder trim to oet constant course and neutral stick.

Figure 7 - A330 FUEL IMBALANCE Procedure

A fuel imbalance is a condition that would not occur unless there is a difference in fuel flow/loss between the right and left inner tanks of the fuel system. An imbalance could occur if one engine is not operating or is operating at lower fuel consumption, or if there was a fuel loss. During normal operations and during training, a fuel ADV would rarely if ever occur. Notwithstanding, the crews frequently experience engine failures during simulator training that require monitoring of fuel load distribution between the left- and right-wing tanks. In these scenarios, the FUEL IMBALANCE procedures are reviewed, but infrequently used to rectify an imbalance because the imbalance is routinely insignificant and the time to landing is relatively short. Consequently, crews view the imbalance procedure as a simple, somewhat routine clean-up procedure.

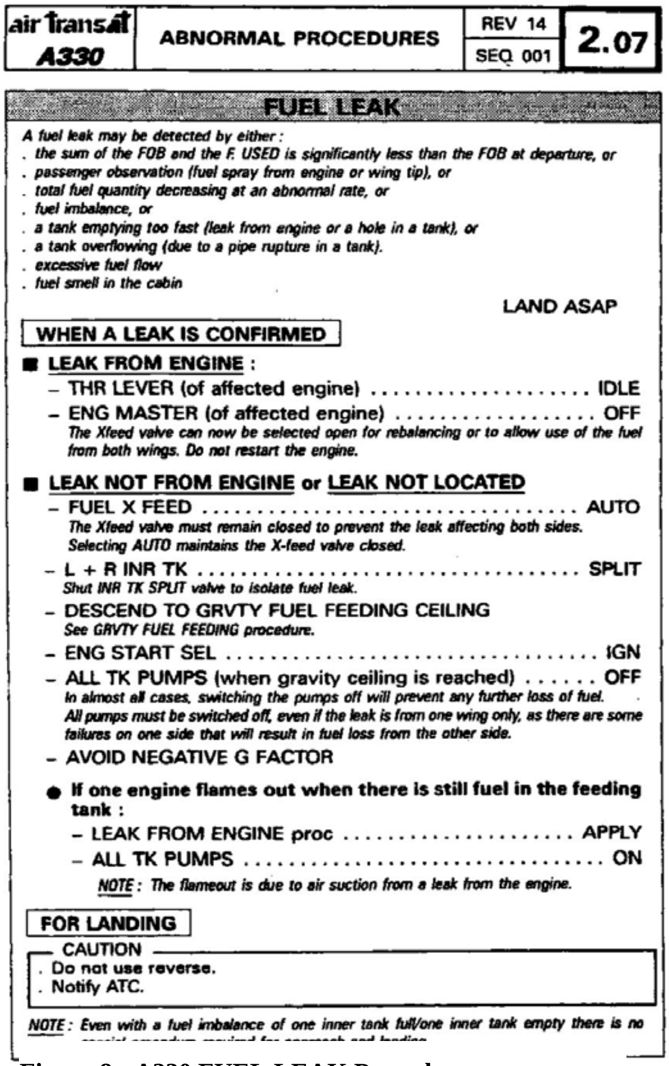
For this occurrence, the Captain reacted to the fuel imbalance ADV by completing the procedure items by memory. Although the selection of the WING X FEED to ON, and the selection of the fuel pumps to OFF on the lighter (right) side was done, the content of the CAUTION note was not considered during the actioning of the procedure.

1.19.2.2 Fuel Leak

A FUEL LEAK is an abnormal condition that is not monitored by the ECAM system; consequently, an ECAM warning is not generated for these conditions. Instead it is expected that the crew's normal monitoring of the fuel system parameters will result in timely recognition that a fuel leak exists or a loss is taking place, and the conclusion that actioning of the FUEL LEAK procedure is required. The only other catalyst that would result in the crew referencing this procedure is the CAUTION note in the FUEL IMBALANCE procedure.

When the conditions of a fuel leak have been ascertained, the crew is required to refer to the appropriate page in the Quick Reference Handbook (QRH), and required to complete the procedure items.

The FUEL LEAK procedure is specifically designed to specify the actions required to mitigate the consequences of a fuel leak affecting either side of the fuel system.



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FUEL LEAK

A fuel leak may be detected by either:
. the sum of the FOB and the F. USED is significantly less than the FOB at departure, or
. passenger observation (fuel spray from engine or wing tip), or
. total fuel quantity decreasing at an abnormal rate, or
. fuel imbalance, or
. a tank emptying too fast (leak from engine or a hole in a tank), or
. a tank overflowing (due to a pipe rupture in a tank).
R *. excessive fuel flow*
R *. fuel smell in the cabin*

LAND ASAP

WHEN A LEAK IS CONFIRMED

■ **LEAK FROM ENGINE :**
- THR LEVER (of affected engine) .... IDLE
- ENG MASTER (of affected engine) .... OFF
The Xfeed valve can now be selected open for rebalancing or to allow use of the fuel from both wings. Do not restart the engine.

■ **LEAK NOT FROM ENGINE or LEAK NOT LOCATED**
- FUEL X FEED .... AUTO
The Xfeed valve must remain closed to prevent the leak affecting both sides. Selecting AUTO maintains the X-feed valve closed.
- L + R INR TK .... SPLIT
Shut INR TK SPLIT valve to isolate fuel leak.
- DESCEND TO GRVTY FUEL FEEDING CEILING
See GRVTY FUEL FEEDING procedure.
- ENG START SEL .... IGN
- ALL TK PUMPS (when gravity ceiling is reached) ...... OFF
In almost all cases, switching the pumps off will prevent any further loss of fuel. All pumps must be switched off, even if the leak is from one wing only, as there are some failures on one side that will result in fuel loss from the other side.
- AVOID NEGATIVE G FACTOR

● **If one engine flames out when there is still fuel in the feeding tank :**
- LEAK FROM ENGINE proc .... APPLY
- ALL TK PUMPS .... ON
NOTE: The flameout is due to air suction from a leak from the engine.

FOR LANDING

CAUTION
. Do not use reverse.
. Notify ATC.

NOTE: Even with a fuel imbalance of one inner tank full/one inner tank empty there is no

Figure 8 - A330 FUEL LEAK Procedure

The conditions that would suggest the presence of a fuel leak are contained as notes at the top of the procedure items. Other than in the FUEL LEAK procedure, the only other reference to fuel-leak symptoms and the fuel leak procedure in a manufacturer or company documentation is in the Air Transat FCOM Volume 3, Standard Operating Procedures (SOPs), relating to flight progress monitoring. Section 03.03.15, in part, requires that, when overflying a waypoint, crews check that the sum of the fuel on board and the fuel used is consistent with the fuel on board at departure. Crews are directed to suspect a fuel leak if the sum is unusually smaller than the fuel on board.

A fuel leak is considered to be an abnormal condition that would rarely, if ever, occur. Other than the procedure itself and the reference in the SOPs, no manufacturer or company documentation exists on the use of this procedure, and no training is provided for this abnormal situation[27].

[27] A review of other airline training programs indicated a similar deficiency in that there was no specific, initial, recurrent, or line oriented flight training on fuel leaks.

The crew stated that, although indications of a lower-than-expected fuel quantity were recognised shortly after receiving the fuel imbalance ADV, they did not consider the FUEL LEAK procedure, until later in the flight[28].

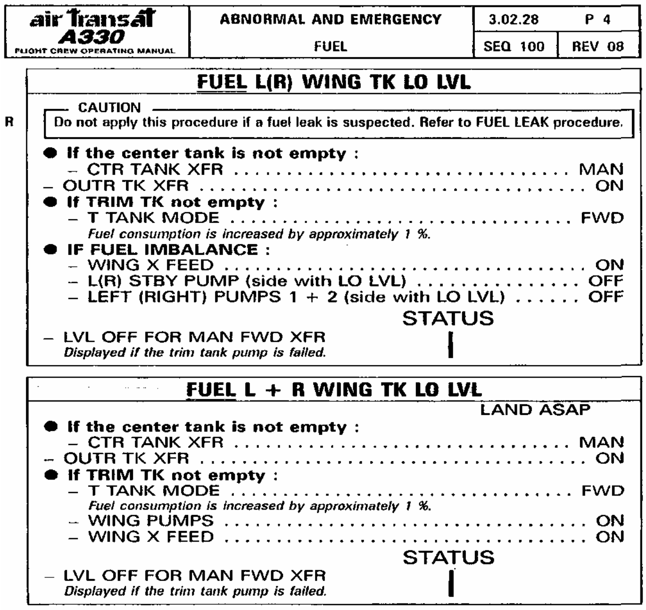
1.19.2.3 Fuel Tank Low Quantity

A fuel tank low level ECAM Caution is generated by the ECAM system when the fuel quantity in the right or left wing tank is less than 1 640 kg for 60 seconds. This condition results in a MASTER CAUTION light and a crew action item procedure and the relevant system synoptic page to be displayed on the SD.

The graphic depicts the wing tank low-level procedures taken from the QRH.

Although the <u>FUEL</u> L(R) WING TK LO LVL procedure contains a caution directing that this procedure is not to be applied if a fuel leak is suspected, the Caution does not appear on the procedure generated on the E/WD.

Both the <u>FUEL</u> L(R) WING TK LO LVL and the FUEL L + R WING TK LO LVL procedures ultimately call for the WING X FEED to be turned ON.



air transat A330 FLIGHT CREW OPERATING MANUAL	ABNORMAL AND EMERGENCY FUEL	3.02.28 SEQ 100	P 4 REV 08

FUEL L(R) WING TK LO LVL

R CAUTION: Do not apply this procedure if a fuel leak is suspected. Refer to FUEL LEAK procedure.

- **If the center tank is not empty :**
  - CTR TANK XFR .... MAN
- OUTR TK XFR .... ON
- **If TRIM TK not empty :**
  - T TANK MODE .... FWD
  - *Fuel consumption is increased by approximately 1 %.*
- **IF FUEL IMBALANCE :**
  - WING X FEED .... ON
  - L(R) STBY PUMP (side with LO LVL) .... OFF
  - LEFT (RIGHT) PUMPS 1 + 2 (side with LO LVL) .... OFF

STATUS

- LVL OFF FOR MAN FWD XFR
  Displayed if the trim tank pump is failed.

FUEL L + R WING TK LO LVL

LAND ASAP

- **If the center tank is not empty :**
  - CTR TANK XFR .... MAN
- OUTR TK XFR .... ON
- **If TRIM TK not empty :**
  - T TANK MODE .... FWD
  - *Fuel consumption is increased by approximately 1 %.*
  - WING PUMPS .... ON
  - WING X FEED .... ON

STATUS

- LVL OFF FOR MAN FWD XFR
  Displayed if the trim tank pump is failed.

Figure 9 - A330 FUEL L(R) WING TK LO LVL

TSC MSN 0250-0271

On the occurrence flight, the caution and associated ECAM messages and procedure were generated at 0558 for the <u>FUEL</u> R WING TK LO LVL condition and at 0608 for the <u>FUEL</u> L + R WING TK LO LVL condition.

The crew did not take any action in direct response to either of these messages.

[28] The crew's consideration of the FUEL LEAK procedure occurred at a time prior to the commencement of the CVR recording.

1.19.3 Cockpit and Fuel Management

1.19.3.1 Fuel & Systems Monitoring

The Air Transat A330 Flight Crew Operating Manual (FCOM) contains SOPs, which consist of inspections, preparations and normal procedures. The SOPs are divided into flight phases and are performed from memory. These procedures assume that all systems are operating normally, and that all automatic functions are used normally. After completing a given procedure, the flight crew uses the related normal checklist to ascertain that it has checked the safety points.

The CRUISE section of the SOP's specifies that the items (DEPICTED ON THE RIGHT) be checked during the cruise portion of the flight.

The SOP's indicate that the ECAM SYS PAGES item of the check be reviewed periodically.

The SOP's also indicate that the FLIGHT PROGRESS item be monitored in the conventional way, and that, when overflying a waypoint, the following should be checked: track and distance to the next waypoint; fuel on board and fuel prediction with flight planned fuel; sum of fuel on board and fuel used consistency with the fuel on board at departure.

CRUISE
ECAM MEMO ....REVIEW
ECAM SYS PAGES .... REVIEW
FLIGHT PROGRESS .... REVIEW
STEP FLIGHT LEVEL ... AS APPROPRIATE
NAVIGATIONAL ACCURACY .... CHECK
RADAR TILT................................ ADJUST
CABIN TEMP .... MONITOR
CRUISE C/L .... COMPLETE

The NORMAL PROCEDURES section of the Quick Reference Hand Book (QRH) depicts the CRUISE checklist as indicated on the right.

CRUISE	
PF	PNF
ECAM MEMO ....CHECK FLIGHT PROGRESS .... CHECK FUEL .... MONITOR STEP FLIGHT LEVEL . AS APPRT NAV ACCURACY .... CHECK RADAR TILT .... ADJUST CABIN TEMP .... MONITOR "CRUISE C/L"	WING A. ICE .... AS RQRD COCKPIT .... SCAN SYS PAGES .... REVIEW ENROUTE WIND ... INSERT

The NORMAL CHECKLIST portion of the QRH specifies the CRUISE CHECK as one item.

CRUISE CHECK
COCKPIT CHECK ... PNF ....COMPLETED

The flight plan log entries indicated that, up to the time that aircraft passed 30º West, the crew had recorded the times, fuel on board, and surplus fuel over the flight planned waypoints. The DFDR indicated that the ECAM system pages were manually selected by the crew only once during the cruise portion of the flight, at 01:15:38, just after the aircraft reached the initial cruising altitude of FL 370.

1.19.3.2 Prior to Fuel Advisory

According to the crew, the flight and fuel consumption progressed normally through to 04:57 when the aircraft passed 30º West. The flight log indicates that the fuel surplus quantity was maintaining within the range of 7.0 ±0.2 tons. The fuel quantity data on the DFDR also indicated normal fuel consumption up to 04:38, the onset of the increased rate of reduction in the fuel quantity. At 04:56, a two-minute, 0.3-ton forward transfer of fuel from the trim tank occurred, and the green TRIM TANK XFR ECAM message would have been displayed: the crew did not mention seeing this message

As part of routine procedures, when the aircraft crossed 030º W at 05:00, the crew would have made a position report, should have reviewed system indications and made the flight plan log entries. DFDR data indicates that, at 05:04, the Engine Page was manually selected, and that, at 05:10, the SD was returned to the Cruise Page.

It was during the check of engine parameters that the low oil quantity was noticed. DFDR data indicates that the Engine Page on the SD was manually selected again at 05:15, and company logs and a HF recording indicate that the crew were in a 3-minute conversation with MCC regarding the oil problem at 05:21. The crew indicated that the sudden change in oil parameters plus the unexplained combination of low oil temperature, low oil quantity and high oil pressure led them to believe that there was a problem with the indications. This opinion was supported by the fact that the crew's review of the aircraft manuals did not discover any reference to this type of system anomaly.

While the trouble-shooting of the engine oil problem was taking place, at 05:11, a 19-minute forward transfer of the remaining 3.2 tons of fuel in the trim tank commenced and a green ECAM memo TRIM TANK XFR would have been displayed. At 05:30, the fuel transfer was complete and a TRIM TANK XFRD message would have appeared in the memo section of the E/WD. The crew did not recall seeing these messages.

1.19.3.3 Fuel Imbalance Situation

The first signs noted by the crew concerning a fuel problem were at 05:33, when the fuel-related ADV message was displayed on the Engine/Warning Display[29]. The crew's de-selection of the Engine ECAM page resulted in the Fuel ECAM page being displayed and the crew becoming aware of a fuel imbalance between the left and right inner-wing tanks. The initial crew action at 05:36 was to address the Fuel Imbalance message by selecting the crossfeed valve OPEN and the right-wing fuel pumps OFF in order to feed the right engine from the left-wing tanks.

Shortly thereafter, the crew became aware that the fuel remaining on board was only 11 tons, or 8.5 tons below the expected amount of fuel. According to the crew, both the imbalance and fuel quantity indications were unusual and unexplainable. Neither of the pilots had ever encountered a fuel leak or an unexplained low fuel quantity either in training or in flight.

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[29] The generation of the fuel imbalance-related advisory message was delayed by about 25 minutes by the 3.5-ton forward transfer of the trim tank fuel.

Because the total fuel quantity was still reducing at an unexplainable high rate, the Captain decided to use up the fuel from the right tank before it was lost, and selected the right wing boost pumps ON and the left-wing boost pumps OFF to establish a crossfeed from the right wing tank to the left (#1) engine, specifically to counter the possibility that the fuel loss was the result of a leak in the right wing tanks. The Post Flight Report printout indicates that the left-wing boost pumps were turned OFF at 05:54, when 5.9 tons of fuel remained on board.

Starting at 05:57, the crew was in a 5.5-minute conversation with MCC to seek advice on the situation. MCC's question whether the fuel loss might be a leak in the left engine, resulted in the Captain to momentarily re-select crossfeed from the left tanks. At 06:05, the crew still estimated that the flight would arrive at Terceira with 1 ton of fuel. However, by 06:08, the crew determined that insufficient fuel remained on board to reach the island.

1.19.3.4 Fuel Distribution

Other than the information provided by the crew during radio communications and on the CVR, there is no recorded data on the specific distribution of the fuel between the left and right wings. Notwithstanding, quantities were estimated based on the DFDR-recorded aircraft gross weight less the aircraft zero-fuel weight, and timings and thresholds of the various fuel-related advisory messages[30].

The DFDR also does not record the position of the crossfeed valve or fuel pump status. However, based on calculations of the figures available the following was determined:

- From the start of the leak at 04:38 to the point that the right-wing pumps were selected off at 05:36, the rate of fuel decrease in the left wing averaged 2.6 tons per hour, which is the normal rate of consumption for one engine at the existing flight conditions.
- From 05:36 to 05:54 when the right wing tank pumps were selected off in preparation for crossfeeding from the left tank, the rate from the left tank was about 18.9 tons per hour, indicating that fuel from the left tank was crossfeeding to the right side and the fuel leak.
- At 05:49, the fuel quantities in the left and right tanks would have been equal at about 3.6 tons.
- From 05:54 to 05:59, the rate from the left tank was 0.0 tons per hour, and the rate from the right tank was 20.0 tons per hour, indicating that left wing tank pumps were off and the left engine was being fed from the right wing tanks.
- From 05:59 to 06:13, when the right engine flamed out, the rate from the left tank was averaged about 11.2 tons per hour, indicating that fuel from the left tank again was crossfeeding to the right side and the fuel leak. During this same period, the rate of fuel flow from the right wing tanks averaged about 4.4 tons per hour, indicating that one or more right-wing fuel pumps may have been on for some or all of this timeframe.
- From 06:13 to 06:26, the rate from the left tank was about was 3.0 tons per hour, indicating the left fuel tank was no longer feeding the leak on the right side.

Based on these determinations it was concluded that the crossfeed valve was opened at 05:36, and that the valve remained in the OPEN position until 06:26, when the left engine flamed out.

[30] Appendix C details the calculation of the fuel quantities in the aircraft fuel tanks.

1.19.3.5 *Crew's Awareness of the Fuel Leak*

According to the crew, the following factors were taken into account to ascertain the problem of the unexplained low fuel quantity:

- Engine indications were reviewed to determine a source of the problem. No abnormal indication was found. Fuel-flow parameters and other engine indications were normal.
- There had been no other in-flight events or conditions that could have led to the fuel loss.
- The cabin crew were asked to visually check outside the aircraft in the vicinity of the wings and engine for signs of a fuel leak, and none were observed due to darkness that prevailed during this time.
- From the time when the fuel imbalance ADV first appeared, the fuel quantity indications and fuel predictions for destination consistently showed an unbelievable fuel loss rate.

The crew stated that because there were no other signs of a fuel loss, other than the lower than expected quantity of fuel on board, and because there had been no other ECAM warnings or cautions both pilots believed that the problem was a computer fault. They also stated that although they had used the term "fuel leak" on many occasions during the occurrence, a logical link to considering the FUEL LEAK check and the possibility that the fuel leak existed did not occur until the aircraft indicated fuel quantity was about 7 tons[31].

When considering the FUEL LEAK procedure, the crew was of the opinion that the leak was probably on the right side, and that the leak was probably from the tank because the right engine was running normally and all engine indications were within limits. The Captain stated that he had decided not to do the FUEL LEAK – LEAK NOT FROM ENGINE procedure because in his mind doing so would require him to descend the aircraft to 20 000 feet, and if the leak was real, he would be losing fuel anyway, and at 20 000 feet he would give up altitude and performance margin in a situation where fuel remaining was critical. Also, if the leak was from the right tank, he could conserve that fuel by crossfeeding it to the left engine. Consequently, he opted to remain at FL 390 and crossfeed from the right tank.

The crew stated that they continued to believe that the low quantity indications were caused by some type of computer error, and continued with this belief up to and beyond the flameout of the right engine.

1.19.4 Cockpit Workload

As a result of the developing emergency, the workload in the cockpit increased. Based upon an examination of interviews and voice recordings (CVR, ATS, and MCC), the crew performed a number of concurrent activities, effectively translating into periods with an increased potential for bottlenecks in performance. The identified activities included:

- flying the aircraft;
- diagnosing the fuel fault, which entailed simultaneously deciding, remembering, looking up information, requesting assistance from cabin crew, requesting information from MCC, and scanning to acquire new information;

[31] Based on DFDR data a fuel quantity of 7 tons occurred at approximately 0550Z, or just after the crew initiated the diversion and the aircraft was 376 nm from Lajes.

- coordinating the diversion to Lajes, which included planning for the diversion, undertaking the diversion, and HF communications with ATS and MCC;
- preparing the cockpit and the cabin for a possible ditching;
- managing the engine failures; and
- carrying out the engines-out landing.

1.19.5 Cockpit Decision-Making

When individuals are dealing with novel situations and are required to problem solve, they are said to be operating at a knowledge-based level. Problem solving in a novel situation, a potentially high-risk endeavour, can be exacerbated if there are ambiguous cues or if there is no compelling information/cues to assist in diagnosing the uncertain and unknown problem.

During decision-making in situations where individuals are operating in a time constrained environment and are confronted with what they perceive as ambiguous data, they are likely to make decisions in order to satisfy immediate goals; decisions which may be based upon an initial assessment of the situation. During problem solving, there are a number of biases and heuristics that can affect the decision-making process of those involved. Additionally, under such circumstances, it is not uncommon for individuals, while attempting to solve a novel problem, to not follow one or more rules as they try to achieve the desired goal. This type of behaviour is commonly associated with high risk, often because the consequences of this behaviour are not fully understood or because the behaviour, although known to have risk, seems inescapable.

The following are three factors that likely continued to affect crew decision-making:

- Framing Bias: Why the crew considered but elected not to carry out the fuel leak procedure;
- Confirmation Bias: Why once they decided that there was a computer malfunction the crew did not modify this viewpoint through to the end of the CVR, at which time the second (left) engine had flamed out; and
- Realignment of a Mental Model: Why the crew did not carry out the fuel leak procedure later in the flight.

1.19.5.1 Framing Bias

Individuals are susceptible to framing bias[32] as they problem solve. In decisions where risk is involved, options are often framed in terms of gains and losses. In the case of losses, when given the choice between a sure loss versus a loss that is less probable but more disastrous, individuals are biased towards the latter, riskier choice.

1.19.5.2 Confirmation Bias

Once an initial understanding (mental model) has been formed, the individual will search his/her memory and the immediate situation for additional data relevant to that mental model. Such data, then, are apt to be recalled and regarded as pertinent only to the extent that they confirm the mental model at hand. Although potentially confirmatory information tends to be taken at face

[32] Kahneman and Tversky, 1986

Jmw

value, potentially disconfirming information is subjected to a more critical and sceptical scrutiny. Several studies have shown that preliminary hypotheses formed on the basis of ambiguous data interfere with the later interpretation of better, more abundant data[33].

An individual's mental model of a situation is likely to correspond to a large part to the reality, even though it may be wrong in some respects. Having expectations frequently confirmed reduces the sensitivity of the error detection mechanism. Confirmation bias is a selective process that favours information relevant to the presently held view. In essence it is a bias towards relevant-appearing information. Additionally acting upon one's beliefs can also increase the psychological costs or "dissonance" involved in changing one's beliefs[34].

Confirmation bias can have such a strong impact that once individuals have developed a mental model of a problem space, and they have confirmed their model, it becomes very difficult to let go of the model, even in the light of contradictory information. The need for a realignment of one's mental model becomes apparent only in the light of one or more extraordinary events that do not fit the model.

1.19.5.3 Realignment of the Mental Model

Individuals do not constantly update or re-evaluate the evidence relevant to their beliefs. During novel situations involving problem solving, if a situation arises that challenges an individual to reassess his or her mental model, the individual will not consider it necessary to go back and reassess all of the evidence that was ever considered in creating the mental model[35]. Rather, individuals will try to adjust their mental model with the new immediate information at hand. The result is that, although they may attempt to realign their model given the current situation, individuals are unlikely to go back and reconsider their previous actions.

1.19.6 Cockpit Automation Management

There are two basic automation management strategies that are implemented in most existing flight deck systems: management by consent, and management by exception.

- In management by consent, the automation must ask for and receive explicit operator permission before taking any action[36]. This approval is meant to increase an operator's awareness and control over the automation behaviour. It does so at a cost of increased communication demands between the automation and the operator.
- With management by exception on the other hand, the automation is allowed to initiate and perform actions on its own. This approach requires relatively little explicit and observable human-machine interaction, but it imposes additional monitoring demands on the operator if there is a problem and it involves the risk of losing system and mode awareness.

The FCMC in the A330 is based upon a management by exception philosophy; the operators are effectively relieved from the active tasks of managing fuel transfers, as all functions are handled by the FCMC. Only those messages considered important are communicated to the crew through the ECAM.

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[33] Lewis and Normal, 1986
[34] Festinger, 1957
[35] Ross and Anderson, 1982
[36] Billing, 1997.

The A330 FCMC system was not designed to consider the type of fuel leak that occurred during this flight. As a result, after the FCMC did what it could do to maintain a fuel level of 4 tons in the right tank and when it was no longer able to maintain that level, it advised the crew that there was an imbalance. Specifically, the FCMC, no longer able to deal with the fuel leak through its pre-programmed fuel balancing, shed the task to the crew. This shedding took the form of a fuel imbalance ADV.

With Management by exception, it is not uncommon to have what have been referred to as “automation surprises”. Although information may be available to crews, this information is not necessarily observable. Observability, in this context, refers to the cognitive work that is required to extract useful information. It results from the interplay between a human user knowing when to look for what information, at what point in time, and the structure of the automated system and how it supports attention guidance.

The challenge is for automation to not merely provide additional data but to reduce the cognitive effort required to locate, integrate, and interpret those data. For this occurrence, the low level of system observability was manifested in two ways:

- The sudden presentation of apparently anomalous and incredulous information; and
- A representation of the system state that does not readily lead the crew to identify and rectify the problem.

1.19.7 Impact of Display Type on Problem Solving

The design of displays can also impact on a crew’s workload. Although a digital or text display is effective for displaying exact quantities or precise wording, this type of display does not provide integrated information, for example in the form of a rate or a predicted trend. As a result, a crew is required to manually calculate the rate of fuel loss, and search elsewhere for additional or missing information, tasks which are both effortful and time consuming.

1.19.8 Engines-out Approach and Landing

From the time that the diversion to Lajes was initiated up to the time that the second (left) engine flamed out, the crew was using the FMS system for navigation guidance. Also, based on the CVR, the crew had visual contact with ground-based lights in the direction of Terceira Island when the aircraft was descending through flight level 370 and at 120 nautical miles northeast of Lajes. Once normal electrical power was lost, the crew no longer had the FMS and had to rely on directional guidance based on the LM VOR and distance information provided by Lajes Approach Control. The crew acquired visual contact with the runway with the assistance of the flashing of the runway lights.

The following table depicts the flight profile as determined from the ATS transcript:

Time (UTC)	Event	Altitude	Dist-ance (NM)	Bearing from La-jes	Average Rate of Descent
06:26:15	Engine 1 Stall	FL345	78		1400 ft/min
06:26:34	On Emergency Power Source		63		
06:31:38	Initial Contact with Lajes Ap-	FL270	33	ENE	
06:34:11	Radar Distance Report		23	E	1000 ft/min
06:35:33	Crew Altitude Report	FL230			
06:36:17	Runway lights reported in sight		14	E	1100 ft/min
06:37:16	Radar Distance Report		11	E	
06:37:??	Crew Altitude Report	FL185	10		
06:38:45	Crew Altitude Report	13 000	8	On final	1700 ft/min
06:40:10	Radar Distance Report		10		2000 ft/min
06:40:44	Radar Distance Report	9 000	12	S	
06:41:55	Radar Distance Report	8 000	9	On final	1800 ft/min
06:42:38	Radar Distance Report		7		
06:43:28	Landing gear confirmed down				
06:43:37	Radar Distance Report		3		
06:45:??	Aircraft Landed				

The Captain reported that he had the flashing runway lights visually from a long way out and that he was confident that he had more than enough altitude to glide to the airport.

Consequently, during the initial glide, he was attempting to fly the aircraft at a speed, between the recommended glide speed and the stall-warning speed, in order to keep the aircraft airborne for the longest time. Other considerations taken into account during the glide were that the aircraft speed could not be higher than 200 knots for gear lowering, the recommended approach speed was 170 knots, the minimum speed to ensure RAT operations was 140 knots, and that he had to adjust the aircraft pitch angle to achieve a glide descent angle to reach the runway. Although he had never received formal training on gliding approaches, he had experienced doing power-off approaches to landing in a number of aircraft types that he had flown.

The Captain reported that during the glide that he did not use manual trim, because he was very busy concentrating on maintaining the correct vertical profile to the runway. In addition, although he knew that the aircraft response to stick inputs would be sluggish, during the flare he did not want to be too aggressive. Following the initial bounce, the nose of the aircraft rose significantly. Because he did not want to become airborne a second time, on the second touchdown, he did not flare and he applied and held maximum braking.

1.19.9 Aircraft Performance Scenarios

An analysis of fuel data was conducted to determine the consequences of the crew determining that a leak was confirmed, and completing the FUEL LEAK procedure at 05:45, the time that the diversion to Lajes, Terceira, Azores. The calculations[37] were made on the following three scenarios: the crew completes the LEAK FROM ENGINE procedure; the crew completes the LEAK NOT FROM ENGINE or LEAK NOT LOCATED procedure; and, the crew does not balance the fuel and the crossfeed valve is kept in the closed position. The calculations are based on the actual fuel load of the aircraft, which included 5.5 tons of fuel that were over and above the fuel required by regulations for the flight.

- The conclusions of the analysis of the crew actioning the LEAK FROM ENGINE procedure were that the aircraft would have reached Terceira and landed at Lajes with a total of 5 136 kg of fuel on board: 3 796 kg of fuel in the left wing tanks, and 1 340 kg in the right wing tanks.
- The conclusions of the analysis of the crew actioning the LEAK NOT FROM ENGINE or LEAK NOT LOCATED procedure were that the aircraft would have reached Terceira and landed at Lajes with a total of 3 785 kg of fuel on board, all in the left wing tanks and none in the right wing tanks.
- The conclusions of the analysis of the crew not taking action to balance the fuel and keeping the crossfeed valve closed were that the aircraft would have reached Terceira and landed at Lajes with a total of 3 854 kg of fuel on board, all in the left wing tanks and none in the right wing tanks.

Another analysis of the consequences not having the extra 5.5 tons of fuel on board was also conducted. This analysis was based on the premises of the crew not taking action to balance the fuel and keeping the crossfeed valve closed, and establishing a diversion in a manner similar to the occurrence flight. The conclusions were the following: the fuel advisory would have been displayed 18 minutes earlier at 05:15; the diversion would have been initiated at 05:27 when the aircraft was 283 nm from Lajes; and, the aircraft would have reached Terceira and landed at Lajes with a total of 2 883 kg of fuel on board, all in the left wing tanks and none in the right wing tanks.

Another analysis was conducted on the timing of the final fuel transfer from the trim tank to the inner wing tanks. This analysis was based on the premise that without a fuel leak on a normal flight from Toronto to Lisbon, the forward transfer would have taken place to keep the inner wing tanks at 4 000kg. Based on this premise and the flight log information, the forward transfer would have been completed and the TRIM TANK XFRD would have been displayed at approximately 05:50 and when the total fuel load was 11 600 kg, distributed as follows:

Outer Tank Left	Inner Tank Left	Inner Tank Right	Outer Tank Right
1 800 kg	4 000 kg	4 000 kg	1 800 kg

[37] Appendix C Fuel Consumption Calculations contains the conditions, bases, and assumptions for these fuel calculations.

1.20 Other Fuel Leak Occurrences

1.20.1 Previous Air France A-320 Fuel Leak Occurrence

1.20.1.1 Occurrence Information

On 24 August 1997, an Air France A-320, F-GHQH, was on a passenger flight from Orly, France, to Lorient, France. On board were 47 passengers, 4 flight attendants and two pilots. The aircraft took off from Orly at 1933 hours with a fuel load of 8.5 tons, which was 2.1 tons over the fuel load required for the trip[38]. At 19:45 hours, as the aircraft approached the planned cruising altitude, the crew received a fuel advisory message indicating that there was a 1 500 kg fuel imbalance between the left and right wings distributed as follows:

Outer Tank Left	Inner Tank Left	Inner Tank Right	Outer Tank Right	TOTAL
680 kg	1 420 kg	3 030 kg	690 kg	5 820 kg

The QRH procedure related to the fault required that the fuel be balanced. Specifically, the crew opened the crossfeed valve and selected the left fuel pumps OFF. The crew also noted that the fuel-on-board was significantly less than expected. Hypotheses considered by the crew for the fuel anomalies were the following:

- An anomaly at the re-fuelling coupling;
- A possible erroneous fuel indication, (the crew was aware of a number of such previous incidents);
- Incorrect fuel load; or
- A fuel leak.

To help determine if there were any visual signs of a fuel leak, the Captain asked a deadheading company pilot, who was previously qualified on the A-320, to examine the wings for signs of a leak. Because it was now nighttime, the inspection was done with the cabin lights turned off and with the aid of a flashlight. No signs of a fuel leak were observed.

At 20:02 hours, the fuel in the left and right tanks became balanced, and the left wing tank pumps were selected ON and the crossfeed was selected to OFF. The descent was initiated, and the fuel load at 20:04, was as follows:

Outer Tank Left	Inner Tank Left	Inner Tank Right	Outer Tank Right	TOTAL
0	1 160 kg	1 120 kg	0	2 280 kg

There was subsequent fuel warning of L WING TK LO LVL. In accordance with the ECAM procedure, the crossfeed was opened. However, the crew believing this action to be not appropriate for the situation turned the crossfeed OFF after about 90 seconds.

[38] The aircraft had been loaded with 8.5 tons of fuel because it had been a backup aircraft for a flight between Paris and Rome. In accordance with the company's procedures, the fuel required for the trip, including reserves, was 6.4 tons.

At 20:08 hours, the fuel load was, as follows:

Outer Tank Left	Inner Tank Left	Inner Tank Right	Outer Tank Right	TOTAL
0	580 kg	1 080 kg	0	1 660 kg

At 20:12 hours, the left engine flamed out, and at 20:19 hours the aircraft landed at its destination with approximately 900 kg of fuel on board.

1.20.1.2 BEA Investigation

Bureau d'Enquêtes et d'Analyses pour la Sécurité de l'Aviation Civile (BEA), the French accident investigation authority, conducted an investigation into this occurrence.

BEA's preliminary analysis of this occurrence and two other serious, fuel-leak occurrences[39] determined that the involved crews could not determine that there was a fuel leak in two of the occurrences, and on the third occurrence, the origin of the fuel loss. Also, the existing checklists were inadequate to effectively determine that a leak existed, and without this precise identification, the existing procedures could lead to inappropriate actions.

Consequently, on 8 September 1997, the BEA recommended that:

> A study be immediately conducted into procedures to address this type of event, and that, in the interim, all crews should be immediately informed of the circumstances of the three fuel leak incidents.

In the BEA final report issued in August 2002, BEA further recommended that this incident and other similar occurrences revealed the critical nature of fuel leaks and deficiencies related to the identification of such leaks.

Consequently, the BEA recommended that:

- DGAC ensure that basic training programs and recurrent training conducted on aircraft take into account the identification and interpretation of all indications of fuel-system failures, and the appropriate actions to be taken;
- Airline operators review their instructions and procedures relating to the fuel systems to ensure that they are adequate for fuel leak situations;
- Airbus studies a system that would alert crews, at an appropriate level, in terms of displays and warnings, of abnormal reduction in the quantity of fuel on board aircraft, and define appropriate procedures for such situations.

1.20.1.3 Actions Taken In Response to BEA Preliminary Recommendation

Based on BEA's 8 September 1997 initial recommendation, on 7 November 1997, the Project Certification Manager sent a letter on behalf of the Joint Aviation Authority (JAA) to Flight Test Centres and some DGAC departments.

[39] Kenya had investigated one of the previous occurrences in 1995 involving an A310 aircraft. The other occurrence involved a United Kingdom A340 aircraft; this occurrence was reported to the Accidents Investigation Branch of the United Kingdom.

The letter stated that, in its review of proposed corrective actions to recent A320 and A340 fuel-leak events, the DGAC identified two areas of possible improvements, technical and operational. For improvement related to crew procedures, the letter included proposed revisions to FCOM procedures. The letter reminded that a fuel imbalance triggers an Advisory on the ECAM with an automatic display of the FUEL page; and, that there is no ECAM crew procedure. The letter, highlighting that there currently was neither a fuel imbalance nor a fuel leak procedure, requested that recipients review the proposal and provide DGAC with its comments. The proposal also contained a proposed revision to SOPs, in part, to include in the FLIGHT PROGRESS CHECK a requirement to check that the sum of the fuel on board and the fuel used is consistent with the fuel on board on departure; if the sum is unusually smaller than the fuel on board at departure, the crews were to suspect a fuel leak.

On 25 September 1997, Airbus Flight Operation Telex (FOT) AI/ST-F 999.103/97 was issued to all known operators of Airbus A320 aircraft. The Operational Recommendation section of the FOT, stated, in part, the following:

- before opening the Fuel X-FEED valve(s) for any unexpected fuel distribution, it is necessary to check if either the fuel imbalance or the fuel low-level warning is not caused by a fuel leak;
- If a fuel leak is confirmed by a significant inconsistency between the sum of fuel on board (FOB) and fuel used compared to the FOB at engine start, the fuel leak procedure applies.

Airbus fleet FCOM Abnormal Procedures were amended to include a FUEL IMBALANCE checklist, including a Caution that the procedure should not be done if a fuel leak is suspected.

Airbus fleet FCOM Abnormal Procedures were amended to include a FUEL LEAK checklist, including notes as to how fuel leaks could be detected.

Airbus fleet FCOM Abnormal Procedure FUEL L(R) WING TK LO LVL was amended to include a Caution that this procedure not be applied if a fuel leak is suspected.

Airbus fleet FCOM Standard Operating Procedures were amended to include in the FLIGHT PROGRESS CHECK a requirement to check that the sum of the fuel on board and the fuel used is consistent with the fuel on board on departure. Crews are directed to suspect a fuel leak if the sum is unusually smaller than the fuel on board.

1.20.2 Previous Virgin A340 Fuel Leak Occurrence

On 13 June 1997, a Virgin Airways A340 was on a flight from London to Tokyo. After 1 hour and twenty minutes of flight, the crew discovered a large difference in fuel quantity between the right and left wings. Over a 15-minute period, the crew monitored the situation and did a visual inspection. All engine parameters were reported to be normal. The crew concluded that a fuel leak existed based on the difference of fuel quantity between both wings and the fact that there was a disagreement between the fuel remaining on board and the fuel quantity expected based on the fuel used by the engines. The crew could not determine whether the leak was from the tank or an engine. The crew turned back toward London, and in accordance with the QRH procedures descended the aircraft to the gravity-feed altitude of 20 000 feet and all fuel pumps were turned off. On landing, a significant amount of fuel was observed on the runway. The total fuel lost during the flight was 20 tons. Post occurrence examination of the aircraft found a fuel leak on the fuel filter on one of the left engines. The flight crew performed the fuel leak procedure in accordance with the published QRD.

A United Kingdom Air Accidents Investigation Branch investigation into this occurrence was not conducted and a report was not published on this occurrence. Reportedly, the only safety deficiencies associated with this occurrence were related to a known technical fuel filter installation fault.

1.20.3 History of Other Fuel-leak Events

A review of aircraft manufacturer and engine manufacturer occurrence databases revealed that since 1994 there have been at least 25 in-flight fuel-leak events. Although some of these events were minor in nature, a number were significant in nature in that they lead to a loss of fuel that resulted in a serious incident, such as an engine fire or a loss of fuel that resulted in a diversion or emergency situation.

Because the fuel leaks were clearly attributable to technical faults, few of the events were investigated and even fewer were analyzed to determine operational factors that may have increased the seriousness of the event.

Prior to the Air Transat A330 occurrence there had not been another recorded occurrence that involved total fuel exhaustion due to a fuel leak, although there had been a number of cases of significant fuel loss, some of which would have been mitigated by following the manufacturer's recommended procedures. Since this occurrence, there has been one commercial airliner occurrence involving a fuel leak that resulted in fuel exhaustion and an off-airfield forced landing, fortunately without any serious injuries to passengers or crew.

1.20.4 Fuel Leak Recognition and Training

For those previous fuel events that resulted in engine fires, actioning the engine fire checklist resulted in the fuel being shut off and the risks of significant fuel losses were effectively mitigated. For the fuel leak events that did not result in a caution or warning, crews had difficulty in ascertaining the existence or location of the fuel leak.

Although some regulatory agencies now require that aircraft flight manuals include procedures that will enable flight crews to identify fuel system leaks, and procedures for crews to follow to prevent further fuel loss, there are a number of commercial aircraft that do not have identification procedures or fuel leak checklists.

Canadian Commercial Air Service Standards (CASS), Subpart 725 - Airline Operations - Aeroplanes, Division VIII, section 725.124 states that an air operator's training program syllabus shall include all applicable subsections of this standard. Subsection (50) Engine Failure/Malfunction Recognition Training requires the following:

a) Initial and recurrent ground and flight training is required for all flight crew members;
b) The ground training shall include:
   i) potential engine malfunctions and their causes,
   ii) proper identification of the malfunctions, and
   iii) proper responses to the malfunctions or failures;
c) Flight training shall be done:

i) in a synthetic training device (where applicable), and
ii) in approved simulators for all flight crews operating High Bypass Ratio Engines.

Neither the Air Transat Training Manual, nor the CASS, specifically requires training on fuel leaks. In addition, prior to this fuel exhaustion occurrence, few airlines, if any, conducted training on fuel leak situations.

1.20.5 Overwriting of CVR Recordings

A review of the Transportation Safety Board of Canada occurrence database was conducted to determine the frequency and circumstances of occasions when CVR recordings were not available to the investigation because they had been overwritten subsequent to the aircraft landing. The review indicates that, from 1990 to 2001, there were 14 such serious incidents. In these events, there was no attempt made to secure the recording, and the losses were directly attributed to either electrical power continuity following engine shutdown, or later reapplication of electrical power.

On 29 August 2002, the National Transportation Safety Board of the United States of America issued Recommendation A-02-24 on "Overwritten Cockpit Voice Recordings". The NTSB, believing that reliable procedures are needed to safeguard CVR data, recommended the following:

> That the Federal Aviation Administration:
>
> Require that all operators of airplanes equipped with a cockpit voice recorder (CVR) revise their procedures to stipulate that the CVR be deactivated (either manually or by automatic means) immediately upon completion of the flight, as part of an approved checklist procedure, after a reportable incident/accident has occurred. The procedures must also ensure that the recording remains preserved regardless of any subsequent operation of the aircraft or its systems. Any doubt as to whether the occurrence requires notification of the National Transportation Safety Board must be resolved after the steps have been taken to preserve the recording. (A-02-24)

Loss of recorded information on serious incidents caused by overwriting or premature erasure is a recurring problem. Commercial Air Services Standards subsection 725.135 (i) requires that the company Operations Manual (OM) contain information regarding FDR and CVR procedures. The OMs, aircraft flight manuals and checklists of Air Transat and other Canadian airlines were reviewed. Although the OMs did contain a reference to the requirement to consider protecting recorder information, there was no specific information, diagrams or procedures as to how the preservation of recordings is to be accomplished. There is also no requirement to train crews on these issues.

1.21 Useful or Effective Investigation Techniques

None

2.0 Analysis

2.1 General

The investigation determined that the double-engine flameout was caused by fuel exhaustion, which was precipitated by a fuel leak developing in the right engine as the result of the use of mismatched fuel and hydraulic lines during the installation of the hydraulic pump. Facilitating the fuel exhaustion was the fact that the crew did not perform the FUEL LEAK procedure that was specifically designed by the manufacturer to reduce the consequences of an in-flight fuel leak.

The maintenance managers, supervisors and technicians responsible for the receipt, planning, installation and associated inspections were qualified to do their assigned responsibilities. The Captain and the First Officer had the proper licences, endorsements and qualifications for their assigned flight-crew duties, and had successfully completed all the required training and check rides. The flight attendants all had the required qualifications and had successfully completed all the required training for their assigned duties.

Up to the point that the crew became aware of the fuel quantity anomaly, the flight was prepared and conducted in accordance with existing regulations and operational directives.

The analysis will focus on the following:

- Why the aircraft maintenance organisation did not detect the mismatch in engine configurations prior to starting the engine change; then why, once the configuration difference was detected during the engine change, the installation of the hydraulic pump and hydraulic and fuel lines was not completed in accordance with manufacturer's specifications; and

- Why a qualified flight crew trained in accordance with approved training programs, while attempting to analyse the situation and taking actions in reaction to the situation, did not take the actions prescribed by the manufacturer to mitigate the consequences of a fuel leak situation, and took action that exacerbated the situation.

2.2 Technical Issues

2.2.1 Engine Receipt

When the spare engine arrived at the company's premises on 1 August 2001, it was processed in accordance with the Air Transat MCM procedures. The process only involved an inventory check and verification that the parts on the Carry Forward Items List were available. Because the engine was positioned at Mirabel, solely as a contingency measure, and there were no immediate plans to install the engine on a company aircraft, the engine remained under the control of the engine manufacturer's representative. Neither the MCM, nor Canadian regulations, require SB's to be checked as part of this type of inventory check.

This check was based on a comparison of the spare engine against the Rework Summary Sheet and the Carry Forward Items List provided by the company that had completed the last shop visit of the engine. Based on the available information and a visual inspection of the condition of the engine, it was assessed that the required parts were available if and when an engine change to one of the company's A330 became necessary. Of importance to this occurrence, the engine receiving process did not identify that the configuration of the loaned engine did not match the configuration of the other A330 engines at the company.

The following factors may have influenced this incorrect assessment:

- Because all the A330 engines in use at the company were in the post-SB configuration and the company personnel had never been involved with pre-SB configured engines, there was no information that would have caused a heightened concern regarding the configuration of the loaned engine.
- The physical appearance of the pre-SB and post-SB configurations are similar and cannot be identified through a cursory inspection such as is conducted during engine receipt.
- The part number of the hydraulic pump, as documented in the carry-forward list, was incorrectly identified as a post-SB hydraulic pump, Part Number 974976; and
- Hydraulic pump, Part Number 974976 was installed on other company A330 aircraft.

2.2.2 Engine Change Planning

2.2.2.1 Role of Service Bulletins

ATA identifies SB's as the only means for the manufacturer to notify operators of a product modification. Comparing the status of non-mandatory SB's on components of the same part number, such as an engine, is not a method generally used to assure inter-changeability, for the following reasons:

- There is no regulatory requirement to do so;
- The absence of documentation on non-mandatory SB's does not constitute a risk to safety;
- The number of non-mandatory SB's that may apply to a major aircraft component may be very large, and conducting the comparison would be time consuming; and
- The IPC contains all the information regarding the applicability of SB's.

A comprehensive comparison of SB's embodied on the engines is the fullest guarantee to confirm the lack of disparities during planning phases. Such a check would only be reasonable once it is known which engine is to be replaced.

The TC-approved MCM did not require that non-mandatory SB's be checked when planning for an engine change; consequently, a comparison of SB's was not carried out at the time of engine receipt, nor during the planning of the engine change.

2.2.2.2 Engine Change Plan

Although the spare engine had been positioned at the company's Mirabel location to facilitate an engine change to one of the company's A330 aircraft, there was no immediate intent to use the engine. Consequently, planning for the engine change did not commence until after the metal particles were found in the engine oil system of the occurrence aircraft and the decision was made to replace the engine in-house.

Because the company maintenance planners were not aware of the differences in configuration between the two engines, the only work cards that were generated were those associated with a normal engine change. Additional work sheets for the installation of the carry-forward items were to be completed during the course of the engine change.

The fact that the differences in engine configuration were not identified during the receipt and planning phases, resulted in a situation wherein the responsibility to detect the incompatibility between the hydraulic pump and the fuel and hydraulic lines was deferred to the technicians doing the engine change.

2.2.3 Engine Installation

2.2.3.1 Initial Detection of the Configuration Problem

During the course of the engine replacement, the interference noticed between the hydraulic pump and the fuel tube was the first indication of a problem with the changeover of the hydraulic pump to the engine that was being installed on the occurrence aircraft.

Once it was realised that the difficulty with the hydraulic pump installation could be related to the differing SB status, the lead technician attempted to view the SB. However, he could not access the SB on the Rolls-Royce EIPC CD from his work station due to a network problem. Not being able to access the SB through the network, the lead technician sought engineering guidance via MCC as per the MCM procedures. Neither the lead technician nor the MCC considered accessing the SB through the Trent EIPC on a stand-alone computer. Had the Trent EIPC been used, access to the SB would have been achieved. Access to the SB would have revealed that there were two interrelated SB's that required replacement of the fuel tube and the hydraulic line, as well as other associated components.

When the lead technician contacted the Engine Controller, the Engine Controller's knowledge of the SB and its background comforted the lead technician into feeling that the Engine Controller had a good grasp of the problem at hand. Acknowledgement by the Engine Controller that the fuel tube needed to be replaced confirmed the lead technician's mental model that this was the only requirement for completion of the installation. The confirmation was reinforced by the fact that the Engine Controller was associated with the engineering department, which had the responsibility for resolving unexpected or non-routine maintenance issues.

During discussions on the estimated time for completing the engine change, the Engine Controller was made aware that the lead technician had been unable to access the SB. Although both individuals acknowledged that the unavailability of the SB's was of concern, the discussion reverted to the issue of work completion time, and no further discussion of the SB took place. Effectively, the Engine Controller and the lead technician agreed to the fuel tube transfer with no further reference to the SB.

There was also the time-pressure factor to complete the work in time for a scheduled flight and to clear the hangar for an upcoming event. This pressure also may have played a role in reliance on direct and personal information about the SB, rather than trying to resolve the existing problem of not being able to access the SB's.

With the solution at hand, being behind schedule, and having spoken to the Engine Controller, the lead technician felt confident that the fuel tube replacement was the only remaining requirement to complete the hydraulic pump installation.

2.2.3.2 Fuel Tube Installation

Exchanging the fuel tube was considered by the lead technician to be a maintenance action similar to the changing-over of other components on the Carry Forward Items List. He believed that the replacement of the fuel tube would establish the engine configuration in the post-mod status.

Although it was recognized that the fuel tube from the replaced engine was different from the one being removed from the engine being installed, the aircraft IPC entry was not referenced.

Adequate clearance between the fuel and hydraulic lines reportedly was achieved during the installation of the hydraulic pump line by applying some force to position the line and holding the line while applying torque to the "B" nut. This clearance subsequently was verified by the lead technician.

Although it is not abnormal that a line be positioned to achieve clearances in this manner, if clamping is not used, the tendency is for a flexible line to straighten when pressurised. This is particularly critical when there is a 90º bend in the tube adjacent to the "B" nut, as was the case for this installation. The risk associated with the application of force while installing mixed construction lines is not well known in the maintenance community, and is not covered in the training of maintenance technicians.

Although the marks on the fuel and hydraulic tubes suggest that some implement may have been used to assist in establishing clearance between the tubes, technicians denied that tools were used in this manner. The investigation could not resolve this issue.

The pressurization of the hydraulic line would have been sufficient to cause the hydraulic line to move back to its natural position and come in contact with the fuel line, which resulted in the chafing and failure of the fuel line.

2.2.4 Quality Control Issues

2.2.4.1 Maintenance Inspection

Post-installation inspections of the engine change were done both by the lead technician and another independent inspector. However, the inspections were limited to ensuring that engine controls were properly connected and secured, and that the remaining work was complete, was within tolerances and was secured. The methods used for these inspections would not very likely detect a mismatch in components, and for the occurrence engine did not detect the incompatibility of the fuel and hydraulic lines that existed.

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2.2.4.2 Quality Assurance Documentation Checks

Neither the aircraft nor the engine log recorded the fuel line change because the technician forgot to make the entry. In addition the verification of the documentation associated with the engine change completed on 18 August 2001 was not done before the occurrence flight. Consequently, the opportunity for the quality assurance review of the documentation to detect the installation error was negated.

Notwithstanding, because it is limited to verifying that the documentation is complete, the quality assurance verification of the aircraft and engine maintenance logs would likely not have detected that the installation of the hydraulic pump and fuel line was not in accordance with applicable SB's.

Rather than relying on a post-maintenance review of the engine documentation, the presence of a quality control representative during the engine installation may have facilitated the research into the interference problem and the full implementation of the SB prior to the release of the aircraft.

2.2.5 Configuration Control

The investigation determined that the engine was received in an unexpected pre-SB configuration to which the operator had not previously been exposed. Also, the identification of a component is first and foremost carried out through its part numbering. The documentation attached to the loaned engine, in using a part number for a post-SB hydraulic pump, may have masked the pre-SB engine configuration until near completion of the engine change. Typically components of different configurations are identified via a part number prefix, suffix or dash number; however, this is not practical for complex components, such as modern aircraft engines.

Non-mandatory SB's may not directly impact on airworthiness when embodied on their own. However, when two or more interrelated non-mandatory SB's, with interacting components, are not carried out in tandem they have the potential to degrade airworthiness, as seen in this occurrence. Although the use of SB's was the only viable method for determining the compatibility of the replacement engine with the engine being removed, the comparison of SB's is not a commonly used means of configuration control, as evidenced in this occurrence.

Even though aircraft configuration is affected by SB's, there is no airworthiness requirement to review all non-mandatory SB's on a component prior to its installation nor is there a system in place to facilitate the checking of SB parity. Although Transport Canada audits include the scrutiny of the implementation of SB's, the management of SB's (assessment of applicability, implementation time frame, embodiment and recording) is left to the carrier's discretion.

In the absence of a requirement to conduct an SB parity check, and of an easy-to-use method of carrying this check out, there is a risk that incompatible components may be installed on aircraft and not be detected by existing maintenance planning processes.

2.3 Aircraft Operational Factors

2.3.1 Uncertain Engine Oil Parameters

Technical investigation and analysis following the occurrence have determined that the unusual oil parameters were caused by high fuel-flow rate through the fuel/oil heat exchanger. The suddenness of the changes and the fact that there were no abnormal procedures or information on a situation of high oil pressure, low oil quantity and low oil temperature created a level of uncertainty in the cockpit. The facts that there were no other unusual engine readings, there were no other system anomalies, and MCC could not explain or provide advice on the unusual readings contributed to this uncertainty.

Because the oil parameters were within specified operating limits, a diversion to an ETOPS alternate airport, based solely on these parameters, would not have been required by regulations, by the company Operations Manual, or by the company's standard operating procedure.

2.3.2 Initial Recognition of the Fuel Loss (04:38 – 05:33)

The fuel leak started at 04:38, but a fuel problem was not noticed by the crew until 05:33, when the fuel ADV was generated. During this time, there were a number of cockpit indications that there was a fuel-loss problem, as follows:

- The fuel on board was decreasing at an unusual rate; this information would have been displayed in the FOB figures on the E/WD page.
- The estimated fuel on board at destination was decreasing; this information would have been displayed in MCDU.
- The full forward transfer of the fuel in the trim tank was premature given the fuel load on departure from Toronto of 46 900 kg. A prolonged, 19-minute TRIM TANK XFR memo between 05:11 and 05:30, and then the TRIM TANK XFRD memo between 05:30 and 05:33 would have displayed this information.

The following factors probably contributed to this delayed recognition of the low fuel quantity problem:

- The only fuel check required by standard operation procedures during this timeframe was done at 04:58 as the aircraft crossed 30° West. At this time, the fuel quantity was unremarkable, because it was within 0.2 tons or 1% of the planned fuel quantity.
- The crew was then involved in position reporting, recording entries on the flight log, and checking of instrument indications.
- The unusual oil readings created a level of uncertainty in the cockpit.
- This uncertainty resulted in the crew becoming occupied in activities to resolve the ambiguities, including reviewing manuals and contacting the MCC.
- The final forward transfer of the 3.2-tons of fuel from the trim tank into the right wing tank delayed the generation of the fuel ADV message by approximately 15 minutes.

Although the TRIM TANK XFR memo was premature given the stage of flight, the initial appearance of the memo would have been unremarkable, because it comes on routinely during flights. Also, given the crew activities associated with resolving the unusual oil readings, it is understandable that, during this time frame, the crew did not recognize the prolonged nature of the TRIM TANK XFR memo, the presence of the TRIM TANK XFRD memo, and the subtle changing of the FOB and EFOB figures.

From 04:38, the time that the fuel leak started, until 05:04, the time when the unusual oil indications were recognized, cockpit activity level was normal. However, the task of resolving the oil indications raised the activity level and drew the attention of the crew away from routine monitoring of other displays.

All of the fuel-related information and messages were provided in the form of text-type status messages and digital counter displays, none of which conveyed a sense of urgency to cause the crew to abandon activities associated with resolving the oil reading anomalies, and none of which conveyed the critical nature of the fuel leak.

Of importance is that during this time, the forward transfer caused the fuel in the trim tank to be loaded into the right wing, delaying the generation of the fuel ADV message, masking the fuel leak problem from the crew. By the time that the fuel imbalance advisory was generated at 05:33, fuel on board had reduced to 12.2 tons and 6.65 tons of fuel had been lost.

In summary, it was highly unlikely that the crew would have become aware of the fuel anomaly during this time frame, given the subtleties of the available indications. The fact that this could occur highlights the limitations of the warning and alert system in this kind of situation.

2.3.3 Reaction to the Fuel Imbalance Advisory (05:33 – 05:45)

After becoming aware of a fuel problem at 05:33, the crew's initial action was to cancel the display of the engine page in order to view the fuel page. Because of the nature of the ADV, the ECAM did not display a checklist procedure and the crew was required to review the indications on the FUEL page to determine the problem.

Based on the flashing displays associated with the right wing tank, the crew assessed that there was a fuel imbalance situation. Then at 05:36, by memory and without reference to the QRH, the fuel balancing procedure was initiated by opening the crossfeed valve and turning off the right wing tank pumps. At this time, fuel on board had reduced to 11 tons and 7.3 tons of fuel had been lost.

The opening of the crossfeed valve resulted in the fuel from the left wing tanks being fed to the leak in the right engine. In doing the fuel imbalance procedure by memory, the crew overlooked the FUEL IMBALANCE Caution that, in the event that a fuel leak is suspected, the FUEL LEAK procedure should be done.

It was just after taking the initial actions to establish the crossfeed that the crew became aware of the following other indications that reflected a fuel loss problem:

- The fuel on board was 7 tons lower than predicted for the stage of the flight.
- The estimated fuel on board at destination had decreased significantly from the planned amount.

The sudden discovery of an unexplainable, lower-than-expected fuel quantity, resulted in the crew attempting to resolve the discrepancy, as follows:

- The fuel loading, flight planning documents and flight records were reviewed for errors; none were found.
- Engine and fuel system indications and displays were reviewed to determine if there were other indications of a problem with the engines, fuel flow or fuel system; none were found.
- There had been no prior sounds or other perceived aircraft symptoms that would suggest an aircraft structural or fuel problem.

When the ECAM ADV alerted the crew to the fuel imbalance, there was a large disparity between the actual fuel system state and the crew's understanding of it. Although there were other indications that the situation was more serious than a fuel imbalance, the crew initially reacted by doing the FUEL IMBALANCE procedure because that was the only anomaly that was exposed by the ECAM system. The crew did the procedure from memory because the crew was familiar with it, having been frequently required to monitor fuel balance during simulator training sessions.

The cockpit activity level during this 12-minute period would have been high, and the crew's attention would have been focused on the perceived ambiguity of the fuel situation and activities involved with the diversion to Lajes. Consequently, the crew would have had little time and limited mental capacity to re-examine its mental model of the situation and to question actions already taken in response to the fuel ADV. Doing the FUEL IMBALANCE procedure fulfilled the immediate, perceived goal of managing the fuel imbalance.

Neither of the crewmembers had ever experienced a fuel imbalance of any magnitude during flying operations, nor been exposed to a fuel leak situation during training or operations.

On 24 August 1997, an Air France A320 aircraft experienced a fuel leak. The crew involved in this event took similar action to balance the fuel.

Once the EFOB at destination reduced below minimums, the Captain made an appropriate decision to divert to the ETOPS alternate of Lajes.

In summary, the crew was presented with an ADV that did not require immediate action. The FCOM required that the crew refer to the QRH before taking action, and CRM principles suggest that, before taking action in response to the Fuel ADV, the crew should have taken into account all available information about the fuel system. Such a review would have revealed that over 6 tons of fuel had been lost. The combination of the fuel-loss indications and the substance of the Caution note in the FUEL IMBALANCE procedure in the QRH should have led the crew to the FUEL LEAK procedure. The FUEL LEAK, LEAK FROM ENGINE procedure requires that the leaking engine be shut down; the FUEL LEAK NOT FROM ENGINE OR LEAK NOT LOCATED requires that the crossfeed must remain closed. Either of these actions would have conserved the fuel in the left wing tanks and allowed for a landing at Lajes with the left engine operating. Opening the crossfeed valve put the fuel in the left tank at risk, and initiated a worsening of the serious fuel-leak situation that existed.

2.3.4 Reaction to the Continued Fuel Loss (05:45 – 06:10)

At the time that the diversion commenced at 05:45, fuel on board had reduced to 8.7 tons, 9.3 tons of fuel had been lost, and fuel from the left wing tank was being used to feed both engines, and the 13 tons-per-hour fuel leak.

During the time when the diversion was being planned, the crew stated that doing the FUEL LEAK procedure had been considered. However, they were still uncertain as to the validity of the fuel quantity indications and the precise nature of the problem. The crew further stated that they discounted doing the LEAK NOT FROM ENGINE or LEAK NOT LOCATED procedure because doing so would require a descent to a lower altitude and would further degrade an already critical situation. Notwithstanding, had this procedure been initiated before 05:54, completing the action to close the crossfeed valve would have conserved the fuel in the left wing tanks and allowed for a landing at Lajes with the left engine operating.

At 05:54, the Captain's reconfiguring the fuel pumps to establish the crossfeed from the right tanks resulted in the fuel in the right wing tank feeding the left engine, thereby isolating fuel in the left tank from the leak in the right engine and conserving the fuel in the left tank that would be normally feeding the left engine. The momentary configuration of crossfeed from the left tanks at 06:02 in reaction to a suggestion from MCC had little consequence on the fuel situation.

From 05:45, the time that the diversion was initiated, to 05:51, when the FD left the cockpit to do the visual inspection for signs of a fuel leak, the level of activity in the cockpit would have been very high. In particular, much of the crew's efforts would have been occupied with preparing the aircraft systems for the diversion and approach to Lajes, and crew's requirement to advise ATC and the FD about the decision to divert, all tasks required by the diversion.

Between 05:57, the start of HF communications with MCC, and 06:13, the time when the right engine flamed out, much of the crew's efforts were involved with communications with MCC totalling over 10 minutes. The workload was sufficiently high that the crew did not have time to action the ECAM action items associated with the FUEL R WING TK LO LVL and the FUEL L+R WING TK LO LVL messages that appeared at 05:58 and 06:08 respectively.

Although not actioning these checklists did not adversely affect the flight, the crew's involvement in non-critical communication with MCC reduced the time available for them to more accurately assess the situation.

Notwithstanding indications that there had been a massive loss of fuel, the crew did not believe that there was an actual fuel leak. The following factors supported this mental model of the situation:

- The combination of the suddenness and the magnitude of the indicated fuel loss were such that it could not be linked to any explainable reason.
- The earlier problem with the oil indications had established a level of uncertainty.
- There was no ECAM warning or caution message indicating a severe problem.
- No other indication of an engine problem was discovered.
- Some information, like the cabin crew confirming that there were no visible signs of a leak, countered the possibility of a leak.

The crew, realizing that the situation was continuing to deteriorate, hypothesized that a computer malfunction would account for the ambiguous indications. The lack of training for a fuel leak situation, never having experienced a fuel leak, and having no knowledge of similar events meant that the crew had no relevant information to counter the basis for their hypothesis.

2.3.5 Reactions to the Engine Failures

At 06:10, the time that the crew stated that all fuel pump switches were selected ON, the aircraft was 175 miles from Lajes, with approximately 1.0 ton of fuel in the left tank and 0.2 tons in the right tank.

It was not until the right engine had flamed out at 06:13:28 that the crew began to reassess their mental model. Even at this point, they were unable to account for the flameout and were under the hypothesis that the indications still could be erroneous.

At 06:21, the crew, attempting to ensure that all usable fuel from the trim tank was available to the remaining left engine, selected the trim tank transfer pump switch to FWD, which resulted in the display of the FUEL TRIM TK PUMP LO PR message, indicating that no fuel remained in the trim tank.

Based on recorder data available, the crew's reaction to the engine failures and actioning of the required checklist procedures were in accordance with procedures specified in the FCOM. The performance of cockpit duties, interface with cabin crew, and communications with air traffic were professional and highly effective.

2.3.6 Approach and Landing

The Captain's handling of the aircraft during the engines-out descent and landing was remarkable given the facts that the situation was stressful, it was night time, there were few instruments available, pitch control was limited, and he had never received training for this type of flight profile.

The Captain's decision to apply and maintain maximum braking on the second touchdown was justified based on the facts that the aircraft speed was well above the recommended speed when crossing the threshold, and that, following the initial bounce, the aircraft touched down significantly beyond the normal touchdown zone.

The First Officer provided full and effective support to the Captain during the engines-out glide and successful landing.

2.4 Aircraft Fuel Issues

2.4.1 Fuel Imbalance Procedure

A significant fuel imbalance during normal operations is a rare and unlikely event. The only time a fuel imbalance would be expected to occur is if there is a significant difference in fuel consumption between the left and right engines, such as when an engine failure occurs. Even in such an emergency situation, the imbalance would remain low unless the time to landing was long. In such a situation, the reason for the imbalance would be easily understood.

A fuel imbalance in the range of the 3.0-ton magnitude required to generate a FUEL ADV would only likely occur if there were a significant fuel leak. Without training on fuel leaks or on other conditions that would lead to such a suddenness of such a change in fuel, flight crews have had difficulty in determining the reason for the change, in particular if other supportive, easily understood, rate-type information was not available.

Although lessons learned from previous fuel-imbalance occurrences resulted in fuel leak checklists and system software changes being established, training on factors that may create a fuel imbalance, and the conditions under which the FUEL IMBALANCE procedure should not be used was never incorporated into training programs.

The perception that a fuel imbalance is a low-risk situation is evidenced by the following:

- The situation is not announced by a caution or a warning or alert.
- The Caution note in the FUEL IMBALANCE checklist that the checklist should not be used if a fuel leak is suspected is not prominent; and

- The conditions that should be used to assess if a fuel leak exists are not located on the FUEL IMBALANCE checklist.
- The exposure of A330 crews to fuel imbalance situations is limited to situations that only require a monitoring of fuel balance, and not to situations that require an active response to a FUEL IMBALANCE advisory.

2.4.2 Fuel Leak Warning and Procedures

Although the fuel leak started at 04:38, the higher-than-normal rate of fuel quantity reduction was not recognized by the crew until after the Fuel page was called up at 05:34 as the result of the fuel imbalance ADV. By the time that the crew was able to take initial actions to the situation at 05:36, more than 7 tons of fuel had already been lost. The suddenness and the magnitude of the indicated fuel loss were perceived as being incredible and not linked to any explainable reason.

As demonstrated in this occurrence and other earlier fuel leak occurrences, flight crews have difficulty in assessing the seriousness of fuel leak situations due to the following:

- The absence of confirming data in the form of knowledge of and the lack of operational exposure to similar events.
- The absence of physical evidence of fuel leaking from the aircraft or abnormally high fuel flow indications.
- The lack of a direct system warning to alert the crew to the precise critical condition.
- The appearance of another system indication that diverts the crew's attention to another more-easily understood situation of lower criticality.
- The lack of training covering conditions likely to cause fuel leaks and the procedures to be followed if a fuel leak is experienced.

The investigation into the 24 August 1997 Air France A320 occurrence resulted in a 6 September 1997 BEA recommendation to DGAC to re-examine the adequacy of systems and procedures, and as an interim measure to notify all crews of the circumstances of the occurrence. The FUEL LEAK checklist was improved, a FUEL IMBALANCE checklist was developed and pilot information was promulgated. At the time of this Air Transat A330 occurrence, a leak-warning system had not been incorporated in any A330 aircraft. Additionally, fuel leak training had not been incorporated into the Airbus A330 training program.

Had the Air Transat crew taken the actions required by the FUEL LEAK checklist when the fuel loss was first recognized at 05:53, the aircraft would not have run out of fuel before reaching Lajes.

2.4.3 Trim Tank Transfer

Although two green TRIM TANK XFR ECAM advisory messages would have been displayed in the memo section of the E/WD during the flight, these two memos would have been unremarkable, first because this type of message comes on routinely during flights, and second because the message is a status type text message that neither conveys urgency or requires immediate action. In addition, the subtle addition of one text letter "D" from the TRIM TANK XFR to the TRIM TANK XFRD message is not a high-salience change and did not draw this crew's attention.

Even the last TRIM TANK XFR message that lasted 19 minutes and the TRIM TANK XFRD message for remainder of the flight did not alert the crew to an urgent situation, in part because they were occupied in higher priority cockpit tasks such as completing flight documentation, communicating, analyzing the unusual engine oil parameter anomalies, and then attempting to resolve the fuel imbalance and ambiguity of the fuel quantity.

Of importance is that the forward transfer caused the fuel in the trim tank to be loaded into the right wing, feeding the leak in the right engine and masking the fuel leak problem from the crew. This masking contributed to an unnoticed loss of 3.5 tons of fuel.

2.5 A330 ECAM System

During training and actual operations, the crews are taught to place trust in the ECAM that the system will provide the needed information for significant, abnormal or emergency situations. For this occurrence, the only alerting provided to the crew was the white ADV message only requiring system parameter monitoring, even though by this time the aircraft had actually lost 6.5 tons of fuel. This low level of alerting created an atmosphere of little or no urgency associated with the situation that was being conveyed.

The current design approach of the automated system not monitoring and analyzing available aircraft information that would be characteristic of a fuel leak situation implies that a FUEL LEAK is very low probability event and a low-risk event. This A330 occurrence and the 1997 A320 occurrence indicate, however, that a FUEL LEAK is not only a high-risk situation that can be misidentified by qualified and trained crews, but also requires clear, unambiguous alerting of the crew and guidance as to the handling of the situation to mitigate the risk.

2.6 Fuel Malfunction Training

Other than FUEL IMBALANCE and FUEL LEAK procedures, there is no mention in any manufacturer or company documentation that provides information, guidance or direction on these two issues. In particular, other than in the QRH procedures and indirectly in SOPs, there is no information or training as to how to interpret symptoms to conclude that actioning of the FUEL LEAK procedure would be appropriate. As a consequence, crews are neither trained in fuel leak procedures nor on fuel imbalance situations caused by fuel leaks. This crew was inadequately prepared to deal with the type of emergency that was encountered on this flight. This situation is not unique to this A330 operator or to operators operating other Airbus aircraft having similar fuel and flight management systems.

Had the crew consulted the caution in the FUEL IMBALANCE procedure according to their SOP´s, there would have been sufficient information to guide them to follow the FUEL LEAK procedure to mitigate the consequences of the fuel leak. Notwithstanding, in a situation of surprise, heightened activity, and stress, and the lack of direct training and clear annunciation of a critical situation, can result in crews resorting to other well rehearsed routines that may not be appropriate for the actual situation, in this case a fuel balancing procedure done by memory.

Some regulatory agencies (e.g. FAA and DGAC - France) already require that aircraft flight manuals include procedures that will enable flight crews to identify fuel system leaks, and procedures for crews to follow to prevent further fuel loss. However, there are a number of commercial aircraft that do not have identification procedures or fuel leak checklists.

There are also no specific regulatory requirements for training on fuel leak scenarios, and prior to this occurrence little if any training on this type of aircraft malfunction was conducted by any airline.

Had this particular crew been trained in the symptoms of fuel leak situations and strategies to identify and counter such a situation, they would have been better prepared to take appropriate actions.

2.7 Passenger Safety Issues

2.7.1 Emergency Exit Door L3 Failure

The investigation determined that there were no anomalies associated with the arming of the door or the procedures used to attempt to open emergency exit door L3 during the evacuation. Although conclusive finding as to the technical causes of the door jam could not be made, because some components could not located after the occurrence, interviews and photos confirm that the slide had not released completely from the door, and that the bustle rails/rail adapters may have jammed.

The previously documented cases wherein improper installation of some components was suspected resulted in the issue, on 30 July 2001, of Goodrich Service Bulletin Number 25-306 to mitigate the risks of improper installation. Airbus had also recognized the problem and had issued SB A330-25-3126, dated 07 August 2001. As of the date of the occurrence, the subject airline had yet to receive either SB.

Neither of these SB's were mandatory, but following the occurrence, DGAC upgraded compliance with these SB's by issuing Airworthiness Directives number AD 2001-465 (B) R1, for the A330, with compliance required no later than 13 October 2004. Until this AD is complied with, there remains a risk that exit doors on other A330 could jam during an attempted evacuation.

For this occurrence the consequences of the door failure were minimal due to the low passenger load in the area of the L3, the immediate availability of other exit doors, and the low-risk circumstances in this evacuation.

2.7.2 Oxygen Flow to Passenger Masks

2.7.2.1 Oxygen Container Doors

Although the initial examination of the aircraft oxygen activation system and oxygen panel doors indicated that electrical current was being supplied to the door latches and that the doors would not deploy, the laboratory examination of the container and components could not duplicate the problem or find a technical defect with the components.

Although the number of masks that failed for undetermined reasons was within the functional test standard of 10 per cent of the number of passenger seats, on this particular flight, 7 passengers and 2 flight attendants would have been required to leave their seats to find another available oxygen mask.

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2.7.2.2 Chemical Oxygen Generator R3 Installation

The presence of a maintenance installation retaining pin in the oxygen generator at flight attendant position R3, and the fact that this installation had not activated since the aircraft was acquired, indicates that the pin was not removed at the time that the generator was installed during the manufacture of the aircraft.

The incomplete installation and inspection of this chemical oxygen generator resulted in a situation wherein the flight attendant was required to don an oxygen mask from a passenger seat that was fortunately vacant across the aisle. Had these adjacent seats not been vacant, the flight attendant would have been required to leave his seat and his safety position at door R3.

2.7.2.3 Oxygen Flow at L3 Position

The examination of the oxygen system at door L3 indicated that the pin had been pulled from the activator squib and that the oxygen generator had generated enough heat to discolour the witness patch. Notwithstanding, there was personal testimony and photographic evidence to suggest that oxygen had not flowed to the mask. Unfortunately, the loss of the mask assembly and other components before they could be fully examined means that definitive conclusions regarding the functioning of L3 oxygen system cannot be made, and deficiencies, if any, could not be identified.

2.7.3 Language of Passenger Safety Briefings

Canadian Aviation Regulations, Commercial Air Service Standards only require that safety briefings be given to passengers in the official Canadian languages of English and French. Notwithstanding, the company's practice of having preflight safety videos with subtitles and crewing of the flight with flight attendants capable in other languages advances safety.

On this particular flight, having three flight attendants capable in the Portuguese language was advantageous, because many of the passengers were having difficulty in understanding the English and French safety briefings being given in preparations for the anticipated emergency ditching and actual land evacuation.

2.7.4 Passenger Life Jackets

Some of the passengers had difficulty in donning their life jackets, because of language comprehension problems. Other passengers had difficulties in securing life jackets straps, because they could not locate the straps that were still tightly bound by elastic bands used to facilitate packing of the life jackets in the containment bags. These problems were easily overcome.

The aircraft was equipped with two types of life jackets. The two-strap type was not addressed during the passenger safety briefings, nor described on the passenger safety card. This condition posed a risk that passengers might not understand the operation of this type of life jacket.

The life jackets were installed on the aircraft by company technicians after the aircraft was acquired by Air Transat. The installation and quality-control process used by the company to ensure that only one type of life jacket is installed on an aircraft did not preclude the installation of some two-strap life jackets on an aircraft that should have been equipped with only the single-strap lifejackets.

2.8 Flight Recorders

2.8.1 Flight Recorder Power Supply

The loss of flight recorder information for the last 19 minutes of the engines-out descent and landing on this occurrence did not adversely affect the investigation to this accident for the following reasons:

- The crew survived and was able to provide factual information.
- ATS recordings provided additional information regarding crew communications and aircraft position data.
- There were no safety-significant events during this phase of flight that could have led to the discovery of underlying factors and the need for safety recommendations.

Notwithstanding, had the circumstances been different, the lack of data following the power loss on both engines would have severely affected the ability of the investigation to make findings as to the causes and contributing factors to this occurrence.

2.8.2 Erasure of CVR Recording

Following the occurrence landing, in order to offload passenger baggage and belongings, there was a requirement to power up the aircraft. The crew was aware that applying power would result in the overwriting of the CVR recording, and sought advice as to how to disable the recorders. Unfortunately, the circuit breakers pulled, did not disable the CVR and disabled the A330 CVR protection circuit breaker, which resulted in the loss of 90 minutes of CVR recording, which deprived the investigation of information that could have resulted in a clearer understanding of the underlying factors to the occurrence.

Contributing to the inadvertent erasure of the CVR recording were the following:

- The advice provided to the crew by company personnel, as to which circuit breakers needed to be pulled to disable the CVR, was incomplete.
- The First Officer was not familiar with the layout of the circuit breaker panel in the avionics bay, nor was he knowledgeable about the location and number of circuit breakers associated with the recorders.
- Although the company's operations manual stated that there was a requirement to preserve recordings following an occurrence, there was no specific information, diagrams or procedures readily available to the crew as to how the preservation was to be accomplished.

The historical record indicates that there have been many occasions when CVR recordings have been lost due to not disabling power to CVR's.

Although NTSB Recommendation A-02-24 "Overwritten Cockpit Voice Recordings" was issued on 29 August 2002, implementation of the recommendation by the Federal Aviation Administration would only affect airplane operators certified to conduct operations in the United States of America.

3.0 Conclusions

3.1 Findings as to Causes and Contributing Factors

1. The replacement engine was received in an unexpected pre-SB configuration to which the operator had not previously been exposed.
2. Neither the engine-receipt nor the engine-change planning process identified the differences in configuration between the engine being removed and the engine being installed, leaving complete reliance for detecting the differences upon the technicians doing the engine change.
3. The lead technician relied on verbal advice during the engine change procedure rather than acquiring access to the relevant SB, which was necessary to properly complete the installation of the post-mod hydraulic pump.
4. The installation of the post-mod hydraulic pump and the post-mod fuel tube with the pre-mod hydraulic tube assembly resulted in a mismatch between the fuel and hydraulic tubes.
5. The mismatched installation of the pre-mod hydraulic tube and the post-mod fuel tube resulted in the tubes coming into contact with each other, which resulted in the fracture of the fuel tube and the fuel leak, the initiating event that led to fuel exhaustion.
6. Although the existence of the optional Rolls-Royce SB RB.211-29-C625 became known during the engine change, the SB was not reviewed during or following the installation of the hydraulic pump, which negated a safety defence that should have prevented the mismatched installation.
7. Although a clearance between the fuel tube and hydraulic tube was achieved during installation by applying some force, the pressurization of the hydraulic line forced the hydraulic tube back to its natural position and eliminated the clearance.
8. The flight crew did not detect that a fuel problem existed until the Fuel ADV advisory was displayed and the fuel imbalance was noted on the Fuel ECAM page.
9. The crew did not correctly evaluate the situation before taking action.
10. The flight crew did not recognize that a fuel leak situation existed and carried out the fuel imbalance procedure from memory, which resulted in the fuel from the left tanks being fed to the leak in the right engine.
11. Conducting the FUEL IMBALANCE procedure by memory negated the defence of the Caution note in the FUEL IMBALANCE checklist that may have caused the crew to consider timely actioning of the FUEL LEAK procedure.
12. Although there were a number of other indications that a significant fuel loss was occurring, the crew did not conclude that a fuel leak situation existed – not actioning the FUEL LEAK procedure was the key factor that led to the fuel exhaustion.

3.2 *Findings as to Risk*

1. The carry-forward items list that accompanied the replacement engine listed a post-modification hydraulic pump model, whereas the fuel and hydraulic tubes installed on the engine were pre-mod.
2. Time pressures, difficulties in accessing the SB and the apparent knowledge of the engine specialist influenced the lead technician to curtail his search for the SB and to rely on verbal advice.
3. The post-installation quality control checks following the engine change did not specifically require checking the installation of the hydraulic pump, hydraulic tube and the fuel tube.
4. In the absence of a requirement to conduct a pre-installation, configuration (SB) parity check, and of a commonly accepted method of carrying out this check, there is a risk that incompatible components may be installed on aircraft and not be detected by existing maintenance planning processes.
5. Not being able to understand and resolve the unusual oil readings in the right engine contributed to the crew's uncertainty.
6. The final forward transfer of the 3.2 tons of fuel in the trim tank resulted in this fuel feeding the leak in the right engine and delaying the annunciation of the fuel Advisory by 15 minutes.
7. There was not a clear, unambiguous indication or warning that a critical fuel leak existed.
8. The seriousness of a fuel imbalance situation caused by a fuel leak is undermined by the facts that such a situation only results in an advisory notice not requiring immediate action by the pilot that reference to a fuel leak only appears in a Caution note in the FUEL IMBALANCE procedure.
9. Following the crew actions to crossfeed the fuel, cockpit activities became so high that the crew had little time and limited mental capacity to re-examine its mental model of the situation, specifically to reassess actions already taken, or to re-evaluate other indications to conclude that a fuel leak existed.
10. The flight crew members had never experienced a fuel leak situation during operations or training, which contributed to their not being able to conclude that a fuel leak existed and that actioning the FUEL LEAK procedure was required.
11. The lack of training in the symptoms of fuel leak situations resulted in this crew not being adequately prepared for the situation encountered on the occurrence flight.
12. The Captain's skill in conducting the engines-out glide to a successful landing averted a catastrophic accident and saved the lives of the passengers and crew.
13. The First Officer provided full and effective support to the Captain during the engines-out glide and successful landing.
14. The CD on the company's network containing the Rolls-Royce EIPC for the Trent 772B and related SB's could not be accessed due to a company computer system fault.

15. The overwriting of 90 minutes of the CVR recording deprived the investigation of data that could have resulted in a clearer understanding of the underlying factors to this occurrence.
16. There was no documentation readily available to the crew regarding the deactivation of the flight recorders; consequently, only two of the three recorder circuit breakers were pulled, which allowed the inadvertent overwriting of the CVR recording.
17. Jamming of the L3 emergency exit somewhat hampered the evacuation of the aircraft.
18. Having three Portuguese-speaking flight attendants enhanced passengers' understanding of the safety briefings being given in preparation for the anticipated emergency ditching and actual land evacuation

3.3 Other Findings

1. The unusual oil parameters on the right engine were the result of the high fuel-flow rate through the fuel/oil heat exchanger after the leak commenced.
2. There is not a readily available, effective, commonly accepted method to compare the SB (configuration) status of engines, placing reliance on other processes to detect configuration differences.
3. The logbook entry detailing the installation of the fuel line from the replaced engine was not recorded.
4. The risk associated with the application of force while installing mixed-construction lines is not well known in the maintenance community, and is not covered in the training of maintenance technicians.
5. Failure of the oxygen container doors to open resulted in the contained oxygen masks to not be available for use by the passengers.
6. The failure to remove the maintenance installation retaining pin from the oxygen regulator at position R3 resulted in the contained masks to be unavailable for use by the flight attendant seated at this position.
7. The installation and quality-control process used to ensure that only one type of life jacket is installed on an aircraft did not preclude the installation of some two-strap life jackets on an aircraft that should have been equipped with only the single-strap lifejackets.

4.0 Safety Action

4.1 Action Taken

4.1.1 Action Taken By Transport Canada

- As a precautionary measure immediately following the occurrence, Transport Canada suspended Air Transat's extended Range Twin Operations (ETOPS) authority effectively requiring it's A-330 overseas flights to alter their routes to remain closer to suitable en-route airports. The ETOPS suspension was to remain in effect until Transport Canada was satisfied that safety deficiencies no longer existed.
- On 24 August 2001, Transport Canada initiated a Special Purpose Audit of Air Transat maintenance and operations. None of the findings of this audit played a role in this fuel exhaustion occurrence.
- On 28 August 2001, at Transport Canada's request, Canadian air operators inspected all of their A-330 aircraft to ensure that the same mechanical conditions that may have contributed to the Air Transat emergency landing did not exist on other aircraft.
- On 30 August 2001, Transport Canada directed Air Transat to immediately implement special training sessions on extended range operations, fuel management and diversion procedures.
- On 6 September 2001, Transport Canada took new measures to limit ETOPS of all Air Transat aircraft. The additional ETOPS measures required all Air Transat aircraft to remain within a maximum of 90 minutes of suitable en-route airports between the point of departure and the destination. This measure affected Air Transat's A-310 and Boeing 757 aircraft and did not alter the current suspension of ETOPS authority for the company's A-330 aircraft.
- On 7 September 2001, Transport Canada, issued Commercial and Business Aviation Advisory Circular (CBAAC) 190, to inform flight crews of the hazard associated with the improper identification of fuel related problems during flight. In this CBAAC, Transport Canada provided information on the symptoms of fuel leak situations, discussed possible leak scenarios, and recommended that all flight crewmembers review technical documents and procedures for fuel leak events specific to the type of aircraft that they operate.
- Transport Canada recommended that a Human Performance in Aviation Maintenance course be given to Air Transat's maintenance personnel. Air Transat provided this training through the Boeing Aircraft Corporation.
- Transport Canada provided regulatory guidance and assistance in the development of Air Transat's safety management system (SMS).
- In November 2003, Transport Canada performed a regulatory assessment of the SMS to determine Air Transat's progress and the effectiveness of the program.

4.1.2 Action Taken By Air Transat

- On 30 August 2001, special training sessions were conducted on fuel management and diversion procedures for all its flight crews operating its B-757, A-310 and A-330 aircraft on extended twin-engine operations.
- Additional training was conducted for it's A-330 crews on the fuel system, identifying lost fuel, the functioning of the cross-feed system, and the checklists for FUEL IMBALANCE and FUEL LEAK.
- Fuel-leak scenarios have been integrated into the initial and recurrent, theoretical and simulator training programs for all company aircraft.
- Standard Operating Procedures on waypoint fuel checking have been standardized between all fleet types, emphasizing a requirement to verify that the sum of fuel on board and fuel consumption are consistent with the fuel on board at take-off and flight planned fuel burn estimates.
- Modifications have been made to the company's flight planning program to improve the accuracy of fuel calculations for ETOPS critical diversion scenarios.
- Air Transat initiated a comprehensive review of the safety of their maintenance and operations program. The company also established a corrective action plan that will improve the performance of maintenance activity, including the hiring of additional maintenance and quality assurance personnel. It instituted human factors training for all technical personnel; reviewed and enhanced quality assurance and quality control procedures; and, introduced a system for detecting and analyzing maintenance errors.

4.1.3 Action Taken by Direction Genérale de l'Aviation Civile of France (DGAC)

- On 20 March 2002, DGAC provided Recommendation Bulletin BR 2002/14(B) to civil aviation authorities with responsibility for A-330 and A-340 aircraft: this distribution included Transport Canada, Civil Aviation Authority of the United Kingdom, and the Federal Aviation Authority of the United States of America. The bulletin was issued to put emphasis on existing AIRBUS operational procedures that enable the detection of potential fuel leaks and to mitigate their consequences on the safety of flight, as follows:
  - Fuel checks during cruise flight;
  - Fuel imbalance procedure;
  - Fuel Leak Procedure;
  - FU/FOB Discrepancy ECAM Amber Caution; and
  - Training on fuel leak situations.

- On 13 November 2002, DGAC provided Recommendation Bulletin BR 2002/48(B) to civil aviation authorities with responsibility for A-330 and A-340 aircraft. The purpose of the bulletin was to recommend a modification of the Flight Warning Computer (FWC) pin programming, compatible with a new FCMC standart, in accordance with Airbus SB A330-28-3080, in order to activate crew alert "FUEL FU/FOB DISCREPANCY". When activated, this fuel leak monitor will alert the flight crew of a discrepancy of more than 3 500 kg (7,700 lb.) between the initial Fuel on Board (FOB) the aircraft and the total of the present FOB plus the Fuel Used (FU), when the aircraft is in typical cruise altitude and configuration.
- On 13 November 2002, DGAC issued Airworthiness Directive 2002-548(B), Fuel Leak Procedure, which is applicable to AIRBUS A-330 aircraft. The AD amends the A-330 FUEL LEAK procedure. Compliance with this AD is mandatory from 23 November 2002, and is applicable for all flights.

4.1.4 Action Taken By Airbus

- On 29 August 2001, Airbus issued an All Operators Telex (AOT) A330-73A3033 requiring a one-time visual inspection to verify that no interference exists between the fuel and hydraulic lines on all A-330 aircraft equipped with Rolls-Royce 700 series engines.
- On 21 May 2002, Airbus issued Service Bulletin A330-28-3080 FUEL – FCMS – ACTIVATE CREW ALERT 'FUEL FU/FOB DISCREPANCY'. This SB provides the instructions for the installation of the necessary wiring provisions, and gives instructions to modify the pin programming of the FWC to activate the FU/FOB warning, Modification No. 49800H14467. Accomplishment of the SB provides the flight crew with a warning of a significant fuel loss in the event of a fuel leak. This warning does not supersede the fuel monitoring procedures that now exist for the flight crew. Compliance with this SB is recommended by Airbus.

4.1.5 Action Taken By Rolls-Royce

- On 29 August 2001, Rolls-Royce issued a World Wide Communication (DBY/CS/00697/2001), advising operators, in part, to check all engines to ensure that adequate clearance exists between the fuel and hydraulic lines.
- On 29 August 2001, Rolls-Royce issued a Non-Mandatory Service Bulletin 73-D-578 recommending the inspection of the clearance between the fuel and hydraulic lines.

4.1.6 Action Taken By UK-CAA

- On 31 August 2001, the United Kingdom CAA issued Airworthiness Directive 005-08-2001, mandating the Rolls-Royce Non-Mandatory Service Bulletin 73-D-578.

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4.2 Action Required

4.2.1 Fuel Leak Detection and Warning

Indications and warning systems should be designed to detect critical events, to provide unambiguous information on critical situations with high risk, and to direct crews to specific actions that would mitigate these risks. Clear indications and warnings are particularly necessary for high-risk, rare events, situations that are difficult to diagnose, and situations that require precise handling, in particular under conditions of high workload and stress.

Historically, fuel leaks were considered to be rare events, and although consequences could be significant, the overall risk was evaluated as being low. It was also considered that routine fuel quantity monitoring and common sense would drive a crew to a prompt precise determination of the cause of the symptoms and to take the required action. The historical occurrence records indicate that, although in-flight fuel leaks are infrequent events, these events continue to occur. Recent occurrences have revealed that crews have had difficulty in diagnosing fuel leak situations, and that the consequences can be significant.

Analyses of past events have resulted in the design and implementation of systems capable of detecting fuel loss events and of alerting crews, and in the creation specific fuel leak checklist procedures. Some civil aviation authorities have mandated the implementation of these capabilities and checklist procedures.

In this occurrence, the crew's routine monitoring did not detect that a fuel leak was occurring until over 6 tons of fuel had been lost. Also, the low-level nature of the Fuel ADV, on its own, did neither clearly indicate the cause of the imbalance nor the severity of the situation that existed.

Although the Airbus A-330 Flight Warning Computer has a FUEL FU/FOB DISCREPANCY Caution alert capability, the implementation of this system capability has neither been mandated for all Airbus A-330 aircraft nor for other Airbus aircraft of similar fuel system design.

Therefore, it is recommended that Direction Genérale de l'Aviation Civile of France:

- *Mandate the implementation of the FUEL FU/FOB DISCREPANCY Caution alert for all A-330 aircraft; and*
- *Mandate the incorporation of a fuel loss alert for other Airbus aircraft with similar fuel system design.*

SAFETY RECOMMENDATION AA/2004

It is also recommended that the civil aviation authorities of other transport aircraft categories manufacturing states, such as Canada, United States of America, and United Kingdom, as well as the European Aviation Safety Authority:

- *Review the adequacy of aircraft indications and warning systems and procedures to detect fuel-used/fuel-loss discrepancy situations;*
- *Review the capability of these systems to provide clear indications as to the causes of these situations; and*
- *Review the capability of these systems to provide alerts at a level commensurate with the criticality of a fuel-loss situation.*

SAFETY RECOMMENDATION AB/2004

4.2.2 Fuel Leak Training

Training is the fundamental approach to ensuring that crews remember/recall, and can easily assimilate symptoms with a required procedure. Training also ensures more accurate completion of the procedure designed to mitigate a given situation, in particular for a rare event, or for situations of high workload and stressful situations.

As a result of previous similar occurrences, fuel leak checklists had been created or improved, and some limited documentation had been added to flight manuals regarding the criteria to be used to determine if a fuel leak exists. Notwithstanding, prior to this occurrence, no or very little training was provided to crews on fuel leak situations. This deficiency is not unique to this A330 operator or to other Airbus operators having similar fuel and flight management systems. For this particular occurrence, had the flight crew members been trained in the symptoms of fuel leak situations and strategies to identify and counter such a situation, they would have been better prepared to take appropriate actions.

Although since this occurrence, some civil aviation authorities and aircraft manufacturers have taken action to improve related checklists and to improve crew awareness of the critical nature of fuel leaks, there are a number of commercial aircraft that do not have identification procedures or fuel leak checklists. There are also no specific regulatory requirements for training on fuel leak scenarios.

The historical occurrence records indicate that, although in-flight fuel leaks are infrequent events, these events continue to occur. The dissemination of information related to this occurrence will enhance safety by increasing crew awareness of the fuel leaks in the short term. Notwithstanding, ensuring safety in the longer term will require other sustained action to ensure that crews are better prepared for these events.

Therefore, its is recommended that Direction Genérale de l'Aviation Civile of France, Transport Canada, Civil Aviation Authority of the United Kingdom, the Joint Aviation Authority, European Aviation Safety Authority, and the civil aviation authorities of other states:

- *Review flight crew operating manuals and checklist procedures to ensure that they contain adequate information related to fuel leak situations;*
- *Review flight crew training programs to ensure that they adequately prepare crews to diagnose and take appropriate actions to mitigate the consequences of fuel leak events; and*
- *Amend regulations and standards to require crew training on fuel leak events.*

SAFETY RECOMMENDATION AC/2004

It is also recommended that, as an interim safety measure, all civil aviation authorities:

- *Promulgate the circumstances of this fuel leak event to all air operators, aircraft manufacturers and flight crew training organizations.*

SAFETY RECOMMENDATION AD/2004

4.2.3 Automated Fuel Transfers

As evidenced in this occurrence, the automated transfer of fuel from the trim tank to the right wing tank and subsequently to the leak in the right engine resulted in over 3.2 tons of fuel being lost. Although the trim tank transfer memos were displayed to the crew, these memos did not reflect the seriousness of the abnormal transfer of a significant amount of fuel to only the set of wing tanks on one side of the aircraft. This transfer also contributed to masking the fuel leak problem from the crew.

Therefore, it is recommended that Direction Genérale de l'Aviation Civile of France, in consultation with Airbus:

- *Review the automated, fuel-transfer systems on Airbus aircraft to ensure that the systems are able to detect abnormal fuel transfers, that systems exist and procedures are in place to inhibit abnormal transfers, and that the crews are notified, at an appropriate warning level, of abnormal fuel transfers.*

SAFETY RECOMMENDATION AE/2004

4.2.4 Significant Fuel Imbalances

As evidenced in this and many other occurrences, significant fuel imbalances between wing tanks would most likely occur if there were a significant fuel leak. It is also apparent that, in such situations, directing crews using a FUEL ADV and the information on the Fuel page to a FUEL IMBALANCE checklist may not provide a definitive indication that a serious fuel leak could exist. Not immediately focussing crews to the probable existence of a fuel leak and to the indications that could be used to interpret the source of the leak has the potential to delay the critical actions required to mitigate the consequences of a fuel leak.

Therefore, it is recommended that Direction Genérale de l'Aviation Civile of France and EASA:

- *Review Airbus aircraft indication and warning systems and abnormal procedures to ensure that, in situations of major fuel imbalances, actioning of appropriate fuel leak procedures becomes a priority for flight crews; and*
- *Consider merging the Airbus FUEL IMBALANCE and FUEL LEAK checklist procedures into one procedure, containing, at the top of the procedure, the conditions that would suggest the presence of a fuel leak.*

SAFETY RECOMMENDATION AF/2004

It is also recommended that the civil aviation authorities of other aircraft manufacturing states, such as Canada, United States of America, and United Kingdom, as well as the European Aviation Safety Authority:

- *Review the adequacy of the fuel indications and warning systems, as well as procedures associated with fuel imbalance situations to ensure that the possibility of a fuel leak is adequately considered.*

SAFETY RECOMMENDATION AG/2004

4.2.5 Safeguarding Recorders

As evidenced in this occurrence, although the crew was aware of the requirement to safeguard the on-board recordings before powering up the aircraft, 90 minutes of the CVR recording was overwritten. In fact, the lack of documentation readily available to the crew regarding the deactivation of the flight recorders lead to the inadvertent disabling of the recorder overwriting protection feature installed on the aircraft. The historical record indicates that there have been many occasions when CVR recordings have been lost due to not disabling power to CVR's.

Although Canadian Commercial Air Service Standards and the Transport Canada approved Air Transat Operations Manual state that there is a requirement to preserve recordings following an occurrence, there was no specific information, diagrams or procedures readily available to the crew as to how the preservation was to be accomplished.

Although NTSB Recommendation A-02-24 "Overwritten Cockpit Voice Recordings", issued on August 29, 2002, recommended that improved information and checklists be available to crews to preserve recordings, actioning of the recommendation by the Federal Aviation Administration would only affect air operators certified to conduct operations in the United States of America.

Therefore, it is recommended that Transport Canada and Direction Genérale de l'Aviation Civile of France and EASA:

- *Review the adequacy of applicable regulations, standards and aircraft manuals to ensure that necessary information and guidance is made available to the crews to properly safeguard on-board recordings following an occurrence.*

SAFETY RECOMMENDATION AH/2004

It is also recommended that the civil aviation authorities of other states, as well as the European Aviation Safety Authority:

- *Review the adequacy of their regulations related to the safeguarding of on-board aircraft recordings.*

SAFETY RECOMMENDATION AI/2004

4.2.6 Recorder Power Sources

Although the loss of flight recorder information for the last 19 minutes of the engines-out descent and landing on this occurrence did not adversely affect the investigation to this occurrence, had the circumstances been different, the lack of data following the power loss on both engines could have severely affected the ability of the investigation to make findings as to the causes and contributing factors to this occurrence.

Although previous recommendations have been issued by aviation safety investigation authorities, and these recommendations are being considered by individual civil aviation authorities and international standards organizations, the Gabinete de Prevenção e Investigação de Acidentes com Aeronaves (GPIAA), the accident investigation authority of Portugal, remains concerned regarding this deficiency.

Therefore, it is recommended that the European Organization for Civil Aviation Equipment, ICAO, all civil aviation authorities and safety investigation authorities:

- *Take into account the circumstances of this particular occurrence in their deliberations on the requirements for independent power supplies for on-board aircraft recordings.*

SAFETY RECOMMENDATION AJ/2004

4.2.7 Major Component Change Planning

Current regulations and industry standards do not mandate that the configuration of major components, such as an engine, be determined prior to the components being installed on the aircraft. In particular, the current method used for assigning a part number to an engine results in a part number that does not reflect which service bulletins have and which service bulletins have not been embodied. The overall number of involved service bulletins complicates the task of determining parity between similar major components. Because there is not a requirement for a major component-change planning process, nor a requirement to determine the precise configuration of the component during such a process, the responsibility for detecting differences in configuration is deferred to subsequent stages of the maintenance process.

For this occurrence, the differences in configuration between the engine being removed and the engine being installed were not detected prior to the start of the engine change. As a result, determining part parity and ensuring integrity of the installation of the right engine rested solely with the level of the technician responsible for the engine change. Effectively, there was only one defence layer that could ensure the safety of the installation. The integrity of the engine changed hinged on using the Illustrated Parts Catalogue and the referenced service bulletins to verify the compatibility of each part being changed with associated/adjacent lines and components. The incompatibility of the hydraulic pump with the adjacent fuel pipe was eventually detected and lead to reference being made to the catalogue. However, difficulty in accessing the SB's, time pressures, prime focus on completing the installation, and other factors caused this one-level of defence to be ineffective in preventing an improper installation.

Therefore, it is recommended that Transport Canada, and Direction Genérale de l'Aviation Civile of France, and the Civil Aviation Authority of the United Kingdom, as well as the EASA and civil aviation authorities of other states responsible for the manufacture of aircraft and major-components:

- *Review applicable airworthiness regulations and standards, as well as aircraft, engines and component maintenance manuals, to ensure that adequate defences exist in the pre-installation, maintenance planning process to detect major configuration differences and to establish the required support resources for technicians responsible for the work.*

SAFETY RECOMMENDATION AK/2004

It is also recommended that Transport Canada, Direction Genérale de l'Aviation Civile of France, and the Civil Aviation Authority of the United Kingdom, as well as the European Aviation Safety Authority and civil aviation authorities of other states, in conjunction with aircraft and major component manufacturers:

- *Review the adequacy of the current standards for identifying the configuration and modification status of major components to ensure that differences between major components of similar part numbers can be easily identified.*

SAFETY RECOMMENDATION AL/2004

Lisbon, 17 September 2004

Frederico J F Serra
The Investigator in Charge
GPIAA- Portuguese Aviation Accidents Investigation Department

Jnw

Appendix A – Calculation of Cabin Pressure Altitudes

The following table depicts the cabin altitude profile as derived from the following:

- Times and reported altitudes contained in the ATS transcript, and
- Manufacturer's data on the maximum admissible production aircraft leakage[43]:

Time (UTC)	Event	Distance to Lajes	Aircraft Altitude	Cabin Altitude	Cabin Leak Rate
06:13:25	Right Engine Flame-out				
06:26:16	Engine 1 Stall	65	FL345	5 700	630 ft/min
06:26:34	On Emergency Power Source	61			
06:31:38	Initial Contact with Lajes App.	33	FL270		
06:34:11	Radar Distance Report	23			
06:35:33	Crew Altitude Report		FL230	11 900[44]	700 ft/min
06:36:17	Runway lights reported in sight	14			
06:37:16	Radar Distance Report	11			
06:37:33[45]	Crew Altitude Report	10	FL185	13 300[46]	
06:37:50[47]	Oxygen Mask Deployment		17 200[48]	13 500	
06:38:45	Crew Altitude Report	8	13 000	13 000[49]	
06:40:10	Radar Distance Report	10			
06:40:44	Radar Distance Report	12	9 000		
06:41:55	Radar Distance Report	9	8 000		
06:42:38	Radar Distance Report	7			
06:43:28	Landing gear confirmed down				
06:43:37	Radar Distance Report	3			
06:45	Aircraft Landed				

[43] The cabin leakage rates versus aircraft cruise altitude are based an assumption of maximum admissible production aircraft leakage. The realistic leakage in production is on average approximately 25-30% less than the maximum value. The leakage rate will increase depending on aircraft age and maintenance quality. The values are only valid for the moment where the double pack shut down takes place. The leakage rate decreases constantly afterwards as the cabin depressurizes.

[44] Cabin altitude based on the average 665 ft/min leak rate and 9.3 minutes between these events.

[45] Time estimated based on the start of the communications at 0617:16 and time estimated for the communications that took place.

[46] Cabin altitude based on the average 700 ft/min leak rate for 2 minutes. This is the worst-case scenario. The leak rate would have been lower given that the cabin altitude at the aircraft altitude of FL 250 was most likely above the scheduled cabin altitude of 3000 feet.

[47] Time estimated using the 700 ft/min leak rate to reach a cabin altitude of 13 500 feet, which is the lowest cabin altitude (14 000 –500/+0 feet) that an oxygen mask deployment should have occurred.

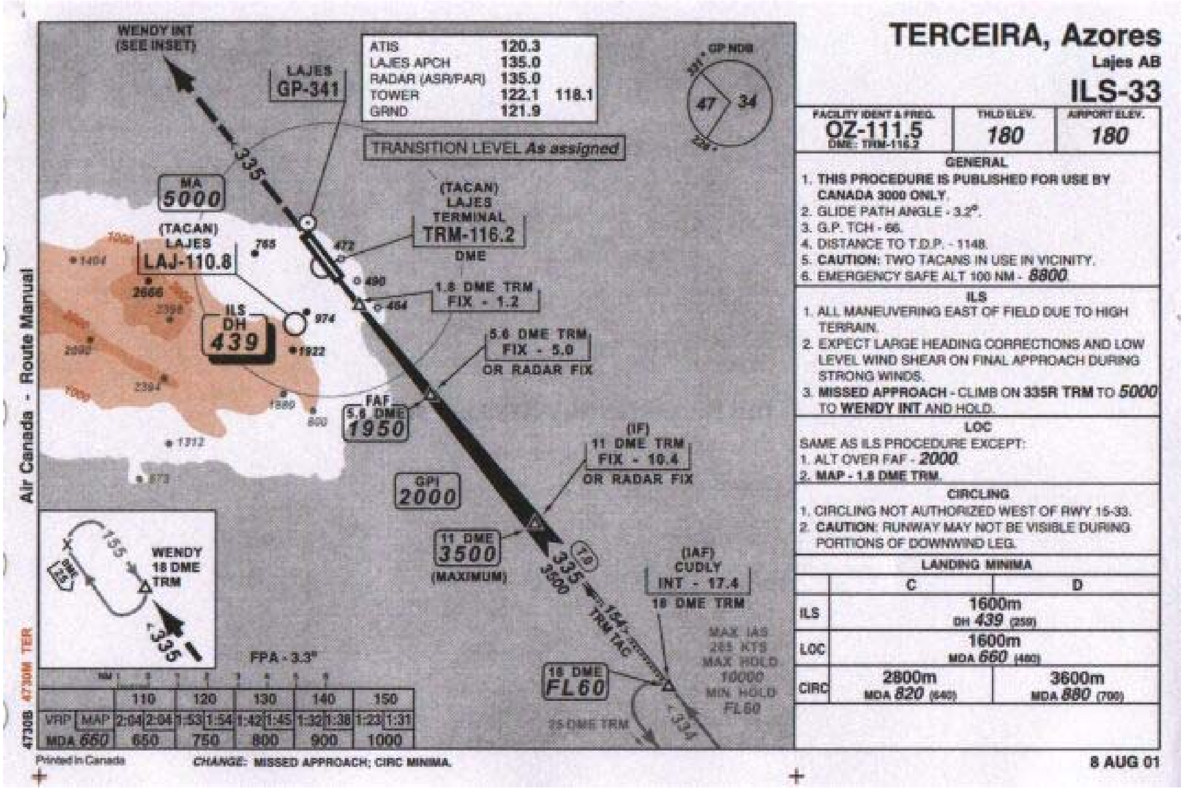
[48] Calculated based on the average rate of decent between FL 185 and 13 000 feet.

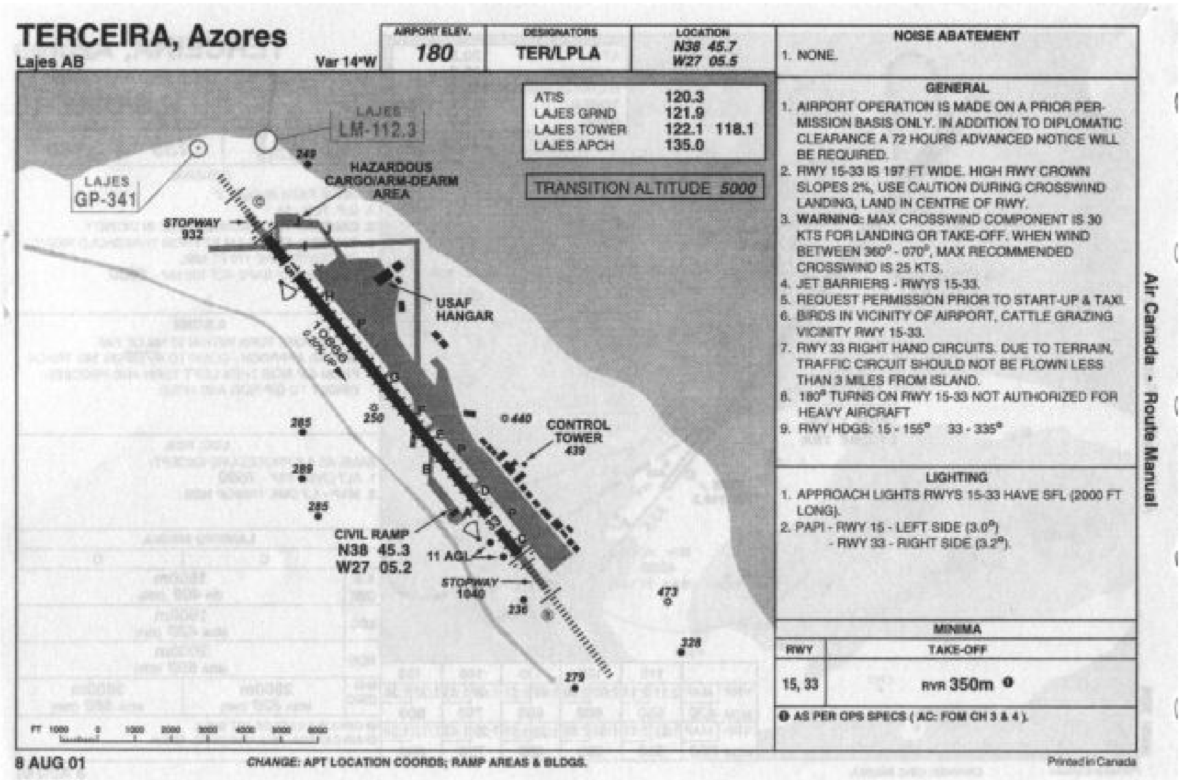
[49] The worst case scenario based on the knowledge that the O_2 masks did deploy.

Appendix B – Overview of Cockpit Activity Level

Time	Events	Comments
04:38	Fuel Leak Starts	No noteworthy indications of a fuel loss during this period Routine ATC communications Routine recording of flight information Flight progress review of system indications
04:57	Passing 30 West	
05:03	Selection of Engine Page	
05:04	First 2+45 min HF with MCC	Unusual oil readings noticed
05:07	End of First HF conversation	Very little definitive information about this time frame is available except for the fact that the crew said they were busy examining information on the displays and looking into manuals for answers to the oil indications
05:33	Fuel advisory Annunciated	
05:34	Fuel Page Selected	Recognition of the ADV and shift of concentration to the fuel problems
05:36	Start of Crossfeed Left to Right	Viewing of fuel displays to determine that a fuel imbalance was the reason for the ADV.
05:45	Initial diversion to Lajes	Crew diverts, modifies flight plan & navigation aids FD advises on special passenger requirements for Lisbon Crew advise FD of the diversion
05:48	Notification to ATC of diversion	
05:50	FD to Flight deck	FD advised of fuel problem and asked to do an inspection
05:54	Change of Crossfeed Right to Left	Action initiated to use up fuel in the right tanks
05:56	Second 5+27 HF with MCC	Crew advises MCC on low fuel quantity readings
05:59	Start of CVR Recording	FD returns to flight deck and waits
06:02	End of Second HF conversations	
06:02	Momentary selection of crossfeed from the left tank	Action precipitated by comments from MCC
06:02	FD in flight deck for 52 seconds	FD Reports on results of the visual inspection FD told to prepare the cabin for ditching
06:03	ATC HF Communications for 90 seconds	ATC passing weather reports Assignment of a VHF frequency ATC provides runway information Crew passes number of persons on board
06:05	Third 56-second HF conversation with MCC	MCC Request for MCDU data Crew advises estimate of 1 ton of fuel at Terceira
06:09	ATC initiated call 2.5 min sec	ATC Requests for information on problem and aircraft fuel and passenger information
06:10	Crossfeed closed	
06:13	FD returns to get further instructions	FD Told to do all further passenger briefings
06:13	Right engine flameout	Checklist procedure carried out Notification of ATC 26 seconds
06:20	Fourth 0+41 HF with MCC	Crew notification to MCC of right engine flameout
06:26	Left engine flameout	Checklist procedure started
06:27	Selection of Emergency Power	End of recordings

Appendix C – Terceira, Azores (Lajes AB) Charts





Appendix D – Calculations of Fuel Distribution

Time	Left tank	Trim tank	Right tank	Total FOB	Events
04:38	10 100	3 500	10 100	23 700	Start of Fuel Leak
04:57	9 264	3 200	8 936	21 400	Fifth forward transfer start
05:11:30	8 750	3 135	6 750	18 600	Final Forward transfer start
05:31:00	8 000	0.0	5 000	13 000	Forward transfer complete
05:36:30	7 750	0.0	3 650	11 400	Crossfeed open

Time UTC	FOB			Rate of fuel decrement Kg/hr		Warning	X-feed position and comments
	Left tank	Right tank	Total FOB	Left	Right		
05:36:28	7 750	3 650	11 400	18.9 t/hr	0 t/hr	Fuel right +Fuel right stby+ fuel wing pump LO pressure (From PFR)	PFR suggest that X-Feed is in the Open position and X-Feeding from left to right. Also supported by crew statement.
05:49:30	3 650	3 650	7 300[50]				Momentary fuel balance achieved.
05:54:34	3 200[51]	2 600	5 800	0.0 t/hr	20.0 t/hr	Fuel left wing pumps LO pressure	PFR support that X-Feed is in the Open position and X-Feeding from right to left
05:57:00	3 200	1 600	4 800			Right wing tank LO level	1 600 kg is based on the fact that the low-level warning is displayed within 60 seconds after the fuel quantity falls below 1 640 kg
05:59:24	3 200[2]	1 000[2]	4 200[2]	10.4 t/hr	4.3 t/hr		Crew reported that X-feed from left momentarily during this timeframe. From this time onward, the positions of fuel tank pump switches uncertain.
06:04:00			2 800[52]				
06:08:34	1 600	350	1 950	12.7 t/hr	4.7 t/hr	L+R tank LO level	1 600 kg is based on the fact that the low-level warning is displayed within 60 seconds after the fuel quantity falls below 1 640 kg
06:10:03			1 300[53]				All fuel switches reportedly selected ON.
06:13:07	650	0.0	650	3.0 t/hr		Eng 2 fail	
06:26:19			0.0			Eng 1 fail	

[50] Fuel balance was calculated based on the assumptions that the cross-feed valve is open, left wing tank pumps are ON and right wing tanks are OFF.

[51] This quantity is supported by the facts that the crew was crossfeeding from right to left between time 0554Z and time 0559Z, and that on the CVR, at 0559Z, the crew reported the quantities as being 3 200, 1 000, and 4 200 kg.

[52] This quantity is supported by the fact that on the CVR at 06:04Z, the crew reported the total fuel quantity as being 2 800 kg

[53] This quantity is supported by the fact that on the CVR at 06:10Z, the crew reported the total fuel quantity as being 1 300 kg

Appendix E - Glossary

AAIB	Aircraft Accidents Investigation Branch - UK
AD	Airworthiness Directive
ADF	Automatic Direction Finder
ADV	ECAM Advisory message
AFD	Assistant Flight Director of cabin services
agl	above ground level
AMO	Approved Maintenance Organization
AOC	Air Operator Certificate
asl	above sea level
APU	Auxiliary power unit
ATA	Air Transportation Association
ATC	air traffic control
ATPL	Airline Transport Pilot Licence
ATS	Air Traffic Services
BEA	Bureau d'Enquêtes et d'Analyses pour la Sécurité de l'Aviation Civile - France
C of A	Certificate of Airworthiness
C of G	centre of gravity
CAR's	Canadian Aviation Regulations
CASS	Commercial Air Service Standards of Canada
CFR	Crash Fire Rescue
CMC	Central Maintenance Computer
CMS	Central Maintenance System
CVR	digital cockpit voice recorder
CYYZ	Toronto Lester B Pearson Airport, Ontario, Canada
DAR	Digital Access Recorder
DFDR	Digital Flight Data Recorder
DGAC	Direction Générale de l'Aviation Civile of France
DME	Distance Measuring Equipment
ECAM	Electronic Centralized Aircraft Monitoring System
EFOB	Estimated Fuel On-Board at destination
EIPC	Rolls-Royce Engine Illustrated Parts Catalogue

ETOPS	Extended Twin-engine Operations
EW/D	Engine Warning Display
FAA	Federal Aviation Administration of the United States of America
FCMC	Fuel Control and Management Computer
FCSC	Flight Control Secondary Computer
FCOM	Flight Crew Operating Manual
FCPC	Flight Control Primary Computer
FD	Flight Director of cabin services
FIR	flight information region
FL	Flight Level
FMGC	Flight Management Guidance Computer
FOB	Fuel on board
fpm	feet per minute
HAESL	Hong Kong Aero Engine Services Limited
HF	High-frequency radio
hr	hour(s)
GPIAA	Gabinete de Prevenção e Investigação de Acidentes de Portugal
IFR	Instrument Flight Rules
ILS	Instrument Landing System
IPC	Illustrated Parts Catalogue
kg	kilogram(s)
LPLA	Lajes Airport (LPLA), Terceira Island, Azores, Portugal
LPPT	Lisbon Airport, Portugal
MCC	Maintenance Control Centre
MCDU	Multi Purpose Control and Display Unit
MCM	Maintenance Control Manual
MFOM	Minimum fuel on board
NDB	Non-Directional Beacon
nm	nautical miles
NOTAM	Notice to Airmen
NTSB	National Transportation Safety Board of United States of America
psi	pounds per square inch
P/N	Part Number
QC	Quality Control
QRH	Quick Reference Checklist

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RAT	Ram Air Turbine
SAT	Static air temperature
SD	System Display
SELCAL	selective calling system
S/N	Serial Number
SOC	Security Operations Centre
SOPs	Standard Operating Procedures
TAS	true airspeed
TAT	Total air temperature
TC	Transport Canada
TCA	Terminal Control Area
THS	Trimmable Horizontal Stabilizer
TSB	Transportation Safety Board of Canada
TTF	Trim tank fuel
UTC	Coordinated Universal Time
VHF	very high frequency
VOR	very high frequency omni-directional range
Z	Zulu (Coordinated Universal) Time