



*Accident
on 25 July 2000
at La Patte d'Oie
in Gonesse (95)
to the Concorde
registered F-BTSC
operated by Air France*

REPORT translation
f-sc000725a

FOREWORD

This report presents the technical conclusions reached by the BEA on the circumstances and causes of this accident.

In accordance with Annex 13 of the Convention on International Civil Aviation, with EC directive 94/56 and with Law No 99-243 of 29 March 1999, the analysis of the accident and the conclusions and safety recommendations contained in this report are intended neither to apportion blame, nor to assess individual or collective responsibility. The sole objective is to draw lessons from this occurrence which may help to prevent future accidents or incidents.

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SPECIAL FOREWORD TO ENGLISH EDITION

This report has been translated and published by the Bureau Enquêtes-Accidents to make its reading easier for English-speaking people. As accurate as the translation may be, the original text in French is the work of reference.

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Glossary

AAIB	Air Accidents Investigation Branch
AD	Airworthiness Directive
ADF	Automatic Direction Finder
ADI	Attitude Director Indicator
ADP	Aéroports de Paris (Paris Airports Authority)
AJ	Adjustable Jet
AMM	Aircraft Maintenance Manual
AOA	Angle Of Attack
ARM	Airworthiness Review Meeting
ASDA	Accelerate Stop Distance Available
ATIS	Automatic Terminal Information Service
BAE	British Aerospace
BRS	Baggage Reconciliation System
CAA	Civil Aviation Authority (UK)
CAM	Cockpit Area Microphone
CAS	Computed Airspeed
CC	Cabin Crew
CEAT	Centre d'Essais Aéronautiques de Toulouse (Toulouse aeronautical test centre)
CG	Centre of Gravity
CMB	Climb
CPEMPN	Principal flight crew medical test centre
CRM	Cockpit Ressource Management
CRZ	Cruise
Cu	Cumulus
CVR	Cockpit Voice Recorder
EADS	European Aeronautic Defence and Space
EGT	Exhaust Gas Temperature
EIC	Equipment in Compartment
FC	Flight Crew
FD	Flight Director
FDAU	Flight Data Acquisition Unit
FDR	Flight Data Recorder
FE	Flight Engineer
FF	Fuel Flow
FO	First Officer
FOD	Foreign Object Damage
FQIP	Fuel Quantity Indicator Panel

ft	Feet
GAETAN	Passenger baggage registration system used by Air France
GEAS	General Electric Aircraft Engine Services
GPWS	Ground Proximity Warning System
HP	High Pressure
hPa	Hectopascal
HSI	Horizontal Situation Indicator
ICAO	International Civil Aviation Organization
IDG	Integrated Drive Generator
IFR	Instrument Flight Rules
INS	Inertial Navigation System
kt	Knots
kW	Kilowatts
LDA	Landing Distance Available
LOC	Tower frequency controller's position
LP	Low Pressure
METAR	Meteorological Aviation Report
MTOW	Maximum Take Off Weight
MWS	Master Warning System
N1	Low pressure turbine rotation speed
N2	High pressure turbine rotation speed
NOTAM	Notice to Airmen
Nx	Longitudinal acceleration (in g)
P/N	Part Number
P7	Jet exhaust pressure
PF	Pilot Flying
PFCU	Power Flight Control Unit
PI	Pilot Instructor
PNF	Pilot Not Flying
Psi	Pounds per Square Inch
QAR	Quick Access Recorder
QFU	Runway orientation
QNH	Altimeter setting to obtain aerodrome elevation when on the ground
QTP	Qualification Test Programme
RFFS	Rescue and Fire Fighting Service
RT	Radio Transmission
SAT	Static Air Temperature
Sc	Stratocumulus
SIGMET	Significant Meteorological Message
TAF	Terminal Area Forecast
TCA	Turbine Cooling Air
TCAS	Traffic warning and Collision Avoidance System
TCU	Throttle Control Unit

TEMSI	Significant weather forecast chart
TODA	Take Off runway Distance Available
TOP	Transoceanic and Polar licence
TORA	Take Off Runway length Available
TRE	Type Rating Examiner
UTC	Universal Time Co-ordinated
Vmca	Minimum air control speed
VmCG	Minimum ground control speed
VOR	VHF Omnidirectional Radio Range
VR	Rotation speed
Vz	Vertical speed
Vzrc	Zero rate of climb speed
ZFW	Zero Fuel Weight

SYNOPSIS

Date and time

Tuesday 25 July 2000 at 14 h 44⁽¹⁾

Aircraft

Concorde
registered F-BTSC

Site of accident

La Patte d'Oie in Gonesse (95)

Owner

Air France

Type of flight

Charter flight
Flight AFR 4590

Operator

Air France

Persons on board

Flight Crew: 3
Cabin Crew: 6
Passengers: 100

Summary

During takeoff from runway 26 right at Roissy Charles de Gaulle Airport, shortly before rotation, the front right tyre (tyre No 2) of the left landing gear ran over a strip of metal, which had fallen from another aircraft, and was damaged. Debris was thrown against the wing structure leading to a rupture of tank 5. A major fire, fuelled by the leak, broke out almost immediately under the left wing. Problems appeared shortly afterwards on engine 2 and for a brief period on engine 1. The aircraft took off. The crew shut down engine 2, then only operating at near idle power, following an engine fire alarm. They noticed that the landing gear would not retract. The aircraft flew for around a minute at a speed of 200 kt and at a radio altitude of 200 feet, but was unable to gain height or speed. Engine 1 then lost thrust, the aircraft's angle of attack and bank increased sharply. The thrust on engines 3 and 4 fell suddenly. The aircraft crashed onto a hotel.

Consequences

	People			Equipment
	Killed	Injured	Uninjured	
Crew	9	-	-	Destroyed
Passengers	100	-	-	
Third parties	4	6	-	

¹ Except where otherwise noted, the times shown in this report are expressed in Universal Time Co-ordinated (UTC). Two hours should be added to obtain the legal time applicable in metropolitan France on the day of the accident.

ORGANISATION OF THE INVESTIGATION

On Tuesday 25 July 2000 at around 14 h 50 UTC, the BEA was informed of the accident to a Concorde in the commune of Gonesse (95) after takeoff from Paris Charles de Gaulle. In accordance with the law of 29 March 1999 relating to technical investigation of accidents and incidents in civil aviation, a technical investigation was launched. A Principal Investigator was nominated as Investigator-in-Charge.

In accordance with the provisions of Annex 13 to the Convention on International Civil Aviation, a British accredited representative and two investigators, accompanied by several experts from BAE SYSTEMS and Rolls Royce, joined the investigation as representatives of the State of Manufacture, along with German (BFU) and American (NTSB and FAA) observers. The NTSB observer was subsequently nominated as Accredited Representative. Air France, EADS and SNECMA made numerous experts available to the BEA.

On July 26, the Minister of Equipment, Transport and Housing established a Commission of Inquiry, in accordance with the law of 29 March 1999. This Commission has assisted the BEA in its work. Eleven meetings were held in the course of which the Commission was informed of the progress of the investigation, then discussed and approved the reports. Several of its members participated in the work of the BEA.

All of the operations which were undertaken at the accident site or on the various parts of the aircraft were performed in coordination with those responsible for the judicial inquiry, strictly adhering to the procedures of that inquiry. The accident site and the various parts of the aircraft were constantly under the control of the judicial authorities.

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The day after the accident, the Investigator-in-Charge established seven working groups to find and collate the information necessary for the investigation. The groups worked in the following specific areas:

- site and wreckage
- aircraft, systems and engines
- preparation and conduct of the flight, personnel information
- flight recorders
- aircraft performance
- witness testimony
- examination of previous events

On 16 August, on the basis of the findings of the investigation, the BEA and its British counterpart the AAIB issued an initial safety recommendation.

A preliminary report was published on 31 August 2000

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After the publication of the preliminary report, the investigation continued as before in close association with foreign air accident investigation organizations and the companies involved and in coordination with those responsible for the judicial investigation.

Four working groups replaced those in the initial organisation:

- wreckage,
- conduct of flight and aircraft performance,
- previous events, certification and regulations,
- technical research.

Work on the wreckage continued, in particular on the left side (dry bay, wing, landing gear well), where the wreckage collected was examined and repositioned somewhat tardily due, amongst other things, to the presence of asbestos.

French and American investigators were able to inspect the aircraft which had lost the metallic strip which has caused the cut in the Concorde tyre. They held a working meeting with the representatives of Continental Airlines at the headquarters of the NTSB in Washington.

Examination of the engines, the Flight Engineer's instrument panel, tyre debris, parts of tank No 5 and the landing gear took place within the context of the judicial inquiry and were subject to the constraints of that procedure. The BEA was a participant at these investigations.

Various tests and additional studies were carried out in France, in the United Kingdom and in the United States of America.

Two interim reports were published, on 15 December 2000 and 10 July 2001.

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In accordance with Annex 13, a draft version of the present report was sent out for consultation to the AAIB, the NTSB and the BFU. Several meetings were held with the AAIB. Those observations which could not be taken into account in the report, in particular those which relate to the investigative procedure itself, are appended to the present report.

1 - FACTUAL INFORMATION

1.1 History of the Flight

On Tuesday 25 July 2000 the Concorde registered F-BTSC, operated by Air France, took off from Paris Charles de Gaulle to undertake charter flight AFR 4590 to New York with nine crew members (3 FC, 6 CC) and one hundred passengers on board. The Captain was Pilot Flying (PF), the First Officer was Pilot Not Flying (PNF).

The total weights of the aircraft and of the fuel on board stated by the Flight Engineer (FE) at the time the aircraft started out were 186.9 t and 95 t respectively. The speeds selected by the crew were V1: 150 kt, VR: 198 kt, V2: 220 kt.

At 13 h 58 min 27 s, the crew contacted ATC on the Flight data frequency and requested the whole length of runway 26 right for a takeoff at 14 h 30.

At 14 h 07 min 22 s, the controller gave start-up clearance and confirmed runway 26 right for takeoff.

At 14 h 34 min 38 s, the Ground controller cleared the aircraft to taxi towards the runway 26 right holding point via the Romeo taxiway.

At 14 h 40 min 02 s, the Loc Sud controller cleared 4590 to line up. At 14 h 42 min 17 s, he gave it takeoff clearance, and announced a wind from 090° at 8kt. The crew read back the takeoff clearance. The FE stated that the aircraft had used eight hundred kilos of fuel during taxiing.

At 14 h 42 min 31 s, the PF commenced takeoff. At 14 h 42 min 54.6 s, the PNF called one hundred knots, then V1 nine seconds later.

A few seconds after that, tyre No 2 (right front) on the left main landing gear was destroyed after having run over a piece of metal lost by an aircraft that had taken off five minutes before. The destruction of the tyre in all probability resulted in large pieces of rubber being thrown against the underside of the left wing and the rupture of a part of tank 5. A severe fire broke out under the left wing and around the same time engines 1 and 2 suffered a loss of thrust, severe for engine 2, slight for engine 1.

By 14 h 43 min 13 s, as the PF commenced the rotation, the controller informed the crew the presence of flames behind the aircraft. The PNF acknowledged this transmission and the FE announced the failure of engine 2. The recorded parameters show a transient loss of power on engine 1 that was not mentioned by the crew. At around 14 h 43 min 22 s the engine fire alarm sounded and the FE announced "shut down engine 2" then the Captain called for the "engine fire" procedure. A few seconds later, the engine 2 fire handle was pulled and the fire alarm stopped. The PNF drew the PF's attention to the airspeed, which was 200 kt.

At 14 h 43 min 30 s, the PF called for landing gear retraction. The controller confirmed the presence of large flames behind the aircraft.

At 14 h 43 min 42 s the engine fire alarm sounded again for around 12 seconds. It sounded for the third time at about 14 h 43 58 s and continued until the end of the flight.

At 14 h 43 min 56 s, the PNF commented that the landing gear had not retracted and made several callouts in relation to the airspeed.

At 14 h 43 min 59 s, the GPWS alarm sounded several times. The FO informed ATC that they were trying for Le Bourget aerodrome. The recorded parameters then indicate a loss of power on engine 1. A few seconds later, the aircraft crashed onto a hotel at “La Patte d’Oie” in Gonesse at the intersection of the N17 and D902 roads.

1.2 Injuries to Persons

Injuries	Crew Members	Passengers	Others
Fatal	9	100	4
Serious	0	0	0
Slight/None	0	0	6

1.3 Damage to Aircraft

The aircraft was completely destroyed on impact.

1.4 Other Damage

The hotel that the aircraft crashed onto was completely destroyed.

1.5 Personnel Information

1.5.1 Flight Crew

1.5.1.1 Captain

Male, 54 years old

- Commercial pilot’s licence No 193067 issued 12 July 1967
- First class Commercial pilot’s licence No 208369 issued on 8 August 1969
- Airline transport pilot’s TOP licence No 195176 issued on 19 February 1976
- Last medical at the CPEMPN (Paris) on 5 May 2000, valid until 5 November 2000
- IFR rating obtained 2 June 1969, valid until 31 August 2000

- B 727 rating on 4 December 1970
- A 300 rating on 24 April 1974
- B 737 rating on 13 December 1977
- Captain on 3 February 1983
- Pilot Instructor from 31 December 1985, valid until 30 June 2001
- A 320 rating on 18 November 1988

- A 340 rating on 27 February 1993
- Concorde rating on 16 August 1999, valid until 31 August 2001
- Pilot's competency check on 9 June 2000, valid until 31 August 2001
- CRM training course on 6 January 1994
- Line check planned for October 2000
- Last C1 base check on 26 January 2000
- Last C2 base check on 12 June 2000

- Total flying hours: 13,477 of which 5,495 as Captain
- Flying hours on Concorde: 317 of which 284 as Captain
- Flying hours in the last six months: 177.91
- Flying hours in the last three months: 95.34
- Flying hours in the last thirty days: 23.86

1.5.1.2 First Officer

Male, 50 years old

- Commercial pilot's licence No 411171 issued on 16 December 1971
- First class commercial pilot's licence No 263672 issued on 9 October 1972
- Airline transport pilot's TOP licence No 232079 issued on 2 February 1979
- Last medical at the CPEMPN (Paris) on 17 January 2000, valid until 17 July 2000

- IFR rating valid until 31 December 2000
- Nord 262 rating on 31 March 1972
- Morane Saulnier 760 rating on 26 March 1972
- Caravelle rating on 1st June 1974
- A 300 rating on 16 November 1979
- Concorde rating on 10 January 1989, valid until 31 December 2000
- Pilot's competency check on 23 (S1) and 24 (S2) November 1999, valid until 31 December 2000
- CRM training course on 9 May 1994
- Line check 1st August 1999, valid until 31 August 2000
- C1 base check on 26 November 1999
- Last C2 base check on 20 April 2000
- Concorde Simulator Flight Instructor from 15 March 1999, valid until 31 March 2000 (Note: since 1997, hours as an instructor are no longer counted at Air France)

- Total flying hours: 10,035 of which 2,698 as FO on Concorde
- Flying hours as instructor: not calculated after 1997 at Air France
- Flying hours in the previous six months: 127.25
- Flying hours in the previous three months: 50.13
- Flying hours in the previous thirty days: 7.64

Note: the Captain's and First Officer's licences are covered by the FCL1 regulations (July 1999), the type rating renewing the licence as long as the medical certificate is valid. For those over 40 years of age, the medical certificate is valid for six months. At the time of the accident, and unlike the previous regulations, its validity ran from a specific date to a specific date rather than to the end of the month. In November 2000, the regulations reverted to end of the month validity.

1.5.1.3 Flight Engineer

Male, 58 years old

- Flight Engineer's Licence No 142568 issued on 22 March 1968, valid until 30 June 2001
- Last medical at the CPEMPN (Paris) on 20 June 2000, valid until 30 June 2001

- Caravelle rating on 8 March 1968
- Falcon 20, rating on 27 March 1968
- B 727 rating on 4 January 1973
- B 737 rating on 28 February 1978
- B 747 rating on 29 May 1980
- B 747-400 rating on 3 November 1990
- Concorde rating on 28 February 1997, valid until 30 June 2001

- Total flying hours: 12,532 of which 937 as FE on Concorde
- Flying hours in the previous six months: 131.64
- Flying hours in the previous three months: 62.19
- Flying hours in the previous thirty days: 23.62

Note: the FE's licence is subject to the former regulations, as defined by the modified Order of 31 January 1981. The licence is valid for one year; the medical check-up is valid from the day of the check-up to the end of the same month the following year. The test and the medical check-up must be carried out in the same month.

1.5.2 Cabin Crew

1.5.2.1 Cabin Services Director

Female, 36 years old

Qualifications:

- Initial training: Safety Certificate on 2 October 1986
- Concorde professional aptitude certificate on 4 May 1992

1.5.2.2 Flight Attendants

Female, 36 years old

Qualifications:

- Initial training: Safety Certificate on 4 March 1991
- Concorde professional aptitude certificate in January 1999

Female, 49 years old

Qualifications:

- Initial training: Safety Certificate on 20 February 1978
- Concorde professional aptitude certificate in July 1990

Female, 27 years old

Qualifications:

- Initial training: Safety Certificate on 2 February 1996

- Concorde professional aptitude certificate in August 1999

Male, 32 years old

Qualifications:

- Initial training: Safety Certificate on 24 February 1993
- Concorde professional aptitude certificate in January 1999

Male, 38 years old

Qualifications:

- Initial training: Safety Certificate on 14 May 1990
- Concorde professional aptitude certificate in June 1997

1.6 Aircraft Information

1.6.1 Airframe

(see three view plan in appendix 1)

1.6.1.1 Information

- Manufacturers⁽²⁾: EADS / BAE SYSTEMS
- Type: Concorde type 1 - version 101
- Serial number: 3
- Registration: F-BTSC
- Entry into airline service on 24 October 1979
- Airworthiness Certificate issued on 23 December 1975, valid until 29 September 2002
- Flying hours up to 25 July 2000: 11,989 hours and 4,873 cycles
- Since type D01 general overhaul on 1st October 1999: 576 hours and 181 cycles.

1.6.1.2 Maintenance

Between 17 and 21 July 2000, the aircraft had undergone a scheduled A01 check in accordance with the approved maintenance programme. During the check, the left main landing gear bogie had been replaced in order to correct an acceptable deferred defect related to the under-inflation detection system.

Since the A check, the aircraft had undertaken four flights, on July 21, 22, 23 and 24. On the 24th, several maintenance operations had been carried out.

² When the aircraft was constructed, these companies were called SNIAS and BAC respectively.

Problems	Maintenance Actions
Slight thrust surges in cruise at mach 2, with illumination of start pump warning light.	Checks on both TCU's, replacement of the N1 limit amplifier, check on the EGT line, ground test OK.
Brake overload warning light illuminated in flight for wheel No 4.	Cable changed.
Slow leak in blue hydraulic system in flight.	Connecting joint on the artificial feel cylinder on the blue hydraulic system replaced.
Tyre on wheel No 5 worn.	Wheel No 5 replaced.

The aircraft was originally planned as a reserve for 25 July, F-BVFA was planned to carry out scheduled flight 002 in the morning and F-BVFC to undertake Flight 4590. For maintenance reasons, there was an allocation change between F-BVFA and F-BVFC. F-BVFA was finally declared unavailable during the night and the reserve aircraft, F-BTSC, was programmed in its place to carry out Flight 4590.

The aircraft was airworthy and there were no acceptable deferred defects for Flight 4590. Prior to the flight, the GARRETT pneumatic motor which activates the engine 2 secondary exhaust nozzle buckets, had been replaced. Tests had been carried out and they revealed no anomalies.

1.6.2 Landing Gear

1.6.2.1 General

The Concorde has a nose gear, an auxiliary gear situated at the rear of the fuselage and two main landing gears, each with a bogie with four wheels. The bogies are equipped with a system that detects under-inflation of a tyre and transmits a visual signal to the cockpit.

This system lights two red TYRE warning lights on each of the pilots' instrument panels and lights a WHEEL warning light on the right pilot instrument panel above the landing gear control lever. An amber TYRE warning light also lights up on the engineer's panel.

This detection system is inhibited when the speed of the front wheels is less than 10 kt or when the steering angle of the wheels is over three degrees and none of the thrust levers is in full forward position. The red TYRE warning lights are inhibited when the indicated airspeed is above 135 kt.

The detection system is self-monitoring. Lighting of a yellow SYSTEM warning light situated on the engineer's panel (next to the amber TYRE lamp) indicates that the self-monitoring mode has detected a fault in the under-pressure detection system.

1.6.2.2 Landing Gear Retraction

Landing gear retraction is electrically controlled by a lever situated on the pilot's instrument panel (three-position lever: up, neutral, down). It is activated by hydraulic pressure from the Green system. There is no emergency system for gear retraction; the Yellow hydraulic system is used for extension, in case of failure of the Green system.

The landing gear control lever can only be moved from the neutral position to the “up” position on condition that electrical power is supplied to it, which requires that the left landing gear shock absorber be uncompressed. The retraction sequence then begins, the “doors” warning lights illuminate and remain lit all the time the doors are opening.

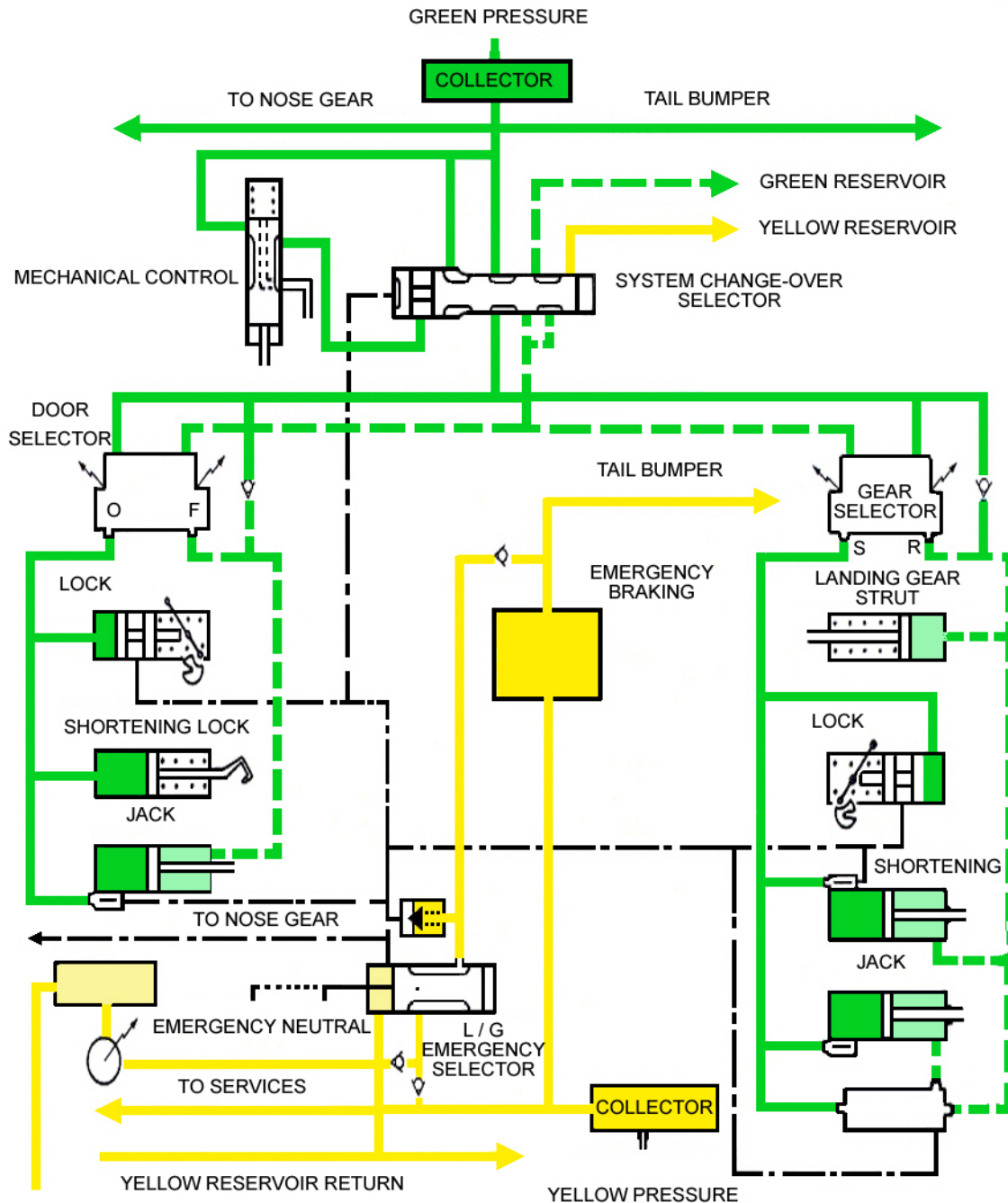


Figure 1: Hydraulic systems for landing gear manoeuvres

The “up” position initiates gear door opening, the doors being kept open by hydraulic pressure throughout the retraction sequence. The wheels are automatically braked.

When all of the doors are seen to be open⁽³⁾, the following conditions are checked:

- perpendicularity of the bogies⁽⁴⁾,
- nose gear centring⁽⁵⁾.

When these conditions are met, the hydraulic pressure is distributed towards the landing gear locks and the retraction jacks⁽⁶⁾ then the landing gear actuating cylinder.

During retraction of the main landing gear, the shock absorbers are retracted into the gear strut to allow it to be stowed in the landing gear well. When the gear is locked in the up position, door closing is ordered.

The gear selector is then placed in “neutral” position to cut off electrical and hydraulic power.

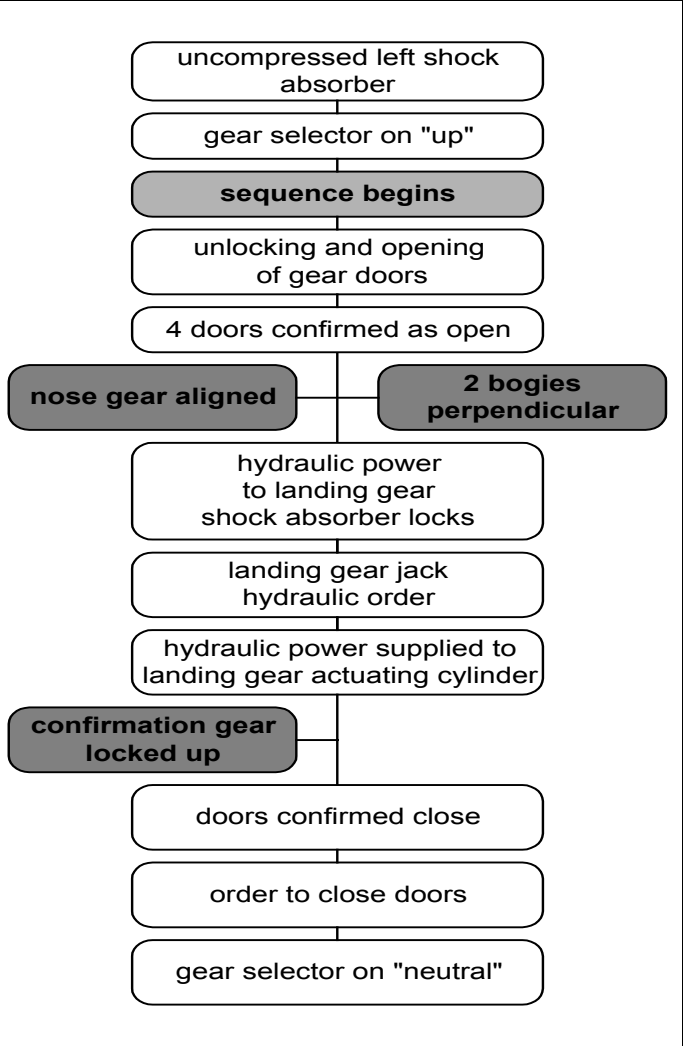


Figure 2: Landing gear retraction sequence

Note: a complete gear retraction sequence lasts, with only one pump, about twelve seconds, divided in the following way: two for door opening, eight for gear retraction, eight for door closing.

³ If one of the “door open” sensors is destroyed, the information transmitted is “the door is not open” and the gear retraction sequence cannot begin.

⁴ The perpendicularity is ensured by two independent pneumatic cylinders filled with nitrogen.

⁵ This centring, which is purely mechanical, is performed by a finger-cam assembly.

⁶ Gear retraction continues even if the retraction jack is defective.

1.6.2.3 Braking

The brakes are manufactured by Dunlop. Braking is electrically controlled and is activated by hydraulic pressure from the Green circuit in normal conditions.

In case of failure in the Green circuit, an automatic switch allows the Yellow circuit to be used. In case of emergency braking, only the Yellow circuit is used in direct hydraulic liaison with the brake pedals.

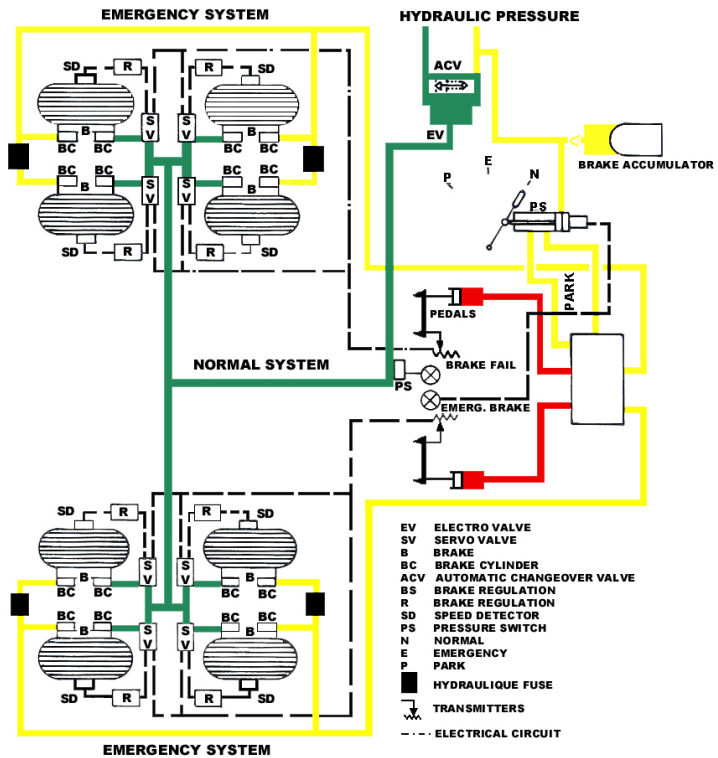


Figure 3: Synoptic diagram of main landing gear braking

1.6.2.4 Deflectors

The deflectors are situated forward of each main landing gear. Their function is to deflect projected water so that it does not enter the engine air intakes. Weighing around four kilos, they are made of composite materials and fibre glass (to make them frangible) except for the bogie fasteners.

In 1995, these deflectors were the subject of an optional Service Bulletin (SST 32-103 of 12/01/95 modified on 28/02/95) which proposed the insertion of two cables in the leading edge in order to retain pieces of the deflectors in case of failure. Air France did not apply the aforementioned Service Bulletin.



Figure 4: Water deflector

1.6.2.5 Wheels and Tyres

The wheels were manufactured by Dunlop, and the tyres used by Air France were manufactured by Goodyear in the United States. No retread tyres have been used since 1996.

On the day of the accident, the main landing gear wheels and tyres on F-BTSC were installed as follows:

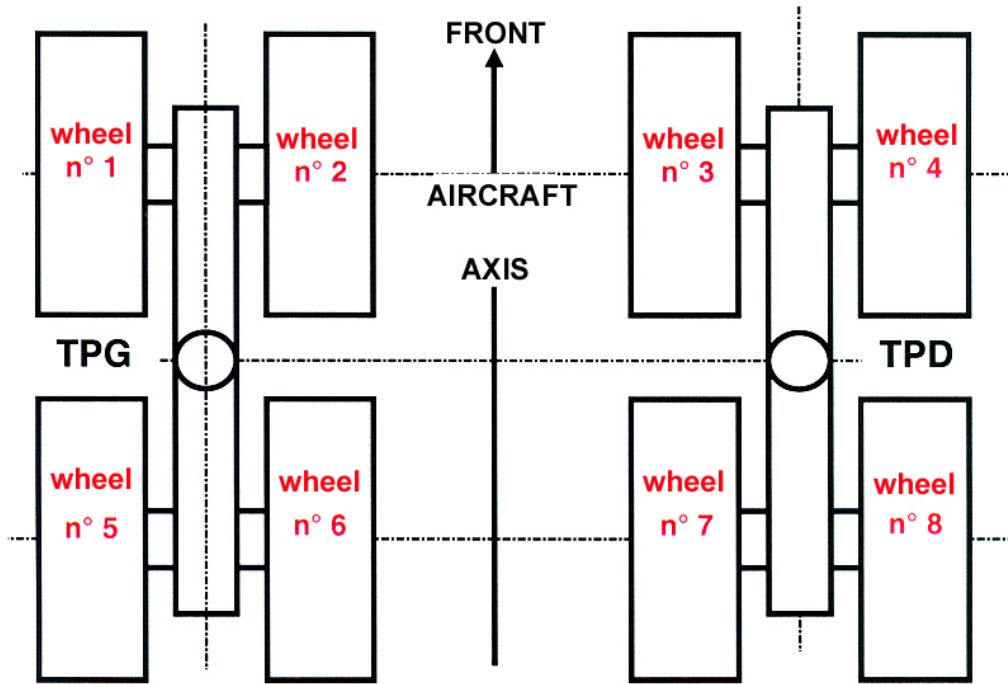


Figure 5: Main gear: view from above

WHEELP/N	WHEEL S/N	Position on aircraft	Workshop issue date	Date installed on aircraft	TYRE S/N	Number of cycles
AHA1216	531	1	09/06/00	10/07/00	91510047	9
AHA1216	579	2	25/05/00	29/05/00	91831651	37
AHA1216	594	3	10/05/00	18/05/00	91801029	45
AHA1216	500	4	17/02/00	22/06/00	91831659	23
AHA1216	446	5	06/07/00	24/07/00	91560078	0
AHA1216	581	6	12/07/00	18/07/00	91570604	4
AHA1216	518	7	22/06/00	24/06/00	91870259	19
AHA1216	591	8	04/07/00	09/07/00	91930448	9

N.B.: notation in bold type refers to left main landing gear.

1.6.3 Fuel

The signal from each fuel gauge is sent simultaneously to the corresponding indicator and to a totaliser. By design, error in measurement of the total fuel quantity must not exceed 5% in extreme flight conditions, and the error in measurement on each of the tanks must not exceed 2%. The quantity of fuel present in a tank is correctly indicated when the reading is greater than zero. In fact, the failure of an electrical connection from a fuel gauge leads to an indication of zero on the corresponding indicator.

Note: a general electrical power cut fixes the last indication supplied by the needles and masks the indications on the rollers with a flag.

The capacity of the thirteen tanks is shown in the table below. These represent maximum capacities, without exceeding the upper level sensors, corresponding to real fill of around 95% (94% for tank 5).

Note: the overfill procedure allowed loading of a maximum of 1,630 litres extra, compared to the quantities mentioned below. This operation can only be performed on the ground.

Function	Number	Capacity (litres)	Quantity (kg) density = 0.792
Engine supply	1	5,300	4,198
	2	5,770	4,570
	3	5,770	4,570
	4	5,300	4,198
Main tanks	5	9,090	7,200
	6	14,630	11,587
	7	9,350	7,405
	8	16,210	12,838
Auxiliary tanks	5A	2,810	2,225
	7A	2,810	2,225
Transfer tanks (CG)	9	14,010	11,096
	10	15,080	11,943
	11	13,150	10,415
Total		119,280	94,470

Before the accident flight, the top up with Jet A1 fuel had been completed at around 13 h 55. An overfill of 300 litres corresponding to a quantity of 237 kg had been added. According to witness statements, this overfill was performed on tanks 1, 2, 3 and 4. The short duration of the wait and the temperature at that moment in time means that it can be considered that there was no significant change in the volume of the fuel before the takeoff. The fuel loader's filling order shows a loaded fuel weight of 94,800 kg.

Note : Conversion from fuel volume to loaded weight depends on a theoretical density. In reality, the density of the fuel can slightly vary from this theoretical value.

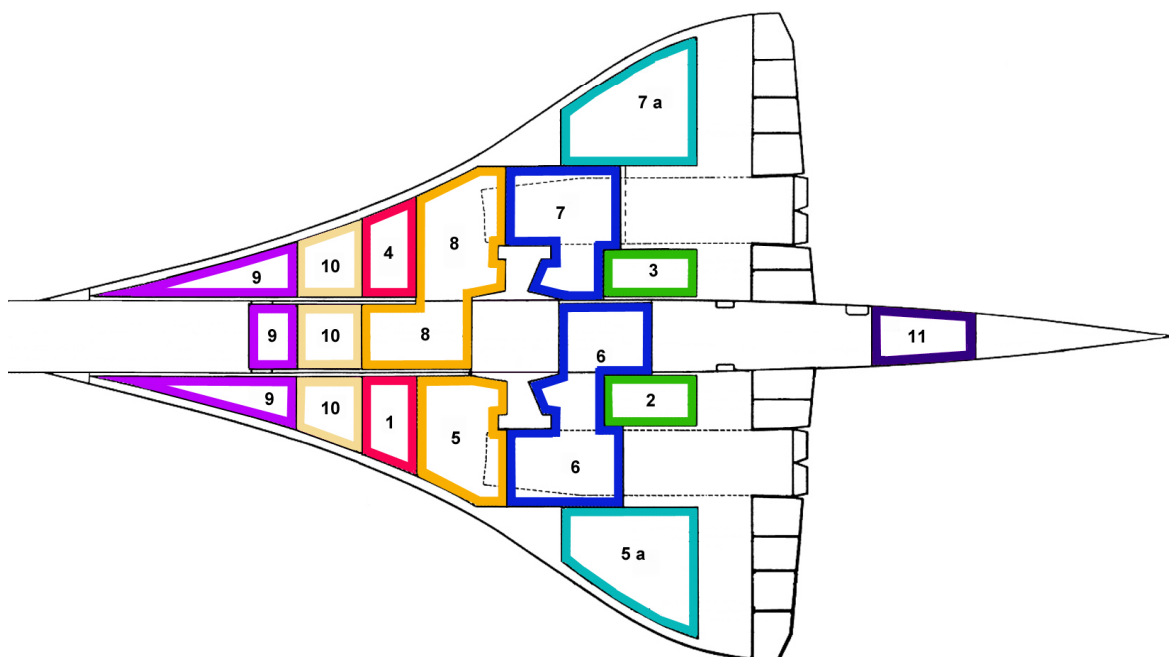


Figure 6: Concorde fuel tanks

1.6.4 Engines

1.6.4.1 General

Power is supplied by four twin spool turbojets installed in pairs, each being equipped with reheat, a variable area air intake and variable primary and secondary exhaust nozzle used to optimise performance. The secondary exhaust nozzle also incorporates the thrust reverser. Reheat provides 18% extra thrust at takeoff. The secondary exhaust nozzle also allows reverse thrust to be provided.

- Manufacturers: Rolls Royce and SNECMA
- Type: Olympus 593 MK 610-14-28

	1	2	3	4
Serial number	CBE031	CBX115	CBE092	CBE051
Installation date	03/02/2000	01/08/1999	14/06/2000	23/08/1999
Total hours	11,200	9,158	8,394	11,670
Hours since installation	342	576	84	576
Cycles since installation	106	181	28	181

Engines 1 and 2 are respectively the outer and inner left engines, engines 3 and 4 the inner and outer right engines.

1.6.4.2 CONTINGENCY Mode

The CONTINGENCY mode can be activated manually or automatically in the case of loss of engine thrust engine on takeoff. Thrust above the maximum takeoff thrust can then be provided by remaining engines. Automatic mode is activated when the following three conditions are met:

- Reheat is activated on any engine,
- The take off monitor is armed,
- N2 on an engine goes below 58.6%.

The power of the other three engines then increases automatically up to a level which may reach around 105% of N2.

1.6.4.3 Reheat Cutout

As soon as an engine's N1 falls below 75%, reheat on that engine is disconnected. Reheat is re-activated when N1 exceeds 81%.

1.6.4.4 Fire Protection

The fire detection system consists of two loops designed so as to detect:

- a fire around the engine
- and/or
- a torching flame fire around the combustion chamber

Each loop includes in series a sensing assembly around the forward part of the reactor, a sensing device around the rear part (these two devices are calibrated for an air temperature above 600 °C) and an intermediate sensing device around the combustion chamber.

The two loops must detect the fault simultaneously⁽⁷⁾ to set off the ENGINE FIRE warning. This results in a red flashing warning light lighting up on the fire handle of the engine in question, accompanied by an aural alarm (chime), then by a gong and the illumination of the corresponding red ENGINE warning light on the Main Warning System.

Actuating the fire handle leads to closure of:

- the air conditioning bleed valve,
- the hydraulic shut-off valves,
- the HP and LP fuel valves,
- the reheat fuel valves,
- the secondary air inlets,
- the auxiliary ground running flap.

⁷ The manufacturer has indicated that the detection time measured during tests was between five and seven seconds against a regulatory requirement of thirty seconds.

The dual head extinguishers are activated by two push buttons (two strikes) located behind each fire handle. Firing one extinguisher leads to the closure of a valve on the cool airflow moving towards the primary and secondary air conditioning exchangers on the engine in question.

Note: the red warning light in the Main Warning System is also associated with alarms for low oil pressure, engine TCA overheat, and detection of liquid in the dry bays.

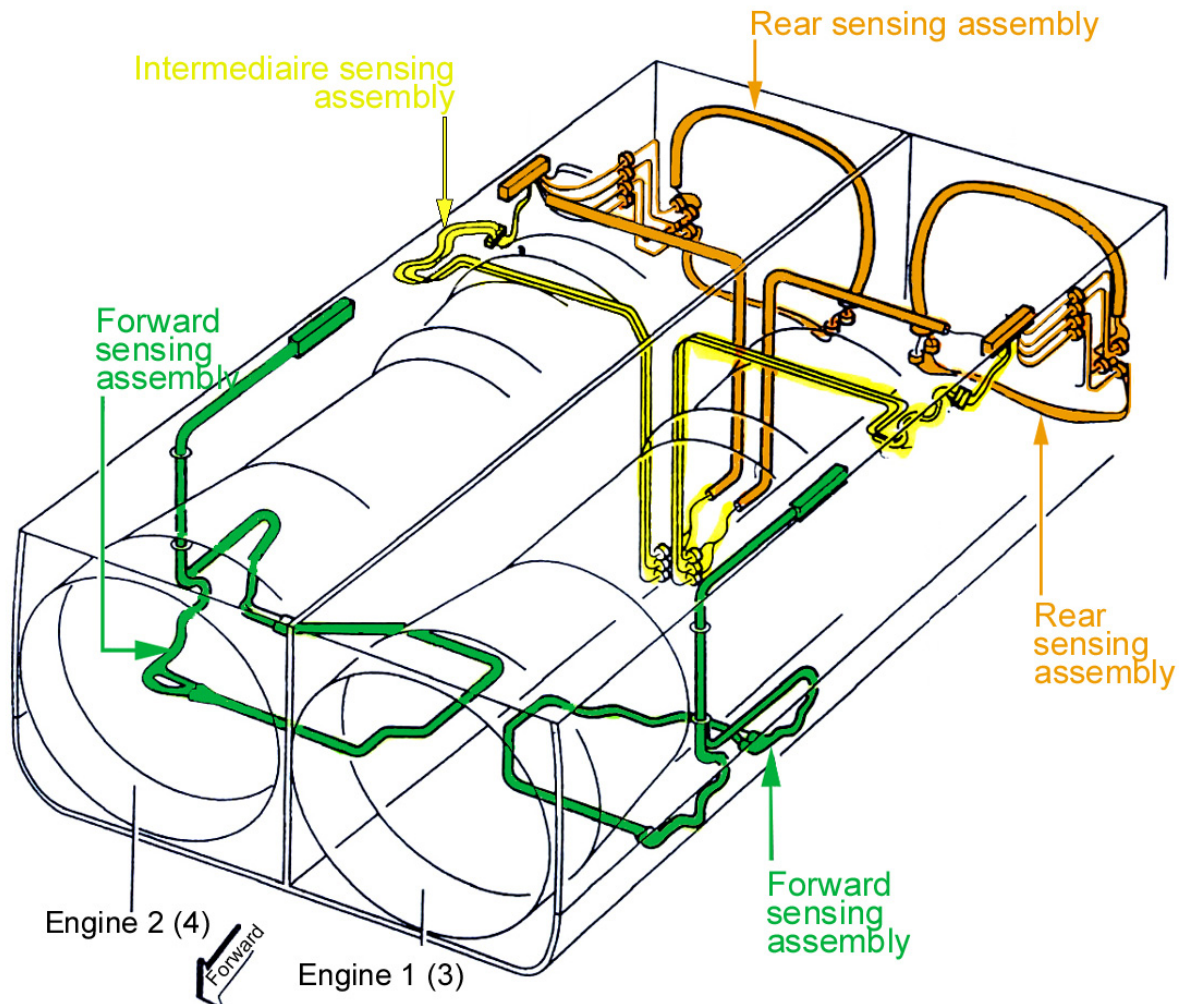


Figure 7: Fire Detection System

N.B.: each sensing assembly is incorporated in the two loops.

1.6.4.5 Engine Maintenance

Each engine consists of twelve modules whose maintenance is undertaken by Air France, by SNECMA Services or by GEAES. The final assembly is performed by GEAES. Tasks performed can be of three types: visual inspection, partial refurbishment or major repair based on the Olympus Maintenance Manual.

Readings taken by the FE during supersonic flight of parameters such as EGT and FF assist in assessment of engine condition. The readings from these engines on previous flights do not reveal any malfunctions.

1.6.5 Weight and balance

1.6.5.1 Weight

The weights listed in the first table below are those which were entered by the dispatcher to establish the forecast weight, then the final weight. The second table shows the weights as established by the investigation, taking into account aircraft loading, probable consumption during taxiing and different methods of evaluating the fixed average weight of the passengers⁽⁸⁾.

Computer-generated weight	Phase 1 forecast (Kg)	Taxi weight (Kg)	Takeoff weight (Kg)
Corrected basic weight	81,560	81,560	81,560
Baggage	1,651	2,131	2,131
Fuel including taxiing	95,400 2,000	94,936 2,000	92,936
Passengers	8,253	8,253	8,253
EIC	0	0	0
Total weight	186,864	186,880	184,880

Real or noted weight	Forecast weight (Kg)	Taxi weight (Kg)	Takeoff weight (Kg)
Corrected basic weight	81,560	81,560	81,560
Baggage	1,651	2,525 (1)	2,525 (1)
Fuel	39,730 (before fill)	94,853	93,853 (2)
Passengers	8,253 (3) 7,759 (4)	8,253 (3) 7,759 (4)	8,253 (3) 7,759 (4)
EIC (5)	60	60	60
Total weight		187,251 (3) 186,757 (4)	186,251 (3) 185,757 (4)

⁸ In practice it is never possible to know the exact true weight of an aircraft, in particular because of the use of fixed average weights.

(1) There were 122 items of baggage loaded on board, with an average estimated weight of 20.7 kg each, making a total of 2,525 kg. Nineteen items of baggage loaded on board were not taken into account, only 103 items appearing on the load sheet (see § 1.16.2).

(2) Allowing that the aircraft consumed a ton of fuel during taxiing.

(3) By applying the fixed average for passengers: one passenger = 84 kg, one child = 35 kg.

(4) By applying the fixed average for men and women: one man = 88 kg, one woman = 70 kg, one child = 35 kg.

Note: for holiday charter flights, it is also possible to use a fixed average of 76 kg per passenger.

(5) The EIC corresponds to 60 kg of newspapers.

The maximum structural weight on takeoff being 185,070 kg, it appears that the aircraft was slightly overloaded on takeoff, regardless of the hypotheses used to make the calculations.

1.6.5.2 CG

1.6.5.2.1 CG Determined during Flight Preparation

The CG indicated on the final load sheet was at 52.3% at Zero Fuel Weight and 54.2% for taxiing with fuel. This CG corresponds to the data in the first table in the previous paragraph.

For takeoff at a weight of 184,880 kg, the CG must be 54.0%. Based on the weight and balance charts, it can be seen that to pass from 54.2% to 54.0% at a weight close to maximum takeoff weight, a fuel transfer from tank 11 of around 700 kg would be necessary.

1.6.5.2.2 CG Determined from Investigation Data

Based on the data in the second table in the previous paragraph, the weight and balance chart calculation carried out by the BEA indicates that the most likely true CG was 54.2% at Zero Fuel and 54.25% for taxiing with fuel.

For takeoff at a weight of 185,757 kg, it can be seen, by extrapolating from the weight and balance charts, that the CG must also be 54.0% and that, to pass from 54.25% to 54.0%, a fuel transfer from tank 11 of around eight hundred kg would be necessary.

Note: an alarm warns the crew if the aircraft CG is outside of the forward or aft CG limits.

1.6.6 Takeoff Performance

The following parameters are used hereafter for performance calculations:

- QNH of 1,008 hPa
- temperature 19 °C
- a dry runway with no gradient
- a CG of 54%

The Operating Manual provides the following maximum structural weights:

- taxi weight: 186,880 kg
- takeoff weight: 185,070 kg

Since the wind readings at different recording sites show a light and variable wind, the calculations are made with calm wind conditions.

Note: the takeoff limitations evaluation gives, with zero wind, a “maximum performance” weight of 186.7 tons. With this weight and the associated speeds (V1, VR, V2), two limitations, the second segment limitation and the tyre limitation have to be taken into account. By increasing the aircraft speed on takeoff, the second segment limitation is pushed back, but this speed is limited by the constraints imposed on the tyres.

At the maximum structural weight at takeoff, the calculations provide the following values:

- V1: between 139 and 162 kt (the crew selected 150 kt)
- VR: 199 kt
- V2: 220 kt (1.125 V_{ZRC})
- Three-engine trim: 12.9°

Note: the speed of 150 is a compromise on the limitations between the takeoff distance (passing 35 ft) and the acceleration-stop distance. The Air France Operations Manual recommends choosing the V1 value in the middle of this range.

The Flight Manual provides the following zero rate of climb (V_{ZRC}) figures.

V_{ZRC} (kt) 185 t	3 engines	2 engines
Gear retracted	193	262
Gear extended	205	> 300

Note: the notion of V_{ZRC} is important for Concorde. It is the cruising threshold speed, which allows the aircraft to remain in level flight at zero rate of climb. On a thrust/speed diagram, V_{ZRC} is located at the intersection of the thrust available curve and the thrust required curve. These points represent an unstable condition.

Ground and air minimum control speeds:

- VMCA = VMCG = 132 kt on three engines
- VMCA = VMCG = 157 kt on two engines

For a V1 of 150 kt:

- TakeOff Run Distance = 3,370 metres
- TakeOff Distance = 3,700 metres

Note: these distances are regulated distances taking into account the failure of one engine.

A calculated simulation can be performed based on these parameters and a serviceable aircraft with four engines operating. Since it is not possible to know the exact weight at brake release (because of utilisation of the average passenger weights, for example), the maximum structural weight at takeoff (185,070 kg) is used for the calculations.

The results of this simulation are as follows (rounded figures):

- V1 is reached 1,150 m, or 33 s, after brake release
- VR is reached 2,070 m, or 43 s, after brake release
- V2 is reached 2,700 m, or 48 s, after brake release
- The wheels leave the ground 2,600 m after brake release
- The distance run to reach 35 feet is 2,950 metres

For all of these values, the influence of an increase in weight of one ton was examined and found to be negligible.

For a tailwind of 8 kt, the takeoff weight is reduced to 183,300 kilograms due to a tyre speed limitation.

Note: for the accident flight, the distance and time values are found for V1. The other values are different since the aircraft no longer had four engines operating.

1.6.7 Aircraft systems

1.6.7.1 Flight Controls

There are three groups of flight controls, related to the rudder⁹, inner elevons and the median and outer elevons.

The rudders are hydraulically activated by twin spool power flight control units (PFCU), each of the spools being supplied by the main Blue and Green hydraulic systems, the Yellow system providing backup to either of the other two systems. Each PFCU is controlled by an electrical system (Blue and Green respectively). The Blue system is active in normal operation, the Green system replaces it in case of failure. The PFCU's switch over to mechanical in case of failure of the Green system. Switching of the control systems is managed by Blue or Green comparators, which control PFCU slaving and by the static logic monitor which generates switching.

The electrical control and slave feedback systems for the various groups are independent. However, power to the PFCU synchros is common to the three flight control groups.

⁹ There are two integral rudders.

1.6.7.2 Air Conditioning

The air conditioning system consists of four independent groups that receive air at high pressure bled from the engines and condition it by cooling, reheating and desiccation. This air is then used to pressurise the aircraft and ventilate certain equipment.

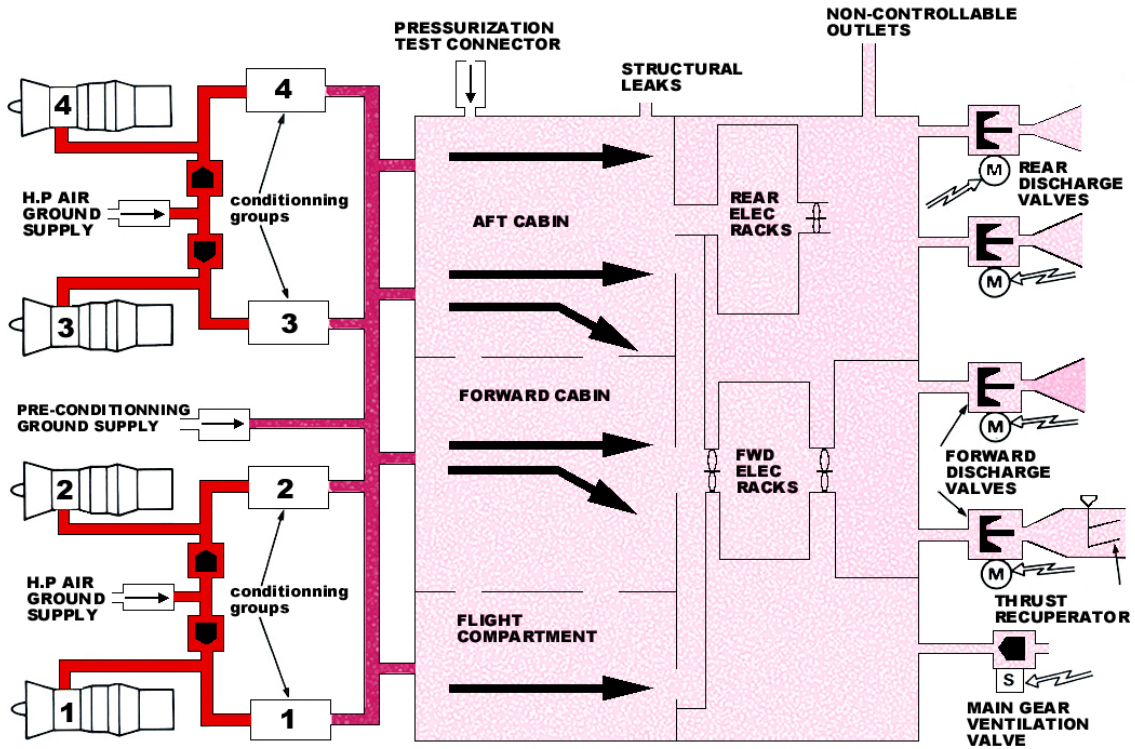


Figure 8: Air Conditioning System

Each group is supplied by the last stage of the engine HP compressor through a dual bleed and pressure limitation valve. The numbers of the groups are the same as for the engines.

The four bleeds are directed towards a collector. When all of the groups are operating, group 1 supplies the flight compartment, group 2 the forward cabin, and groups 3 and 4 the aft cabin. In case of an engine failure, the collector shares the air between the different areas.

Each group is protected against over-pressure, abnormal increases in temperature or the presence of smoke. When smoke is detected (detector situated at the collector entry) the "Smoke" warning light lights up on the control panel and the group valve is automatically shut.

1.6.7.3 Le GPWS

The GPWS installed on F-BTSC was a Sunstrand "Mark 1" with five function modes.

The alarm identified on the CVR is that of the GPWS mode 3 which is set off when the following three conditions are met:

- nose $\leq 12,5^\circ$,
- radio altimeter height > 50 feet,
- loss of barometric altitude greater than that defined by a zone in relation to the radio altimeter height.

1.7 Meteorological Conditions

1.7.1 General Situation at 12 h 00

1.7.1.1 At Altitude

At level 500 hPa (around 5,500 m), a depression associated with a pocket of cold air (temperature $< - 16^\circ\text{C}$) was centred over the Gulf of Gascony. It was moving from the southwest towards the northeast and arrived over the Paris region during the night. It was associated with the rear of the disturbance covering the southwest of the country.

An analysis of the meteorological situation at 12 h 00, performed using the Météo-France, Aladin model, with a mesh of 0.1° at heights of 100, 200 and 500 m above the ground, showed a small anti-cyclonic cell centred on the Seine et Marne which was moving north-east at forecast times of 15 h 00 and 18 h 00. Because of its progression, this cell maintained an easterly flow over the whole Paris region during the afternoon.

1.7.1.2 On the Ground

A succession of low-pressure areas stretched from La Coruña to Leningrad. At midday one of these low-pressure areas was centred over the Poitou and Auvergne regions and was moving northeast. In front of its warm front, in the cool wet air left by the previous day's disturbance, the cloud cover was essentially made up of cumulus and stratocumulus with little vertical development.

This slightly subsiding intermediate zone had a weak pressure gradient. Consequently, it produced variable winds of less than 10 kt, locally calm.

1.7.2 Situation at the Aerodrome

After the dispersal of morning mist at around 10 h 00, the increase in temperatures provided visibilities and ceilings which removed any operating restrictions on the aerodrome.

At 14 h 42 the average wind at threshold 26 was $090^\circ/04$ kt.

At 14 h 43, visibility was 15 km, the sky was cloudy with $2/8$ Cu at 540 m, $2/8$ Cu at 720 m and $5/8$ Scat 1,020 m. The temperature was 19°C and the humidity 74%. The average wind at the threshold of runway 26 was $090^\circ/3$ kt and $320^\circ/3$ kt at the threshold of runway 08.

At 14 h 44, the average wind at the threshold of runway 26 was 020°/3 kt and 300°/3kt at the threshold of runway 08.

Between 14h and 15 h, the surface wind varied in strength at the two thresholds between 0 and 9 kt and between 300° and 170° from the north in direction.

Note: wind measurements are taken every half a second and averaged over two minutes. The runway was dry.

1.7.3 Documents Supplied to the Crew

The meteorological dossier supplied to the crew consisted of wind and temperature charts with forecasts at flight levels 300, 390 and 530 at 12 h and 18 h, two TEMSI charts for the north Atlantic between flight levels 250 and 630 for the same times and TAF, METAR and SIGMET reports valid for the destination and alternate aerodromes.

1.8 Aids to Navigation

Not applicable.

1.9 Telecommunications

1.9.1 Radar Track

In order to obtain a precise position of the aircraft on the runway, the track was based on data from the AVISO system, the digitising system for the analogue ground radar.

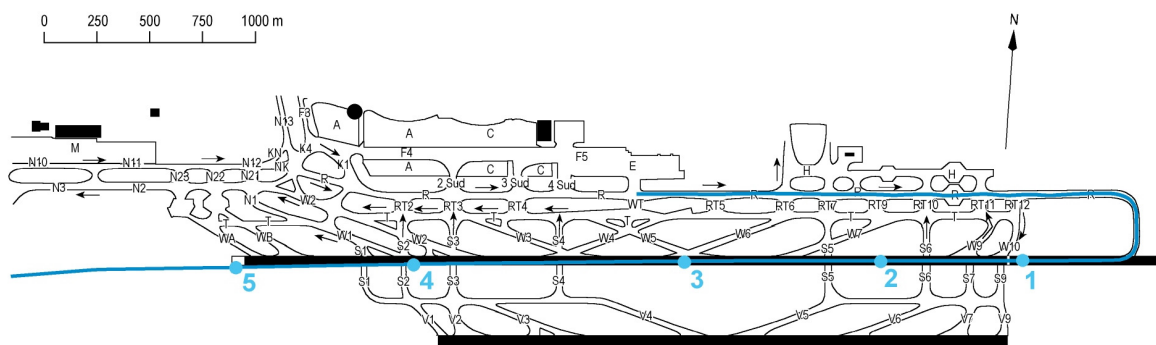


Figure 9: Track of F-BTSC based on AVISO data

N.B.: the numbers on the track refer to § 1.11.3.

1.9.2 Telecommunications

Flight AFR 4590 was contacted successively on the following frequencies:

- ATIS on 126.175 MHz
- Flight data on 126.65 MHz
- Traffic on 123.6 MHz
- Ground on 121.8 and 121.975 MHz
- Loc South on 120.9 MHz

Relevant communications are mentioned below. (Translator's note: all RT communications were in French).

1.9.2.1 ATIS

The "X RAY" recording at 12 h 10 included:

- Takeoff runways 27 and 26 right
- Runway 27 LDA 2,630 metres
- TORA 2,900 metres
- ASDA 2,900 metres
- TODA 2,900 metres
- Wind 350°/ 7 kt
- Temperature 16 °C
- QNH 1008

The "Yankee" recording at 13 h 50 included:

- Takeoff runways 27 and 26 right
- Runway 27 LDA 2,630 metres
- TORA 2,900 metres
- ASDA 2,900 metres
- TODA 2,900 metres
- Wind 010°/ 4 kt
- Temperature 19 °C
- QNH 1008 Hpa

1.9.2.2 Flight Data Frequency

At 13 h 58, the crew requested *"Concorde for New York on Echo 26 we need the whole length of 26 right"*

At 14 h 07, the controller confirmed *"...plan for 26 right ..."*, the crew read back *"... on 26 right ..."*.

1.9.2.3 Ground Frequency

At 14 h 34, the controller said *"Air France 45 90, good morning, taxi to holding point 26 right via Romeo" then added "... do you want Whisky 10 or do you want taxiway Romeo".* The crew confirmed *"we need the whole runway"*. The controller replied *"OK so you're taxiing for Romeo, Air France 45 90"*. The crew read the information back.

1.9.2.4 Loc South Frequency

At 14 h 40 min 02 s, the controller transmitted *"45 90 line up 26 right"*, then crew replied *"we line up and hold on 26 right, 45 90"*.

At 14 h 42 min 17 s, the controller said *"45 90 runway 26 right wind 090 8 kt cleared for takeoff"*, the crew replied *"45 90 takeoff 26 right"*.

At 14 h 43 min 13 s the controller stated *"... 45 90 you have flames ... you have flames behind you"*. The crew acknowledged this transmission.

At 14 h 43 min 28 s, a transmission, whose source could not be identified, was made on the frequency *"it's really burning and I'm not sure it's coming from the engines"*.

A 14 h 43 min 31 s, the controller confirmed *"45 90 you have strong flames behind you"* and he continued *"... as you wish you have priority for a return to the field"*. The crew acknowledged this transmission.

A 14 h 44 min 05 s, the controller transmitted *"Fire Service Leader err ... the Concorde I don't know his intentions get into position near the southern parallel runway"* then *"Fire Service Leader correction the Concorde is returning on runway 09 in the opposite direction"*. The crew then transmitted *"we're trying for Le Bourget..."*

A 14 h 45 min 10 s, the controller told the Fire Service Leader *"The Concorde has crashed near Le Bourget Fire Service Leader"*.

A 14 h 46 min 09 s, the controller announced *"For all aircraft listening I will call you back shortly we're going to get ourselves together and we're going to recommence takeoffs"*.

A 14 h 55 min 47 s, an aircraft informed the controller *"...there is smoke on runway 26 right, there's something burning apparently, for information ..."*

A 14 h 57, a runway vehicle (Flyco 9) told the controller *"there's tyre"* then *"pieces of tyre which are burning"*.

1.10 Aerodrome Information

1.10.1 General

Paris Charles de Gaulle Aerodrome currently has one northern runway 09/27 and two southern parallel runways 08/26. Work was being carried out on the north runway, from

15 June to 17 August 2000, and its available length was reduced during this period of time from 3,600 to 2,700 metres, its width being unchanged at 45 metres. Runway 08L/26R (26 right) is 4,215 m long and 45 m wide. Runway 08R/26L is 2,700 m long and 60 m wide.

Runway 26R has 600 m of tarmac followed by 7.5 metre square concrete slabs, its threshold being at an altitude of 312 feet.

On the day of the accident, only runway 26 left had a windsock, located near the ILS GLIDE antenna, about 1,000 from the threshold of runway 26 right.

The aerodrome has two fire fighting centres, a north RFFS and a south RFFS. Each centre is able to mobilise the men and equipment required for a Category 9 airport such as Paris Charles de Gaulle.

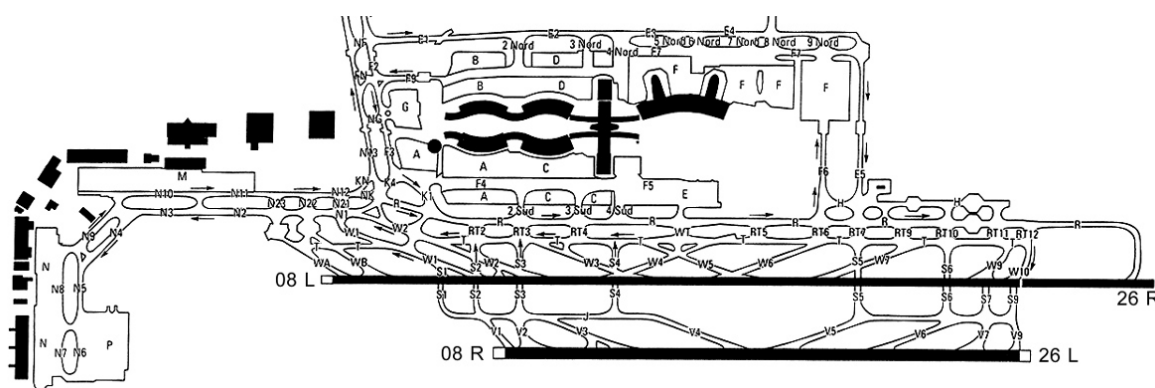


Figure 10: Paris Charles de Gaulle south double runway

1.10.2 Runway Inspections

1.10.2.1 Regulations

At the time of the accident, there were no national regulations relating to surveillance of the movement areas⁽¹⁰⁾ on French aerodromes, such as those derived from standards and practices recommended in Annex 14 to the Chicago Convention.

For an aerodrome of the size of Paris Charles de Gaulle, Annex 14 recommends carrying out inspections at least twice a day in order to monitor the condition of the movement area and to communicate information relating to operations or concerning aircraft performance.

The ICAO Airport Services Manual, in its 1983 edition, part 8 – Operation, and that on surface movement guidance and control systems (SMGCS) also contains indications on daily inspections of the movement area.

Aéroports de Paris note 10/AD/98 specifies three daily inspections in addition to the lighting inspection: before 7 h 00, around 14 h 00 and around 21 h 00 local time.

¹⁰ Movement area : that part of an aerodrome which is used for takeoffs, taxiing and parking aircraft. It includes the manoeuvring area and the apron.

1.10.2.2 The inspections on 25 July 2000

On July 25 at around 4 h 30⁽¹¹⁾, a “Follow Me” vehicle performed a runway inspection in two passes. Nothing unusual was reported.

At around 14 h 30, a “Follow Me” vehicle performed a partial runway inspection in the area of taxiway W2 following a suspicion of a bird strike.

Between 14 h 35 and 15 h 10, an exercise with several fire brigade vehicles took place on runways 26 right and 26 left. Taking into account this exercise, the runway inspection planned for 15 h 00 was put back. It had not been carried out at the time the Concorde took off (16 h 42 min 30s).

1.11 Flight Recorders

1.11.1 Recorder Types and Readout

Two flight recorders were installed on board F-BTSC, in addition to a Quick Access Recorder (QAR). All three recorders were read out for the investigation.

The flight recorders were found at the accident site by a technical investigator four hours after the accident. They were recovered as soon as conditions at the site permitted. They were placed under seal and taken to the BEA by two police officers.

1.11.1.1 Cockpit Voice Recorder (CVR)

The CVR, with a recording time of thirty minutes, had the following references:

- Make: Fairchild
- Type number: 93-A100-83
- Serial number: illegible

The CVR was opened, read out and a copy of the recording made during the night of the 25/26 July.

The outer casing of the CVR showed signs of exposure to fire and impact damage. The serial number was illegible because of marks left by fire. Nevertheless, the CVR's thermal protection had functioned and the tape was found intact inside its protective box.

In the following days, a transcript of the entire length of the recording was made. The validation of the identity of the voices of the crewmembers was made with pilots from the Air France Concorde flight division. Access to the recording was then limited to relevant members of some of the working groups, as well as members of the Commission of Inquiry.

¹¹ In this paragraph, times are given in local French time.

1.11.1.2 Flight Data Recorder (FDR)

The flight data recorder, whose magnetic tape has a recording duration of twenty-five hours, bore the following references :

- Make: Sundstrand
- Type number: 981-6009-011
- Serial number: 3295

Since the equipment normally used for the readout of this type of recorder at the BEA was temporarily unavailable, the recorder was taken to the Bretigny Flight Test Centre by a police officer, in accordance with the agreement between the two organisations. The recorder was opened during the night of the 25/26 July, in the presence of two technical investigators.

The outer casing of the FDR was damaged by impact and showed signs of exposure to fire. After the protective box was opened, the following was noted:

- the tape wind mechanism appeared to be in good condition,
- the tape was in position, not stuck to the read and record heads,
- there were black marks on the tape and various mechanisms,
- the read and record head cables were stuck at the level of the protective box joint, some black marks being visible there inside the casing.

The tape, after extraction, was cleaned with distilled ethyl alcohol. It was strengthened at one point where the beginnings of a tear had been observed.

Readout of the whole of the tape, with simultaneous synchronisation of the signal being read out, was performed with Sundstrand IAE (Incident Analysis Equipment/PN 960-0145-002).

Because of the condition of the tape, readout of the recording was of medium quality, and this caused a certain loss of signal synchronisation. This first readout made a preliminary analysis possible, but it was decided to seek better quality data at the same time, either by reading out the QAR or by a new readout of the FDR tape with digitisation of the signal so as to improve synchronisation by using algorithms appropriate to a poor quality signal.

1.11.1.3 QAR

The quick access recorder had the following references:

- Make: Dassault
- Model: EQAR F6217
- Type number: 1374-100-000
- Serial number: 290

The QAR is an unprotected recorder. It contains a copy of the FDR data on a magneto-optical disc and is used by Air France for flight analysis. The write procedure for the disc uses three backup memories whose role is to stock data sent by the Flight Data Acquisition Unit (FDAU) until such time as the vibration conditions detected by an internal

accelerometer in the QAR are favourable for writing on the disc. The memories are volatile and must remain powered for the information they contain to be conserved.

The data readout was performed on 1st and 2nd August at Thomson CSF's premises, the manufacturer of the QAR, in the presence of a judicial expert and a BEA investigator.

The QAR's box was crushed and the magneto-optical disc was deformed. The memory card, visible through the half torn-off casing, seemed to be in good condition. It was therefore decided to concentrate the work on this card. Two of the three memories had been torn off at impact. The third was still in place and was powered.

Tests were performed on check sample cards so as to define a method of data extraction, since this operation had never been carried out before. The method used was to connect a parallel power supply to the memory so as to be able to transfer it from its card to a receiver card. An uninterrupted series of zeros had first been written onto the two other memories of the receiver card.

The content of the third memory could thus be read out and a copy of the disc was given to the BEA. After analysis, it appeared that the parameters of the accident flight were present on the only one of the three memories which had remained powered. The quality of the recording, because of the technology used, was excellent and there was no de-synchronisation. It was not therefore necessary to try to read out the magneto-optical disc nor to proceed with further acquisition work on the FDR tape signal.

1.11.2 Cockpit Voice Recorder

1.11.2.1 CVR Readout

The Fairchild A-100 type CVR is a four-track magnetic tape recorder. The theoretical bandwidth is between 150 Hz and 5 kHz, though it is possible to obtain information up to 8 kHz if the information has a lot of energy.

The four tracks contain recordings of:

- radio communications on tracks 1 and 4,
- communications with the cabin crew on track 1,
- communications with the ground engineer on tracks 1, 2 and 4,
- the CAM on track 3.

The CAM is located in the middle of the upper instrument panel in the cockpit. The control box for test, erase and listening functions is located at the foot of the Flight Engineer's station. This box includes a microphone that is not connected to the CVR.

1.11.2.1.1 Time-base

After opening, the tape was read out on a read-out device whose recording function was inhibited and which was equipped with two CVR heads in order to obtain optimum quality.

The recording speed of the tape was adjusted to the speed of the recording. For this, the interference created by the aircraft's on-board power supply was used (400 Hz). On a real-time spectral representation of the signal, it corresponds to an energy peak of 400 Hz

whose exact frequency varies according to the readout speed. This is thus adjusted so that the energy peak is precisely at a 400 Hz value.

However, the value of the frequency of the on-board power supply can fluctuate slightly around 400 Hz during the various phases of flight. For better accuracy, the audio recording was synchronised with the parameter recording.

This synchronisation was carried out mainly by studying the radio communications. In fact, a discrete recorded every second on the FDR changes condition (0 to 1) during a communication. As the speed of the CVR recording influences the length of the communication, the recorders can be synchronised precisely by ensuring that the beginning of the communication recorded on the CVR corresponds to the variation of 0 to 1 of the discrete on the FDR, and that the end of the communication corresponds to its return to 0.

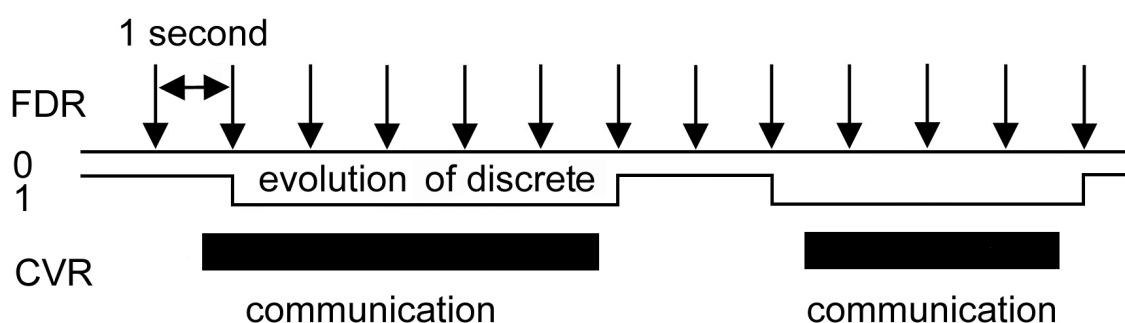


Figure 11: Synchronisation

Finally, the time-base used by the control tower, when validated, was used for the CVR transcript. To this end, the transcript of the radio communications recorded by the CVR was compared with the one made from the tower recording. It should be noted that problems were encountered when determining this time-base: because of a technical problem, the UTC time on each of the tower's two recorders was slightly different.

1.11.2.1.2 Software Used

a) At the time of the first readout of the recording, a digital copy was made using Samplitude software. This software permits signal visualisation of all four tracks with resolution up to sample level. In addition, it has highly developed filtering capacity to improve the intelligibility of speech. Nevertheless, since the filtering technique can induce phase rotations, all of the spectral analysis was carried out on an unfiltered signal.

Work was carried out on the four tracks simultaneously, which allowed synchronisation of events present on different tracks. The signals were deliberately under-sampled at 44.1 kHz so as not to lose information during copying.

An archive corresponding to a raw copy with no filtering was then made on a compact disc. It includes four files to .wav standard and files specific to the software allowing them to be read out.

b) Three different representations of the signal were studied with Xwaves spectral analysis software. This approach was confirmed with the head of the AAIB flight recorder division, who was present during the last series of tests. By common agreement, the time-frequency representation appeared to be the most useful. The three representations are as follows:

- temporal representation, commonly used by linguists. Time is on the x-axis and amplitude on the y-axis. This representation is difficult to use in fact, taking into account the presence of a strong background noise and the strong and random signals to be handled.

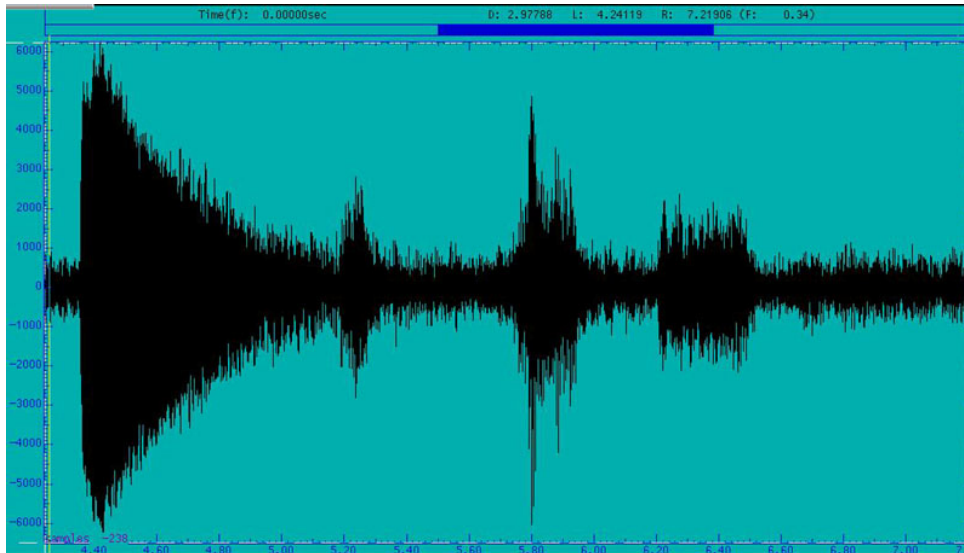


Figure 12: Temporal representation of signal

- the time-frequency representation, where the time is on the x-axis, the frequency on the y-axis and energy in a third dimension represented by the colour. The colour varies from dark blue to white, passing through red and yellow, the white representing the highest levels of energy.

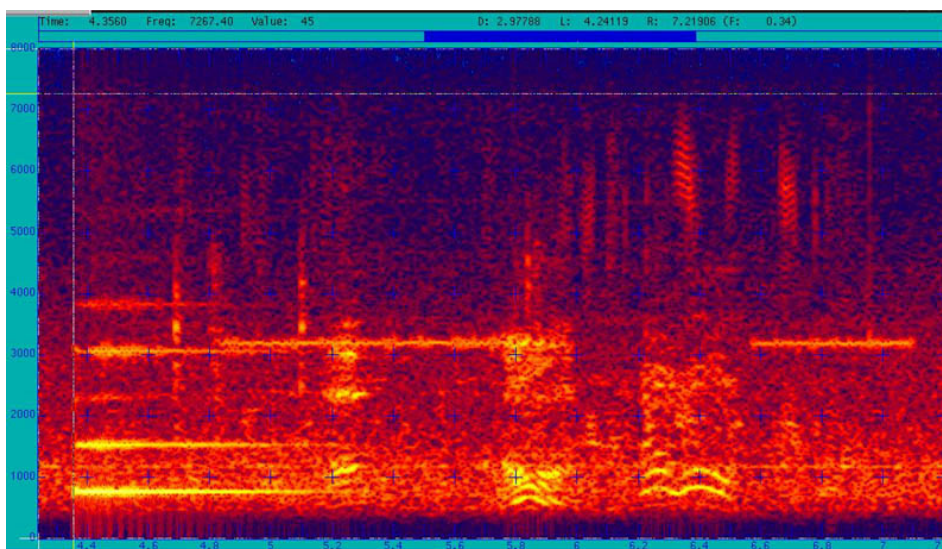


Figure 13: Time-frequency representation of signal

- frequential representation where the frequency is on the x-axis and energy on the y-axis. This representation makes it possible to know the division of energy in relation to frequency at any given moment of time. It gives a cross-section of the signal in the time-frequency domain.

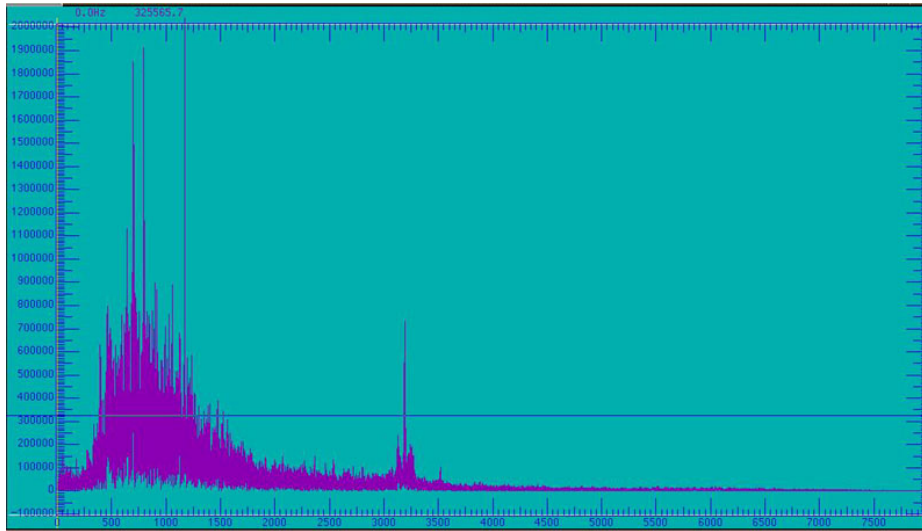


Figure 14: Frequency representation of signal

1.11.2.2 Transcript of the Recording

The method used to transcribe the recording consisted of faithfully reproducing, almost phonetically, what was heard, without interpretation or extrapolation. However, knowledge of procedures and technical terms currently in use is sometimes very helpful for the comprehension of certain words or parts of words. This was why several aircrew who knew the voices of the crew, the background noise of a Concorde cockpit and the various alarms joined in with this work. In addition, filtering adapted to the flight segment allowing reduction of the parasite background noise was used to improve the intelligibility of the recording.

The beginning of the recording was at 14 h 12 min 23 s. Item 17 on the checklist, “*cockpit check*” was under way. This was followed by the “*pre-start-up*” checklist, engine starting, the “*post start-up*”, “*taxi*” and “*pre-takeoff*” check lists. The complete transcript of the recording is included in appendix 2.

Of the whole thirty minutes on the CVR, the following elements are of note:

14 h 13 min 13 s, FE “*so total fuel gauge I’ve got ninety-six four with ninety-six three for ninety-five on board*”.

14 h 13 min 46 s, FO “*fire protection*”, FE “*tested*”.

14 h 14 min 04 s, FO “*ZFWZFCG*”, FE “*so I’ve got ninety-one nine and fifty-two two*”.

14 h 14 min 17 s, Captain *"the reference speeds so V1 a hundred and fifty, VR one hundred and ninety-eight, V2 two hundred and twenty two hundred and forty two hundred and eighty it's displayed on the left"*.

14 h 14 min 28 s, FO *"trim"*, Captain *"it's thirteen degrees"*.

14 h 14 min 53 s, Captain *"next the control lever is at fourteen and you'll have N2 of ninety-seven and a bit"*, FE *"ninety-seven"*.

14 h 22 min 22 s, Captain *"ok we're going to do one hundred eighty-five one hundred that's to say we'll be at the... structural limit"*, *"structural err fifty-four per cent CG (*) see"*.

14 h 37 min 51 s, FO *"hey, you've got the indicators going into Green all the time..."*.

14 h 38 min 55 s, FE *"you're right, we'll stay in Yell... in Green"*.

14 h 38 min 59 s, FO *"we'll stay in Green, eh"*.

14 h 39 min 04 s, Captain *"so the takeoff is... at maximum takeoff weight one hundred eighty tons one hundred which means four reheats with a minimum N2 of a hundred and three and a failure N2 of ninety-eight"*, *"Between zero and one hundred knots I stop for any aural warning the tyre flash"*, *"tyre flash and failure callout from you right"*, *"Between one hundred knots and V1 I ignore the gong I stop for an engine fire a tyre flash and the failure callout"*, *"after V1 we continue on the SID we just talked about we land back on runway twenty-six right"*.

14 h 40 min 19 s, Captain *"How much fuel have we used?"*, FE *"We've got eight hundred kilos there"*.

14 h 41 min 09 s, FE *"Brake temperatures checked one hundred fifty..."*. The Captain asks *"Is it hotter on the left or the right there?"*. The FE answers *"it's about the same"*.

14 h 42 min 31 s, Captain *"top"*.

14 h 42 min 54.6 s, FO *"one hundred knots"*.

14 h 42 min 57 s, FE *"four greens"*.

14 h 43 min 03.7 s, FO *"V1"*.

Note : the CVR working group had detected a low frequency noise at 14 h 43 min 07 s, during the takeoff roll, which was transcribed in the preliminary transcript. Subsequent advanced filtering work showed that this low frequency noise was in fact present throughout the tape: it is a noise associated with the recording induced by the tape itself or the recording circuit. It was thus removed from the final transcript.

14 h 43 min 10.1 s, noise followed, from 14 h 43 min 11 s to 14 h 43 min 13.8 s, by a change in the background noise. In the same time period the FO announces *"watch out"*.

14 h 43 min 11.9 s, an unintelligible sound is heard, then at 14 h 43 min 13.0 s, the FE says *"watch out"*.

14 h 43 min 13.4 s, message from the controller indicating flames at the rear and read back by the FO.

14 h 43 min 16.4 s, FE “(stop) “.

14 h 43 min 20.4 s, FE “*Failure eng... failure engine two*”.

14 h 43 min 22.8 s, fire alarm.

14 h 43 min 24.8 s, FE “*shut down engine two*”.

14 h 43 min 25.8 s, Captain “*engine fire procedure*” and in the following second the noise of a selector and fire alarm stops.

14 h 43 min 27.2 s, FO “*watch the airspeed the airspeed the airspeed*”.

14 h 43 min 29.3 s, fire handle pulled.

14 h 43 min 30 s, Captain “*gear on retract*”. In the course of the following eight seconds the crew mention the landing gear several times.

14 h 43 min 42.3 s, second fire alarm.

14 h 43 min 45.6 s, FO “*(I’m trying)*”, FE “*I’m firing it*”.

14 h 43 min 46.3 s, Captain “*(are you) shutting down engine two there*”.

14 h 43 min 48.2 s, FE “*I’ve shut it down*”.

14 h 43 min 49.9 s, FO “*the airspeed*”.

14 h 43 min 56.7 s, FO “*the gear isn’t retracting*”.

14 h 43 min 58.6 s, third fire alarm.

Between 14 h 43 min 59 s and 14 h 44 min 03 s, three GPWS warnings are heard and at the same the FO announces “*the airspeed*”.

14 h 44 min 14.6 s, FO “*Le Bourget Le Bourget*” then a few seconds later “*negative, we’re trying Le Bourget*”, in reaction to the instructions given to the fire chief by the controller.

14 h 44 min 31.6 s, end of the recording.

Note: some words in the flight part of the recording, “*stop*” for example, were doubtful. These portions of the recording were sent to the CNRS linguistics laboratory in Aix-en-Provence. The work on signal filtering and phoneme analysis carried out by the researchers at the lab did not clear up the doubts.

1.11.2.3 Identification of the Alarms and Noises

In order to determine the origin of the alarms and selector noises heard and to obtain information on the revolving parts of the engines from the recording, a series of measurements were performed on the ground on an Air France Concorde.

1.11.2.3 1 Procedure

a) Identification of the noise of a selector is based on the comparison of its spectral representation with that of the sound of a known selector. The characteristic elements compared are the duration of the signal, the distribution of the energy in relation to the frequency and the cadence. Certain selector movements imply the generation of several energy peaks. Thus, it is sometimes necessary to move the selector from its initial position, actuate it then release it: the cadence is the time between these peaks.

For example, in figure 9 below the cadence is of 170 ms, the duration of the first noise is 30 ms, that of the second 40 ms. The spectrum located on the left side shows an energy peak around 2,900 Hz which corresponds to release of the selector.

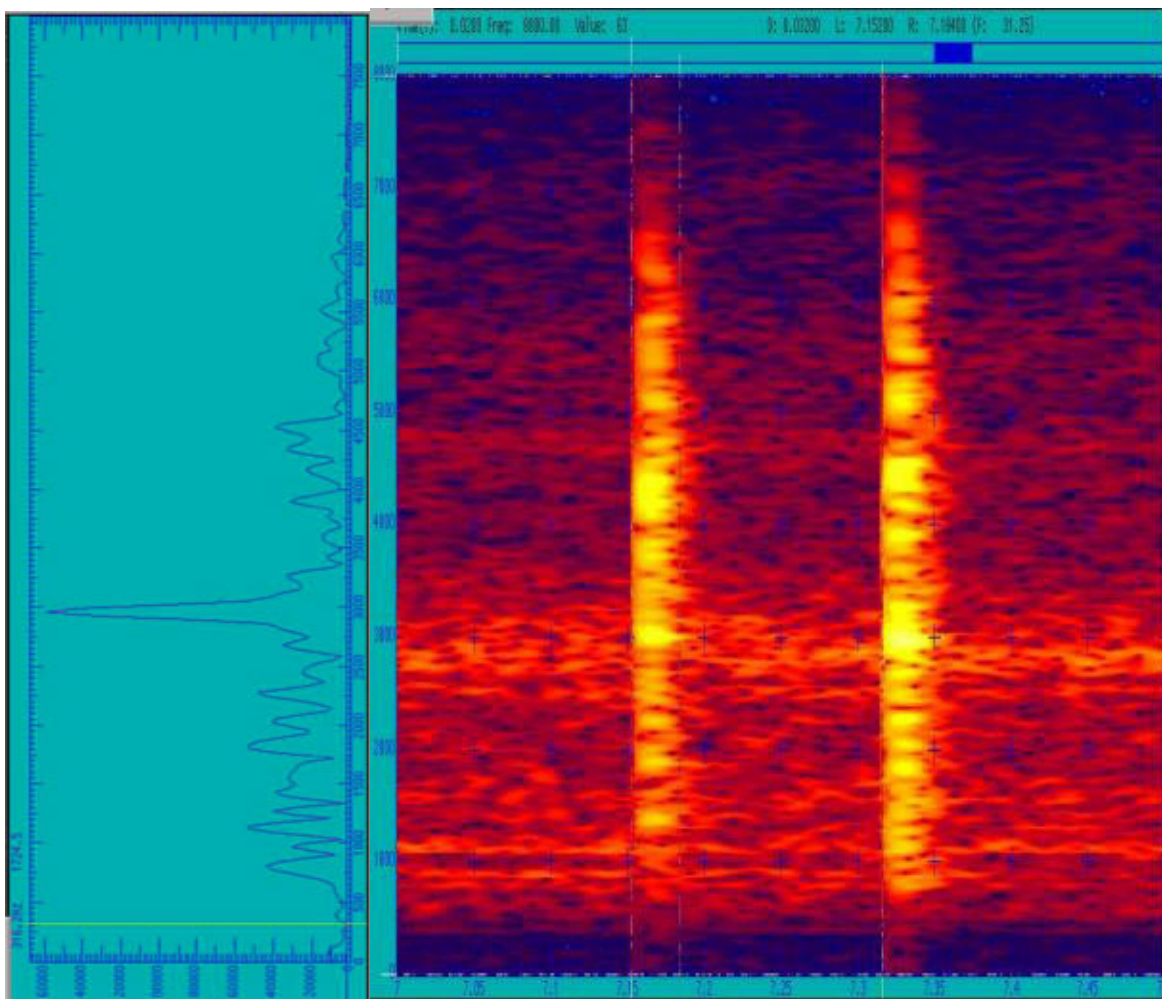


Figure 15: Identification of a selector noise

b) It is difficult to compare selector noises if the background noise is not itself analogue. This consistency is even more necessary when the automatic amplification control function attenuates high amplitude recordings in order to avoid saturation of the signal. Thus, the presence of the 400 Hz and its high energy harmonics can alter the signal to be analysed or hide the energy peaks at certain frequencies.

The figure below shows the time-frequency representation of the noise produced by the movement of an identical selector, on the left on a Concorde with a high level of spurious noises and on the right on F-BTSC.

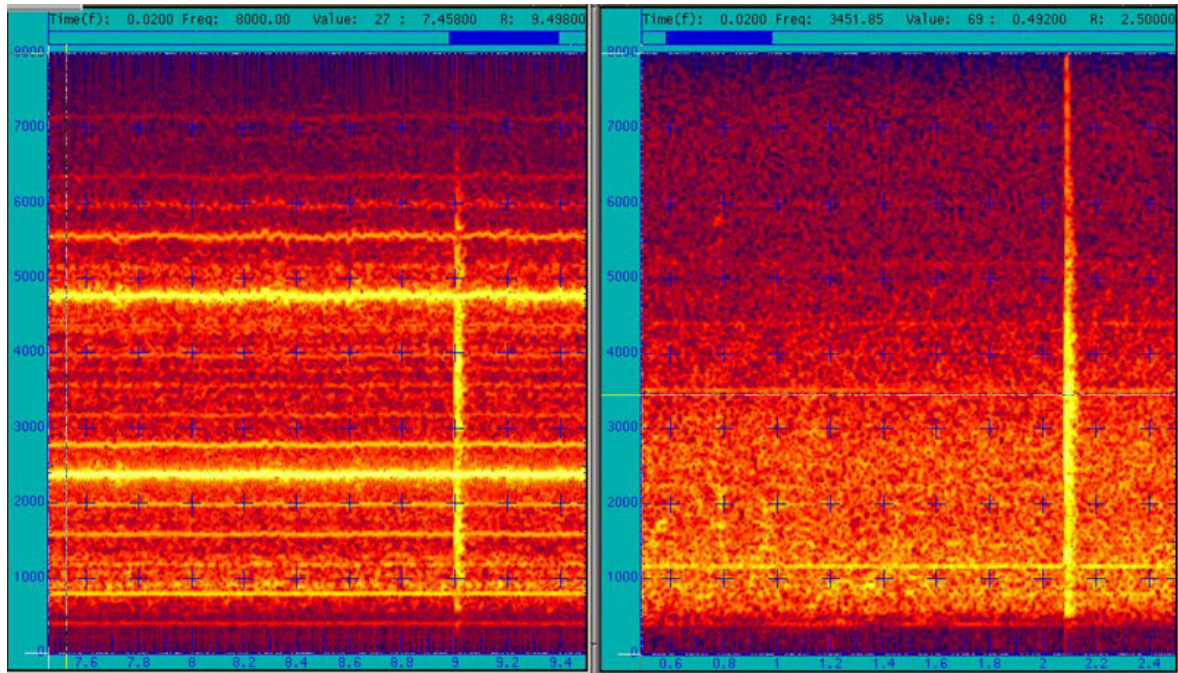


Figure 16: Identical sound with different background noises

The recording method makes it impossible to reason in absolute values, expressed for example in dB. The terms relative amplitude and non-dimensional energy can be used.

Furthermore, it was necessary to find a test aircraft with background noise analogue to that on the accident aircraft.

Equally, the movements of the selectors were performed with and without the fire alarm on. The presence of the fire alarm also meant the person actuating the selectors was under stress.

c) There can be other limitations to the identification of selector noises, such as:

- The way the selector is moved. The same person may move a selector in several ways. One of the aims of the tests was thus to find a common point in the spectral representations of the movements of the same selector actuated in different ways. In order to validate this common point, several people also actuated the selectors.

- A response in a different frequency for selectors which were notionally identical, as exists in the case of engines, for example. The spectral representations of the movement of each of these selectors were compared to evaluate this parameter.

Engine operation does not, however, have a significant effect on the background noise, as shown by the recordings below; the first with engines shut down (left) and the second in flight (right).

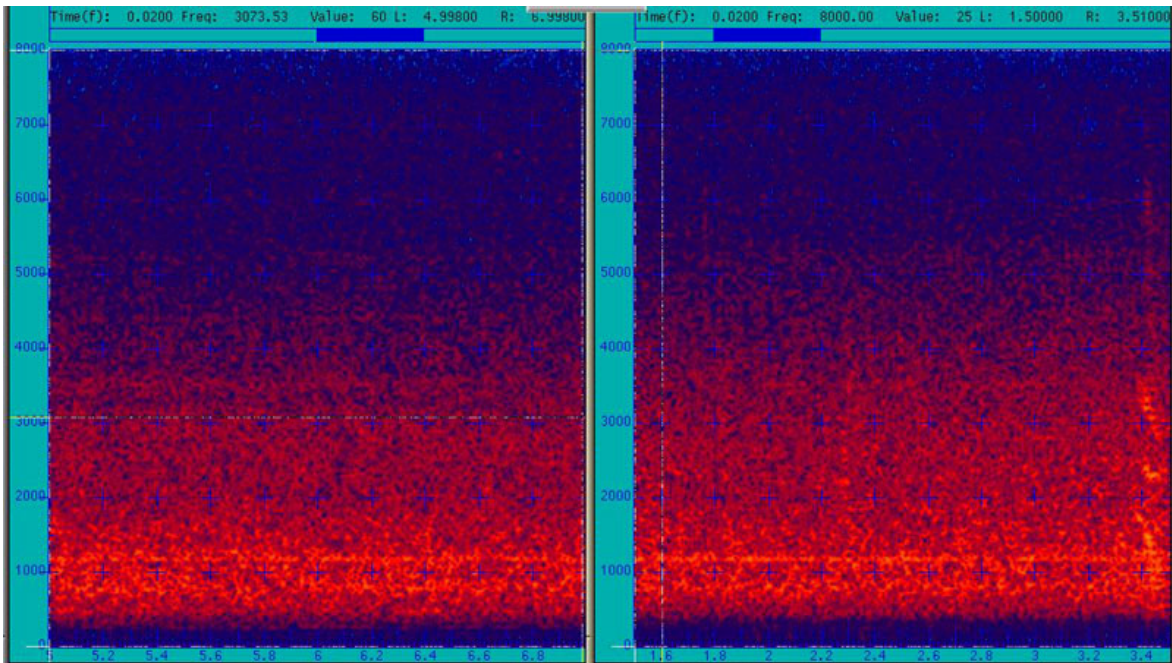


Figure 17: Engine operation: shut down on the left, in flight on the right

This explains why the analyses did not demonstrate the frequencies related to the behaviour of the engines during spool up or in flight. Equally, the noises specific to taxiing are not perceptible.

d) One factor to be taken into account but which is not quantifiable is human feeling. In reality, the best receivers and filters remain the human ear and brain. They are capable of integrating aspects of spectral representation and thus have the feeling of resemblance even if analysis makes it impossible to get complete similitude.

e) Finally, the range of hypotheses can be reduced thanks to exchanges between crew members. Some selector noises are expected when the pilots carry out a specific procedure.

1.11.2.3.2 Supplementary Research

1.11.2.3.2.1 Recordings in flight

To complete the work on measurements, CVR recordings on takeoff were used, even though such recordings are difficult to find since they are normally wiped out after thirty minutes of a normal flight.

The following flights are considered:

- Takeoff of F-BVFC from New York on 14 June 1979,
- Takeoff of F-BVFC from New York, during the ferry flight on 21 September 2000.

During this flight, a copy of the CVR was made using the control recording output on the control box. As a result, all four tracks of the CVR are mixed on the copy.

Note: a recording by hand microphone on a normal recorder would not be usable, the measurement system not taking into account the structural transmissions.

These recordings did not bring to light any additional information, taking into account the differences in the background noise and the small number of selector movements during these takeoffs.

1.11.2.3.2.2 400 Hz demodulation

Some vibrations of an aircraft's structure can propagate to the CVR and leave a trace through a modulation of the 400 Hz. Analysis of this frequency then allows for identification of a transitory characteristic and, consequently, knowing the moment when the phenomenon causing the vibration occurred. The following figures were obtained in this way during a series of explosive tests on a jumbo jet aircraft on the ground. The time is on the x-axis and the non-dimensional energy on the y-axis.

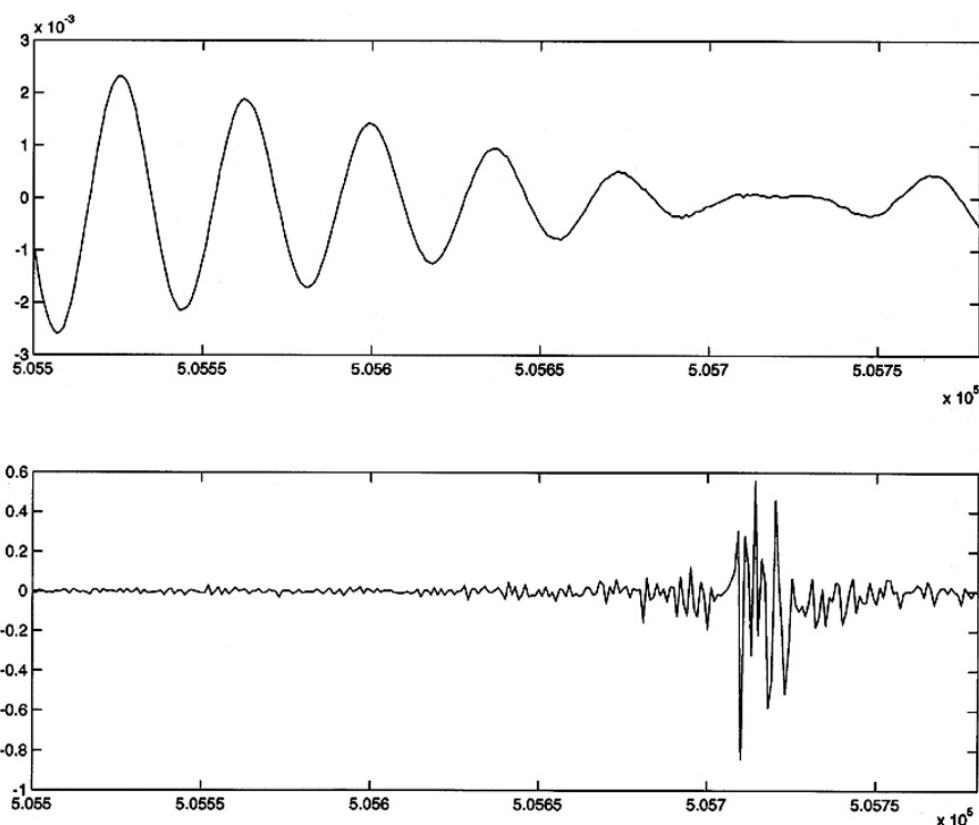


Figure 18: 400 Hz demodulation

In collaboration with a specialist from the University of Southampton *Institute of Sound and Vibration Research*, research into possible tyre explosion or debris impacts on the structure was carried out using F-BTSC's CVR recording.

This study, carried out using Matlab software did not produce any usable results. It is likely that the possible vibrations were not of sufficient amplitude to register on the signal recorded.

1.11.2.3.3 Research Results

The detailed results of the research undertaken are given in appendix 3. To summarise, the following facts were deduced from analysis of the recorded noises:

- The selector noise at 14 h 42 min 30.4 s is the click of the thrust levers brought to their stop.
- The noise of the selector at 14 h 42 47.5 s is the change of position of the "Engine 4 takeoff N1 limiter" selector.
- The selector noise at 14 h 43 min 21.3 s is the movement of the TCU selector that switches from "main" to "alternate".
- The alarm that appears and disappears several times from 14 h 43 min 22.8 s is the engine fire alarm.
- The selector noise at 14 h 43 min 26.2 s corresponds to a reduction on a thrust lever or cutting a HP fuel cock (see § 1.16.9.1.3.3).
- The selector noise at 14 h 43 min 27.5 s corresponds to movement of the electric pitch trim actuators.
- The selector noise at 14 h 43 min 29.3 s corresponds to the pulling of a fire handle.
- The alarm at 14 h 43 min 32.6 s is the forward toilet smoke alarm; the cockpit door is open.
- The selector noise at 14 h 43 min 44,7 s is similar to firing the extinguisher with the first shot pushbutton.
- Two or three noises between 14 h 44 min 24 s and 14 h 44 min 27 s appear to correspond to a reduction on a thrust lever or shutting a HP fuel cock.

Note: movements of the landing gear control lever are not detected, as is confirmed by the ground recordings.

1.11.3 FDR Readout

1.11.3.1 The Flight

1.11.3.1.1 Analysis of Parameters

The recorded parameters were decoded with the aid of documents provided by Air France and EADS. Specifically, the previous flights provided by the Air France Flight Analysis Service were analysed in order to validate the parameters and for purposes of comparison. Four hundred parameters were recorded. Some of these parameters posed validation problems, in particular for their neutral or reference values. The SAT recording was invalid.

The values of some recorded parameters must be corrected as follows:

- Fuel Flow Parameters

The recorded values were compared with the expected value during slowdown and debowing phases and to the readings carried out by the FE in supersonic cruise. The comparison showed that at low thrust the calibration error is a few hundred kilograms, the recorded values being lower than the true values. Thus, for a true value of 500 kg/h, the recorded value is zero.

- N1 and N2 Parameters

The recorded values were compared with the values expected when the engines produce full thrust and to those read out by the FE.

- o N1 Parameter

At high thrust, the calibration error is about 2.3%, the values recorded being lower than the true ones. Thus, for a true value of 100%, the recorded value of N1 was 97.7%. However, the calibration error was greater for engine 3, it being about 7%.

- o N2 Parameter

At high thrust, the calibration error is about 1.7%, the values recorded being lower than the true ones. Thus, for a true value of 103%, the recorded value of N2 was 101.3%.

- EGT Parameter

The recorded values were compared with the values expected when the engines produce full thrust. The comparison showed that the calibration error is about 20°C, the recorded values being lower than the true values. Thus, for a true value of 750°C, the recorded value was 730°C.

- Rudder Parameter

The recorded values for F-BTSC's takeoff line-ups were compared with that expected, that's to say 0° deflection. The comparison showed that the calibration error is about 1.7%, the recorded value being lower than the true value. Thus, for a true value of zero, the recorded value was -1.7° (right).

- Pitch Trim Parameter

The value recorded during takeoff was compared with that announced by the crew during trim selection, -that's to say 2.5°. The comparison showed that the calibration error is about 0.4°, the recorded value being lower than the true value. Thus, for a true value of 2.5°, the recorded value was 2.1°.

- Heading Parameter

The value recorded during takeoff was compared with the magnetic heading of the runway. The comparison showed that the calibration error is about 1°, the recorded value being higher than the true value. Thus, for a true value of 268°, the recorded value was 269°.

- Radio Altitude Parameter

The value recorded when the aircraft is on the ground, shock absorbers compressed, was compared with the expected value. The comparison showed that the calibration error is about 13.1 feet the recorded value being lower than the true value. Thus, for a true value of - 6.9 feet, the recorded value was - 20 feet.

1.11.3.1.2 Values of Parameters

Graphs derived from the recorded parameters for the whole of the flight are shown in appendix 4. Details of some significant parameters are listed below.

For a given generated time, the associated parameters are values sampled at a specified moment in the course of the corresponding second. This indication does not appear in the tables. In addition, only the parameters of one engine are recorded each second. Thus, the parameters of each engine appear only every four seconds.

The parameters of an engine are sampled within a second at the following exact times : N1 + 0.72 s ; N2 + 0.81 s ; EGT + 0.47 s ; FF + 0.22 s et P7 + 0.52 s.

N.B.: The numbers (❶, etc.) refer to the track shown in 1.9.1.

- 100 kt callout, generated time 97585 ❶

CAS: 100 kt

Control Column: 0.4°

Trim: 0.4°

Heading: 270°

Rudder bar: - 0.6° (right)

Lateral acceleration: between - 0.04 and 0.01

Longitudinal acceleration: 0.27

Time	Engine	N1	N2	EGT	FF t/h	P7
97585	4	93.16	102.83	723.6°	20.27	40.19
97586	1	94.10	102.63	750°	21.57	41.08
97587	2	93.96	103.04	750°	21.49	41.21
97588	3	89.94	102.83	763.7°	22.11	42.39

- one second after the V1 callout, generated time 97595 ❷

CAS: 151 kt

Control Column: 0.4°

Trim: 0.4°

Heading: 269°

Rudder bar: - 1.8 (right)

Lateral acceleration: between - 0.05 and - 0.04

Longitudinal acceleration: 0.28

Time	Engine	N1	N2	EGT	FF t/h	P7
97595	2	94.54	103.13	756.8°	22.34	42.49
97596	3	89.88	102.77	769.5°	22.92	43.47
97597	4	93.84	102.83	730.5°	21.23	41.96
97598	1	94.51	102.54	755.9°	22.54	42.89

- flames reported by the controller, generated time 97604 ③

CAS: 188 kt

Control column: - 3.8°

Trim: 1.3 (up)

Heading: 267°

Rudder bar: - 6.4 (right)

Lateral acceleration: between - 0.11 and - 0.17

Longitudinal acceleration: 0.16

Time	Engine	N1	N2	EGT	FF t/h	P7
97604	3	90.12	102.74	756.8°	23.33	44.11
97605	4	94.16	102.89	769.5°	21.67	42.88
97606	1	86.95	98.58	730.5°	18.28	38.04
97607	2	48.69	73.30	755.9°	0.95	17.30

- radio altitude positive, generated time 97614 ④

CAS: 201 kt

Control column: 0.6°

Trim: 12.8° (up)

AOA: 13.35°

Heading: 270°

Rudder bar: - 16.4 (right)

Radio altitude: 6 ft

Time	Engine	N1	N2	EGT	FF t/h	P7
97614	1	50.77	74.77	480.5°	1.32	17.54
97615	2 *	57.07	77.52	446.3°	3.48	19.54
97616	3	90.67	102.69	770.5°	22.97	43.72
97617	4	94.72	102.92	732.4°	21.47	42.33

*: engine fire warning

- request to retract landing gear, generated time 97621 ⑤

CAS: 199 kt
 Control column: 0.5°
 Trim: 11.1°(up)
 AOA: 12.27°
 Heading: 266°
 Rudder bar: - 11.9 (right)
 Radio altitude: 100 ft

Time	Engine	N1	N2	EGT	FF t/h	P7
97621	4	94.66	104.12	758.8°	23.87	44.08
97622	1	91.08	100.9	648.4°	14.22	41.04
97623	2	15.97	33.9	320.3°	0	13.78
97624	3	90.97	103.89	801.8°	25.67	45.16

- non retraction of gear noted, generated time 97647

CAS: 211 kt
 Control column: 1.7°
 Trim: 9.3°(up)
 AOA: 11.89° then 13.28°
 Heading: 271°
 Rudder bar: - 12.5 (right)
 Radio altitude: 182 ft

Time	Engine	N1	N2	EGT	FF t/h	P7
97647	2	6.27	13.92	235.4°	0	13.37
97648	3	91.64	104.00	796.9°	25.60	45.21
97649	4	95.13	104.21	762.7°	23.82	43.65
97650	1	94.92	103.54	758.8°	22.43	42.57

From generated time 97649 to generated time 97653, GPWS "Whoop Whoop Pull Up" alarm.

- OPL "Le Bourget Le Bourget", generated time 97665

CAS: 208 kt
 Control column: 1.9°
 Trim: 10.6°(up)
 AOA: 12.08°
 Roll: - 2.57° then - 4.69° (to the left)
 Heading: 270°
 Rudder bar: - 18.1 (right), Mechanical mode
 Radio altitude: 199 ft

Time	Engine	N1	N2	EGT	FF t/h	P7
97665	4	95.01	104.18	758.8°	23.67	43.82
97666	1	43.56	81.36	855.5°	3.64	15.01
97667	2 *	5.60	12.92	182.6°	0	13.88
97668	3	90.91	103.68	793.9°	25.52	44.97

*: engine fire warning

- message *"negative we're trying for Le Bourget"*, generated time 97673

CAS: 181 kt

Control column: 7.6°

Trim: 16.5°(up)

AOA: 19.52°

Roll: - 38.82° then - 40.93° (left)

Heading: 238°

Rudder bar: - 22.5° (right), Mechanical mode

Radio altitude: 300 ft (see note)

Time	Engine	N1	N2	EGT	FF t/h	P7
97673	4	95.13	104.21	757.8°	23.22	42.53
97674	1	25.17	51.39	640.6°	0	14.35
97675	2 *	5.19	12.30	168.9°	0	14.05
97676	3	91.41	103.98	798.8°	24.55	42.33

*: engine fire warning

- four seconds before the end of the recording, generated time 97677

CAS: 136 kt

Control column: 3.4°

Trim: 13.2°(up)

AOA: 25.15°

Roll: - 95.58° then - 108.17°(left)

Heading: 193°

Rudder bar: - 28.3 (right), Mechanical mode

Radio altitude: 459 ft (see note)

Note: for generated times 97673 and 97677, the radio-altimeter readings are no longer representative due to the extreme roll attitude of the aircraft.

Time	Engine	N1	N2	EGT	FF t/h	P7
97677	4	96.39	104.62	764.6°	22.90	40.04
97678	1	20.04	42.60	585.9°	0	13.71
97679	2 *	5.13	11.98	164.1°	0	14.02
97680	3	55.11	80.60	776.4°	14.63	17.75

*: engine fire warning

1.11.3.2 Track (end of report)

In the absence of recorded parameters relating to the position of the aircraft (longitude, latitude), its track was calculated by several integration methods, by fixing the first and last points on their known position. A reasonable approximation of the ground track was thus obtained, in particular while the aircraft was on the runway. Bearing in mind the method used, the tolerance is of the order of about a dozen metres. The exactitude of the calculation diminishes in the second part of the flight, the tolerance becoming around a hundred metres, especially in the final phase, after the loss of engine 1, since the aircraft's attitudes no longer guaranteed a representative ground track.

1.12 Wreckage and Impact Information

1.12.1 The Runway

Various debris and marks were found on the runway after the accident (see appendix 12). They are identified in the following by the grid number of the concrete slab where they were found, the distances being measured in relation to the eastern end of the tarmac part of the runway (see § 1.10). Thus, for example, an element identified at Slab 180 level was found 1,950 m from the point of origin (600 m + 180 x 7.5 m). Debris was also found under the aircraft's flight path.

Note: the point at which the brakes were released is located between 65 and 85 m from the beginning of the runway.

1.12.1.1 Water Deflector

Parts of the water deflector of the left main landing gear were found between Slabs 139 and 166, that is 1,642 to 1,845 m from the beginning of runway 26 right, more precisely at 139, 149, 151, 157 and 166. The parts found did not include metallic parts.



Figure 19: Part located at line 157 - right part of deflector

1.12.1.2 Pieces of Tyre

Pieces of tyre from the Concorde were found at slab levels 146, 152, 166, 180, 186 and 187. The parts found at Slab 152 level (a piece measuring 100 x 33 cm and weighing about 4.5 kg) and that found at Slab 180 level fitted together. Visual inspection revealed a transverse cut about 32 centimetres long.



Figure 20: Piece of tyre at line 180 - piece of tyre at line 152

1.12.1.3 Piece of Metal

A strip of metal about 43 centimetres long, bent at one of its ends, was found on the runway shoulder at Slab 152 level. Its width varies from 29 to 34 mm and it has drilled holes, some containing rivets, similar to the Cherry aeronautical type. The holes are not at regular intervals.

On visual inspection, the piece appeared to be made of light alloy, coated on one side with epoxy primer (greenish) and on the other side with what appeared to be red aircraft mastic for hot sections (RTV 106). It did not appear to have been exposed to high temperature.

This piece was not identified as part of the Concorde.



Figure 21: Piece found at line 152

1.12.1.4 Structural Element



A ribbed structural part measuring about 32 x 32 cm was found at Slab 160 level. It was white on the external side and dark on the ribbed side. It came from the aircraft's No 5 fuel tank. It showed no signs of impact damage.

Figure 22: Part found at line 160

1.12.1.5 Brake Servo Valve Cover



An inboard alloy part, identified as the brake servo valve cover, from the left main landing gear, was found at Slab 175 level. This part was sooted and had clearly been overheated. It had impact deformation.

Figure 23: Part found at line 175

1.12.1.6 Piece of Concrete and Signs of Explosion

Signs of an explosion and a piece of concrete separated from the runway were found at the Slab 181 level. The piece of concrete was about one centimetre thick, 10 centimetres wide and 25 to 30 centimetres long. Found intact, it was later broken in two. A very pronounced black mark was noted around this part.

1.12.1.7 Lighting

The runway left edge light at the Slab 293 level (about 2,800 m from the origin) was broken and small pieces of the light were found nearby. Ground marks showed that this light was broken by the Concorde's left main landing gear.

1.12.1.8 Tyre tracks

From Slab 161 level to Slab 232 level, that is between 1,807 and 2,340 m, the mark of a deflated tyre with an incomplete tread was observed.

This mark was parallel to the runway axis (at about 3.8 m) then diverged at about 2,200 metres.

When this mark disappeared at about 2,340 m, its displacement from the centreline was about 8 m. This corresponded to the right front tyre of the aircraft's left landing gear.

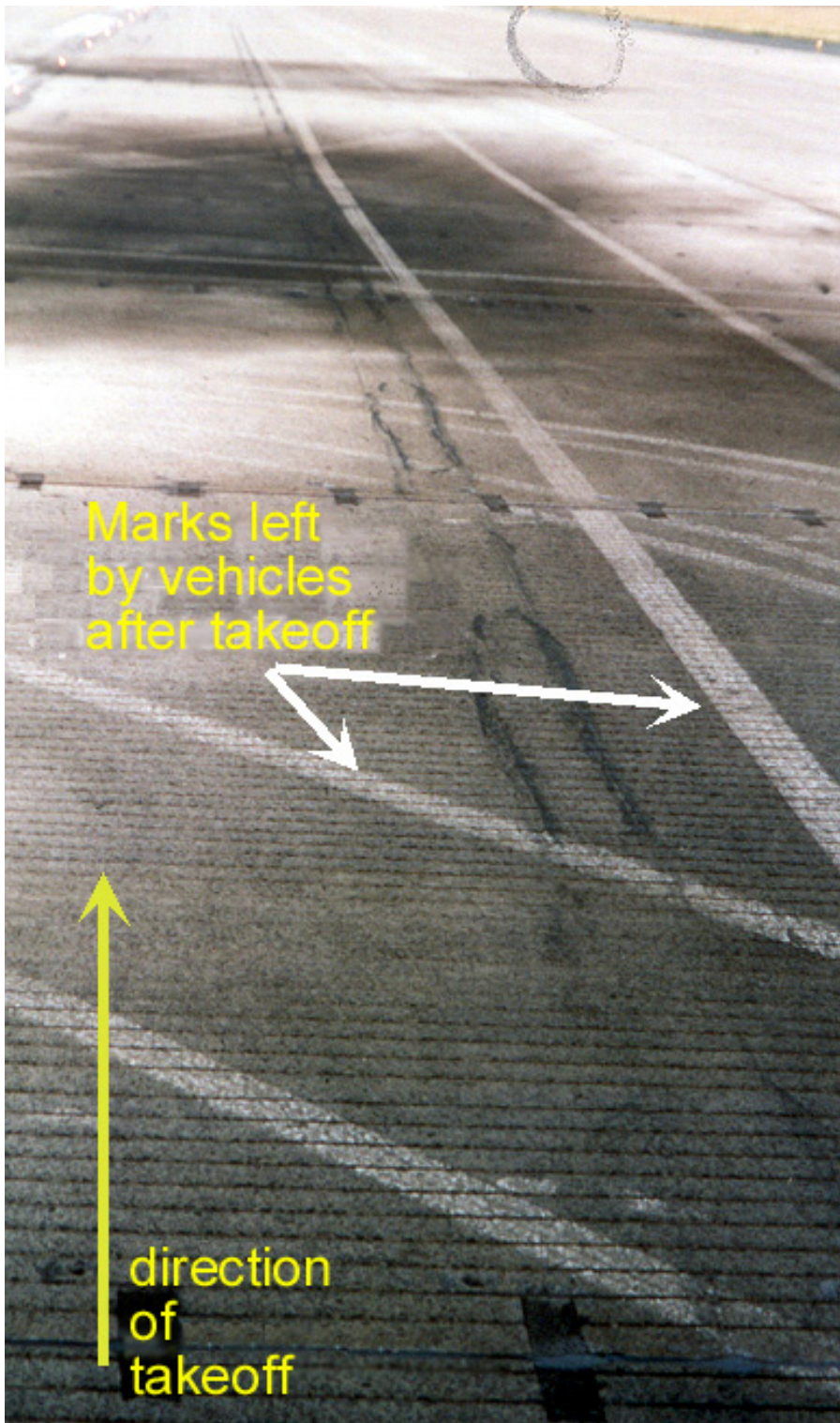


Figure 24: Marks of Wheel No 2 and soot on the runway

Further on, some irregular tyre tracks from the left landing gear were noted up to the broken edge light (2,800 metres).

After that point, the tracks become intermittent then disappear at about 2,830 metres from the runway threshold



Figure 25: Marks of left bogie tyres and edge light

1.12.1.9 Soot Deposits on Runway

A mark 15 m x 15 m identified as probably being kerosene was noted around line 163, 1,820 metres from the threshold. Then, traces of soot, produced by incomplete

combustion of kerosene, were apparent on the runway 1,860 m onward from the origin (Slab 168). These were large and dense up to 2,300 m and then became less dense and rich in carbon up to taxiway S4, at 2,770 metres. The traces, which were on average 7 m wide, were initially centred on the damaged wheel ground mark and progressed towards the left.



Figure 26: Soot marks on the runway

A further sooted area was apparent after taxiway S4 up to the broken edge light.

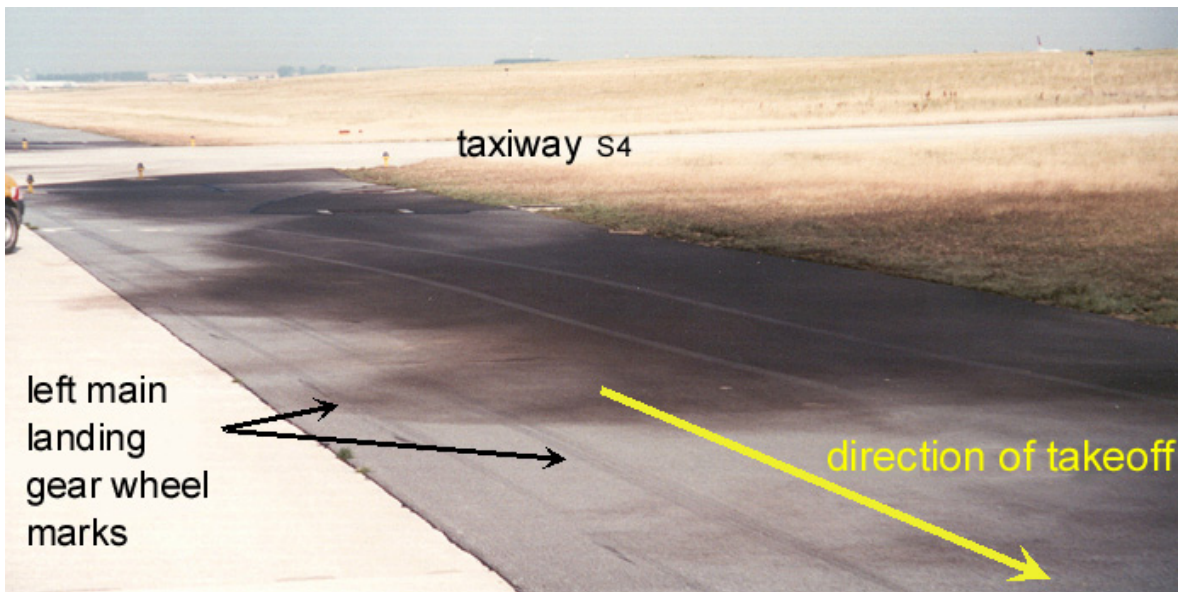


Figure 27: Left main gear wheel marks

The grass was burnt adjacent to the runway edge, between 2,902 and 3,165 metres. This area, also featuring soot deposits, indicated that there was an extensive flame after the aircraft became airborne.



Figure 28: Burnt grass on the edge on the runway

1.12.2 Between Runway 26 Right and the Accident Site

The following elements were identified

- in the 1,000 m after the end of the runway, near the extended centreline:
 - o a piece identified as coming from a repair on the left inner elevon
 - o the tail cone anti-collision light,
 - o a severely fire-damaged inspection panel from the wing lower surface,
 - o seven inspection panels identified as coming from the upper surface of the left wing dry bay, with no signs of fire,
- from 1,000 to 2,500 m after the end of the runway:
 - o an inspection panel also coming from the upper surface of the left wing dry bay and showing no signs of fire,
 - o a fire-damaged piece of duct,
 - o fire-damaged structural parts that appear to have come from the aircraft tail cone.

Burn marks on the ground were visible where certain items of debris were found, particularly where the tar had melted adjacent to items found on the roofs of buildings in the freight zone. A wheat field was damaged by fire 2,500 m from end of the runway.

- beyond threshold 08 left, the following was noted:
 - o two hydraulic shutoff valves, one damaged by fire,
 - o two lower inspection panels from the engine nacelle, one melted, the other intact,
 - o debris from the wings, in particular fuel tank parts,
 - o a fire-damaged hydraulic line,
 - o The left MLG inspection panel.

Leading up to the crash site, many small pieces of metal, honeycomb components, pieces of riveted structure and parts of the rear fuselage, were found. Most of these parts show traces of fire and their distribution was continuous along the aircraft's track.

1.12.3 The Accident Site

1.12.3.1 Description of Site and Plan

The crash occurred south-west of Paris Charles de Gaulle airport at about 9,500 m from the threshold of runway 26R in a level area. The altitude of the area is 400 feet. The wreckage was at the intersection of the N17 and the D902 roads.

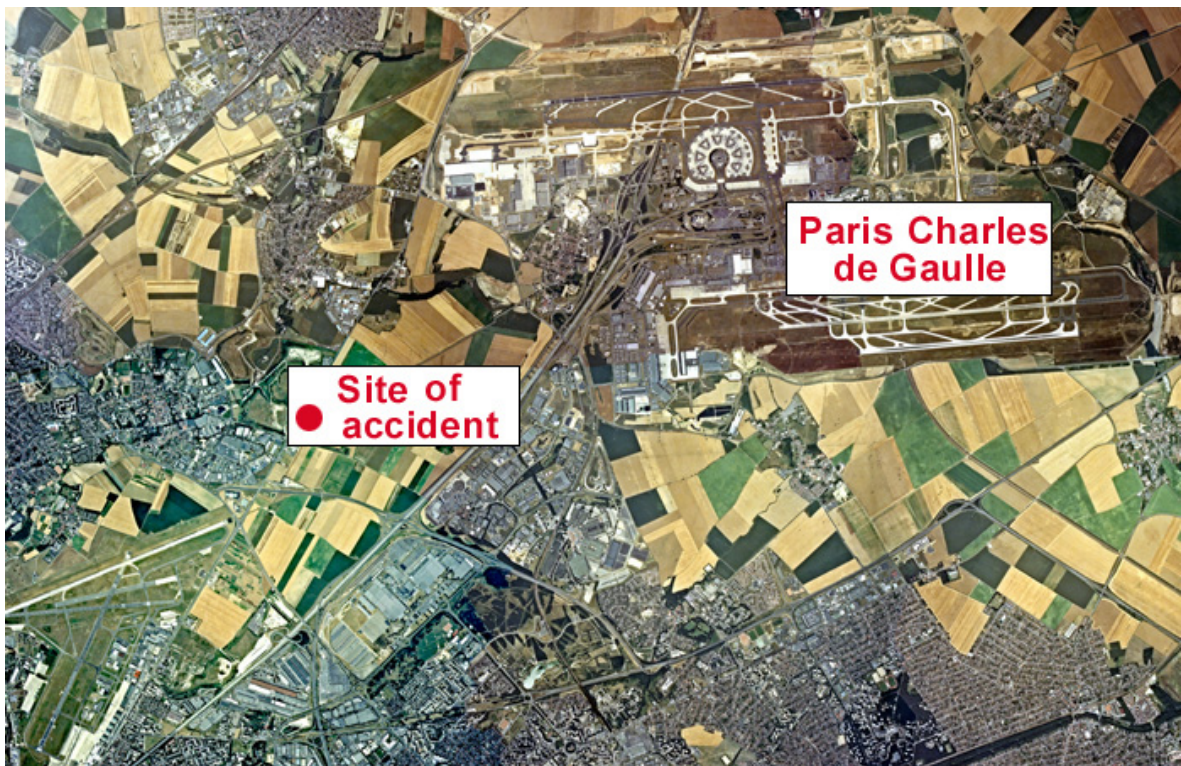


Figure 29: BEA/IGN/FLEXIMAGE image - Aerial photo of the accident site

The crash site was divided into a grid. The various areas were referenced to this grid.

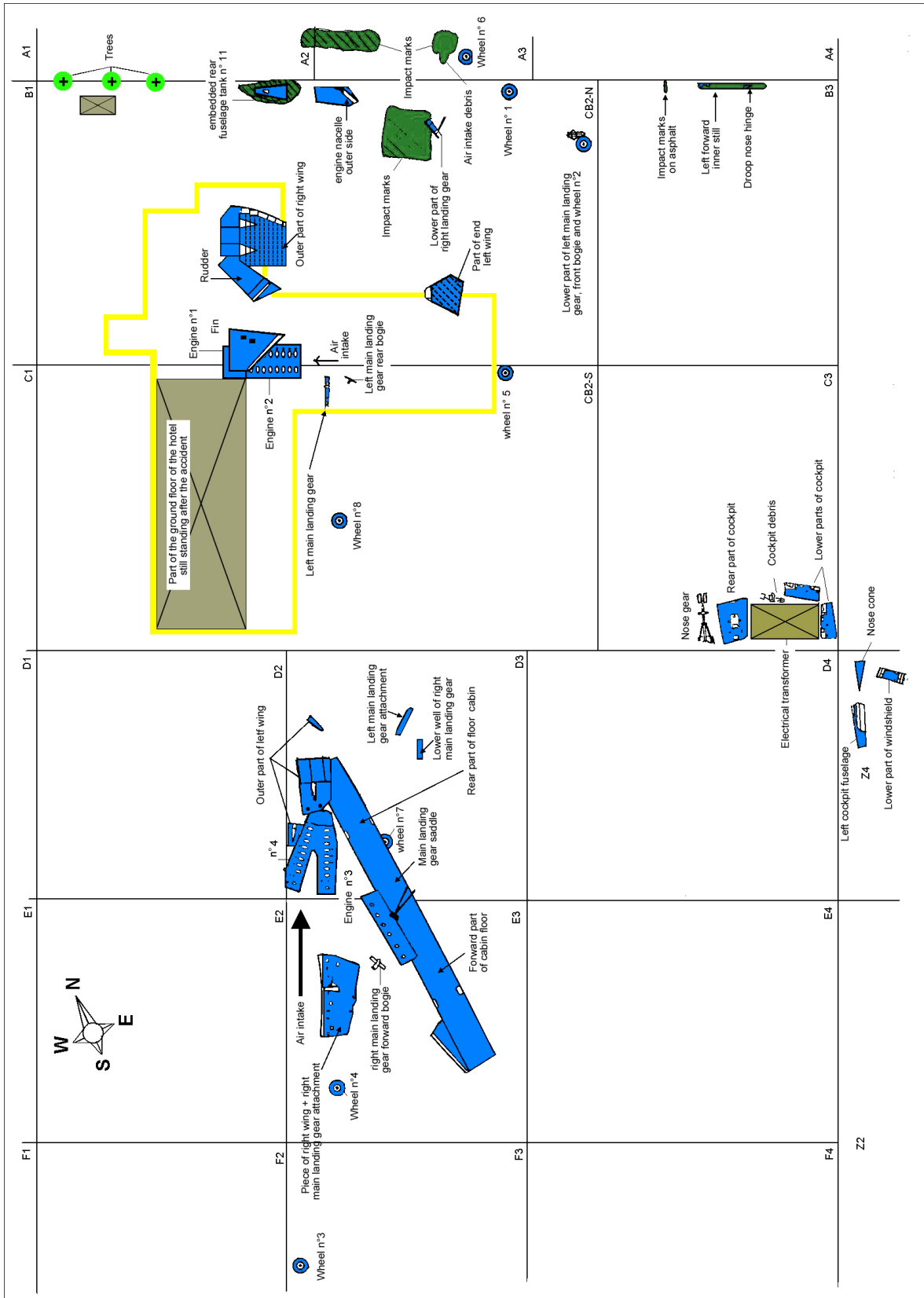


Figure 30: Wreckage distribution plan

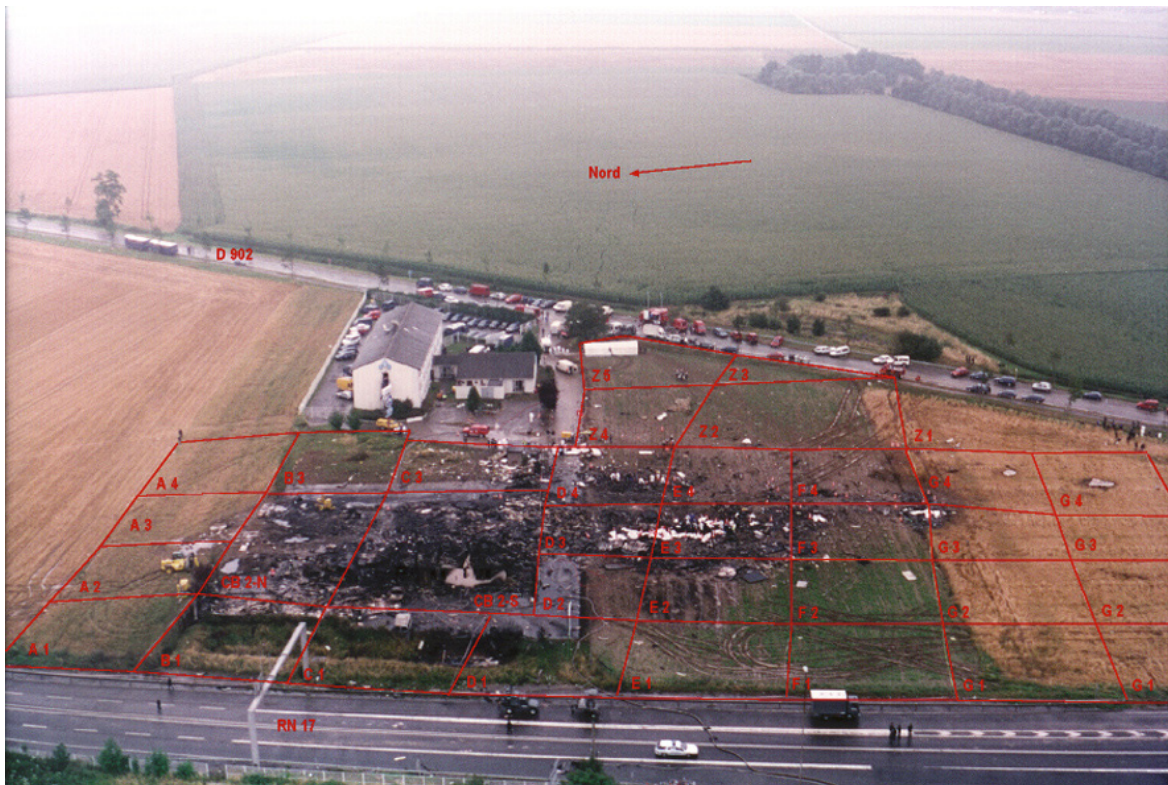


Figure 31: Aerial view with indications of zones

Examination of the site showed that the aircraft had struck the ground on heading 120° left, practically flat with little forward speed. After the impact, it broke and spread generally to the south, with the aircraft upright.

The wreckage was extensively burnt. Only the front parts of the aircraft, found mainly in areas C3, D4 and Z4 escaped the ground fire, together with a few pieces of the fuselage scattered over the site. Most of the wreckage, with the exception of the cockpit, remained within a rectangle measuring a hundred metres long by fifty metres wide (areas CB2, D3 and E3).

Signs of ground impact were found to the north of the site at the intersection of areas A and B. There was a row of trees about three metres high, oriented east to west, then a crater at the bottom of which was rear tank 11. Pieces of engine air intake were found half-buried at A3 and signs of ground impact were apparent at A3 and CB2-North. Wheel No 6 was embedded in the ground.



Figure 32: Impact marks

At B3, an impact mark was visible in the asphalt. Forward parts of the aircraft were in a line embedded in the earth, including the front left door sill and a hinge from the aircraft's droop nose. Near these items of debris, the grass was sparse.

The hotel located at CB2-North was almost entirely flattened. The lower parts of the left and right main landing gears were close to the initial impact marks. In the part of the hotel which was destroyed, a punctured lower skin panel and an upper skin panel from tank 5 were found.

The outer part of the left wing, with the outer elevons still attached, was found melted on the ground. Nearby was the inner part of the wing with the left dry bay with engines 1 and 2 still attached. The rudder was found between these two parts. The fin was resting on the dry bay. The left inner elevon was found beneath the two engines, still linked to part of the wing (this assembly is normally located between the left power plants and the fuselage). The engines were resting on a water tank 1.5 m in height. Many wing parts were found nearby, including the lower surfaces of tanks 6 and 10.

The left main landing gear leg, still connected to its side strut, was found at CB2-South. Examination of the strut's locking mechanism showed that the landing gear was down and locked at the time of impact.

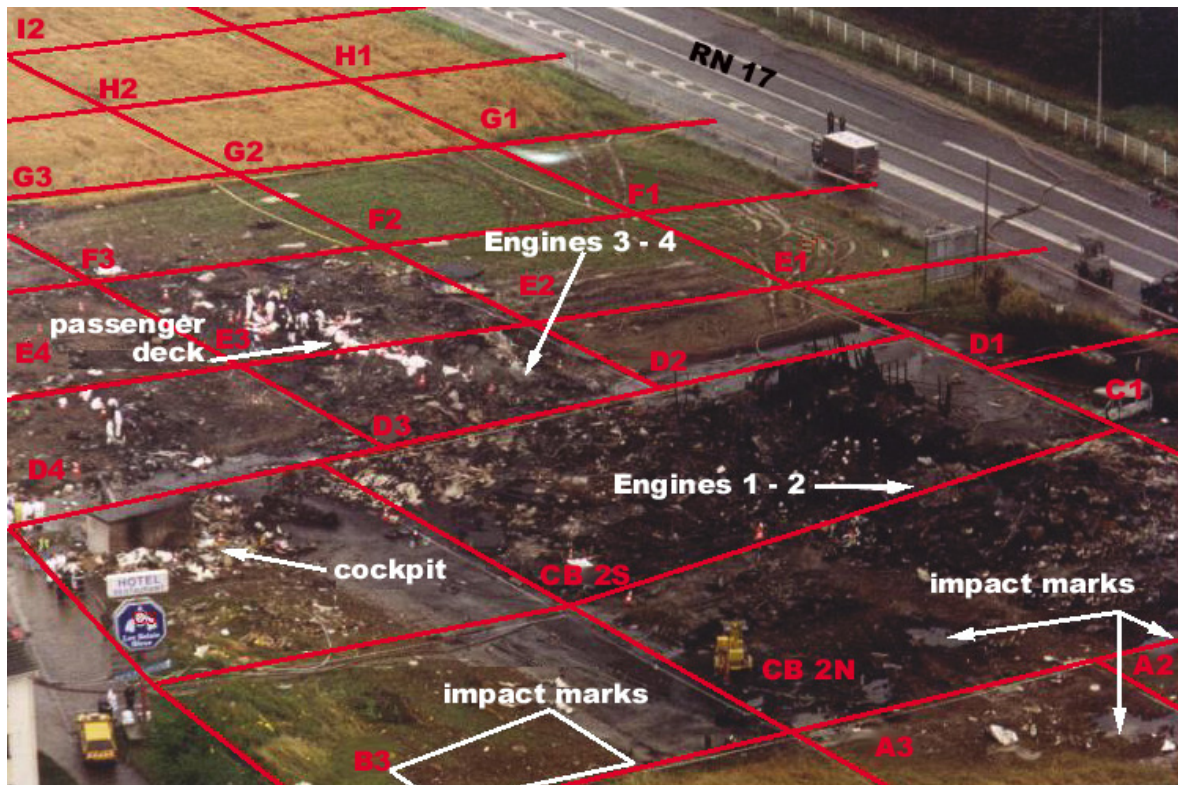


Figure 33: Aerial view with position of main parts

In the western area of the CB2-South rectangle, part of the ground floor of the hotel was still standing. A large number of items of debris from the building were found in the eastern area.

At C3, a large number of parts belonging to the cockpit had impacted an electric power transformer. The pilots' seats, the throttle levers and the autopilot control unit were found at this point. The seven landing gear ground lock pins were found with their stowage bag.

Next to this there was a section of the fuselage in which it was possible to recognise the aisle between cockpit and cabin. From this wreckage the QAR and the main components of the flight crew instrument panels were extracted (description follows).

Nearby, the nose landing gear was found, extended.

The main components of the Concorde's structure were found at D3 and E3, along the axis of the wreckage scatter. The passenger cabin was identifiable from pieces of fuselage, together with a large number of items of debris from the hotel. The passenger seats and most of the victims were found in these areas. The hydraulic tanks normally located in the rear hold and the CVR were found at E3 and the radio altimeters installed in the forward hold were found at D3. The structures of the main landing gear wheel well were grouped together at the intersection of areas D3 and E3, near the landing gear legs.

The right dry bay with engines 3 and 4 still partially attached was found at D3, to the right of the passenger cabin. Nearby, a large number of pieces of the right wing were found, including the three PFCU's that control the right elevons. The left main landing gear attachment structure was found to the left of the passenger cabin.

The right main landing gear attachment structure and a melted piece of the right wing were found at E3, to the right of the passenger cabin.

Pieces of fuselage were found in the peripheral areas H and I and in Z2.

1.12.3.2 Instrument Indications

The emergency landing gear extension selector on the rear of the flight deck centre console was not selected. The following indications were noted on the instruments found on the central panel:

- Engine speed indicators

	Engine 1	Engine 2	Engine 3	Engine 4
N1	Absent	Absent	52%	58%
N2	28%	4%	80%	85%

- Fuel Flow indicators

	Engine 1	Engine 2	Engine 3	Engine 4
FF	0	Burnt	Burnt	Close to 0

For engine 4, a (yellow) pre-set display showed 19.6 kg/h x 1,000.

- EGT indicators

	Engine 1	Engine 2	Engine 3	Engine 4
EGT	580 °C	220 °C	600 °C	600 °C

- Brake pressure indicator: 400 Psi left and 1,500 Psi right.

- AJ indicators: unreadable, the needles were missing for engines 3 and 4.

A Primary Nozzle Area Indicator, S/N AA115, and one unidentified and unreadable temperature indicator were also found..

On the FO instrument panel, the following items were noted:

- the Nose/Visor lever was in the "Down" position
- the landing gear selector was towards the "Down" position, past the gate
- on the rudder position indicator (damaged on impact), the rudder indicators were at 20° left for the upper control surface and 12° right for the lower control surface on "G" (Green). The indicators for the elevons were on "M" (Mechanical) and provided no information
- the airspeed shown on the airspeed indicator was 99 Kt, "STBY" flag, and V2 bug was on 230 kt
- HSI heading 105°, ADI 30° roll to the left and 32° nose down. Vz - 1,800 ft/min, altimeter - 240 feet "STBY" flag, radio altimeter unreadable, VOR1 028°, VOR2 038°
- FD switch on number 2
- attitude selector on ATT INS3, comparator on COMP2, deviation on DEV2, navigation on NAV INS2
- clock on 14 h 45 UTC



Figure 34: Overall view of instrument panel

On the Captain's instrument panel, the following items were noted:

- HSI heading 105°, ADI 15° roll to the left and 75° nose down, standby horizon 90° roll to the left and 18° nose-up, Vz – 1,200 ft/min, altimeter - 250 feet STBY, radio altimeter on 0, angle of attack indicator unreadable, RMI ADF heading 100°
- trim indicator on 54.3%
- the TCAS was broken

On the coaming the following items were noted:

- auto-throttle 1 and 2: Off
- autopilot 1 and 2: Off
- flight director 1 and 2: Off
- auto-throttle, selected speed 285 kt
- altitude selected 9,500 feet
- left display, heading 329°, course 285°
- right display, heading 338°, course 287°

On the overhead panel, the following items were noted:

- servo-control hydraulic selectors on "normal"
- Engine Flight Rating switches: No 1 CRZ, No 2, 3 and 4 CMB
- Auto Ignition 1, 2 and 3 switches "On", No 4 melted
- auto-throttle 1, 2, 3 and 4 switches "On"
- Engine Rating Mode switches 1, 2, 3 and 4 on "Take-Off"
- HP Valve selector switches damaged and on positions: 1 "Open", 2 broken, 3 "Shut", 4 "Open"
- engine shutdown/fire handle No 2 pulled and pointing upwards
- extinguisher bottle fired indicators unreadable
- flying control electrical system selectors:

	1	2
Auto stab	Unreadable	Pitch axis: "Off" Roll axis: unreadable Yaw axis: "Off"
Artificial feel	Blue circuit Pitch axis: "Off" Roll axis: unreadable Yaw axis: "Up"	Green circuit Pitch axis: "Off" Roll axis: "Off" Yaw axis: "Off"
Electric trim	"Off"	"Off"

- inverter controls difficult to read, with the following possible positions:
 - blue inverter on "Power Off" and control broken
 - green inverter on "Off"
- flight control mode selectors damaged, in the following possible positions:
 - outer and middle elevon on "Mech?" (Mechanical)
 - inner elevon on "Green?"
 - rudder on "Blue?"
 - anti-stall 1 and 2 unreadable

The warning panel was destroyed, separated from the rest of the upper panel and most of the covers and bulbs were missing.

On the flight engineer's lower left panel, the following items were noted:

- fire loop selectors: 1 "both", 2 "loop A", 3 "loop B", 4 "neutral", switch twisted and blocked

On the flight engineer's lateral left panel, the following items were noted:

	Engine 1	Engine 2	Engine 3	Engine 4
P7 indicators	18 Psi	12 Psi	18 Psi	18 Psi

The rest of the right part of this panel was unreadable. The left part relating to the air intakes was not read at the site.

On the flight engineer's upper left panel, the following items were noted:

- Engine Control Schedule function: selector on "Flyover", switch blocked on "HI"
- brakes hydraulic pressure: 6,000 Psi with flag
- brakes fan switch on "On"
- clock stopped at 14 hours 45 UTC
- brake temperature: 170 °C, pushbutton No 3 crushed and deformed

	Engine 1	Engine 2	Engine 3	Engine 4
Secondary nozzle indicators	0°	15°	5°	broken

The pressurisation system indications featured on this panel were not read out at the site.

On the flight engineer's central upper panel (fuel and air conditioning), the following items were noted:

- Tank 9
 - indicated quantity of fuel "11 t",
 - left pump on "Auto", right pump on "On"
 - main left Inlet Valve on "Shut" (free movement of the switch which has no locking device), Override on "O/ride"
 - main right Inlet Valve on "Auto", Override on "Off"
- Tank 10
 - indicated quantity of fuel "12 t",
 - left pump on "Off", switch damaged, right pump on "Auto"
- Tank 5A
 - indicated quantity of fuel "2.4 t",
 - two pumps on "On"
- Tank 7A
 - indicated quantity of fuel "2.2 t"
 - two pumps on "On"
- Also
 - Standby Inlet Valves 5, 6 and 1 on "Open", 2 on "Shut"
 - Standby Inlet Valves 3, 4, 10 and 7 on "Shut", 8 on "Open"
 - Jettison tank switches 1 and 3 in intermediate position, 4 on "Open", 2 on "Shut"
 - Master Jettison and Trim Pipe Drain switches unreadable

On the flight engineer's central panel (fuel), the following items were noted:

- Tank 5
 - indicated quantity of fuel "2 t"
 - pump switches unreadable
- Tank 6
 - indicated quantity of fuel "4.6 t"
 - left pump switch unreadable, right pump switch on "On"
- Tank 1
 - indicated quantity of fuel "4.2 t"
 - main pump on "On", STBY1 on "On", STBY2 on "Off"
- Tank 2
 - indicated quantity of fuel "0.1 t"
 - three pumps on "On"
- Tank 7
 - indicated quantity of fuel "6.6 t"
 - pump switches unreadable
- Tank 8
 - indicated quantity of fuel "12.8 t"
 - two pumps on "On", right pump switch damaged
- Tank 3
 - indicated quantity of fuel "4.3 t",
 - pump switches unreadable
- Tank 4
 - indicated quantity of fuel "4.3 t"
 - pump switches unreadable
- Tank 11
 - indicated quantity of fuel "10 t"
 - left hydraulic pump on "Auto", right on "Off"
 - position of electric pumps unreadable
 - main left Inlet Valve on "Shut", Override unreadable
 - main right Inlet Valve and Override unreadable

The FQIP (Fuel Quantity Indicator Panel) had the following pre-setting indications:

- ZFW (Zero Fuel Weight): 91.9 t
- CG 52.29%
- "Main" lane
- Total Contents indicator: 78.8 t with flag

On the flight engineer's right upper panel (electrical and hydraulic generation), the following items were noted:

- Green Circuit
 - Level below zero with flag
 - Shut Off Valve indicators of pumps 1 and 2 with flags
 - hydraulic pumps 1 and 2 indicators on "On"
 - hydraulic pumps 1 and 2 switches on "On"
 - hydraulic pressure 2,000 Psi with flag
- Yellow Circuit
 - "6 US Gal" level with flag
 - Shut Off Valve indicators of pumps 2 and 4 with flags
 - hydraulic pumps 2 and 4 indicators on "On"
 - pump selector switches 2 on "Auto", pump 4 on "On"
 - pressure unreadable
- Blue Circuit
 - "2.7 US Gal" level with flag
 - Shut Off Valve indicators of pumps 3 and 4 with flags scratched
 - hydraulic pumps 3 and 4 indicators on "On"
 - pump selector switch 3 on "Off", pump 4 on "On"
 - hydraulic pressure 6,000 Psi with flag
- Also
 - "Yellow Pump" switch on "Normal"
 - IDG 1, 2 and 3 indicators unreadable, 4 on "60 KW"
 - all alternator switches on "On"

On the flight engineer's right side panel (electrical generation), which was heavily damaged and burnt, only the following items providing information were noted:

- transformer rectifier unit (TRU) ammeters: 1 burnt "0", 2 broken "0", 3 "30A", 4 broken "70A"
- TRU selectors: TR1 unreadable, TR2 on "Normal", TR3 on "Isol", TR4 selector missing
- Eng 1 & 4 and Eng 2 & 3 nozzle safety switches on "Normal" but damaged on impact
- fuel tank pressure: "0" (touching red index)

On the flight engineer's lower right panel, which was heavily damaged and burnt, the following items were noted:

- passenger oxygen pressure: 40 Psi with flag
- crew oxygen pressure indicator damaged, indicating "0"
- oxygen selector missing
- four fire extinguisher cartridge indicators: "Full"
- extinguisher check selector unreadable

Note: the position of the controls and the indications on the instruments at the site may not correspond to their position at the time of impact because of the loss of electrical power, movement due to the shock and/or because of fire.

1.12.3.3 Examination of Engines

1.12.3.3.1 Secondary exhaust nozzles

The upper secondary exhaust nozzles were still in place on engines 1, 2, 4 and separated from the nozzle structure on engine 3. The lower secondary exhaust nozzles were separated from the structure and three of them were found intact. The upper actuators from engines 2 and 4 were attached to the structure and to the nozzles. The lower actuators were found at the site with the exception of that of engine 3.



Figure 35: General view of engine 4 upper nozzle

1.12.3.3.2 Primary exhaust nozzles



The primary exhaust nozzle from engine 3 was separated from the structure of the secondary nozzle. The latter was torn away from the rest of the engine. The nozzles from engines 1, 2 and 4 were in place but flattened by the impact with the ground.

Figure 36: Engine 2 exhaust nozzle

1.12.3.3.3 General findings

The primary and secondary nozzles showed no signs of overheat on any of the engines. Black marks were visible on the inner panels of the engine 1 nozzles. Traces of soot were also found on the upper right part of the structure of the engine 2 nozzles. No trace of damage caused by an uncontained engine burst was noted.

The position of engines 1 and 2 nozzles was about 21°, a position compatible with the takeoff phase or the shutdown of an engine. The position of the engines 3 and 4 nozzles was 0°.

Examination of engine 2 appears to indicate a negligible N1 before impact. The rotor of the LP compressor of engine 1 apparently made less than a quarter of a revolution after the impact before being stopped by the casing being crushed.



Figure 37: Engine 1 LP compressor

Engines 1 and 2 showed signs of damage (FOD) by a soft object on the LP compressor rotor blades. Engine 1 also showed signs of FOD by a hard object. The damage found on engines 3 and 4 showed that they hit the ground with an N1 much higher than that of engine 1.

None of the engines showed signs of any fire occurring before the crash.

1.12.3.4 Examination of Wheels and Tyres

1.12.3.4.1 Wheel No 1

The entire wheel was burnt. The tyre, although burnt, showed no abnormal absence of material before impact at the accident site. There was black powder, the residue of combustion, on the base of the wheel. No trace of fire prior to the crash was observed. The two half rims were complete.

The brake pack was separated from the wheel, being found about two metres away in an area affected by fire. It was covered with a deposit of soot.

1.12.3.4.2 Wheel No 2

The tyre was damaged by fire. The two beads were not linked by the tread. The outer bead of the tyre was complete and almost intact. The inner bead was broken and the metal wires of the bead cores were exposed and broken all precisely at the same point. The wire's protective rubber was burnt.

The sides showed local ruptures oriented at about 45°. There was an abnormal lack of material at the site. The black material which is left after the rubber combustion that would have corresponded to the volume missing at the base of the tyre could not be found. The two half rims were complete.

The wheel coloration was still blue, which indicates that it had not suffered from fire prior to the crash.

The brake pack was in place on the wheel axle.

1.12.3.4.3 Wheel No 5

The tyre showed no abnormal lack of material. It had a static rupture characteristic of overload. The entire wheel appeared normal except for the part exposed to the ground fire where the tread had been superficially burnt. This wheel and tyre did not suffer from fire during flight.

The two half rims were complete.

The brake pack was in place in the wheel.

1.12.3.4.4 Wheel No 6

The tyre showed no abnormal lack of material. It had a static rupture characteristic of overload. The entire wheel had a normal appearance, without traces of burning.

The two half rims were complete.

The brake pack was in place in the wheel.

1.12.4 Work on the Wreckage

1.12.4.1 Reconstruction of the Wing and Examination of the Debris

Following a first phase focused on the lower wing around the gear well, a second reconstruction phase centred on the parts of the wing between spars 46 and 72 and between ribs 21 left and right took place from 1 October 2000 to 31 January 2001. This operation was undertaken by the BEA and the AAIB with the active collaboration of their respective advisers.

The parts found at the accident site were sorted according to geometrical criteria, so as to create groups of pieces before identifying and positioning them. The pieces of the wing were laid flat on two areas representing the upper and lower wing surfaces. The condition of the wreckage did not, however, allow much useful information to be gleaned for the investigation.

Note: the presence of asbestos released when the accident occurred caused some difficulties, mainly as a result of the need to install special equipment.

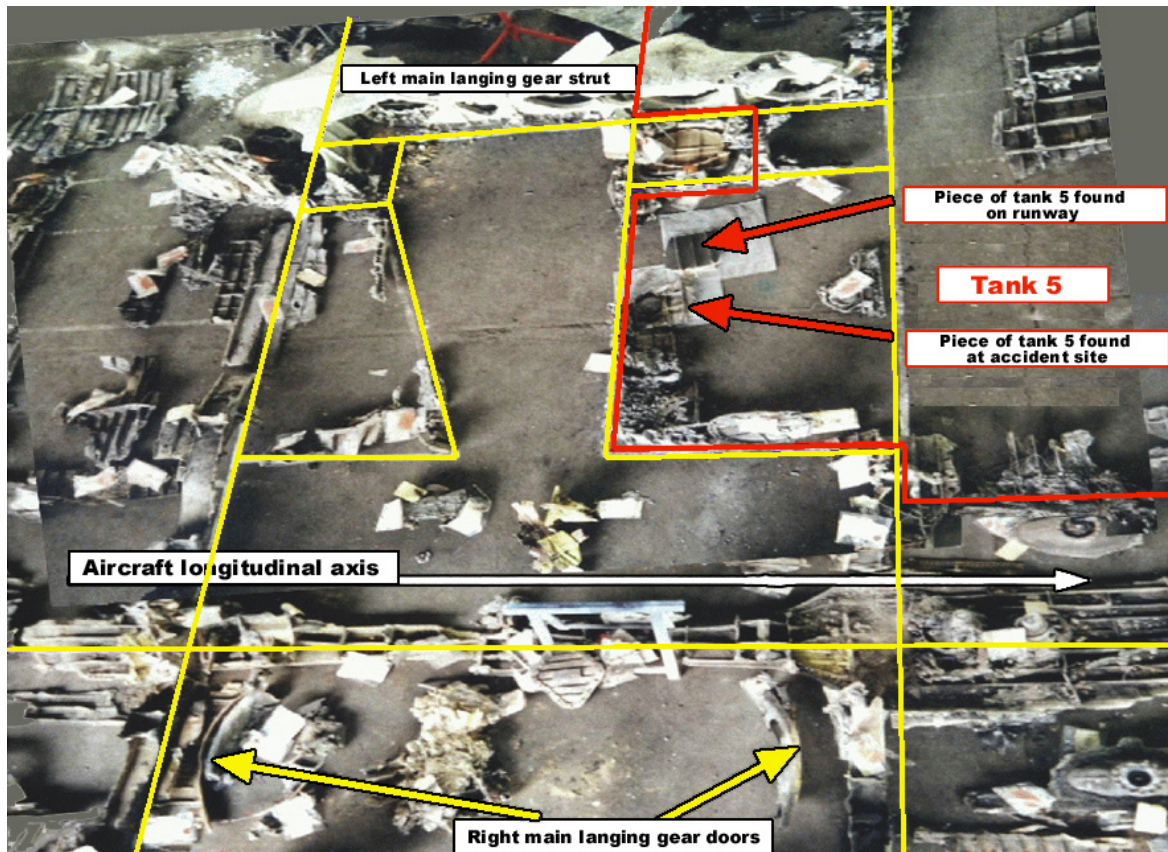


Figure 38: View of wing reconstruction in hangar

1.12.4.1.1 Upper Wing

It was not possible to reconstruct the surfaces located near the landing gear well, nor the majority of the right wing. A melted piece appeared to have some small punctures.

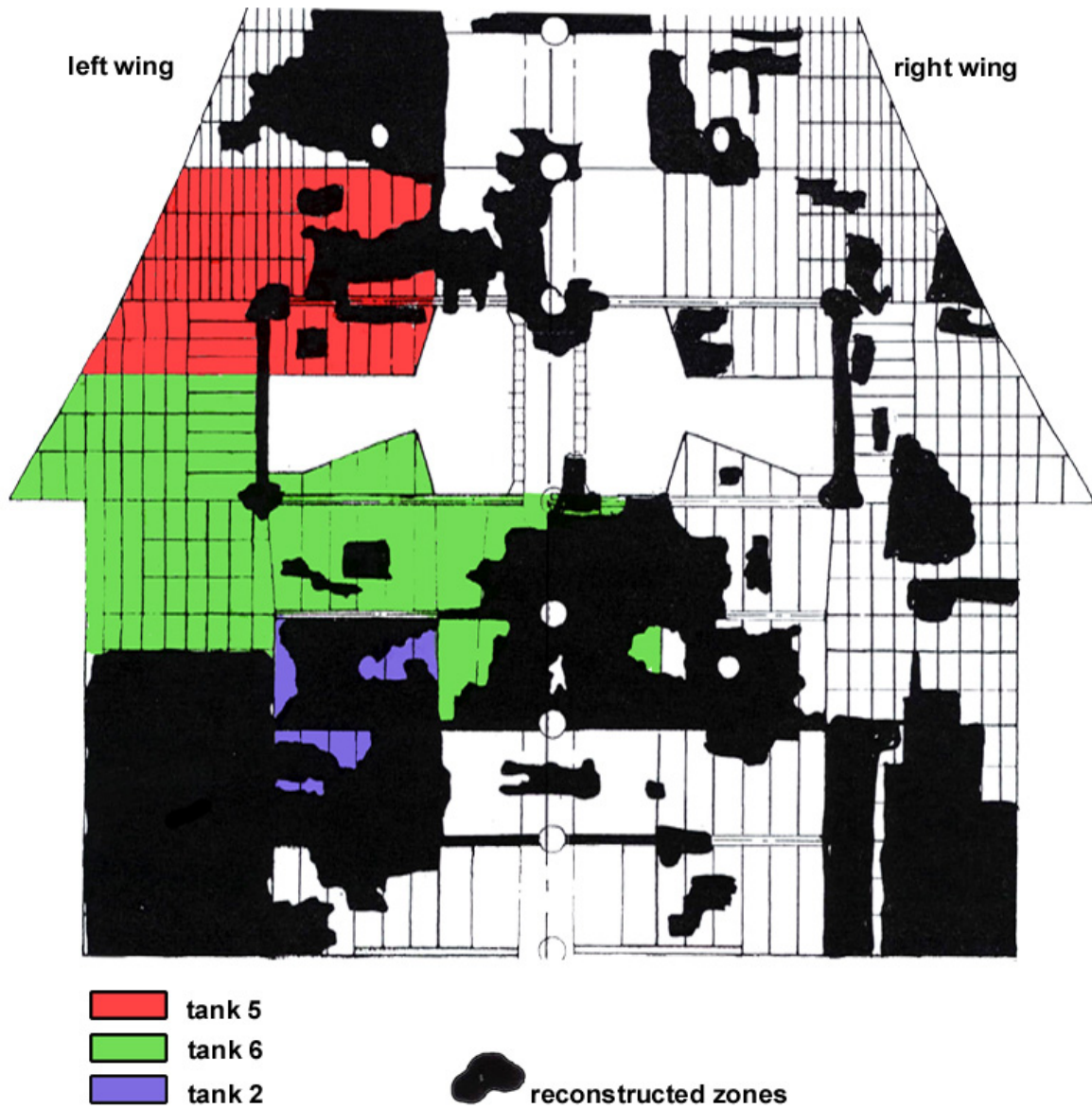


Figure 39: Computer reconstitution of upper wing

1.12.4.1.2 Lower Wing

Almost nothing from tank 5 was recovered. Only one part of the edge of the landing gear well and two probe locations were still visible near the location of the piece found on the runway. These parts showed no puncture or impact marks, except on one of them.

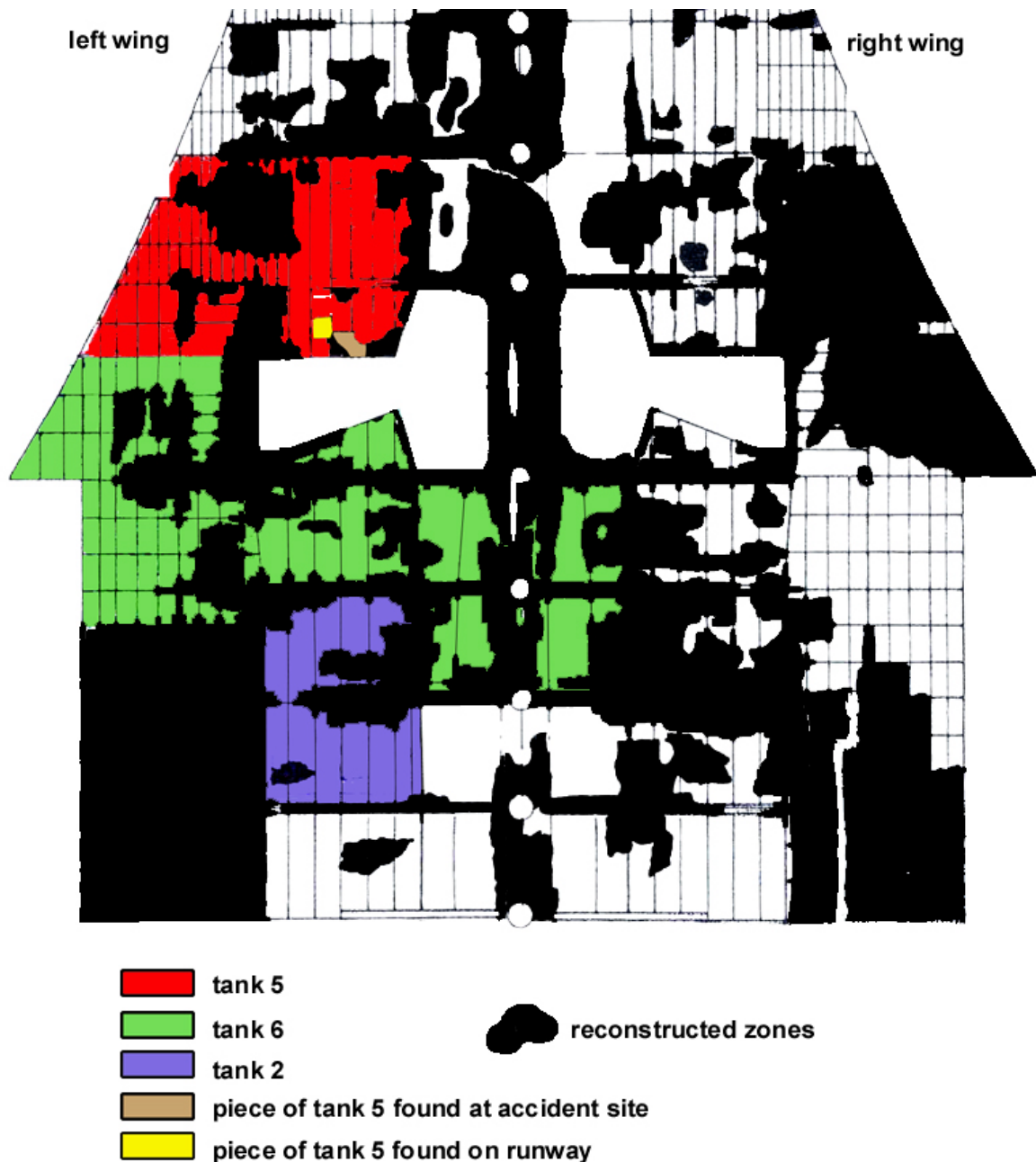


Figure 40: Computer reconstruction of lower wing

1.12.4.2 Aft part of Fuselage

One part of the vertical bulkhead separating tank 11 from the tail was identified. The piping from the Jettison system pass through this bulkhead in order to reach the tail cone where the fuel dump vents are located. The part of this bulkhead on the tank 11 side showed no traces of fire or meltdown. The face located on the cone side did, however, bear marks of soot and combustion. This is consistent with the parts of the cone found melted under the flight path. It is probable that the fire propagated to the tail cone via the auxiliary gear door.

1.12.4.3 Examination of the Seats

The seats in the cockpit were examined. Their position was consistent with the normal position for takeoff, in particular for the FE who had his seat in the forward position. The FE positions himself between the Captain and the FO for takeoff (and for landing), facing the centre instrument panel. From this position he cannot actuate some selectors on the FE instrument panel located laterally at the rear of the cockpit. Apart from the takeoff and landing phases, he sits facing the FE panel.

Note: none of the normal or emergency procedures requires movement of the selectors on the FE instrument panel during takeoff or landing.

1.12.4.4 Examination of the Landing Gear

In the context of the reconstruction of the wing, it was possible to add to the observations made at the site of the accident, in particular concerning the landing gear and associated mechanisms.

This examination revealed the following points:

- The left main landing gear was extended and locked at the level of the side-stay. The right main landing gear was severely damaged but clearly identifiable in the extended position. The nose gear was unlocked with its locking pin out.
- The two main landing gear door locks were in the open position.
- The left nose gear door closing actuator was unlocked with movement of 100 mm. The normal course of this actuator is 35 mm when the door is closed and 195 mm when the door is open.
- The main landing gear door closing actuator was broken. An examination of this actuator did not allow its position at the moment of impact to be determined.
- The central hinge of the left main landing gear inner door was identified. The drips of melted metal indicate that the "kill beam" which separates the two landing gear bays was in a flat position after the aircraft broke up, with the hinge in the closed position.

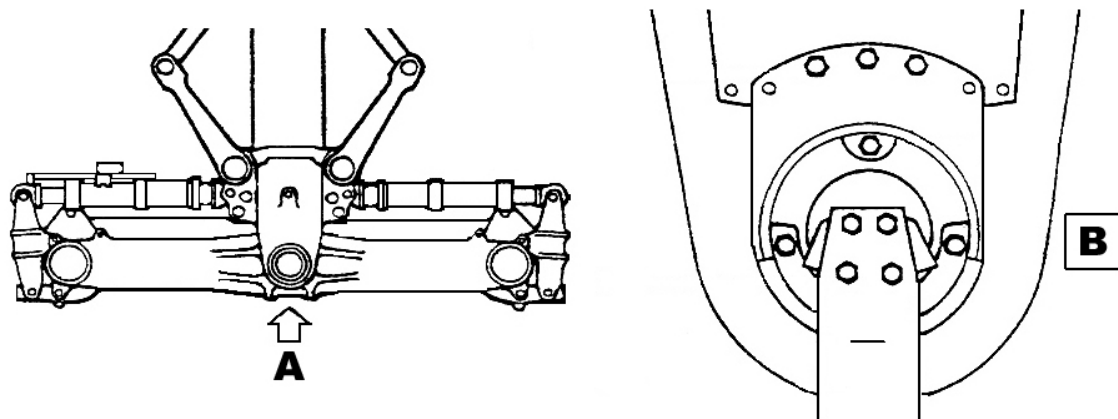


Figure 41: Leg-bogie coupling

- The forward and rear hinges of the right main landing gear inner door were identified.. The forward hinge was blocked in a position consistent with a closed door. The rear hinge was limited to a movement of about 20° around the normal closed position.
- A spacer, which holds two lateral rings in position, was missing from the oleo/bogie coupling on the left main landing gear. This retainer had not been re-installed during the A01 check performed from the 17 to the 21 July 2000.

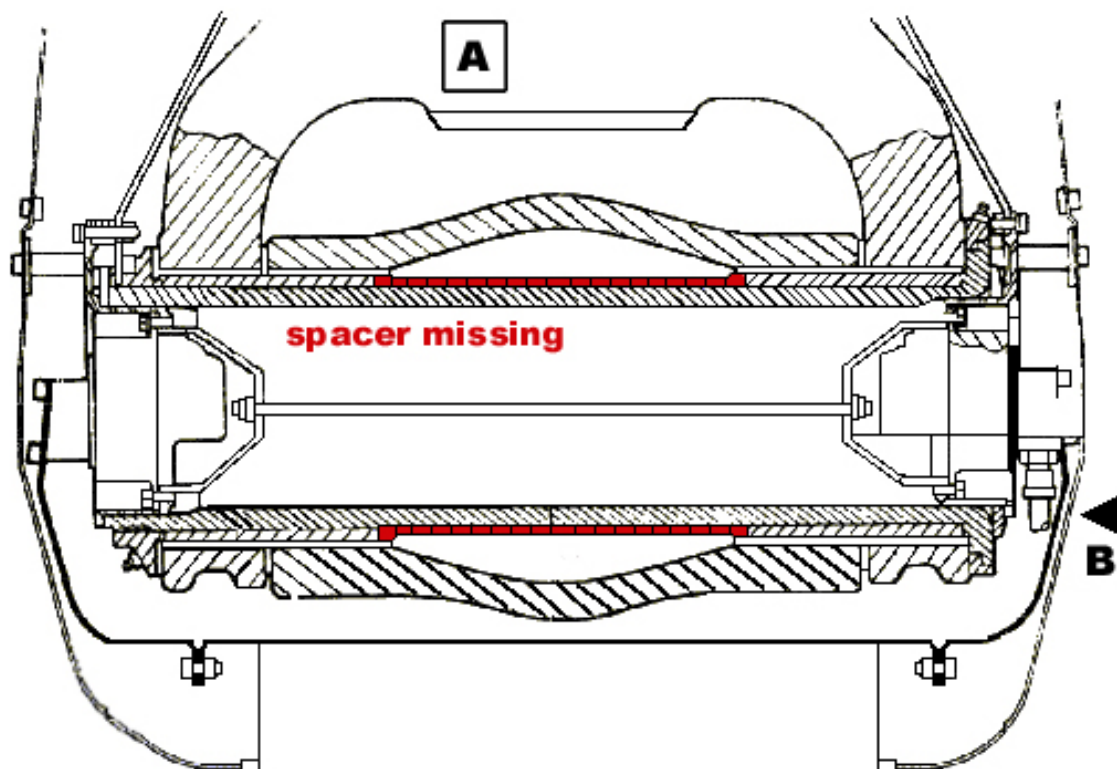


Figure 42: Cross section of leg-bogie coupling

1.12.4.5 Examination of the Dry Bays

1.12.4.5.1 Description

Above each engine compartment there is an area called the dry bay. This area is divided into two parts:

- the forward part, defined by spars 64 and 66 and ribs 12 and 21. The fuel supply lines coming from the feeder tanks as well as, for each engine, a hydraulic/fuel heat exchanger,
- the aft part, between spars 66 and 72 and ribs 12 and 21. This area communicates between spars 69 and 72 and the area stretching from the wing root zone to the wing tip. A fuel/air heat exchanger installed in line with a cold air unit turbine is installed in this area for each engine.

Each dry bay is separated from the engine nacelles by a heat shield. The structure of the engine cowlings also prevents the wing structure being destroyed in case of an engine fire⁽¹²⁾.

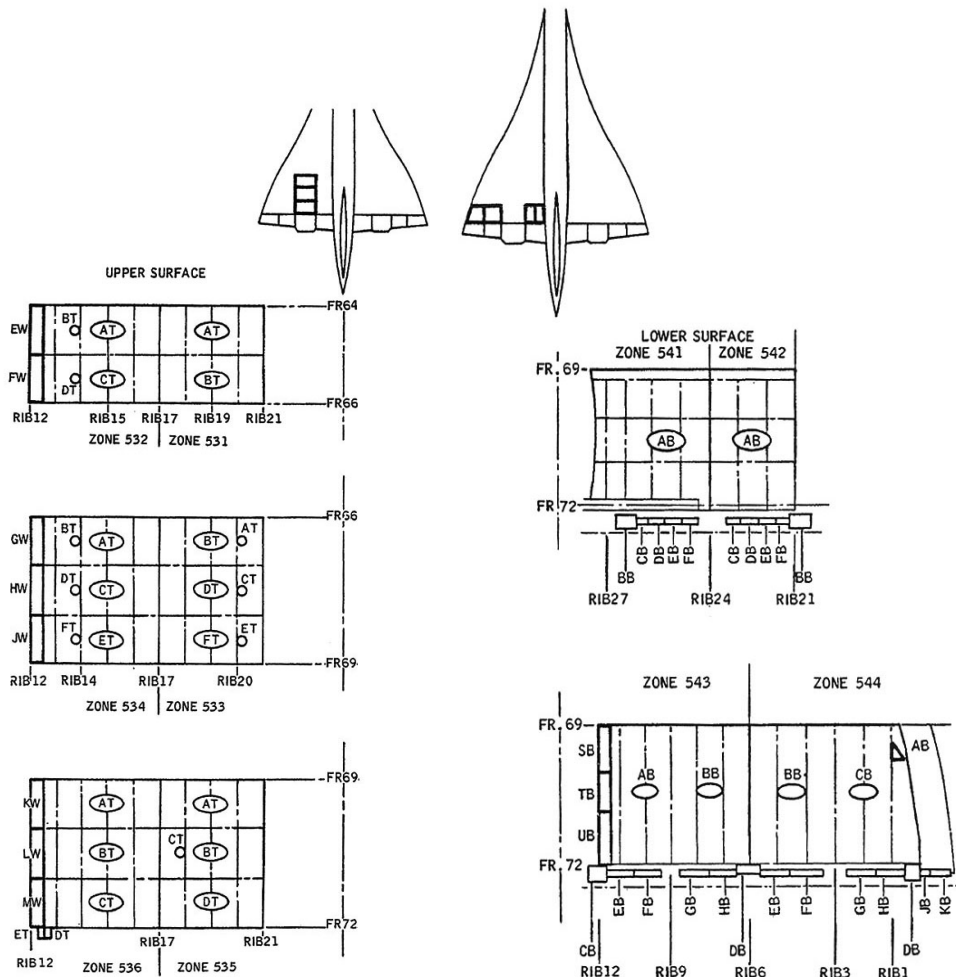


Figure 43: Dry bays

¹² The manufacturer stated that, in accordance with the SST, these heat shields resisted for at least three minutes.

1.12.4.5.2 Examination

The dry bay located above engines 1 and 2 was examined by the BEA investigators and their advisors. At the time of impact, it was broken off between ribs 12 and 21. All of the lateral bulkheads were destroyed. The heat shield was generally intact except for an indentation on impact at the level of the engine 2 nacelle.

1.12.4.5.2.1 Forward Part

Door 531BT was still attached to the upper surface of the bay. Door 532C was found melted into its housing. These two doors provide access to the forward part of the dry bay. This bore no signs of overpressure, there were no traces of fire inside and the bulkhead separating them from the aft part was generally intact. Only the tank 2 LP fuel supply valves were found there.

1.12.4.5.2.2 Aft Part

Eight doors located on the upper surface and providing access to the aft part of the dry bay were found under the path of the aircraft on the runway centreline extension. None of the doors bore any traces of fire. Two of the doors were equipped with an overpressure valve which opens at a pressure estimated at 200 mbar. The two valves were closed and door 535AT was bulged out as a result of overpressure directed from the inside to the outside. The valve opening rods had buckled under the effect of the distortion, which shows that the valves had no time to open. Lower surface door 541AB, which communicates with the aft part of the dry bay, was also found in the runway extension area. The section of the wing surrounding this door was found at the crash site. Both parts bore traces of soot clearly indicating the passage of the flame over the lower surface of the wing.

The air ducts situated between the air/fuel exchanger and the engine 2 CAU were intact with the exception of a broken sensor and air intake, very likely ripped on impact. On engine 1, the ducts were displaced in the longitudinal and lateral axes. The rest of the ducting showed no anomalies.

Examination of parts and of the wreckage found under the aircraft track showed that the aft part of the dry bay as well as the communicating areas suffered a very violent overpressure after takeoff, leaving no time for the overpressure valves to open. The door latches broke off as a result of this overpressure. The manufacturer estimates that a pressure of about 450 mbar on a door could lead to the rupture of the most loaded axis. Combustion of an air/kerosene mixture in the enclosed space of the dry bay could generate an overpressure which could reach a few bars in a few tenths of a second (stoichiometric mixture). Transition from combustion to detonation (propagation of a wave of combustion at supersonic speed) can generate a shock wave equivalent to pressure rise of several dozen bars.

1.12.4.6 Structural Resistance to Fire

Concorde's specifications show a rapid deterioration with temperature of the mechanical characteristics of the alloy used for the majority of its structure. At around 300 °C, these characteristics are already six times lower than at normal temperature.

Digital modelling was performed by EADS at the request of the BEA to study the influence of temperature on the parts of the structure exposed to the flame, as well as on the lower wing skin at tanks 2 and 6.

The case studied is based on a fire attached to the main landing gear well and on a flame with a temperature of 1,100 °C located between the fuselage and the nacelle. The effects taken into account are those of convection and radiation exchange between the flame and the structure. Under these conditions, in seventy-five seconds, the time the structure was exposed to the flame in flight:

- the average temperature of the lower surface of tanks 2 and 6 is nearly 300 °C,
- the average temperature of the fuel contained in tank 2 reaches 25 °C while that in 6, less exposed to the flame, is about 20 °C.

Note: the model does not allow local temperature gradients to be shown due to the partial exposure of tank 6, but rather to make an average estimate over the whole tank.

- the average temperature of the structural parts other than the tanks, taking into account neither the radiation nor the internal convection of those parts not containing fuel, reaches around 650 °C.

Note: the results of this study are average values. The projections of melted aluminium noted on the parts found under the aircraft's flight path show that, locally, higher temperatures were quickly reached (the melting point of aluminium is 660 °C). Some essential components such as the inner elevons directly exposed to the flame suffered very significant damage (note that a piece of elevon was found on the runway centreline extension).

1.13 Medical and Pathological Information

There was no evidence of medical or pathological factors likely to be relevant to the accident.

1.14 Fire

An intense fire started under the left wing while the aircraft was accelerating between V1 and VR.

On impact with the ground, the aircraft was immediately engulfed in fire. The intensity of the fire caused exposed plastic parts of the neighbouring hotel to be melted together. This is characteristic of a high temperature fireball.

Alerted by a fireman, the brigade from the south fire station at Paris Charles de Gaulle aerodrome immediately set out. At the same time, at 14 h 43, the crash alarm was

activated via the local network by the controllers on duty at the southern lookout post. Eight minutes later, firemen from Le Bourget aerodrome were first to arrive at the scene of the catastrophe. Faced with the scale of the fire, they were only able to limit the fire and provide aid to the injured.

The Paris Charles de Gaulle Rescue and Fire Fighting Service then intervened with their major equipment: twelve vehicles including six with foam fire-fighting systems and two for liaison. More than 180,000 litres of water and 3,800 litres of emulsifier were used.

Reinforcements from the neighbouring fire stations enabled the fire to be brought under control after three hours .

1.15 Survival Aspects

The crew were all found at their takeoff positions and the passengers in the seats assigned at boarding. The seats were fragmented. All the seat belts found were fastened.

The circumstances of the accident and the damage to the aircraft meant that the accident was not survivable.

1.16 Tests and Research

1.16.1 Flight Preparation for AFR 4590

1.16.1.1 Flight Preparation at Air France

Four units take part in preparing for flights within Air France: Flight Planning, Flight Departure, Ramp and Traffic.

1.16.1.1.1 Flight Planning

Preparation for the flight starts around $h - 5$ hours , h being the time planned for departure. The agent responsible for the plan draws up a flight dossier, parts of which are required by regulations to be archived for one month. He uses a computer program (AOGE) which includes the characteristics of each aircraft and, among other things, informs of NOTAMs, danger areas, aircraft limitations in relation to the prevailing conditions and generates the flight plan. As far as Concorde is concerned, certain elements, particularly the forecast takeoff weight and the fuel required for the flight, are calculated manually. Once the preparation is finished, the computer-processed part of the flight dossier is sent on automatically to the flight departure section while the manual part is passed on by the agent.

1.16.1.1.2 Flight Departure

The crew come to "Flight Departure" to collect and study their flight dossier. The latest meteorological information available is generally added to this dossier one or two hours

before departure. Once he has studied the dossier, the Captain signs the fuel loading sheet. This sheet is archived for one month.

1.16.1.1.3 Ramp

The personnel preparing the aircraft on the ramp is as follows:

- an aircraft service technician responsible for supervision and inspection of equipment for aircraft assistance on the ground. He does this from H - 150 minutes to H + 15 minutes.
- two all-purpose personnel who prepare runway equipment, assist mechanics and provide assistance for departure.
- a supervisor responsible for checking and loading baggage (C2). This agent signs the load sheet handed over to the dispatcher after the baggage loading has been completed.
- four aircraft service handling operatives.

1.16.1.1.4 Traffic

From H - 2 hours to about H - 1, the dispatcher undertakes what is called the "D1" role for flight preparation and planning. In this context, he performs the following tasks:

- drawing up a forecast for the weight of freight and passengers,
- drawing up a loading plan for the aircraft,
- drawing up a forecast for the final weight of baggage according to the number of passengers planned, using the GAETAN system to determine the baggage already registered,
- calculation of the CG forecast from the basic weight of the aircraft, the basic index, possible tolerances, etc.

From h -1 hour, he co-ordinates any actions on the aircraft on the ground and undertakes the final "D3" role of updating the data for the GAETAN system. At h - 10 minutes, the weight and balance data have to be finalised. The corresponding sheet is handed over to the crew and signed by the Captain.

Note: the quantity of fuel taken on-board is requested directly by the flight crew. In no event can the dispatcher modify this without the approval of the flight crew.

1.16.1.2 Preparation of Flight AFR 4590

1.16.1.2.1 Flight Planning

The preparation of flight AFR 4590 began at 9 h 12. The dispatcher's work screen indicated QFU 27. In addition, the non-availability of thrust reverser engine 2 thrust reverser (secondary nozzle) led to a reduction of 2.5% in the maximum weight in operation.

Based on data on the wind (a twelve kt headwind), the QNH (low, 1008 hPa), the temperature (higher than the norm) and the usable length of the runway, the dispatcher

calculated the maximum weight as 177,930 kg. However, flight preparation showed a takeoff weight of 184,400 kg with the one hundred passengers checked in.

At about 9 h 30, the dispatcher informed the duty officer of the weight problem, without however specifying the QFU used for the calculation. The duty officer first thought of using another aircraft, then tried to resolve the technical problem with the reverser and finally thought of loading the baggage onto another flight. On his side, the dispatcher studied alternative routes (one direct and one with an optional technical stop) and loading so that the flight would be feasible.

A little before 10 h 00, the crew called the dispatcher who informed them of the problem. The crew informed him that they had asked for the replacement of the failed pneumatic motor on reverser 2, asked him to file a direct ATC flight plan and told him that they were going to take over the flight preparation themselves.

Note 1: The central flight preparation service and the flight preparation centre where the crews work are not located in the same building.

Note 2: work had been under way on runway 27 for three weeks. The instructions to assist flight preparation stated that they should "favour (runway 27) for Concorde, because of noise pollution", runway 26 being used only "exceptionally". However, information relating to the runway configurations, in particular runway length, was available.

The meteorological data used by the dispatcher were not archived. No directives instructed him to do so. The preparation undertaken by the crew was not archived either. The technical investigators therefore redid the calculations with the flight dispatcher, using the meteorological data of the day of the accident, runway 26 right and without the acceptable deferred defect limitation due to the reverser. In these conditions and at this stage of the flight preparation, the estimated takeoff weight would have been² 184,802 kg for a MTOW of 185,070 kg.

1.16.1.2.2 Flight Departure

It was impossible to discover whether the crew took possession of the flight dossier, even though it had become redundant. The load sheet, including the fuel loading sheet and the Captain's signature, was not found.

1.16.1.2.3 Ramp

The flight being delayed, its handling began at 11 h 00 and finished at 14 h 45. All aspects of the flight preparation were dealt with by at least one agent.

The baggage loading plan was not signed by agent C2 since the bags indicated as red (not recognised) by the baggage reconciliation system (BRS) had been taken on board (see § 1.16.2). The authorisation to load was given by the aircraft manager and the aircraft service technician signed the final loading plan without which the load sheet could not be established.

1.16.1.2.4 Traffic

Note: the following is based on the loading log, that's to say the list of actions performed by the aircraft manager on his screen and copies of screen printouts.

The aircraft manager began preparing the flight at 11 h 13. At 11 h 34 the one hundred passengers and seventy-nine items of baggage had been checked in. Since the baggage represented a total weight of 1,651 kg and the loading had not yet been completed, he estimated the final weight of the baggage at 1,700 kg. It should be noted that the screen showed an average weight per bag of 20.9 kg.

The aircraft manager entered the total fuel weight and the taxi fuel weight of 95.0 and 1.9 tons at 11 h 55, of 95.5 and 2 tons at 12 h 14, of 95.4 and 2.1 tons at 12 h 15 finally of 95.4 (including two tons for taxiing) at 12 h 16, which corresponds to the first column in the first table in paragraph 1.6.5.1. At 14 h 01 the final load sheet was established, the data from which is included in the second and third columns of the same table.

Note: the fuel allowance for taxiing at Paris CDG allocated by Air France is one ton.

1.16.2 Aircraft Loading

On the day of the accident, a certain number of items of baggage present on the aircraft (twenty-nine in all) were declared to be unidentified by the the Baggage Reconciliation System (BRS), , which permits checks to ensure security regulations are respected.

When baggage is checked in, the GAETAN system sends information to the BRS, (the BRS allowing for cross-checking as required by regulations for security purposes) enabling the baggage to be identified (label number or tag, passenger's name, etc.). This information is stored in the BRS database and GAETAN simultaneously updates the baggage load condition on the aircraft manager's screen in real time.

During loading, the supervisor uses his portable terminal to read the number on the label attached to the baggage. This information is transmitted to the BRS, which authorises loading. If the number is not present in the database, the response will be "tag unknown". For flight AFR 4590, the seats were assigned by name and a collective ticket issued in Paris. On departure of feeder flights (e.g., Dusseldorf – Paris), items of baggage were registered in GAETAN for those flights only, although they were labelled on to New York. Separate entry of data (weight and tag) therefore also had to be made for flight AFR 4590, though it appears that this was not done systematically, which explains why certain items of baggage were not known to the the BRS.

These items of baggage were finally loaded once the aircraft manager had checked that all the passengers were on board, that all baggage was clearly labelled and that they had all gone through X-ray inspection, the flight being high security.

A comparison of the GAETAN and BRS printouts for flight AFR 4590 and the feeder flights shows that the items of baggage with "tags unknown" had not, in fact, been taken into account by GAETAN. As a result, they were not accounted for on the computerised load sheet used by the aircraft manager to calculate the weight of baggage loaded on board.

However, ten items of baggage planned for the flight and accounted for in GAETAN were not loaded, which brings to nineteen the number of additional items of baggage taken on board as compared with the load report.

1.16.3 Observation and Pictures of the Event



The following information comes from examination of the pictures available of the accident flight and from reports from various people who were at the airport or saw the aircraft flying.

The general opinion was that the first phase of the takeoff was completely normal. The four jets from the reheats were perfectly visible. During the acceleration, several people heard explosions. The first was heard when the aircraft was in the vicinity of W6 and was followed by the appearance of a flame. The initial conflagration occurred under the wing, between the left engine nacelles and the fuselage, a few seconds before the beginning of the rotation, the aircraft being in the region of zone W7 or S5.

Some people reported seeing pieces fall on the runway immediately after the first noise of explosion. The noises of explosion were immediately interpreted as being from engine surges by mechanics in the technical and freight areas.

Several people described the conflagration as being in two phases, describing a small flame or a blowtorch-like flame which suddenly appeared before growing much wider (it enveloped the left engines) and longer (about the length of the fuselage). This flame was accompanied by thick black smoke.

For many people used to seeing and hearing Concorde, the noise of the aircraft was perhaps different than usual. Several people noticed a slight swerve to the left, with the track being stabilised slightly off centreline, according to some observers.

Figure 44: Copying forbidden - Source Buzz Pictures/Corbis Sygma

After the takeoff, numerous small pieces were seen to fall from the aircraft all along its track.

After having passed the freight zone, the aircraft was no longer climbing, the angle of attack seemed to be constant, and the landing gear was extended. It flew over the RN 17 at around 200 feet, and then it made a sharply banked left turn, went nose up and struck the ground left wing low after a heading change of nearly 180°. There was a conflagration followed by one or more explosions.

Cabin crew rated or having been rated to fly Concorde were unanimous in their descriptions of the usual sensations during takeoff: noises, smells, characteristic noise of landing gear retraction, etc. In addition they stated that the cabin crew could not, given their experience, have failed to notice the significant changes during aircraft takeoff, in particular the engine surges, the lateral and longitudinal accelerations and the smells.

1.16.4 Previous Events

1.16.4.1 Nature of Events

Research was undertaken to find incidents which had involved tyres or landing gear on the Concorde since its entry into service. The information collected to establish the list of events came from the archives of EADS, Air France, British Airways, BEA, AAIB, DGAC, CAA and Dunlop.

The list in appendix 5 shows information from events coming from at least two different sources or for which reports or detailed information exist.

In the list, there are fifty-seven cases of tyre bursts/deflations, thirty for the Air France fleet and twenty-seven for British Airways:

- Twelve of these events had structural consequences on the wings and/or the tanks, of which six led to penetration of the tanks.
- Nineteen of the tyre bursts/deflations were caused by foreign objects.
- Twenty-two events occurred during takeoff.
- Only one case of tank penetration by a piece of tyre was noted.
- None of the events identified showed any rupture of a tank, a fire, or a significant simultaneous loss of power on two engines.

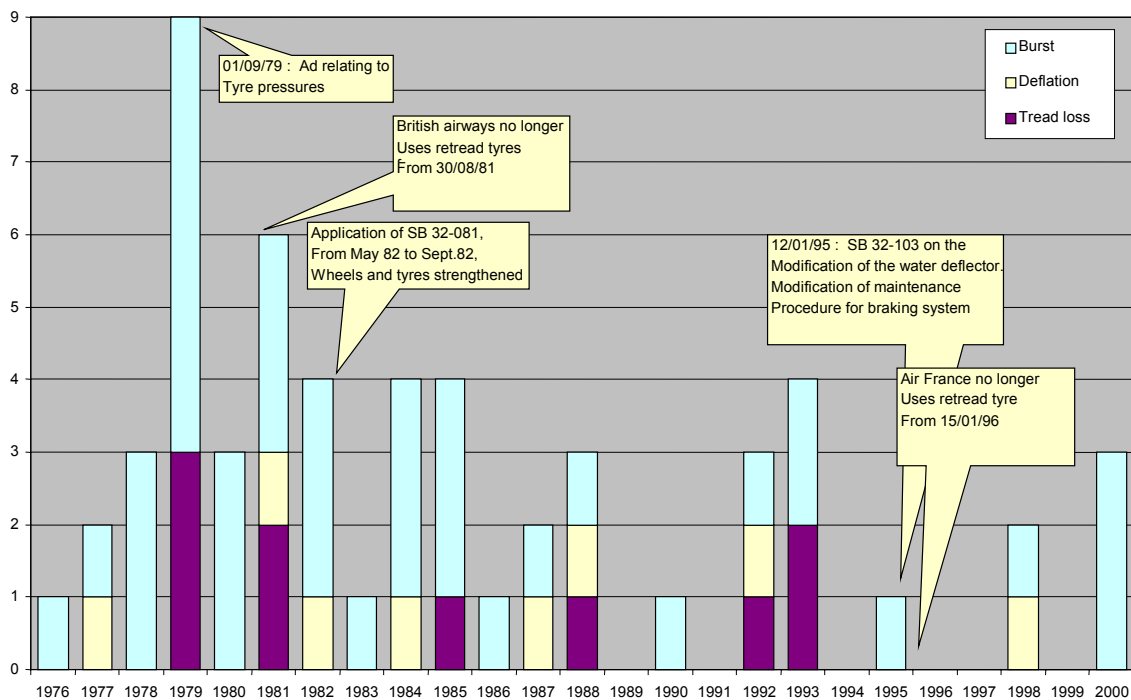


Figure 45: History of Concorde tyre events

Twenty-one other events were notified by a single source, but no reports or detailed information exist for them. No mention was made of damage to the structure or the tanks in any of them.

1.16.4.2 Events which caused Structural Damage to Tanks

14 June 1979: F-BVFC on takeoff from Washington Dulles. Deflation of tyre No 6 followed by loss of tread, leading to burst of tyre No 5 and the destruction of wheel No 5 and small punctures in tanks 2, 5 and 6. After some unsuccessful attempts to retract the landing gear, the loss of the Green hydraulic system and a drop on the Yellow system to the first low level, the crew landed the aircraft back at Washington twenty-four minutes later.

9 August 1981: G-BOAG on takeoff from New York JFK. Burst of No 1 and No 2 tyres leading to minor penetration of tank 5.

5 November 1985: G-BOAB on takeoff from London Heathrow. Burst of tyre No 5 causing damage to the landing gear door. Minor penetration in tank 5, probably by a piece of the door mechanism.

29 January 1988: G-BOAF on takeoff from London Heathrow. Loss of ten nuts from wheel No 3. A bolt punctured tank 7.

15 July 1993: G-BOAF on landing at London Heathrow. Burst of tyre No 4 leading to damage to the gear door mechanism. Tank 8 was damaged, probably by a piece of this mechanism.

25 October 1993: G-BOAB during taxiing at London Heathrow. Burst of tyre No 2 leading to damage to the water deflector. Tank 1 suffered minor penetration, probably from a piece of the deflector.

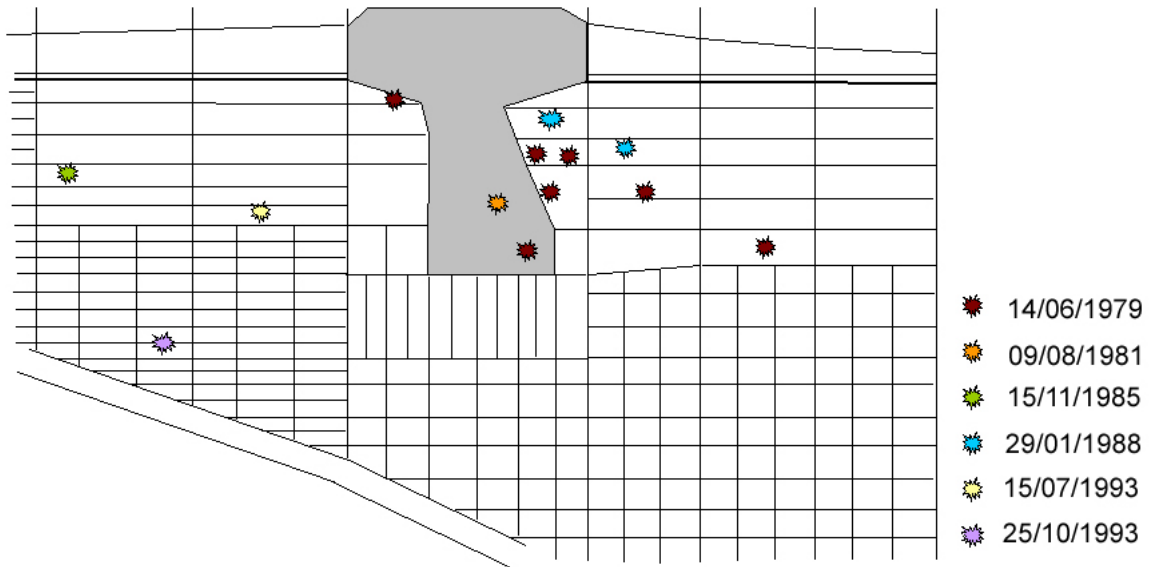


Figure 46: Location of impacts with punctures during various incidents

It can be stated that:

- Four of these events occurred during takeoff. Amongst these, in one case the tyre damage was caused by an object on the runway, in two cases the tyre burst occurred for reasons which were not determined, the final case being due to tyre deflation while the aircraft was rolling at high speed. One of these events resulted in an aborted takeoff. In the three others, the aircraft took off and then returned to land.
- One event occurred on landing. The tyre burst was caused by a braking system jam.
- The last event occurred during taxiing when the aircraft was leaving the runway. The tyre burst was also due to a braking system jam.

1.16.4.2.1 Event on 14 June 1979 at Washington

Among the events which led to tank penetration, that of 14 June 1979, which occurred to F-BVFC at Washington, was both the first of its type and that which caused the greatest damage.

Most of the structural damage resulted from impacts from pieces of wheel rim on the wing, aft of the tyres. Three penetrations were also observed in the area of tanks 2, 5 and 6, whose skin thickness is 1.2 mm. One of them was caused by a piece of rubber from a tyre. The resulting fuel leak from all of the penetrations was 4 kg/s.

Following this accident, a report was made by the BEA and a study was carried out by Aerospatiale to find solutions aimed at limiting any risks linked to tyre bursts on the Concorde.

This study concluded that the risk was higher in probability and consequence than that which had been taken into account at the time of certification. The observed and potential consequences were mentioned and the major risks identified. In case of a tyre burst during takeoff, these included:

- Risk to the nacelle. The study indicated that, during certification, it was shown that damage suffered by the nacelles in case of impact by four pounds of tyre debris at a speed of 217 kt was not liable to compromise engine function.
- Risk to engine. The study recalled the conclusions of the work on debris ingested by the engines. In case of ingestion of large debris, loss of thrust was rapid and total, only the inner engines were liable to be affected, and this only in the case of an outer tyre burst. This analysis was based on considerations of size and of the position of the air intakes in conjunction with the study of the trajectories of the debris. In the case of smaller debris, and based on experience gained in service from aircraft with similar geometry (Vulcan, Comet, Nimrod), a significant loss of thrust was considered to be extremely unlikely.
- Risk of penetration of feeder tanks. Taking into account the separation of the feeder tanks supplying two adjacent engines, the study considered that the risk of simultaneous penetration of the two feeder tanks was sufficiently low. Continued fuel supply to the engines in case of a leak was also considered and the study concluded that these two engines could continue to run for at least twenty minutes.
- Risk of fire. Based on the data about the leak in the accident, the study concluded that the risk of fire was limited, considering:
 - o that the size of the penetrations and the rate of flow of the leak are sufficiently low;
 - o that ignition cannot be caused by rubber or metal debris penetrating the tank;
 - o that the fuel leaks from tanks 6 and 7 follow the flow under the wing and remain generally parallel to the aircraft axis without meeting areas of separation and thus dissipate via the wing trailing edge. The secondary nozzle's temperature is too low to ignite the fuel;
 - o that fuel from leaks in tanks 5 and 8 may accumulate in the landing gear well. Only the electrical circuits in this compartment constitute a possible source of ignition;
 - o that ignition of the fuel on contact with hot brakes would not definitely occur, bearing in mind the average temperature reached by the brakes;
 - o that in case of penetration of the tanks forward of the air intakes, leaks would be limited (due to the limited size of the debris taken into consideration) and could only enter the engine at a very low speed (after landing) and at a high thrust level.

Most of the solutions then proposed were in fact put into effect and were the subject of Airworthiness Directives:

- AD of 14/01/8, applied from 21/01/81, calling for the installation of a system for detection of main landing gear tyre under-inflation. An improved version of this system was then applied by AD on May 15 1982,
- AD of 14/01/81, applied on 21/01/81, calling for improvements in protection in the normal braking hydraulic system,
- AD of 5/05/82, applied on 15/05/82, defining an inspection procedure for the main landing gear tyres and wheels before each takeoff,
- AD of 5/05/82, applied on 15/05/82, calling for the installation of new reinforced wheels in order to limit damage in case of contact with the ground and for new reinforced tyres capable of bearing twice the normal load (the regulations require one and a half times).

As a result of studies carried out on the risks of damage from pieces of tyre and on trials performed at the CEAT in 1980 to justify the integrity of the structure in case of direct penetration, it was concluded that it was not necessary to install protection for the underside of the wings.

1.16.4.2.2 Other Events

All of the tank penetrations that occurred after the Washington event involved aircraft operated by British Airways. It should be noted that after the modifications carried out after this event, tank penetrations following a tyre burst were caused only by secondary debris. In most cases, this debris came from the destruction of equipment located in the landing gear area, probably dislodged by pieces of damaged tyre. The parts in question include the water deflector and the gear door latch.

The deflectors were the subject of an optional Service Bulletin (see § 1.6.2.4).

A study, initially carried out by British Airways and EADS, to limit the consequences of a rupture of the gear latch door through the installation of a restraining cable was not concluded. This modification is, however, ongoing.

In addition, the recommendations of a working group responsible for studying braking problems after the 1993 incidents were implemented in the form of modifications to maintenance procedures.

1.16.5 Tyre destruction Mechanism

1.16.5.1 Experimental Tests

Test were carried out in the United States at a Goodyear technical centre to reproduce the conditions leading to damage to a tyre from a curved metallic strip with comparable dimensions to the one found on the runway.

Two new Concorde tyres were used for these tests. One of the strips used was made of titanium, the others made of a stainless steel whose mechanical strength characteristics are similar to titanium.

The tyres were installed on the side of a trolley towed by a truck. The load spread out on the trolley allowed each tyre to bear a load of about twenty-five tons, equivalent to that on each main landing gear tyre on Concorde. Taking into account the test equipment and the load, the speed of the truck was around 10 km/h. The sample strips were stood on edge on a concrete surface.



Figure 47: Tyre Test Truck

During the tests:

- an initial positioning of the strip, done with the titanium strip, resulted in its being flattened by the tyre,
- in a second position, the strip remained stable on its cutting side and the tyre was cut into,
- the tyre cut went right through its thickness, practically all across the width of the area in contact with the ground and in accordance with the shape of the strip,
- this cut continued as tearing onto the tyre shoulders and sidewalls through a static rupture in the direction of the reinforcing material of the tyre body,
- the static tear spread as far as the tyre beads, in other words slightly more deeply than the tear noted on the remains of tyre No 2 on F-BTSC.

Extension of the lines from the tear demonstrates that the piece that could be released was comparable to the piece of tyre found after the accident near to the strip.



Figure 48: Position of the metallic strip under the tyre



Figure 49: Tyre cut

1.16.5.2. Theoretical Study of Metallic Strip Cutting Tyre

In the course of the investigation, the Mechanical Industries Technical Centre (CETIM), which is specialised in the study of polymers, plastics and composites, was asked to determine the theoretical behaviour of a tyre running over an obstacle like a metallic strip standing on edge. In order to do this, the CETIM conducted a study using finite element modelling on a bias ply carcass tyre with characteristics similar to those fitted on F-BTSC.

The mechanical and chemical characteristics of the materials were supplied by Goodyear, the manufacturer. Those of the metallic strip corresponded to the characteristics of the one found on the runway.

Two cases were considered:

- a so-called "short" strip of which at least one end is inside the contact area between the tyre and the ground,
- a strip that was long enough to protrude beyond the contact area.

This theoretical study shows that at the ends of the strip, the damage caused was typified in both cases by separation of the different reinforcing layers and a clear perpendicular cut in the tread by the edge of the strip.

1.16.5.3 Tests Carried out at the CEAT

The objective of the tests at the CEAT was to run the Concorde tyres over metallic strips made of titanium to establish a catalogue of the various aspects of fracture topography relative to the parameters selected.

Some metallic strips similar to those found on the runway were spot-welded onto thin metal plates. These slid along two cables to be introduced between the tyre and the drum on the test rig which drove the tyre at the predetermined rotation speeds.

1.16.5.3.1 Low-speed Tests

Various tests were carried out with a load of 22,900 daN with the inflated tyre running at low speed. These tests showed that the impact speed is an important parameter for strip penetration.

A tyre carcass was cut with a knife on ten of the fourteen doublers. During re-inflation, the upper edges of the cut on the tyre tread separated by about 5 mm as soon as pressure of 3 bars was reached⁽¹³⁾. This shows that the metallic strip could not have remained trapped in the tyre. After inflation, the tyre was rotated. The rupture occurred at 60 m/s and the main piece of tyre released from the cut weighed about 2.5 kilos.

¹³ The nominal pressure of Concorde tyres is 16 bars.

1.16.5.3.2 Metallic Strip Dynamic Penetration Test

Two tests were carried out with a tyre rotating at high speed.

For these tests, after simulating a three thousand meter taxi, the wheel accelerated to simulate a takeoff run. The metallic strip was then introduced edge on between the drum and the tyre.

For the first test, the mechanism was activated when the tyre was running at 60 m/s. It immediately burst. Two pieces, one of eleven the other of seven kilos, were ejected, along with a long piece of the tread.

For the second test, the speed was increased to correspond to a translation speed of 75 m/s. the tyre also burst as soon as the strip was introduced, releasing several pieces with a total weight of 17.6 kilos. The two heaviest pieces weighed 5.9 and 5 kilos.

The pieces exhibited clean cuts in the contact area with the strip and similar shapes to those seen on tyre No 2.

1.16.5.4 Examinations Carried out at the LRCCP

The Rubber and Plastics Research and Test Laboratory (LRCCP) was ordered by those in charge of the judicial inquiry to carry out examinations on the debris of tyre No 2.

In the first instance, reconstitution of the tyre led to the conclusion that more than 30% was missing and that the metallic strip had been struck from its concave side.

The laboratory also checked that the characteristics of the tyre were comparable to those of the other Concorde tyres examined.

On the surface of the cut, the material reinforcement fibres were cut through the major part of the thickness and some of the areas of rubber were iridescent, with spacing corresponding to those of the holes on the metallic strip.

Various pieces of the tyre cut during the tests conducted in the USA and at the CEAT were examined at the LRCCP. Observation showed the resemblance of their rupture topography with that of tyre No 2.

The photo below shows the positioning of three pieces coming, from top to bottom, from tyre No 2 (speed of around 85 m/s), from a tyre tested at the CEAT with impact at 65 m/s and a tyre tried in the United States with impact at 2.5 m/s.



Figure 50: Cuts in various Concorde tyres

1.16.6 Metallic Strip found on the Runway

The metallic strip found on the runway after the accident appeared to be an aviation part that did not belong to the Concorde. A search was therefore undertaken to identify the aircraft from which the part had fallen. This search was focused on the aircraft that had taken off from the same runway after 13 h 00. In addition, research on several types of aircraft showed that the part could be a wear strip from a CF6-50 engine fan reverser cowl.

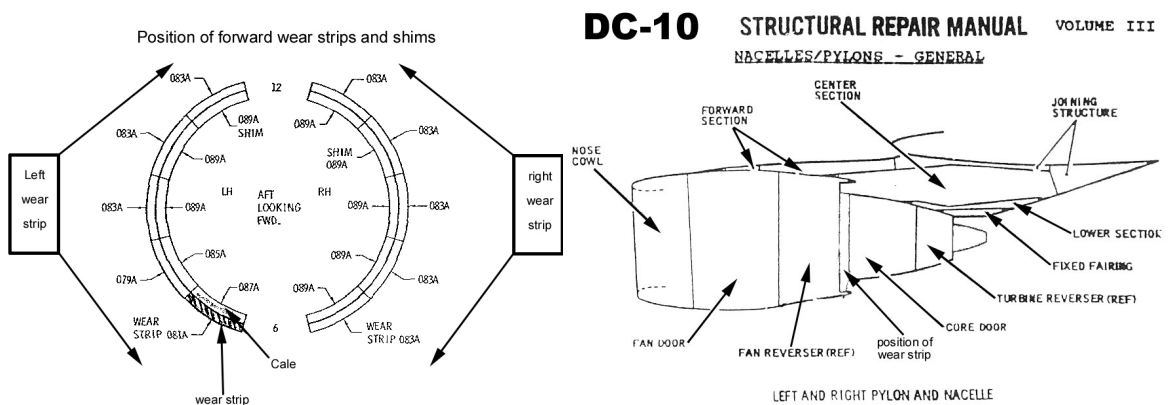


Figure 51: Diagram showing the position of the wear strips

The DC 10 registered N 13067, operated by Continental Airlines, had taken off five minutes before the Concorde to undertake Paris-Newark flight COA 55. Since this aircraft, seen briefly at Paris Charles de Gaulle on 30 August 2000, could be the aircraft which had lost the part, a technical investigator assisted by the Accredited Representative of the NTSB and by FAA specialists visited its base at Houston to examine it in the presence of representatives of the operator.

Note: only one aircraft, an Air France Boeing 747, had taken off between the DC 10 and the Concorde.

1.16.6.1 Observations on N 13067

The following observations were made on the aircraft's right engine (engine 3):

a) Fan reverser aft support

- the lower left wear strip, about forty-four centimetres long, was missing. When closed, the forward part of the core door usually rests on the wear strip,
- the support was painted with green epoxy primer,
- in the position where the missing part would be, the support was covered in red type RTV 106 mastic,
- there was no trace of RTV 106 on the other parts of the support,
- there was no trace of RTV 106 on the wear strips which are in place,
- there were numerous paint runs on the support and on the wear strips and the paint,
- partially overlapped onto the fan reverser cowl,
- in the position of the missing part, the support still possessed several rivets,
- the support was drilled with thirty-seven holes, of which some had gaps between them,
- that were less than twice the diameter of the holes.





Figure 52: Pictures showing the position of the wear strip

b) Wear strips

- the right wear strips appeared to be original parts made of stainless steel (angled section at the tip),
- the left wear strips had been replaced, and did not appear to be original parts, spacing between rivets on the wear strips in place and their alignment appeared to be correct,
- the level of wear on the strip adjacent to the missing strip had clearly exceeded the tolerances accepted by the manufacturer.

c) Lower right wear

- strip a rivet was missing on the lower right wear strip, which was deformed and there was play of six millimetres in relation to the support,
- the rivet at the end was broken off, the part remaining on the support prevented the strip from sticking to the support, which prevented correct closure of the door,
- in comparison with an original part, this strip was too long.

d) Left fan door from the exterior,

- there was no apparent anomaly on the left fan door,
- inside, deep wear marks were observed, in particular on the part which usually rests on the strips,
- to the right of the bearing point of the strip adjacent to the missing strip, severe wear of around two millimetres was observable on the cowl.

e) Fan and reverser assembly closed

- When closed, the fan/reverser cowl assembly made it practically impossible to note the absence of the lower strip.

Some photographs were taken and some samples of materials (mastic and paint) were taken. A rivet was also removed from one of the remaining strips. At the request of the investigators the engine fan and reverser cowls were removed and stored by Continental Airlines.

1.16.6.2 Manufacturer's Documentation

1.16.6.2.1 Disassembly and Repair of Wear Strips

The manufacturer's documentation specifies the conditions for disassembly and repair of the wear strips. Instruction sheet 78-32-03 (disassembly and repair) of the Aircraft Maintenance Manual indicates, on pages 901 to 905, the equipment and materials to use and what to do. The sheet specifies that no special tools are required. This operation is classified as a "minor repair" (that's to say one which does not imply the replacement or repair of structural elements) and requires no particular inspection after completion.

The wear strip is made of stainless steel 0.055 inch (1.40 mm) thick and one inch wide. The sheet specifies that this strip can be manufactured in the workshop from stainless steel, the dimensions then being 0.055 inch (1.40 mm) thick and 1.395 inches (35.43 mm) wide without the angled section.

It is specified that a template must be made in order to use the existing holes in the support and to drill the new wear strip with the correct dimensions. The rivet holes must have a diameter between 3.63 and 3.73 millimetres.

Delaminated shims are inserted between the wear strip and the support in order to ensure that the diameter of the cowl support is 72.18 inches \pm 0.09 inch. The wear tolerance of the wear strip is 0.030 inch.

Note: it appears that checking this diameter is difficult to do using the method recommended by the manufacturer. Consequently, either repairers do not insert the shims, which leaves too much play between the forward and aft cowls, or the shims are inserted in a uniform manner under all the wear strips, the lower strip then being easily removable with a screw so as to remove its shim if it's not possible to close the door.

Assembly procedures for reverser cowls have evolved with time. Some wear strips machined with holes could not be adjusted to fit existing supports. The manufacturer therefore published Service Bulletin 78-206 on 7 July 1983 that details the procedure to follow to drill new holes on the support.

This service bulletin recommends filling the existing holes with an EA 934 NA epoxy adhesive, then drilling new holes using the wear strip as a template. A footnote specifies that it is unnecessary to fill in the old holes if they do not interfere with those of the wear strip. To install wear strips that have not been pre-drilled, (which is the case of wear strips made in the workshop) the service bulletin refers back to the procedure, which implies the use of a template to drill the holes.

The maintenance procedure states in a note that alternative solutions can be used for the tools, equipment and consumables recommended. The manufacturer told investigators that this note would not apply to the wear strip, which, even when it was made in a workshop, had to be made of stainless steel to be in compliance with the requirements of the maintenance manual.

1.16.6.2.2 Space between the Core Door and the Fan Reverser Cowl

The play between the core door and the fan reverser cowl must be between 0.030 inch (0.7 mm) and 0.5 inch (12.7 mm) as shown hereafter;

During the investigation, it was noticeable on various aircraft that the play measured with engines stopped could exceed these values without touching the width of the wear strip. However, with the engine running, particularly when under takeoff thrust, the pressure inside the cowls is very high. Their deformation then seems to explain loss of a wear strip, which would no longer be attached to its support.

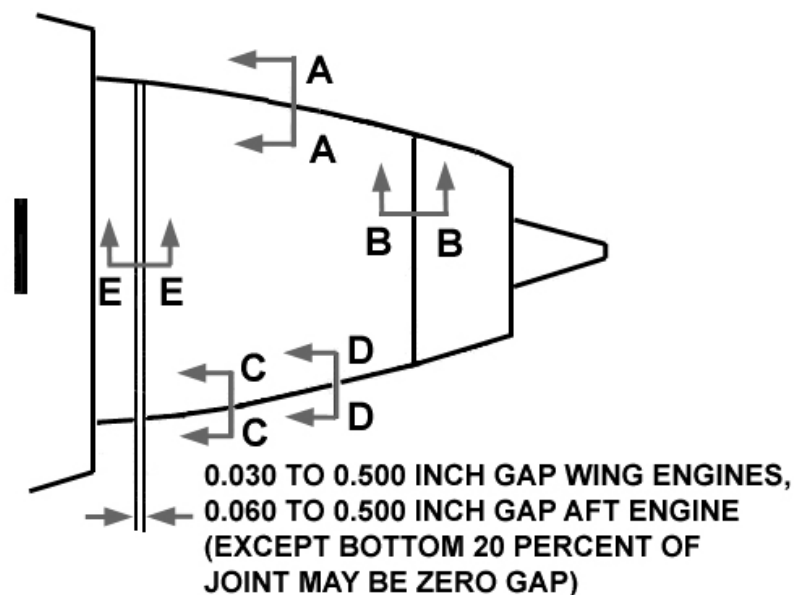


Figure 53: Diagram of cowl

1.16.6.3 Maintenance on N 13067

N 13067's maintenance documents show that the left wear strips on engine 3 were replaced at Tel Aviv, by Israel Aircraft Industries, during the C check completed on 11 June 2000.

Further work was carried out at Houston on this engine's reverser cowl. The mechanical report states that the lower left wear strip was changed during the job. The technician who completed this report stated that he had noticed a twisted wear strip that was sticking out of the cowl. The job was performed specifically to replace it.

The absence of the wear strip is not easy to notice when the cowl doors are closed. Between 9 July and 3 September 2000, the cowl doors on engine 3 were opened at least once (August 25). No maintenance documents refer to the wear strips during this period.

1.16.6.4 Examination of the Wear Strip

The wear strip found on the runway was subjected to laboratory examination:

- the strip was 435 mm long, 29 to 34 mm wide and about 1.4 mm thick. It was made of a type TA6V alloy composed of titanium (89.67%), aluminium (7.03%), vanadium (2.28%) and iron (1.02%). It was covered on one side in green primer composed of an epoxy bisphenol A resin containing elements of silicate and pigments of strontium chromate. The other side was covered in red silicon mastic for high temperatures. The rivets, of Cherry Max type, were made of an aluminium alloy bush - magnesium AG-5 or 5056 - and a steel stem with an alloy of chrome-nickel-molybdenum covered with a layer of cadmium,
- the strip possessed twelve drill holes with random spacing, some off centre with the longitudinal axis,
- the presence of circular indentations on the mastic side bears witness that the part opposite it possessed extra drill holes. Seventeen hole marks were counted in addition to the twelve holes drilled in the strip,
- black marks were noted on the outer side of the strip and black elastomer debris was found jammed in one of the rivets. The spectra of these marks and deposits are similar to the Concorde tyre.

1.16.6.5 Examination of Samples taken from N 13067

The samples taken during the examination of N 13067 in Houston were examined in the lab:

- the primer paint from the cowl is similar to the residues of paint taken from the mastic on the strip,
- the red mastic sampled from the cowl in the area of the missing piece is silicon mastic of the same type as that present on the strip,
- the rivet taken from another strip, of Cherry Max type, is made up of alloy aluminium–magnesium A-G5 bush and a steel stem with lightly alloyed 40NVD 2 type alloy (AISI 8740 steel). The material the stem is made of is slightly different from that of the rivets in the strip.

1.16.6.6 Analysis of the Photos of the Cowl on N 13067

The photos of the engine cowl taken during examination of N 13067 were compared with the metallic strip:

- the unoccupied part of the joint on the cowl closing area has comparable dimensions to those of the strip,
- the cowl has thirty-seven drill holes of the same diameter as those of the strip; they correspond to the drill holes and circular marks visible on its mastic-coated side,
- eight rivets are in place, in holes which do not correspond to those on the strip and which appear to result from a previous installation,
- there is a relation between the torn and unstuck zones on the mastic present on the strip and on the engine cowl.

Note: most of the findings reported in paragraphs 1.16.6.4, 1.16.6.5 and 1.16.6.6 were made at the Saclay Engine Test Centre.

In conclusion, investigation and examinations carried out show a clear relation between the metallic strip and the joint area on the cowl of engine 3 on N 13067.

1.16.7 Rupture of Tank 5

Three pieces found after the accident were identified as coming from tank 5. One was found on the runway, the other two at the accident site.

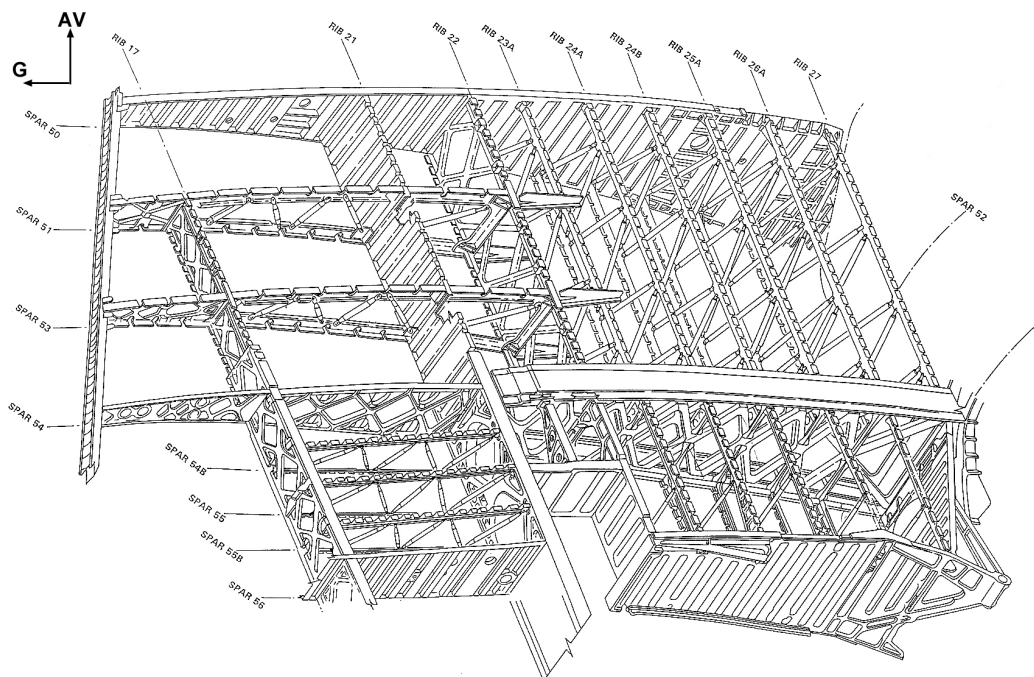


Figure 54: Plan of tank 5

1.16.7.1 Examination of the Pieces of the Tank

1.16.7.1.1 Piece Found on Runway

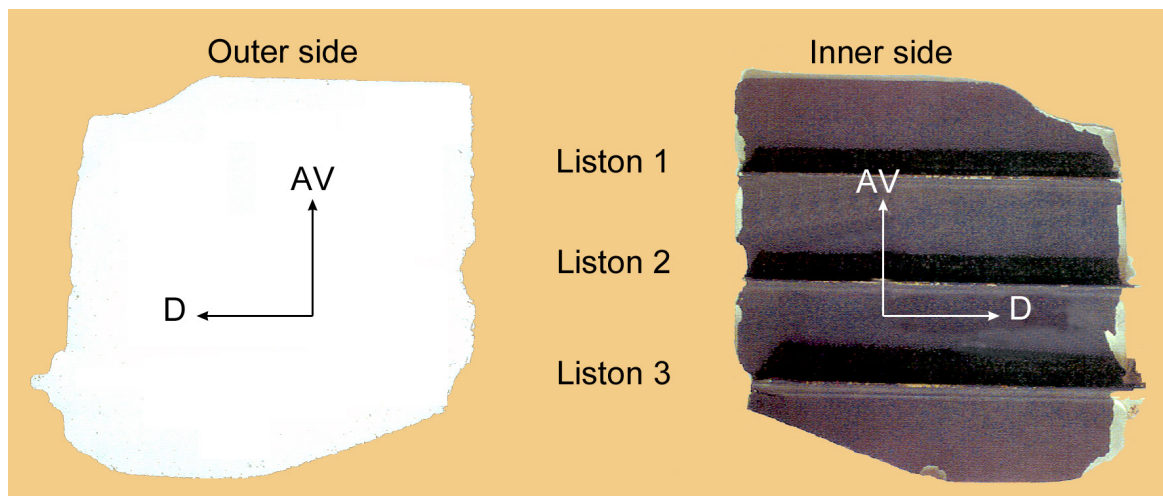


Figure 55: Piece of tank 5 found on the runway

The structural part found on the runway measured 32 x 32 cm. It was covered in white paint on its outer side and with a black mastic (viton) on its inner side. It had three stiffeners (strakes) separating four cells. A dimension check enabled it to be identified as coming from the underside of tank 5, and to locate it between spars 55 and 56 and ribs 23A and 24A. The piece and a skin thickness of 1.2 mm.

This part had not been exposed to fire and showed no signs of impact after the rupture. Measurements of hardness and conductivity showed values in accordance with the specifications of the alloy used on the tank (AU2GN in condition T651).

Dimension, visual and fractographic examinations showed that:

- some of the damage noted on the rear part was caused by impact with the ground,
- the cells possessed bulge deformations whose main line was perpendicular to the stiffeners. the radius of curvature measured in the areas away from the point of impact with the ground was of the order of 1.2 m,
- the ruptures in the thin skins were matt for the most part; the rupture face was angled at 45°, which indicates that these were static ruptures,
- the ruptures on the stiffeners displayed roughness characteristic of violent static ruptures following an abnormally high load.

The overall findings on this part show that it suffered pressure directed from the inside of the tank towards the outside, causing it to rupture in three phases as shown in the following figure:

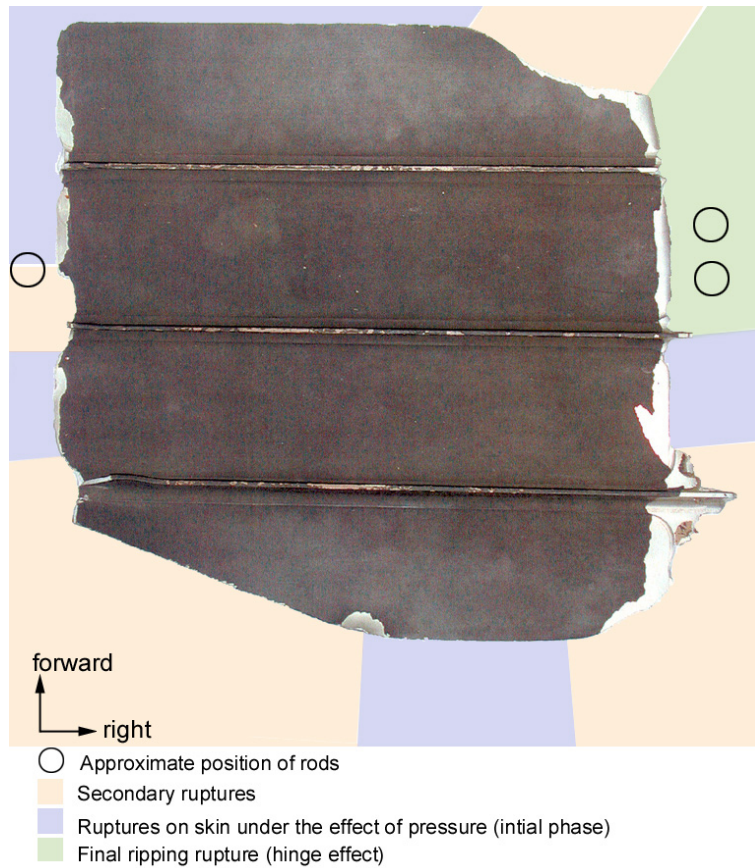


Figure 56: Rupture sequence for piece from tank 5

1.16.7.1.2 Piece of the Underside Found at the Accident Site

A part found at the site was identified as coming from the underside of tank 5. It was located along spar 56 between ribs 24A and 24B.

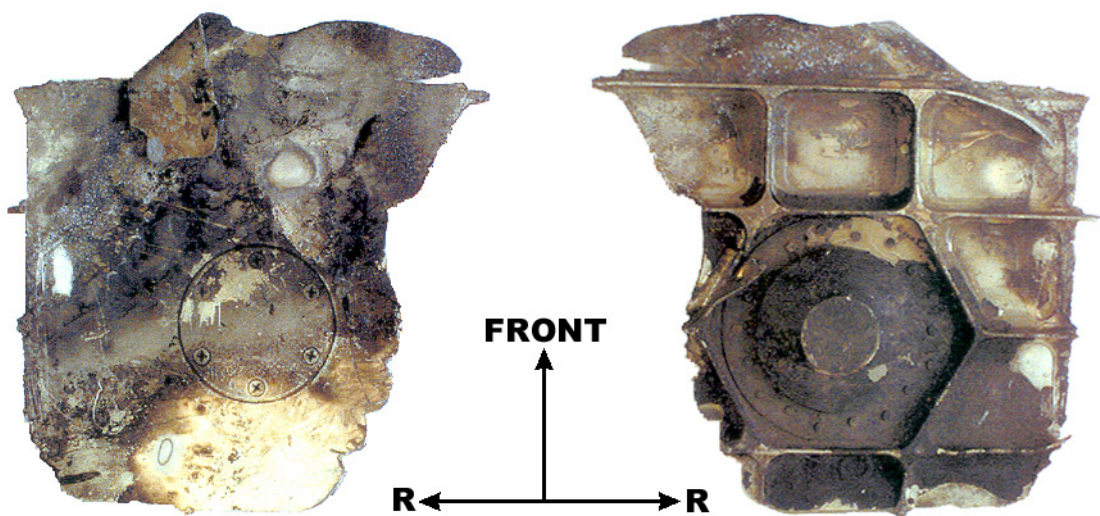


Figure 57: Piece of tank 5 found at site

The piece had not melted but the external paint and the internal black mastic were damaged on three-quarters of their surface and the material was overheated in this area. Only the remaining quarter, in the rear part, was intact.

A 40 X 10 mm hole is noticeable on the front right part of the piece. Examination thereof revealed the following details:

- the impact occurred from the outside towards the inside of the tank, from the left to the right and more or less from the rear towards the front,
- the puncture showed clear petal-shaped structure, implying a high-energy penetration, which appears to indicate that it was not due to the final impact.

Analysis was unable to provide details on the makeup of the penetrating object. Its probable trajectory shows that it could have come from the area of the left main landing gear.

1.16.7.1.3 Other Piece found in the Aircraft Wreckage

A melted piece with a generally highly deformed shape, also found at the site, appears to come from the upper part of tank 5, between spars 55 and 56 but its deformed condition made it impossible to perform thickness measurements so as to confirm its location. This part bore three holes that were attributed to gravity acting on melting metal.

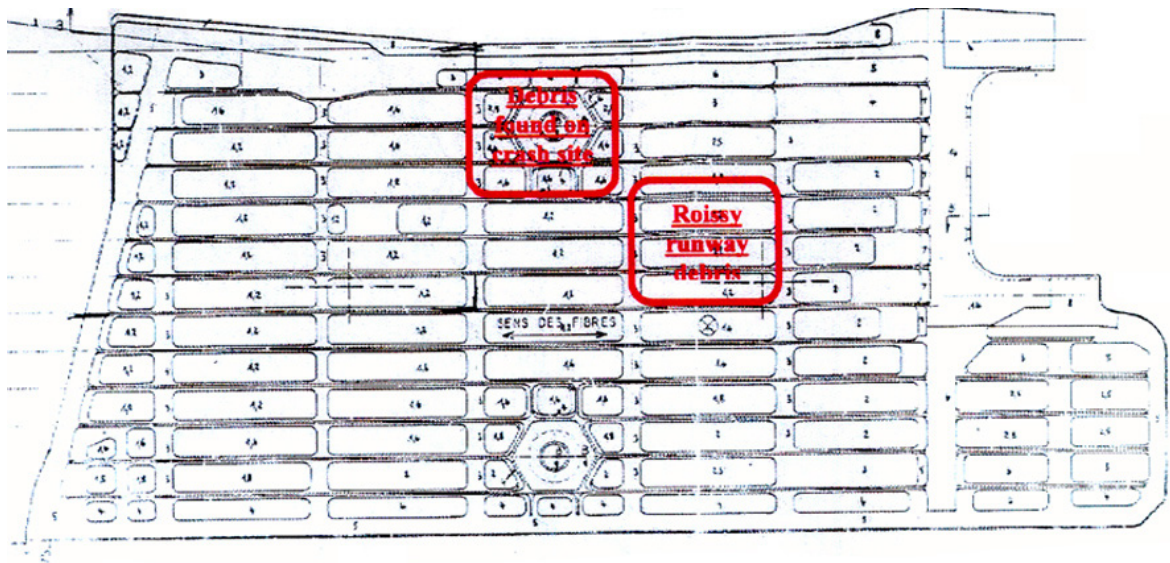


Figure 58: EADS diagram

1.16.7.2 Tank Rupture Mechanism

Examination of the piece found on the runway allowed investigators to exclude the possibility that the destruction of this part of the tank resulted from a direct puncture by a large object or by tearing off of the piece as a result of a puncture. To explain the rupture from the inside towards the outside of the underside of the panel, a lot of theoretical and

practical work was undertaken, which is detailed in the appendices. Based on available information, two scenarios were considered:

a) Impact of a piece of tyre

- On a self-stiffened panel a shock leads to:
 - in the impact area, deformation in the direction of the impact (direct mode);
 - in neighbouring areas, deformation in the opposite direction by continuity effect on the structural elements (indirect mode).
- When the box contains liquid, a secondary effect can appear which contributes to the indirect mode, an effect due to:
 - the wave of pressure that is propagated in the liquid at the speed of sound, that is to say at about 1,400 m/s. This wave diminished rapidly and after an initial pressure of two hundred bars, it was only about ten bars in the area where the indirect mode was expected;
 - the successive displacements of the liquid itself, at a speed of a few dozen metres a second. Because of the incompressibility of liquids, and in as much as the tank is “full”, that is to say there is no free surface too near the impact area that disturbs the phenomenon, this displacement tends to push the tank structure towards the outside, first of all in the nearest areas.

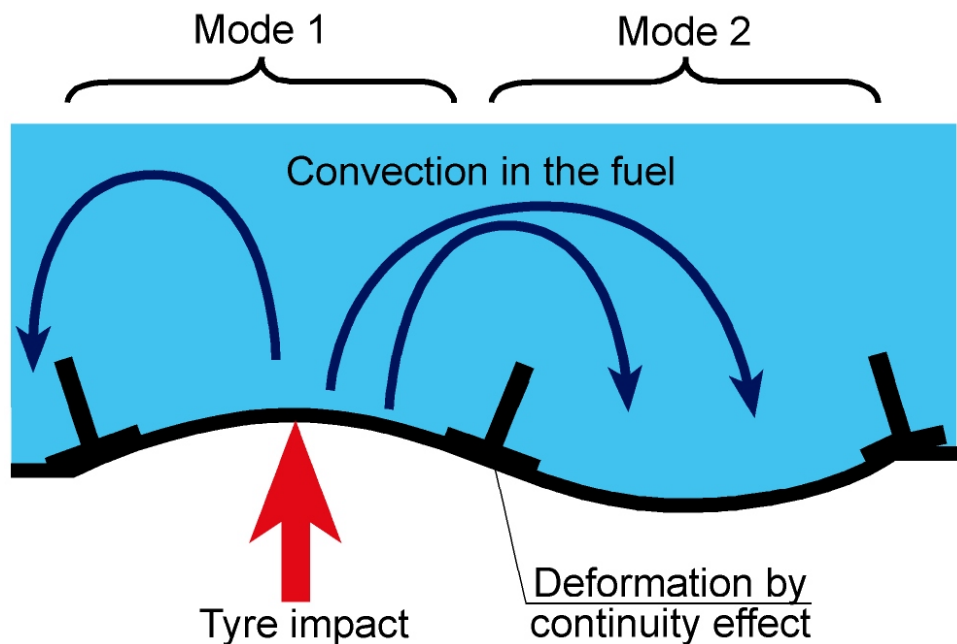


Figure 59: Effect of impact on wing box filled with fuel

b) Rupture by hydrodynamic pressure surge:

Methods used in the military field have shown that the puncture of a tank by a high-speed projectile can have catastrophic consequences through generation of what is known as a pressure surge: on penetrating the liquid, the projectile is rapidly slowed down. During this slowing, its kinetic energy is transferred to the liquid, and a cavity of a certain volume is created around it. In case of confinement, that is to say when the tank is full, the fluid, being incompressible, transmits to the structure a mechanical load dependant upon the volume of the cavity.

Note: a backshock can also be generated when the cavity collapses.

The investigation therefore tried to determine if these scenarios could be applied to the case of the Concorde accident and explain the damage to tank 5.

1.16.7.2.1 Rupture by Tyre Impact

1.16.7.2.1.1 *The Principle*

The initial shock, by pushing the walls, displaced a certain amount of fuel, which caused a displacement movement within the liquid. It was this displacement that pushed out the surfaces neighbouring on those on which the impact occurred. It might be the neighbouring areas on the underside or the vertical walls, depending on the local geometry and the location of the impact.

To effectively reach the level of rupture:

- the zone where the indirect mode can appear must be an area of thin skin,
- it must be surrounded by an area notably more rigid to withstand the initial shock and to limit the possibility of deformation beyond the area where the indirect mode can appear,
- displacement of the fluid must be partially channelled in a particular direction due to a lateral wall, for example,
- very local variations in geometry such as in the stiffener fillets are potential incipient rupture zones, through concentration of stresses.

Note: the piece of the tank found on the runway responds to these criteria.

1.16.7.2.1.2 *Tests*

In the context of the investigation and also for the work performed to return the aircraft to service, a series of tests to damage a tank with heavy projectiles was carried out at the CEAT in the first half of 2001. During these tests, pieces of tyre were fired at high speed at test boxes. So as to be as representative as possible, the box used for the last firing was made out of a panel from tank 5 taken from a Concorde. However, the exact shape of the tank walls, their size and internal equipment could not be represented precisely. The boxes were filled with a liquid whose mechanical characteristics and viscosity were similar to those of kerosene. They were equipped with load sensors and pressure sensors.

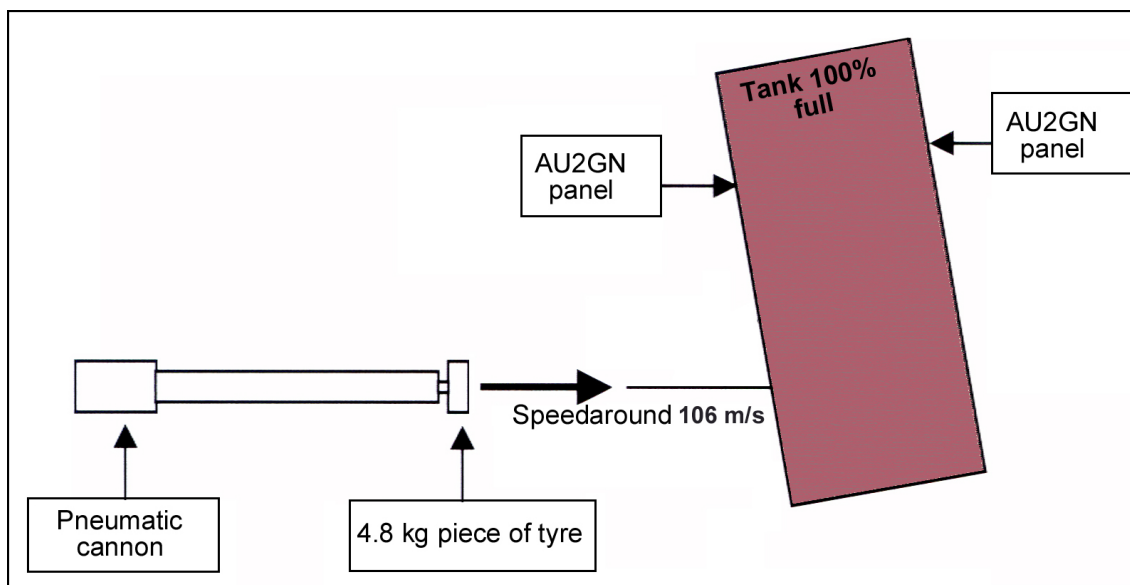


Figure 60: Firing test principle for a piece of tyre

The major limitations on the tests due to existing equipment were as follows:

- maximum projection energy imposed by the weight and speed of the projectile (4.8 kg – 106 m/s),
- horizontal firing,
- attitude imposed on projectile,
- limited size of boxes,
- limited number of firings and boxes.

Bearing in mind the large number of parameters enabling the impact to be defined and the limitations of the available test equipment, it was not possible to reproduce the rupture noted at the time of the accident. Nevertheless, the overall result of the tests performed enabled the scenario to be developed - the indirect mode certainly existed - and to confirm the theoretical models used to quantify this phenomenon.

1.16.7.2.1.3 Calculations

Theoretical studies were undertaken on the basis of the overall tank 5 structure-fuel model using the RADIOSS software programme. This code, still called the “crash” code, is recognised as the state of the art in dealing with rapid dynamic phenomena and fluid/structure interconnections at the same time.

The computer models were based on Concorde’s tank 5 and on the boxes defined and manufactured for the ratification tests. The procedure was carried out in two stages:

- identification of the most sensitive areas in the structure;
- detailed modelling of these areas with sample backup tests to adjust the parameters.

The rupture criteria were the subject of a specific study.

The results of the calculations were in accordance with the facts and measurements taken during the study, under the conditions in which they were carried out, that is to say below the energy level required to bring about a rupture.

1.16.7.2.1.4 Possible Energy Sources

Taking into account the preceding analysis and the known accident conditions, the level of energy locally necessary to cause the rupture can be calculated through the impact of a piece of tyre of around 4.5 kg with a speed of around 140 m/s. On the basis of the calculations made, this piece of tyre could have reached this speed through a combination of effects resulting from rotation of the tyre and the tyre burst.

However, it cannot be ruled out that the level of energy necessary could have been reached through the added effect of other phenomena such as:

- the impact of one or more other pieces of tyre,
- greater concentration of the energy in the fillets. This can be achieved by special impact conditions in terms of position, attitude and perhaps rotation speed of debris. The movement of the fuel and its interaction with the internal structure of the tank may also influence this,
- the previous weakening of the structure in the rupture initiation area.

1.16.7.2.2 Rupture by Pressure Surge

ONERA (the National Aerospace Study and Research Office) developed a method for numerical analysis of the pressure surge phenomenon in the context of tank punctures via high-speed projectiles, and the BEA asked them to study the relevance of this scenario in the case of the Concorde accident.

The objectives of the study were:

- to determine if the hydrodynamic pressure surge phenomenon can occur at relatively low speeds (in comparison with the speed of a bullet which is about 1,000 m/s),
- to determine if the hydrodynamic pressure surge phenomenon can be the cause of an "indirect mode" rupture of the tank structure,
- in case of tank rupture, to determine if it starts from the puncture location.

1.16.7.2.2.1 Method Employed

ONERA did not model the puncture process on the lower skin, the simulation beginning after the projectile entered the fluid. The finite element calculation code was the same as that used by EADS, that's to say the RADIOSS code.

The theoretical characteristics of a characteristic projectile, in accordance with the characteristics of the hole found on the piece of tank discovered at the site, correspond to a small cylinder with a weight of forty-five grams. Its speed in the fluid was fixed at 120 m/s. Finally, its point of impact was chosen as the location of the puncture observed on the piece of tank 5 found at the Gonesse site, which corresponds to a skin thickness of 1.6 mm. It should, however, be noted that some of the trajectory characteristics chosen are not entirely compatible with observations made on the piece of the tank.

Note: the speed of 120 m/s is an estimated maximum speed, consistent with:

- the linear speed of the aircraft at the time of the tyre burst (85 m/s),
- the increase in speed imparted to the debris by the tyre destruction mechanism,
- the loss of speed due to the puncture.

Based on knowledge acquired in the military field, it was also hypothesized that the projectile had an initial slope angle in the fluid of 30° in relation to the skin it struck and that it was turning round during the first moments of its passage. It has been established that this type of configuration can generate a hydrodynamic pressure surge on the skin underside, the latter being even greater when the turn occurs near the skin. This is the most onerous case known.

Several calculations were made, always with the tank fully filled, using various material laws, with or without rupture criteria, as well as different projectile turn kinematics. It should be noted that the phenomenon described diminishes very rapidly, or even disappears, if a free surface is located near the puncture area.

1.16.7.2.2.2 The Results

The significant results of the particular case studied were as follows:

- the calculations for each simulation took place normally, without any accumulation of energy errors or numerical instability, which shows that the method was reliable;
- a hydrodynamic pressure surge phenomenon was observed following penetration and turning of the projectile in the tank;
- the loads transmitted to the structure did not lead to a rupture in the area affected by the pressure surge. However, they can lead to structural damage in the connection areas : the shock wave created overpressure that loaded the rib laterally and the resulting bending could initiate a local rupture at the base of the rib;
- the crack did not initiate in the puncture area itself.

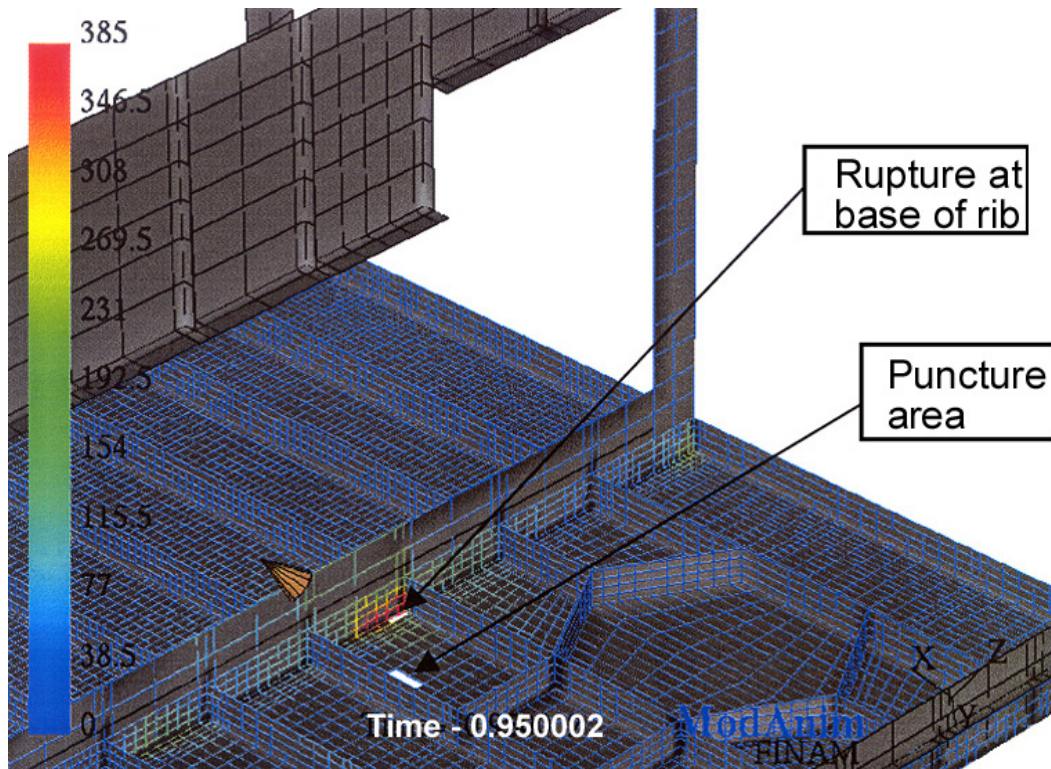


Figure 61: Position of the rupture areas on the lower skin

Result of the test with a projectile with an initial firing speed of 120 m/s using material behaviour law 36

1.16.7.3 The Fuel in Tank 5

To complete the work on the rupture process, the fill level of the tank was the subject of specific studies. In fact, the theoretical studies, confirmed by the tests on the boxes, revealed that a free surface near the impact area disturbed the liquid's transmission of energy to the tank structure. As a result, it seemed to be necessary to determine the quantity of fuel really contained in tank 5 at the time the tyre was destroyed.

It has been established that the aircraft began taxiing with tanks completely full. Before line-up, the crew carried out fuel transfer so as to bring the CG to 54% for takeoff. During this operation, the fuel burnt from the feeders during taxiing was replaced by the fuel contained in tank 11.

As a result of the transfer, feeder tanks 1 to 4 were full before line-up. In addition, main tanks 5 and 7, which had not been called on during taxiing, had remained full.

Between 14 h 41 min 55 s and 14 h 43 min 10 s, the time when the tank ruptured, the quantity of fuel burnt by each engine is estimated at 219 kg (15 kg between 14 h 41 min 55 s and engine power-up, 204 kg between power-up and the rupture). This was therefore the quantity of fuel taken from each feeder tank.

The transfer of fuel from tank 5 to feeder tank 1 deliberately only starts when the level in the feeder reaches 4,000 kg, that is to say 198 kg less than full. This leads to estimate that $219 \text{ kg} - 198 \text{ kg} = 21 \text{ kg}$ was the quantity of fuel taken from tank 5.

In the same way, the transfer of fuel from tank 5 to feeder tank 2 only starts when the level reaches 4,320 kg in the feeder, that's to say 250 kg less than full. There was therefore no transfer of fuel.

Taking into account these calculations, we may consider that the quantity of fuel in tank 5 was practically that which was loaded on the apron, which represents around 94% of the total volume of the tank. As a result of longitudinal acceleration of the aircraft at the time of takeoff, the free surface of fuel was at the front of the tank, thus at some distance from the impact area. This analysis demonstrates that tank 5 could be considered to be full, in the physical sense, at the time of the rupture.

1.16.7.4 Conclusion

The scenario whereby the 4.5 kg piece of tyre striking the underside of the wing led, via a displacement phenomenon in the fuel, to the ejection of the piece of tank 5 appears to be the most representative of the general physics of the event, without however excluding the contribution of other energy inputs.

The study of the puncture also showed that the hydrodynamic pressure surge phenomenon could occur at speeds considered as low, without however leading in a direct manner to the ejection of a piece of skin on the underside. Nevertheless, such a phenomenon could have locally significant consequences by generating damage and weakening a rib base.

How full the tank was had a significant bearing on the consequences of the phenomena studied.

1.16.8 Possible Origin of Combustion

On the basis of the known facts and based on the known properties of turbulent flames, three points were studied:

- the stabilisation of a quasi-stationary turbulent flame under the wing of the Concorde during the takeoff run and flight;
- estimation of the fuel flow coming from the leak under the wing of the Concorde;
- the mechanisms that may have led to the ignition then the propagation of the flame under the aircraft's wing.

1.16.8.1 Flame stabilisation and retention

When an obstacle is placed in an airflow, the development of turbulence is observed with re-circulation zones. In these zones, the flow can move in the opposite direction to that of the main flow in some areas. This re-circulation zone allows a flame front to stabilise through two mechanisms:

- the re-circulation generates an area of low speeds,
- the re-circulation zone contains burnt gases and acts as a reservoir for hot gases that contribute to the ignition, slightly downstream, of the fuel-air mixture.

These mechanisms may explain the stabilisation of the flame in the left landing gear bay, as can be seen on photos of the aircraft on takeoff. Indications of stabilisation of the flame are not therefore necessarily apparent on the gear leg, partly because the flame is slightly stabilised downstream and in part because the leg is continuously cooled by the flow from upstream.

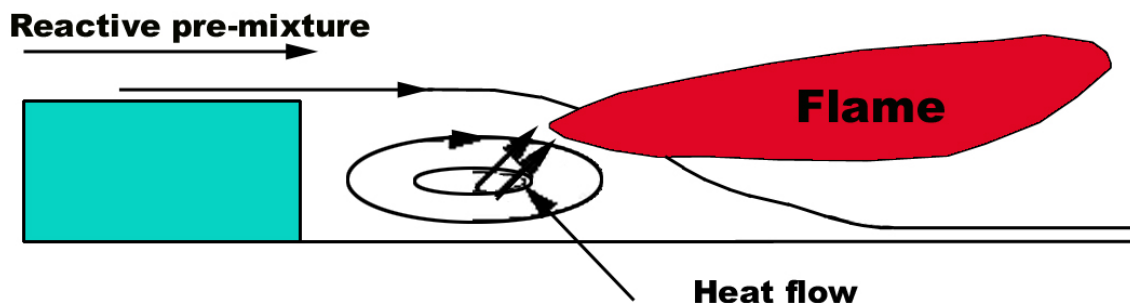


Figure 62: Re-circulation zone

1.16.8.2 Estimation of fuel flow

Based on photos and videos of the accident flight, the estimation of the average fuel flow was carried out using three approaches, which give similar results. The first uses the *Magnussen* model, a simple model developed to describe the reaction rate of non-pre-mixed turbulent flames, that is to say where the reactive elements are injected into the reaction zone separately. Taking the hypothesis of a flame three metres in diameter, fifty metres long and ten centimetres thick, modelling leads to fuel consumption close to 60 kilograms per second.

In the second method applied, the coherent flame (*pourquoi en italique ?indeed*) model equates the flame with a surface, and the reaction rate becomes the product of this surface and a surface reaction rate estimated according to a laminar flame model. According to this method, and in relation to the parameters selected for the size of the surface, the fuel consumption varies between 20 and 130 kilograms per second, with a peak in probabilities (corresponding to average and realistic values of the size of the flame) of around sixty kilograms per second. This model thus confirms the overall rate established with the first model.

The third estimate was made from the quantity of fuel remaining in tank 5. The quantity loaded was 7.2 tons and the gauge indicated two tons after the accident. The flight time between the estimated rupture of the tank and impact was around eighty-one seconds. The estimated fuel flow rate, apart from the leak due to the small puncture and (the) consumption by engines 1 and 2 (around 350 kg) was therefore around 60 kilograms per second.

In conclusion, the overall flow rate of the leak is several dozen kilograms per second, thus about ten times greater than in the Washington event. The high rate of flow from this leak contributed to the ignition of the fuel since it led to a fuel/oxidizer mixture, which was almost a stoichiometric mixture, thus perfectly flammable.

1.16.8.3 Ignition and Propagation of the Flame

Various potential sources of ignition of the fuel were identified in the course of the investigation. Three were selected and were the subject of extensive study:

- an engine surge,
- an electric arc,
- contact with the hot sections of the engine and/or reheat.

No evidence was found of previous ignition of a hydraulic leak. No trace of any hydraulic leak was found at any stage of the investigation.

1.16.8.3.1 Engine Surge

Ingestion of solid or liquid elements by an Olympus 593 engine can cause a surge in the high-pressure compressor, which would generate a wave of pressure towards the front of the engine. This phenomenon can lead to the appearance of a flame spreading toward the auxiliary air intake then the main air inlet. Fuel ingestion tests carried out by Rolls Royce confirmed the appearance of such a flame with duration of eighty to a hundred milliseconds.

Other tests conducted by BAE Systems showed that a flame coming from the auxiliary air intake can propagate forward in the turbulent airflow located downstream from the left landing gear and attach itself on it.

Nevertheless, this hypothesis was rejected, since the appearance of the fire preceded the surges, as shown by the chronology of events (pool of unburned kerosene and traces of soot on the runway) and the nature of the surges identified (ingestion of hot gases and not of liquid fuel).

1.16.8.3.2 Electric Arc

A study conducted at the CEAT showed that it was possible to generate an electric arc by a short-circuit on an electric harness situated in the area of the main landing gear and that the energy produced was compatible with igniting vaporised kerosene.

The tests simulated a short-circuit in the case of damage by crushing, tearing or cutting through the insulators of the electric line supplying the brake ventilators (3-phase 115 V, 400Hz). During the tests, the circuit breakers never tripped, apparently because the phenomenon was of too short a duration for them to detect it. The successive sparks had an energy estimated at twenty-seven joules, clearly above that required to ignite the vaporised kerosene, including in turbulent air conditions.

Tests carried out in Great Britain (see appendix 7) confirmed that the immediate ignition of vaporised kerosene was possible in the area of the gear well with an electric spark of three joules. The flame then attached and stabilised directly on contact with the landing gear bay, in the re-circulation zones.

Although the electric cables are partially protected by the gear leg, possible damage due to the destruction of tyre No 2 cannot be entirely ruled out. It should, however, be noted

that after the modifications carried out following the Washington event, no further cases of damage to these cables has been reported by the operators.

Figure 63: Tests (Warton): electric sparks generated in the gear well



Figure 64: Ignition after spark

1.16.8.3.3 Contact with the Hot Sections of the Engine

After the rupture of the tank, kerosene ingestion through the nacelle/engine assembly could have occurred through:

- the auxiliary air intake and/or the ventilation door,
- the air conditioning air bleed exchangers.



Figure 65: In red, the lateral air conditioning air bleed door used for the air conditioning

The kerosene ingested could have ignited on contact with the hot walls of the engine or on contact with the gas coming from the reheat, at the level of the thrust nozzle. In this area, many obstacles allow the development of re-circulation zones and ensure retention of the flame in the rear part of the engine. It should, however, be noted that no traces of fire were discovered during the examination of the engines.

For this hypothesis on ignition to be applied to the 25 July 2000 accident, it is necessary to explain how the flame could then have “propagated forward” to get to and attach itself behind the landing gear well. A study conducted in the context of the investigation by two CNRS researchers shows that two routes are possible: via the outside of the inside of the nacelle.

- The airflow speeds inside the nacelle, of around 20 m/s, would allow the flame to flow back quickly enough so as not to cause engine damage. No trace of any fire was in fact brought to light during examination of the engines. The forward propagation of the flame could not possibly have occurred through the air conditioning circuit, whose exchanger mesh is too fine. It is possible, however, in the direction of the second secondary air bleed, which would take the flame to the area of the re-circulation zone that develops behind the gear leg. The tests in Great Britain showed that by igniting the main air flow at the level of the first secondary air bleed, thus about one metre upstream of the second, a flame was created that flowed back rapidly to attach itself to the gear well. Nevertheless, it must be underlined that it is not easy for the flame to come out of the nacelle at the level of this air bleed.

Note: the hypothesis on kerosene ingestion through the air conditioning air bleed and its ignition on contact with hot gases had been studied by the manufacturers after the Washington event. The result was that the risk of ignition was real but that the flame could not propagate against the airstream because of the exchanger mesh. The absence of a fire and the low flow rates noted explain why this hypothesis was not developed further.

- Forward propagation of the flame via the outside of the nacelle meets a theoretical obstacle: the propagation speed of a turbulent flame can barely exceed a few metres per second whereas the airstream under the wing of the aircraft is about 100 m/s. It is, however, sufficient for the flame to encounter locally, at a given moment, airflow that is sufficiently slow for it to be able to flow back. The complex geometry of Concorde’s lower wing, in particular the presence of a fairing between the nacelle and the wing, the disturbance to the airstream by the presence of the flame itself and the wake from the landing gear are three elements which make it possible to envisage sufficiently low speeds to be born by the flame

Note 1: Because of the chaotic nature of the turbulent combustion, a numerical simulation would be too inconclusive since the results would be too dependent on the model and the hypotheses selected. Flame forward propagation from the rear of the aircraft could not be produced during the tests conducted in Great Britain, but it was not possible to reproduce the exact conditions of the accident.

Note 2: although it happened under different conditions, an accident which occurred on 5 June 1966 to a HS125 brought to light a case of forward propagation of a flame: following the rupture of the wing in flight, a kerosene leak of about 70 litres a second ignited behind the engines and the flame propagated by flowing forward.

1.16.8.3.4 Conclusion

The work summarized above leads to the conclusion that two hypotheses can be accepted to explain the appearance of the flame. The hypothesis on ignition by electric arc explains the retention of the flame in the gear bay, but also supposes that the destruction of tyre No 2 also resulted in damage to the cables in the landing gear well.

The hypothesis on ignition on contact with the hot sections of the engine explains the appearance of the flame but implies that the latter flowed back a long way thanks to the re-circulation zones and occurred in a sufficiently short time period so as to be consistent with the observations made on the runway.

In the course of working sessions and meetings on the subject, the various specialists associated with the investigation could not agree on the respective probability of these two hypotheses.

The technical investigators from the AAIB, from their side, consider that the hypothesis of ignition by electric arc, which was able to be reproduced during the tests on the test rig, is the most probable.

1.16.9 Engines

1.16.9.1 Observations on the Engines

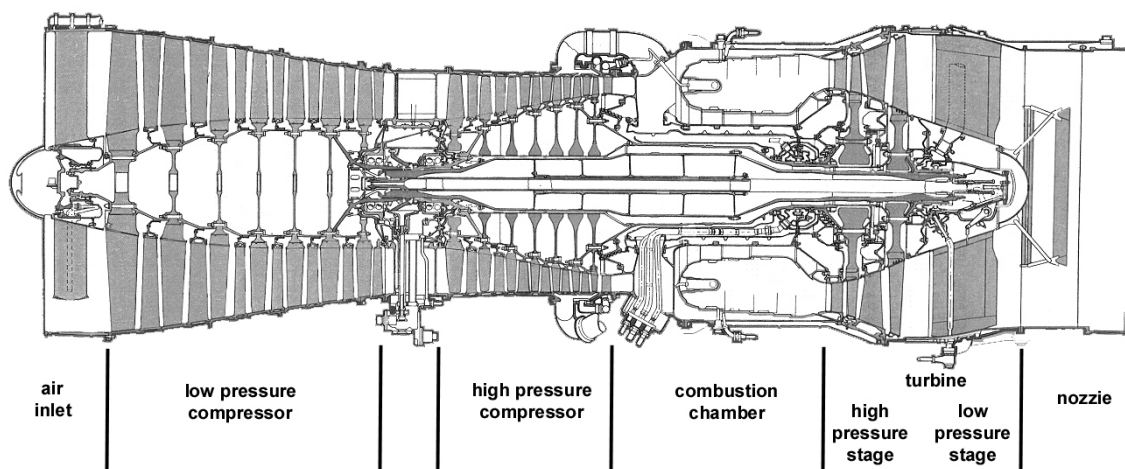


Figure 66: Olympus 593 – Representative diagram of airflow

1.16.9.1.1 Disassembly of Engines 1 and 2

The technical investigators made observations on engines 1 and 2 during disassembly at the CEPr facilities in Saclay.

Note: the engines, as well as disassembled inner parts, were washed in order to eliminate all possible traces of asbestos.

1.16.9.1.1.1 Engine 1

- BP compressor module

Ten blades from the No 1 stage of the LP compressor showed hard impacts with material pick-up. In particular, blade 6 showed metal pick-up that appears to result from impact with a small piece of metal. From rotor stage 2 to rotor stage 4, impacts with loss of material were noted on the tops of the leading and trailing edges of the majority of the blades. These result from plastic deformation of the blades and untwisting towards the blade tips, with clashing⁽¹⁴⁾ on the opposite stators of stages No 2 to 4.

Stage No 4 of the compressor showed blade deflection in the opposite direction to that of rotation in the lower sector and to a lesser degree in the upper sector. This distortion corresponds to the crushing of the casing at the time of impact with the ground.

On the upper half of the compressor discs, traces of overheating after impact are noticeable, related to prolonged exposure to temperature. The lower part of these discs is blackened with a soot deposit.

Taking into account the slight deflection of the blades, it appears that the LP compressor was turning slowly at the time of impact with the ground.

- HP compressor module

The HP compressor module shows marks of ingestion of hard bodies. The blades from stages 1 to 7 show significant impact marks.

- Combustion section

The combustion section showed no damage or oxidation related to any particular thermal constraints. Deposits of magnetic and non-magnetic materials were found there.

- Turbine

Small debris, traces of metallisation and impact are visible on the HP and LP turbine disc blades.

- Control assembly

Examination of the control assembly did not reveal any malfunction in any of the elements of the air and fuel circuits.

1.16.9.1.1.2 Engine 2

- BP compressor module

Three blades of stage No 1 of the LP compressor showed soft body impacts. No trace of metallisation, ingestion or damage related to hard bodies was noted. The deformations

¹⁴ Interaction of the rotor blades and stator vanes.

noted on the lower part of the rotor stages No 1, 2 and 3 correspond to the crushing of the casing on impact with the ground.

- HP compressor module

All seven stages of the HP compressor module showed deformations on the lower part due to the impact with the ground. Some blades from the rotor stage No 2 were bent. From stage 3, there are clear signs of damage related to clashing on the leading and trailing edges of many of the rotor and stator blades. The fracture topography observed on these blades shows that the clashing resulted from a high load failure caused by the impact with the ground. The module showed no signs of ingestion of foreign bodies or of secondary impact.

- Combustion section

The combustion section showed no damage or oxidation related to any particular thermal constraints. Small debris was found there during disassembly.

- Turbine

The LP and HP turbine stages showed no marks of damage due to a foreign object. Overall, the turbine had suffered no deformation, apart from the part that had struck the ground. The turbine showed no signs of rotation on impact with the ground.

- Control assembly

Examination of the control assembly did not reveal any malfunction in any of the elements of the air and fuel circuits. Observations on the FCU showed that the throttle valve was positioned at around seven degrees. This position is indicative of an engine shutdown.

1.16.9.1.2 Examination of Engines 3 and 4

Visual examinations of engines 3 and 4 were performed so as to determine their level of external damage. An intrascope examination of the airflow was also performed on both engines in order to determine their internal condition.

1.16.9.1.2.1 Engine 3

- External examination of the engine

Engine 3 showed signs of overheating on its lower sector due to the fire on the ground. Its general appearance was comparable to that of engines 1 and 2.

The impact with the ground caused generalised distortion of the casings, more serious than that noted on engines 1 and 2. The LP compressor casing was completely flattened. The deflection distortion of the blades on the first stages of this module indicate that its rotation was blocked in less than one revolution.

The ends of the flange on the aft part of the LP compressor casing were forced several centimetres apart. The HP and LP turbines and their nozzles were seriously damaged on

impact under a high vertical load. The violence of the shock contributed to the sudden halt to rotation of the LP body.

The left accessory gearbox remained in place with all of the parts of the fuel circuit, severely damaged by the impact. Observation of the FCU showed that the throttle valve was set at sixteen degrees, a position close to idle.

- Intrascope examination

The intrascope examination of the LP compressor showed more significant damage on this engine than on engine 1. The stator vanes on the first four stages that could be inspected were very severely damaged and for the most part torn off their inner attachment points. In the most distorted sectors, some rotor blades showed pick-up on their leading edges, similar to the clashing observed on the engine 1 LP compressor.

Examination of the HP compressor in the only sector visible through the inspection covers showed that the blades from all of the stages were bent and more or less entangled with the stator vanes. This damage appeared more significant than that observed in this area on the same components on engine 1. The blade airfoils showed no impacts such as those affecting the HP compressor on engine 1.

1.16.9.1.2.2 Engine 4

- External examination of the engine

The external aspect of engine 4 was similar to that of engine 3.

Forward, the LP compressor casing is flattened and the air inlet vanes have been torn off. The twist distortion of the first stages of the compressor probably resulted from more rotation on impact than that of engine 3. The ends of the flange on the aft part of the LP compressor casing were forced several centimetres apart. The HP and LP turbines and their nozzles were seriously damaged on impact under a high vertical load.

The left accessory gearbox remained in place with all of the parts of the fuel circuit, severely damaged by the impact. Observation of the FCU showed that the throttle valve was set at fourteen degrees, a position close to idle.

- Intrascope examination

The intrascope examination of the LP compressor showed more significant damage on this engine than on engine 1. The blades on the four compressor stages showed pick-up or clashing in their leading edges, as well as the beginnings of shearing on the trailing edge. There were no impact marks on the airfoils examined.

The blades on all stages of the HP compressor were deflected and entangled with the stator vanes. The pick-up and tears on the airfoils examined on a very limited angular sector were more significant than those observed on the same parts of engine 3. However, they showed no impacts such as those affecting the HP compressor on engine 1.

1.16.9.1.3 Laboratory Research

Research was carried out in a laboratory on the parts of engines 1 and 2, which seemed to possess marks of foreign object damage. Analysis was performed on deposits sampled from the engines in order to determine their nature and their possible origin.

Note: the marks and deposits associated with operation of the engines may have been altered by the debris and various elements coming from the environment of the accident site.

1.16.9.1.3.1 Engine 1

The marks found on blade 6 of the first stage of the LP compressor, as well as on blades 13 and 14, were caused by a piece of stainless steel. It was not possible to determine if it was the same piece.

The soot deposits and the compressor disc colouring indicate that they were subject to thermal constraints whose distribution was not uniform. Considering these colourings, the estimated temperature was around 550 °C to 600 °C.

The highest temperatures affected the upper inner parts of the airflow. This tends to show that this was a consequence of the fire on the ground and the chimney effect produced in the airflow.

Traces of aluminium alloy coming from the airframe were identified in the samples analysed. It was impossible to determine the origin of other elements identified, such as cadmium, tungsten or cobalt.

Antimony was found on numerous impact marks. Antimony is used in certain paints designed to be subjected to thermal constraints, but also in most fire extinguisher products. This element is also used in the vulcanisation of rubber, though not in the manufacture of Concorde tyres, as analyses confirmed.

Other elements such as sulphur, zinc and some traces of iron were identified. These elements, used in the manufacture of tyres, were not however present in sufficient quantities to be able to assert that tyre debris had been ingested. In addition, in the hypothetical case of tyre debris ingestion, it is normal not to find carboniferous residues, carbon not leaving any residues with temperatures over 500 °C.

Finally, several fragments of glass fibre material were identified among the debris found in the combustion chamber.

According to the studies carried out in the United Kingdom, the marks of clashing observed on the blades of the LP compressor could result from ingestion of soft bodies such as tyre debris (as in the Washington event), from ingestion of an appreciable quantity of liquid fuel, or even from water deflector debris.

1.16.9.1.3.2 Engine 2

Although numerous particles of lead were found around the impact points, the analyses could not determine the nature of the bodies involved in the soft body impacts found on three first stage rotor blades in the LP compressor.

Only two neighbouring blades (blades 6 and 7) of the third stage LP compressor sustained hard body shocks on their leading edges. Analysis showed that an iron-based body was the origin of one of them. Some traces of antimony and zinc were also found, without it being possible to associate them with the iron-based body.

A fragment of glass fibre was found, its structure being identical to that of the fragments found in engine 1.

Two adjacent blades from the LP compressor first stage and fifteen blades from the HP compressor third stage showed some loss of material on their airfoil, just under the peak. This resulted from an overload sustained on impact with the ground. This observation is confirmed, both through an examination of the fracture topography (9th blade in particular) which shows the same blue colouring as the blade leading edge, and through the fragments resulting from these fractures, which remained in the vicinity of the HP compressor. This tends to show that it was the ground fire and not ingestion of hot gases that caused this colouring.

The soot deposits and the colouring of the discs on the different stages of the LP compressor indicate that they sustained thermal constraints. These overheating marks seem more uniformly distributed than on engine 1. Their examination shows that the thermal constraints were lower than those born by engine 1 and that they occurred during prolonged exposure to high temperature, with the engine stopped.

As on engine 1, it is probable that after impact with the ground, the fire destroyed certain clues. It was no longer possible to discern any possible traces of hot gas ingestion.

1.16.9.1.3.3 Examination of the HP fuel valve selectors

There are four selectors (one per engine) situated on the upper centre panel. They are used in the normal engine shutdown procedure and cut the supply of fuel.

The four fuel HP valve selectors found in the wreckage were examined in the workshop. The mechanical position of the selectors as well as electrical tests on the contacts indicated that the four selectors were in the OPEN position.

Note: this fact leads to the conclusion that the noises recorded at 14 h 43 min 26.2 s and between 14 h 44 min 24 s and 14 h 44 min 27s could not come from shutting an HP cock and that it was thus movements of the thrust levers.

1.16.9.2 Tyre Debris Ingestion during Operation

Of the nineteen cases of damage to engines resulting from ingestion of tyre debris, six cases leading to a loss of thrust during takeoff have been reported.

Date	Registration	Engine affected	N2 Drop	Loss of thrust
14 June 1979	F-BVFC	2	1%	9%
21 July 1979	F-BVFD	2	*	14%
23 Sept. 1979	F-BVFB	3	3%	12%
6 October 1979	G-BOAA	3 4	0,3% 0%	1% 0%
19 February 1981	F-BTSD	1 2	2% 0%	9.5% 0%
14 December 1981	G-BOAC	1 2	3% 18%	0% 5%

Note: the indications above correspond to the analysis of the stabilised parameters after a transitional phase, which was not usable due to sampling (every four seconds).

1.16.9.3 Data Readout

This paragraph presents a synthesis of the engine parameters and the CVR recording, consistent with the observations made during disassembly of the engines. You are reminded that these parameters are recorded every four seconds. The following elements come from extensive analysis of the available data. Times were identified with a precision of a tenth of a second.

Powering up of engines and their behaviour during the initial phase of takeoff, up until 14 h 43 min 11 s, is normal on all four engines with a longitudinal acceleration (Nx) of 0.268 g.

Time	Engine 1	Engine 2	Engine 3	Engine 4
14 h 43 min 11.7 s and 14 h 43 min 12.3 s	The parameters are normal.			
14 h 43 min 12.7 s and 14 h 43 min 13.3 s		The EGT, P7, N1, N2, Aj show deviations.		
14 h 43 min 12.0 s and 14 h 43 min 13.0 s	Surge.	Surge.		
14 h 43 min 13.0 s	The Nx is recorded at its minimal value of 0.133g.			

Time	Engine 1	Engine 2	Engine 3	Engine 4
14 h 43 min 121 s to 14 h 43 min 14.1 s	The GO LIGHT lamps go out.			
14 h 43 min 15.7 s and 14 h 43 min 16.3 s	Confirmation of the surge. The thrust is equal to about 75% of the nominal thrust.			
14 h 43 min 16.1 s and 14 h 43 min 18.1 s	The GO LIGHT lamp lights up.			
14 h 43 min 16.7 s and 14 h 43 min 17.3 s		Thrust (about 3% of nominal thrust) is hardly above the level corresponding to idle.		
14 h 43 min 18.1 s and 14 h 43 min 20.0 s	The GO LIGHT lamp goes out ⁽¹⁵⁾ .		The GO LIGHT lamps go out ⁽¹⁵⁾ .	
14 h 43 min 19.7 s and 14 h 43 min 20.3 s	Thrust is equal to about 80% of nominal thrust.			
14 h 43 min 20.7 s and 14 h 43 min 21.3 s		The engine is in recovery phase. Thrust is equal to about 15% of nominal thrust.		
14 h 43 min 20.9 s and 14 h 43 min 21.9 s	Surge.	Surge.		
14 h 43 min 22.8 s		The fire alarm sounds, as well as the associated gong.		
14 h 43 min 23.7 s	Thrust is close to idle and equal to about 4% of nominal takeoff thrust.			

¹⁵ This is a normal consequence of the uncompressed state of the left main landing gear shock absorber. The lag which appears on the data recorder results from sampling over four second periods.

Time	Engine 1	Engine 2	Engine 3	Engine 4
from 14 h 43 min 24.7 s to 14 h 43min 25.3 s		Thrust is equal to about 12% of nominal takeoff thrust.		
14 h 43 min 24.8 s		The FE "shut down engine 2".		
14 h 43 min 25.8 s		The Captain calls for "engine fire procedure".		
14 h 43 min 26.2 s		The thrust lever is moved to its stop in idle position.		
14 h 43 min 27.7 s and 14 h 43 min 28.4 s	Recovery from surge. N2 reaches 89.7% and the thrust is at around 45% of takeoff thrust.	N2 drops below 58%.		
14 h 43 min 28.7 s and 14 h 43 min 29.3 s		N1 and N2 have a curve, which is typical of an engine running down normally. The fire handle is pulled.		
14 h 43 min 28.3 s			The parameters show behaviour consistent with a switch from TAKE OFF to CONTINGENCY. The fuel flow, primary nozzle and P7 pressure are consistent with reheat operating on these engines.	
14 h 43 min 35.5 s	The engine is operating in CONTINGENCY mode, although the P7 indicates a shortage of thrust of about 5%.			
14 h 43 min 42.3 s		A second fire alarm and the associated gong are heard.		

Time	Engine 1	Engine 2	Engine 3	Engine 4
14 h 43 min 58.6 s		The fire alarm an associated gong sound for the third time although the alarm had stopped four seconds before. The alarm continues until the end of the recording.		
14 h 43 min 59.5 s and 14 h 44 min 11.5 s	Fuel Flow and P7 show signs of fluctuation. The engine is in underspeed and suffers a final surge.			
14 h 44 min 24.7 s to 14 h 44 min 27.0 s			Probable reduction of the thrust levers by the crew.	
14 h 44 min 25.5 s and 14 h 44 min 26.5 s			Surge due to distortion of the airflow in the air inlets.	

1.16.9.4 Engine Operation

1.16.9.4.1 Engine 1

The first loss of thrust was caused by a surge. The parameters show that it occurred a short time after the tyre destruction, between FDR times 97602.8 (14 h 43 min 12.3 s) and 97603.4 (14 h 43 min 12.9 s). The disassembly of the engine brought to light the ingestion of foreign bodies probably linked to the explosion of the tyre, apparently the cause of the surge. However, since the surge on this engine happened practically at the same time as that on engine 2, it is also possible that the cause was the same for both engines, that's to say related to ingestion of hot gases.

The second loss of thrust was caused by a further surge that happened when the aircraft angle of attack was 13°. The loss of thrust (the remaining thrust is comparable to that of an engine at idle) was much greater than the loss of thrust recorded in the past during ingestions of tyre debris. This surge was probably caused by the ingestion of a kerosene/hot gas mixture, facilitated by the change in the aircraft's attitude.

After the second surge, the engine returned to almost normal operation in CONTINGENCY mode commanded by the fuel regulation system. A thrust deficit of around 5% is, however, recorded. This loss of thrust was probably due to the mechanical

damage the compressors suffered as a result of ingestion of debris caused by the destruction of the tyre. The ingestion of hot gases and/or fuel-air mixture is unlikely considering the subsequent stability of the parameters.

The engine then operated in a stable manner for twenty-two seconds. Then the Fuel Flow parameter is disturbed due to the ingestion of kerosene by the main or auxiliary air intakes, causing regulatory action to occur.

Fifteen seconds after the fluctuations in the fuel flow, the engine surged again and decelerated rapidly. According to Rolls Royce, analysis of the parameters shows that the engine suffered a final severe surge due to probable ingestion of debris such as pieces of aluminium or glass fibre or honeycomb structures belonging to the aircraft structure. The surge might also have come from ingestion of a large quantity of fuel. It was responsible for serious damage (clashing), which was observed on the LP compressor when the engine was disassembled.

1.16.9.4.2 Engine 2

The loss of thrust was caused by a surge that occurred at practically the same time as that on engine 1. The thrust then available is comparable to that of an engine at idle. It has been established through testimony, marks noted on the runway and recorded data that the fire was burning before the engine surge. What's more, the facts noted during disassembly, as well as experience acquired in service, show that the internal damage to the engine before the impact was not sufficient to cause a surge. The only mechanism consistent with a surge leading to a great loss of thrust is ingestion of hot gases.

Between times 97611.2 (14 h 43 min 20.7 s) and 97611.8 (14 h 43 min 21.3 s), the parameters show the engine recovering. The acceleration value is consistent with the thrust equivalent to that delivered by three engines and is explicable as the consequence of an increase in thrust from engines 1 and 2. A short time later, the longitudinal acceleration fell again as well as the engine 2 parameters. This is the result of a second surge probably caused by ingestion of hot gases through the auxiliary air intake that opened again since the aircraft had started to accelerate again.

Engine fire alarm actuation and the very low values on the parameters led the crew to shut down the engine after the Captain called for the engine fire procedure. In fact, the movement of the throttle control lever to its idle stop is heard and, a short time later, pulling of the fire handle. In addition the deceleration of the engine, established from the recorded parameters, is consistent with a commanded engine shut down.

1.16.9.4.3 Engines 3 and 4

Engines 3 and 4 operated normally until 14 h 44 min 17.5 s (14 h 44 min 18.5 s, taking into account the sampling rate of the recording.). Fuel flow is recorded as decreasing from 14 h 44 min 21.5 s (22.5 s). The same is true for the P7 parameters at 14 h 44 min 25.5 s (26.5 s). The engine parameters show a rapid decrease at 14 h 44 min 29.5 s (30.5 s). Certain sounds recorded on the CVR between 14 h 44 min 24 s and 14 h 44 min 27 s probably correspond to the idle stop position of the throttle control lever. However, the loss of thrust is too sudden to be only the result of a commanded reduction in power. A surge due to distortion of the airflow probably caused by the roll and the high angle of

attack of the aircraft at that moment in the flight also contributed. All of the internal damage noted resulted from the impact with the ground.

1.16.9.4.4 Conclusion

The observations and examinations carried out on the four engines brought to light no malfunction of any of their basic equipment or components, or any indication of any behaviour outside of the certificated norms. None of them showed any signs of overheat or overspeed prior to the impact with the ground. The behaviour not commanded by the crew resulted from abnormal outside factors such as the ingestion of soft and hard bodies, hot gases and fuel.

1.16.10 Origin of the Non-retraction of the Landing Gear

The CVR recording shows that the crew noticed the non-retraction of the landing gear at 14 h 43 min 56.7. Eleven seconds pass between the presumed beginning of the manoeuvre (announcement saying *"I'm trying"*) and the announcement *"the gear isn't retracting"*.

Examination of the wreckage did not bring to light the cause of this malfunction, the few facts established not really being usable:

- the landing gear selector was found between the "down" and "neutral" positions, outside of the detent but under the mechanical guard,
- the locking catch on the left main landing gear door was open. Nothing can, however, be concluded from this, since during an emergency gear extension, door opening is ensured by means of rods linked to the structure. These rods may have been activated at the time of the impact,
- the retraction lock on the right main landing gear shock absorber was blocked. This lock is only released when the initial conditions are met (door confirmed open, nose gear straight and bogies perpendicular).

Observation of the movements of the door actuators found at the crash site was not relevant either. The left gear door actuator is in fact a double-effect model without a mechanical lock, hydraulic pressure alone maintaining it in position. During the impact, the destruction of the hydraulic pipes caused a loss of hydraulic pressure. The pistons could thus move freely in the body of the actuator.

It is therefore necessary to conduct a systematic analysis of the possible causes of the non-retraction of the landing gear, based on the description of the system in paragraph 1.6.2.2.

A precondition to gear retraction is the movement of the control lever towards the "up" position. The lack of comment from the crew leads to the supposition that the gear selector moved in a normal manner.

A malfunction in the door opening cannot, however, be excluded, whether it be as a result of an incorrect indication or a mechanical blockage leading to the non-opening or partial opening of a door.

If there was no door-opening problem, the sequence continued with a check on the position of the nose gear and the bogies. Nothing indicates any suspicion of a failure in the mechanical nose gear alignment system during takeoff, and main gear perpendicularity is recorded at that time on the FDR.

After opening of the doors, the landing gear elements operate independently. If a partial hydraulic failure, linked to a rupture of a pipe in the Green hydraulic system, had then occurred, only the landing gear located on the side of the rupture would have been affected. No mention was, however, made by the crew of any asymmetry in the landing gear display and no remarks were made on a partial retraction of the gear.

In addition, total loss of the Green hydraulic system would have caused a gong to sound via a PFCU fault. No such gong was recorded on the CVR. Furthermore, this failure would have led, at the same time, to a switch to mechanical by the rudder (see § 1.16.11). This switch occurred, however, almost five seconds after the announcement that the gear was not retracting.

In conclusion, taking into account the examination of the failure, only a partial opening of the door can explain the non-retraction of the landing gear. It was probably the left landing gear door, the only one located in a part of the aircraft, which could have suffered damage linked to the destruction of the tyre and to the fire.

1.16.11 Rudder Switch to Mechanical Mode

The CVR recording shows that at the beginning of the flight, because of a failure in the Blue electrical system, the crew decided to leave with the rudders on the Green system. This is in accordance with acceptable deferred defect limitations in the minimum equipment list (MEL). During the flight, at 14 h 44 min 01 s, about half a minute before the impact, the rudder switched to the mechanical system. Three hypotheses can in theory explain this switch:

- Loss of the green hydraulic system

In accordance with the flight control system logic (see § 1.6.7.1), the loss of the Green hydraulic system leads to a switch of the rudders to mechanical mode. However, the loss of a hydraulic system would generate a gong that was not identified during analysis of the CVR though such a gong could have been masked by the fire alarm recorded 14 h 43 min 59.4 s.

Note: according to this hypothesis the movement of the emergency hydraulic selector “from Yellow to Green” then the use of the reset button makes it possible to regain the Green system.

- Detection of a Failure

Possible detection by the computers of a servo failure on the Green electrical system of one of the rudder PFCU's (false or real alarm) leads to a switch to mechanical mode for the rudders. Since nothing connects the appearance of such a fault to the damage caused by the chain of events linked to the accident at that time, such a cause of failure is also unlikely.

- Loss of Green hydraulic system

Power supply to the Green electrical system of the inner elevon PFCU's, located in the field of the flame, could have been damaged. This power supply being common to the three control surface groups, the Green electrical system would then have been lost to all of the PFCU's.

However, since at the time of the switch to mechanical mode the "inner" and "outer and centre" elevon PFCU's were working normally on the Blue electrical. So the rudder PFCU's could be directly affected by the loss of the Green electrical system, which explains why only the rudder switched to mechanical mode.

1.16.12 Alarms

1.16.12.1 Toilet Smoke Alarm

A toilet smoke detection alarm was recorded at 14 h 43 min 32.6 s. Since the air conditioning in the toilets comes from the forward cabin, this alarm can be explained by passage into the conditioning circuit of a combustible mixture ingested by engine 2, which had just stopped, or by engine 1 (see § 1.6.7.2).

It is also possible that it was a false alarm. Although this type of event is not in fact usually followed up, several people told investigators that false toilet smoke alarms were not unusual on the Concorde.

1.16.12.2 Engine Fire Alarm

The engine fire alarm was noted three times during the flight. Three potential causes were identified:

- The flame⁽¹⁶⁾ established under the lower wing surface heated up the forward (aluminium) and aft (titanium) cowlings enough for the temperature to reach intermediate trigger threshold (350°C). According to a BAE study, the alarm originated in the intermediate assembly.

Note: the external fire could set off this alarm through the titanium aft cowling and melt the aluminium forward cowling in a time of between six and thirteen seconds.

- The fuel ingested through the air-conditioning low-speed air inlet located at the junction between the nacelle and the wing ignited on contact with the hot sections of the engine. In this case there would be an alarm on the aft assembly. When the fire handle is pulled, a valve closes the air bleed at the level of the last stage of the compressor.

The fuel entering through the ground running flaps ignites on contact with the hot sections of the engine.

The first alarm, recorded at 14 h 43 min 22.8 s, eleven seconds after the beginning of the external fire, stopped after four seconds. It may have been caused by the temperature of

¹⁶ Estimated convection temperatures of around 1,000 °C and radiation temperatures of around 1,500 °C.

the intermediate or aft assemblies exceeding the threshold value until the modification in airflow due to the aircraft taking off made it drop temporarily below this threshold. A transitory flame could also have been the cause of the alarm.

The second alarm was heard sixteen seconds after the first stopped. A fire extinguisher being fired by the FE, leading to cooling of the assemblies, explains why it stopped for four seconds. Then, since the cause external to the engine continued, the temperature of the assemblies went past the initiation threshold and the alarm was reactivated, from that moment until the end of the flight.

1.16.13 Study of Aircraft Track

1.16.13.1 Flight Simulator Tests

Various failure scenarios for the left engines were simulated using a training simulator with the help of a crew with Concorde type rating. The conditions reproduced were those of the day of the accident (wind, temperature, runway, weight). The pilots were informed of the failures programmed.

According to the pilots who participated in these tests, the noises and the accelerations occurring in the cockpit were not realistic and were much less than those experienced during takeoff in a Concorde.

After some takeoffs in the course of which all of the parameters were nominal, a takeoff was performed with a failure on engine 2 and a rotation at 183 kt. A clear pull of the track to the left was noticeable.

During the following two takeoffs, a failure of both left engines was simulated by reducing the thrust levers, completely for engine 2 and halfway on engine 1. The rotation speeds programmed were, respectively, 183 kt and 198 kt. On each occasion, the track noted was close to that of a lateral runway excursion. The following tests showed improvements in holding the centreline, clearly due to a familiarisation/training effect.

Note: during these tests, the acceleration time measured from the takeoff "top" to V1 (150 kt) was thirty-three seconds.

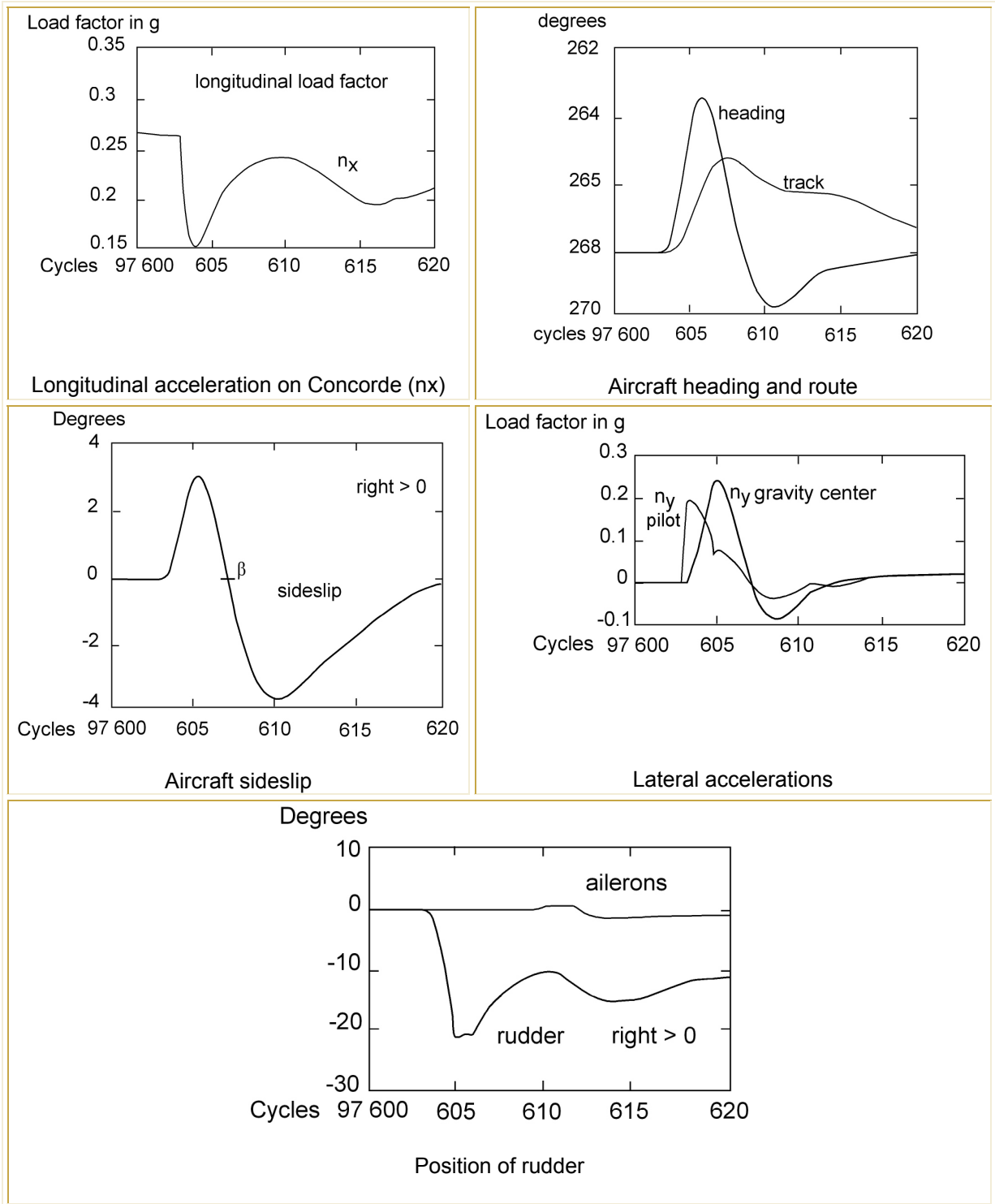
1.16.13.2 Deviation from the Track

At the request of the investigators, EADS performed various numerical simulations of the aircraft's track on the ground, by evaluating through calculation the lateral accelerations felt in the cockpit (nyp). The data entered for the simulation were drawn from the readout of the flight recorders, in particular the position of the roll and rudder controls and the thrust from the engines.

Generally speaking, it was noted that by entering the thrust and control movement parameters recorded on the aircraft into the model, values for acceleration, heading and lateral and longitudinal trim are obtained that are similar to those which were recorded. This confirms that the model was representative of the aircraft.

The simulation showed that when engines 1 and 2 suffered their first surges, the aircraft was subjected to a severe loss of thrust almost like a double engine failure, the longitudinal acceleration was then halved (figure longitudinal acceleration on Concorde (n_x)). It was practically at the same moment that the pilot began the rotation.

Note: in the figures in this paragraph, the figures on the y-axis correspond to the generated FDR time. For example, for "600", read "97600".



Under the effect of the loss of thrust the aircraft suffered a strong yaw movement to the left. Its heading was then to the left of its route, which corresponds to a slide to the right (*figures Aircraft heading and route and Aircraft sideslip*). This slide, of 3°, resulted in lateral acceleration of more than 0.2 g.

The thrust asymmetry was countered by the rudder: around 20° rudder to the right. This was enough to counter the yaw moment from the engines and the heading returned to the right from cycle 97605. However, the recorded parameters indicate that the rudder pedal was released from 97606.02: the rudder returned to 13° and this value remained approximately the same throughout the takeoff (figure Position of rudder). However, one second before this release, the calculations show that the lateral acceleration felt in the cockpit lost half of the force it had reached during the initial swerve, whereas the lateral acceleration at the centre of gravity – which indicates the effective movement from the track – was at its maximum. This lag between the lateral accelerations felt in the cockpit and those acting on the aircraft's track at the centre of gravity provides an explanation for the pilot's action on the rudder.

In the following seconds, the longitudinal trim was continuing to increase, the useful visual field of the pilot was reducing and it became difficult to appreciate the track. The heading moved noticeably back towards the runway centreline, the deviation from this centreline only increasing slightly.

The simulation shows, at the moment of takeoff, that is to say around cycle 97612.4, a gap of twenty-two metres between the aircraft and the runway centreline. The marks on the runway show that at that moment the real gap was 22.5 metres.

1.16.13.3 Effect of the Early Rotation

To study the effect of the early rotation on the aircraft's initial climb, a model of the aircraft's track in the vertical plane was made based on the following hypotheses:

- VR = 198 kt and trim = 13°, values written on the takeoff sheet,
- loss of engine thrust identical to that on the accident flight.

Note: the 13° trim is what is planned to counter an engine failure on takeoff.

In these conditions, at cycle 97660, thus before the final loss of thrust on engine 1, the altitude would have been 470 feet and the speed 200 kt.

These values would not have made it possible to counter the loss of a second engine.

1.16.13.4 Consequences of Aborting the Takeoff

Two simulations of a possible acceleration-stop were performed, one based on the aircraft's speed when the rotation was commenced (that is to say in fact the first moment when the crew could have been warned by unusual sensations), at 183 kt, the other at 196 kt, when the FE said what can be understood as "stop".

The simulations were conducted with the following hypotheses:

- braking on seven wheels, to take into account the destruction of tyre No 2,
- braking torque available at nominal value until the maximum energy indicated in the Flight Manual (70 MJ), increased by 10%,
- use of thrust reversers on engines 1, 3 and 4.

With this set of hypotheses, it appears that the residual speed of the aircraft at the end of the runway would have been 74 kt for a takeoff aborted at 183 kt and 115 kt for a takeoff aborted at 196 kt.

These figures show that an aborted takeoff would have led to a runway excursion at such a speed that, taking into account the fire, the result would probably have been catastrophic for the aircraft and its occupants.

1.17 Information on Organisations and Management

1.17.1 Concorde Operations at Air France

1.17.1.1 Flight Crew

At the time of the accident, the Concorde division contained around thirty people and possessed six aircraft. In comparison, the Airbus division contains more than a thousand flight crew, of whom about one hundred are instructors and possesses more than a hundred aircraft.

The management is organised in the following way:

- a head of division, Captain, flight crew executive and Concorde type rating examiner (TRE),
- a flight safety officer, Captain, flight crew executive,
- a ground attaché,
- a Captain, Concorde TRE who supervises two other Concorde TRE's,
- a technical attaché, FE,
- an FE executive who supervises two Concorde FE instructors and the FE technical attaché.

Although not included in the organisation chart, a FO also participates in instruction tasks. The other members of the division are Captains, First officers and Flight Engineers.

Unlike in other divisions, the head of the division deals with all line release of captains. The aircrew have a special status in their professional context.

The division has an average age higher than in other divisions. The Concorde type rating is on a voluntary basis and based on service time, and the aircrew who join are generally highly experienced.

According to persons interviewed in the course of the investigation, the limited size of the division had a rather favourable effect on relations within the crews and with the hierarchy.

1.17.1.2 Cabin Crew

Unlike the flight crew, the cabin crew attached to Concorde operations also flew on other long-haul aircraft. However, the normal and maximum working hours, limitations regarding flights, stopovers and post-flight rest times were all subject to specific arrangements outside of the normal work contract.

1.17.1.3 Maintenance

Concorde maintenance is the responsibility of a joint A310/Concorde department attached to the Long-Haul Operations Directorate within the Air France Maintenance Directorate.

The A310/Concorde department is organised in specific control units for Concorde (general overhaul, technical) and Airbus (technical) and in common control units (production, logistics). Management, human relations, human factors and a secretariat are placed under the direct control of the head of department.

The A310/Concorde Production control unit carries out inspections and maintenance operations up to the C check.

1.17.1.4 Operations Manual

The Air France Operations Manual contains three parts:

- General Operations Manual (GEN.OPS)
- Operations Manual- User section (TU)
- Routes and aerodromes
- Training and skills maintenance

1.17.1.4.1 Procedures from the GEN.OPS

- Aborted takeoff

Paragraph 2, Aborted takeoff, EXP 08.03.00 page 1, specifies that: “[...] *Air France has established instructions to be applied in the case of an aborted takeoff, in particular by adopting a notion of high and low speeds for each aircraft specified in each TU manual.*

In the high-speed range, the decision to abort takeoff before V1 must only be taken in case of a significant loss of thrust or fire on an engine, or with the certainty that the aircraft will be unable to fly (loss of an essential structural element, for example...). In all other cases it is preferable to continue the takeoff [...].”

Paragraph 3, Failure on takeoff, EXP 08.03.00 page 1, states that: “*In case of a failure on takeoff, no action will be taken before 400 feet AAL, apart from ensuring the track and gear retraction”.*

Paragraph 2.3, Distribution of tasks on takeoff, EXP 08.03.00 page 9, specifies that in case of a decision to abort the takeoff: *"the Captain has his hands on the controls and announces STOP"*.

Paragraph 2.4, Distribution of tasks in flight, EXP 08.03.00 page 10, specifies that the callout of a failure can be made by *"ANY (member of the crew)"*, that the track is followed up by *"the PF" and that measures to deal with the failure are initiated by the Captain"*.

- Takeoff Briefing

Paragraph 3, Briefing before takeoff, EXP 08.03.00 page 11, specifies that: *"the PF calls out the parameters for takeoff, takeoff track and the means to check it, the track to follow in case of failure, safety altitudes, special takeoff characteristics" and the Captain calls out "conditions for performing and aborting takeoff"*.

1.17.1.4.2 Extracts of Procedures from Concorde TU Manual

Paragraph 10, Wind limit, page II-01.10.4, specifies that the tailwind limit for a takeoff is 20 kt.

- Wheel alarm (in flight)

Page II-02.10.42 specifies that the first actions to take are:

*"Gear position GEAR EXTENDED OBSERVED
Leave the gear extended unless safety conditions require it.
[...]"*

- Fire or Severe Engine Damage Procedure

Page II-04.20.1 specifies that the first actions to take are:

*"GEAR, on takeoff..... RETRACT C/P
AUDIO CANCEL..... PRESS Ts
Thrust lever..... IDLE C
FIRE HANDLE..... PULL M
When green FIRE light on, FLAPS lit or after 7 seconds,
Button 1 SHOT FIRE M
[...]"*

- Engine Failure Procedure

Page II-04.20.3 specifies that the first actions to take are:

*"GEAR, on takeoff..... RETRACT C/P
Thrust lever..... IDLE C
FIRE HANDLE..... PULLED M
[...]"*

- Takeoff Briefing

The pre-takeoff briefing item in the "Taxiing" checklist states on page II-06.31.5:

“During the takeoff briefing, the Captain calls out the specific conditions for the takeoff.”
Number of reheats required, minimum N2 and failure N2.

- Aborted takeoff

1) *Before 100 kt, takeoff aborted for:*

- o All non-inhibited alarms
- o ‘Failure’ callout by FE
- o TYRE indicator lights up

2) *Between 100 kt and V1, the Gong is ignored, takeoff aborted for:*

- o ‘Failure’ callout by FE
- o TYRE indicator lights up
- o Fire alarm

Note 1

An aborted takeoff is performed by the PF before handover and by the Captain after handover.

Note 2

The FE calls out ‘FAILURE ENGINE X’ in case of:

- o significant loss of thrust (- 5% of minimum N2)
- o before 100 kt, loss of a reheat in comparison to the number defined
- o after 100 kt, loss of two reheats in comparison to the number defined, extinction of a green GO light with abnormal parameters or more than one green go light off.

[...]”

1.17.1.4.3 Concorde Flight Manual Procedures

Procedures in the Concorde Flight Manual relating to the shutdown of an engine are the same as those included in the Air France Operations Manual (TU). However, in contradiction with the Air France GEN.OPS which, on takeoff, requires waiting until reaching four hundred feet, the Flight Manual requires an immediate reaction in case of a red alarm. Specifically, in the emergency procedures section, it is specified that:

“An emergency is a predictable but unusual situation in which swift and precise action by the crew will considerably reduce the probability or the gravity of an accident.”

“A red warning light and a gong sounding will draw the crew’s attention to occasional emergency situations requiring immediate action.”

Note: as has been shown in § 1.6.4.4, fire corresponds to a red alarm.

1.17.1.4.4 Fuel Transfer Procedures

The procedures to follow for fuel transfer are extracted from the Concorde Operations Manual.

During preparation of the flight and the cockpit, the pumps on main tanks 5, 6, 7 and 8 are placed in the OFF position. There is therefore no possibility of supplying the feeder tanks from the main tanks.

The STAND BY INLET VALVES selectors for feeder tanks 1 to 4 are checked as being OFF during the check of the FE's station. These selectors allow the fuel to pass through the main balance transfer pipes to the corresponding feeder tanks.

After start-up of all four engines, the twelve pumps for the four feeder tanks are placed in the ON position, which allows each engine to be supplied from its feeder tank.

Before takeoff, the transfer procedure allows the centre of gravity to be moved to 54% in case of completely full tanks. To do this the STAND BY INLET VALVES of feeder tanks 1 to 4 are positioned on OPEN and the electric pump selectors for tank 11 are positioned on ON. This allows topping up of the fuel consumed from the feeder tanks during start-up and taxiing with the fuel contained in tank 11. A centre of gravity of 54% on takeoff is only authorised if all of the front tanks are full (R1 to 10 and 5A, 7A). This limits the fuel ballast to tank 11 only. The only transfer possible to adjust the centre of gravity to 54% is thus a transfer from this tank towards the feeder tanks.

After the end of the transfer and before takeoff, the STAND BY INLET VALVES and the pump 5 and 7 selectors are positioned on ON. The pump 6 right and 8 right selectors are positioned on ON. From this time, feeder tanks 1 and 2 are supplied from tank 5. In the same way, feeder tanks 3 and 4 are supplied from tank 7. The balance transfer is not undertaken during the takeoff phase.

1.17.2 Airworthiness Oversight

1.17.2.1 General

Concorde was the first civil aircraft to be developed under international co-operation and, quite exceptionally, a parallel process for primary certification was undertaken in the two partner countries. Concorde thus possesses two type certificates which means that, from a strictly regulatory perspective, the aircraft flying under the French flag and those under the British flag correspond to two different models. However, in practice, the DGAC and the CAA carry out airworthiness oversight jointly. These two authorities have each named a Project Certification Manager (PCM) who leads a team of specialists. It should be noted that in France, the PCM's have frequently been replaced: five changes in the last ten years.

Airworthiness oversight is organised around an annual meeting called the Airworthiness Review Meeting (ARM) with the representative of the manufacturers, EADS and British Aerospace. In addition to the ARM, some other regular meetings are also organised, such as on problems encountered in service which affect airworthiness.

Feedback is ensured by the operators who transmit incidents noted to the manufacturers. The latter present a monthly report to the two authorities.

Note: significant events, accidents or serious incidents are also notified directly to the investigation bodies.

It should be noted that, despite twenty-five years of commercial operations, the total number of cycles or flying hours performed by Concorde is clearly lower than that of other civil transport aircraft carrying out comparable stages. Some figures from the time of the accident are included in the following table:

Type of Aircraft	Flying Hours	Cycles
A300	5,645,000	3,468,000
A300-600	4,673,000	2,398,000
A310	7,258,000	2,755,000
A330	1,193,000	417,000
A340	2,757,000	439,000
Concorde	235,000	84,000

The airworthiness of the Olympus engines is subject to specific oversight that also involves the DGAC and the CAA. Twice-yearly meetings are held with both engine manufacturers, Rolls-Royce and SNECMA, in the course of which cases of in-flight shutdowns and aborted takeoffs are analysed. In 1998, a complete review of engine safety was carried out in the context of long-term continued operation of the supersonic aircraft. Other meetings are held regularly between the engine manufacturers and regulators.

1.17.2.2 Points Related to Tyres and Structural Damage

Actions taken related to tyre resistance and aircraft protection in case of a tyre burst that have been undertaken in the context of the airworthiness oversight are dealt with in paragraph 1.16.4.2.

After the event in Washington in 1979, reinforcement to the lower wing was considered in the first instance then, in the light of the results of tests and studies, it was considered that it was unnecessary to modify the structure (see § 1.16.4.2.1). This point was not re-opened subsequently, incidents not having brought to light any particular weakness in the aircraft's structure. Only equipment directly causing punctures was subject to modifications.

The following elements provide a statistical representation of the evolution of events linked to tyres. At the time of certification, it was considered that a double burst of tyres on Concorde could be considered as extremely rare (less than one occurrence per 10^7 flying hours). In the light of in-service experience, the study undertaken by Aérospatiale after the event on 14 June 1979 defined this occurrence as rare (probability between 10^{-5} and 10^{-7} per hour of flight). No occurrences of this type have been reported since 1979.

As of 25 July 2000, it appears that the rate of tyre deflation/destruction on Concorde was on average one occurrence per 1,500 cycles (or 4,000 flying hours). This rate fell over time and the proportion was no more than one occurrence per 3,000 cycles (or 8,000 flying hours) between 1995 and 2000. By way of comparison, on long-haul aircraft, such as the Airbus A340, this rate is of the order of one occurrence per 100,000 cycles⁽¹⁷⁾.

If only events on takeoff are considered, since they are representative of the accident, it is noticeable that damage to tyres was caused in 50% of cases by foreign bodies.

The rate of events on takeoff per number of cycles can also be calculated. Three periods can be distinguished:

- before 1982, when no modifications to the landing gear or to the tyres had been carried out,
- between 1982 and 1994, when all of the aircraft had been subject to modifications as described in § 1.16.4.2.1,
- after 1994, when maintenance procedures on the braking system had been modified and the British Airways aircraft had been equipped with modified deflectors.

	Cycles	Events on takeoff	Rate
1976-1981	24,052	13	$5,4 \cdot 10^{-4}$
1982-1994	42,628	8	$1,9 \cdot 10^{-4}$
1995-2000	17,261	1	$0,6 \cdot 10^{-4}$
Total	83,941	22	$2,6 \cdot 10^{-4}$

In relation to the number of cycles, the number of events over time is represented as follows.

¹⁷ This rate is calculated from airline incident reports. This reporting should be considered as non-exhaustive, the percentage of unreported incidents being unknown. This figure can be considered as being optimistic.

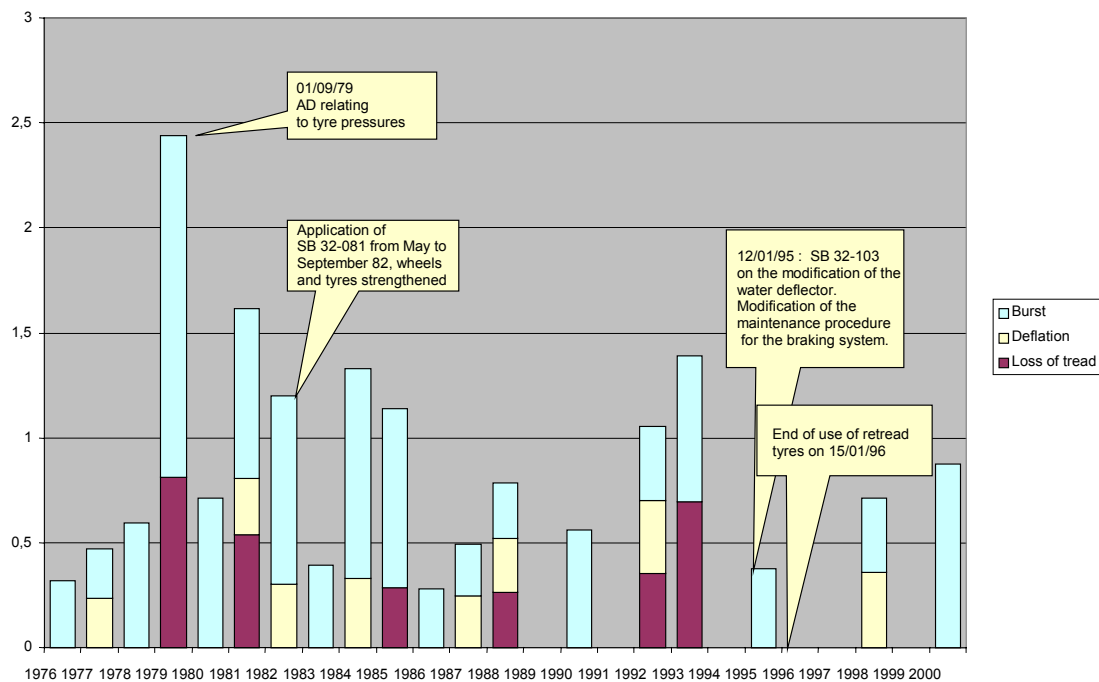


Figure 67: Number of events per thousand cycles

Note: taking into account the small number of events included in this statistical approach, the evolutions shown on the graph can only give an overall qualitative idea. However, the significant fall in events in these areas attests to the effectiveness of the measures taken.

1.17.2.3 Other Significant Areas in Airworthiness Oversight

Several points appear in a regular way in the ARM reports over the last ten years. These include power plant reliability, in particular, for which the raw statistics show a rate of in-flight shutdowns much higher than for other civil aircraft types, the hydraulic system and the emergency evacuation systems.

Thus, the findings of low reliability of escape slides is noted in all of the ARM reports from 1994 to 1999. This point was raised again in June 2001 during a meeting between the airworthiness authorities.

1.18 Additional Information

1.18.1 Certification of Landing Gear and Tyres

1.18.1.1 General

Concorde was certificated according to specific regulations known as SST Standards. In the regulations, texts relating to the landing gear are in chapter 5-6 and those relating to

the tyres in 5-3.2. Chapter 5-6.9 specifies the requirements in case of tyre burst or damage to the landing gear.

1.18.1.1.1 Requirements for Tyres

The tyres must be in conformity with certain physical and chemical characteristics. Amongst other things, the tyre-wheel-brake assembly must be subjected to static tests as well as to endurance and burst tests. In the case of the burst, the tyre, filled with water must not burst under a pressure four times the nominal pressure.

There are no requirements for the tyre burst mode. Specifically, no study is made of the way in which it disintegrates, the size or the weight of the debris. There are no dynamic tyre destruction tests.

Note: these requirements are not specific to Concorde. To meet certification requirements, tyre manufacturers normally depend on the dispositions of TSO-C.62d. In the case of Concorde, these dispositions had been adapted into a document called the Qualification Test Program (QTP). They mainly varied from the TSO in the character of the tyre on the machine, with more severe tests, particularly in load resistance (inflated and flat).

1.18.1.1.2 Landing Gear Requirements

In accordance with chapter 5-6.9 of the SST, the parts and equipment located in the area around the landing gear must be protected so as not to endanger operation of the aircraft in the following situations: tyre burst with the landing gear extended, retracted or in intermediate position, strike by a tyre strip in a position where the wheel is able to turn, overheating of a wheel due to excessive braking.

1.18.1.2 Substantiation Provided for Certification

At the time of certification, the aircraft was equipped with Kléber or Dunlop tyres. These tyres complied with the QTP and had been subjected to the load, aircraft installation, and airproofing tests as well as all the static and endurance tests.

Compliance with § 5-6.9 of the SST (resistance to tyre burst) was checked by the authorities on 5 October 1973 on aircraft 1. This was the subject of report 410.198.73 in which no comments were made.

After the Washington event, certification constraints imposed reinforcement of the QTP, in order to increase the tyres' resistance so that they could bear twice the normal load (versus 1.5 for other aircraft).

Note: the Goodyear tyres installed on F-BTSC complied with the new requirements of the QTP.

1.18.2 Absence of the Spacer on the left main Landing Gear

Examination of the landing gear (see § 1.12.4.4) revealed the absence of the central spacer from the left main landing gear. This spacer not having been re-installed during the

“A01” check carried out from 17 to 21 July 2000. It was thus appropriate to study the circumstances of this omission and any possible contribution to the accident on 25 July. With reference to the latter:

- a thorough examination of the left main gear bogie and tyres was carried out at the aeronautical test centre (CEAT) in Toulouse within the framework of the judicial investigation,
- a study was undertaken by the CEAT in collaboration with Messier-Dowty, the designer of the landing gear,
- the ground trajectories of the aircraft on 25 July and on its previous flights were studied.

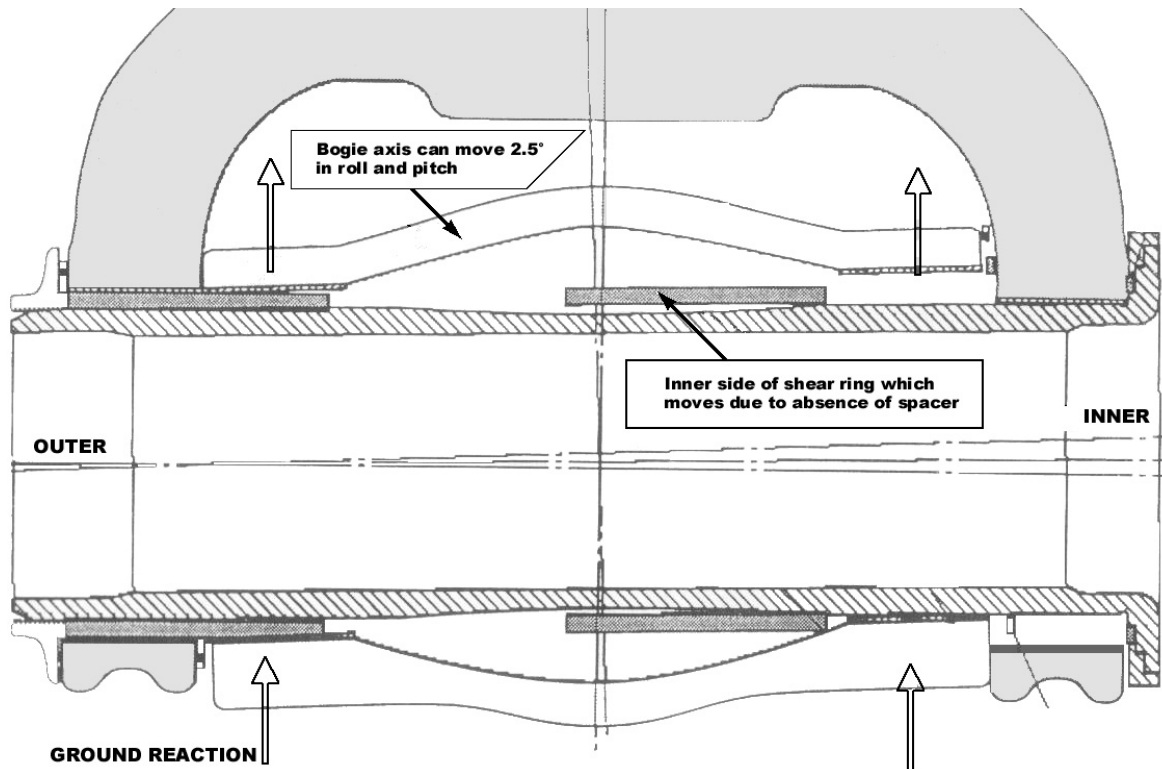


Figure 68: Cross-section of landing gear bogie beam coupling

1.18.2.1 Maintenance Operations

During the “A01” check, the replacement of the bogie on the left main landing gear was carried out on the 18 and 19 July by the personnel in the Air France A310/Concorde Production control unit.

It should be noted that this was the first time that a change of bogie had been undertaken on Concorde at Air France.

1.18.2.1.1 Documentation

The Concorde Maintenance Manual (Chapter 32-11.28) used by the maintenance personnel details the procedure for removal and re-installation of a bogie. This document specifies simultaneous removal of the main axle, the two shear bolts and the spacer, with the aid of a special extractor.

This extractor is referenced as P/N 253300/78 in the Concorde Maintenance Manual and in the Concorde Illustrated Tool and Equipment Manual (Chapter 32-11.00). It is known in the Air France tool reference system under the code C32-048.

For the re-installation of the main axle, it is specified that the two shear rings and the spacer recovered from the removed bogie be installed, then this assembly is to be installed through the bogie and the shock absorber with the aid of a guide.

Note: it appears that Concorde is the only aircraft whose bogies are designed with shear rings and a spacer.

1.18.2.1.2 Work performed

The replacement of the bogie was carried out in the course of two shifts. A first shift (A shift) undertook removal of the bogie on 17 July from 6 h 00 to 18 h 00. A second (B shift) undertook the reinstallation of the bogie from 18 h 00 on July 17 to 18 h 00 on July 18. The personnel concerned possessed the requisite qualifications and authorisations.

Note: Each shift worked for 12-hours. This choice, made with the agreement of the interested parties, was intended to avoid having to pass on multiple instructions. It is in compliance with the regulations relating to ground personnel.

During removal of the bogie, the extractor tool was not used. Only the bushes were extracted after removal of the axle. The spacer remained on the bogie. Because they were using the tool reference in their working document, the AMM, the personnel did not find the extractor in the store. A check carried out after the discovery of the anomaly on 23 October 2000 confirmed, however, the presence of two extractors.

During reinstallation, the shear rings were positioned directly in their end bogie beam shock strut bores, before the axle was reinstalled. This made it impossible to detect the absence of the spacer on the new bogie.

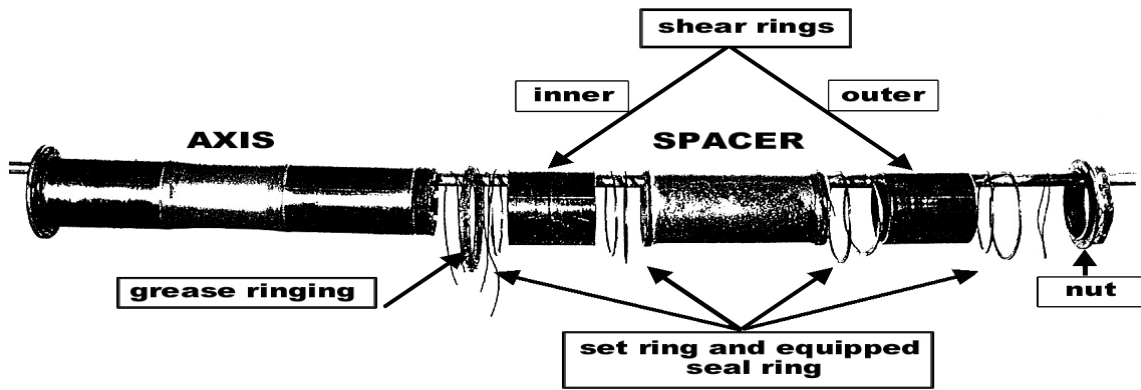


Figure 69: Landing gear, parts of the bogie beam

The checks and tests carried out before reintroduction into service brought no anomalies to light. These included manoeuvring the landing gear so as to extend and retract it. It should however be noted that, since the landing gear is not in contact with the ground, any possible alignment problems would not be noticeable.

1.18.2.2 Examination of the Bogie

When the bogie was disassembled in the workshop, no traces of debris from the spacer or traces of melted metal were found. Since this tube-shaped part could not come off the axle completely, the above evidence confirms that it was not present on the aircraft before the accident. It was also noted that the inner shear ring had escaped from its housing.

The condition of the various pieces (shear rings, bronze bearings, seals) show that the inner shear ring had moved from its position incrementally during the last few flights. The marks indicate that the mechanism was operational although the shear ring was no longer in its position on the bronze bearings of the shock absorber and bogie.

The exact chronology of this displacement is, however, difficult to determine since the ring was not new and certainly bore marks related to its previous usage. The only marks observed on the mechanical parts correspond to movements in the vertical plane alone or to normal oscillations of the bogie.

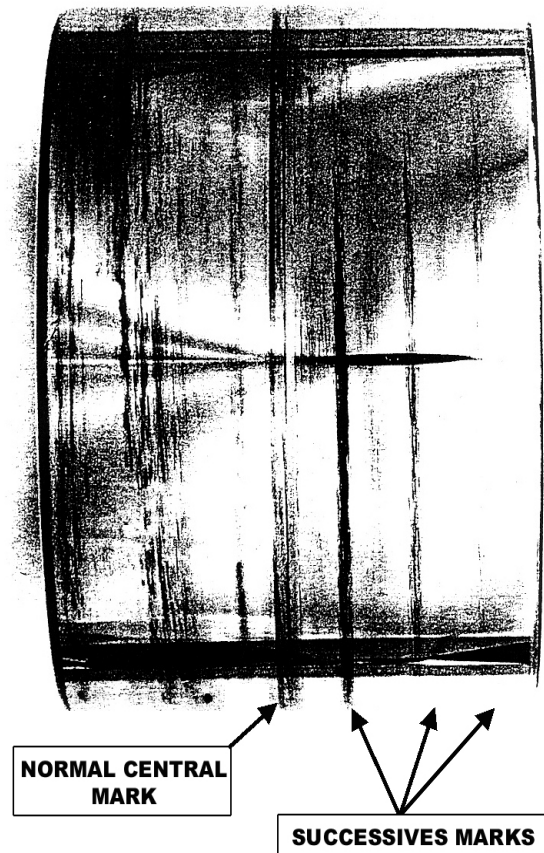


Figure 70: Left landing gear, inner shear ring

1.18.2.3 Possible consequences on the Landing Gear of the Absence of the Spacer

1.18.2.3.1 Mechanical Aspect

In case of complete displacement of the shear ring, the end of the bogie beam can move within the inner bearing of the shock strut to the extent of the play created by the absence of the shear ring, that is to say 7.25 mm at the radius.

The bogie beam can move by the same amount in relation to the axis of the shaft, disregarding the residual guidance provided by the outer shear ring.

Maximum displacement of the geometrical axis of the bogie beam results from the combination of the two movements described above, which corresponds to 14.5 mm at the radius, thus a cone angle at the apex of 5° , the tip of the cone being located at the centre of the outer bearing.

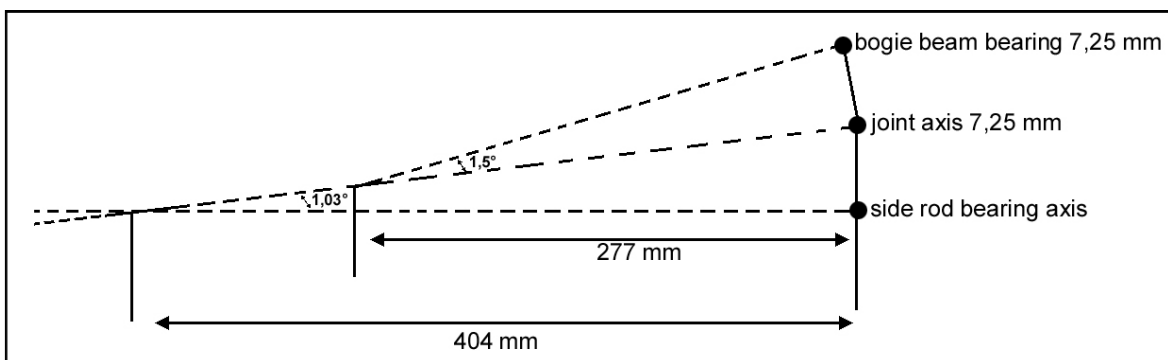


Figure 71: Effect of the lack of ring on the axle geometry

1.18.2.3.2 Effects on the Electrical Wiring and Pipes

An examination was undertaken to determine what might be the consequences of displacement of the axle on the shoulder side in the shock strut bearing. This displacement results in a relative movement between the attachment points of the wires and the pipes on the shock strut on one side and on the bogie on the other.

The electrical wires are long enough to take up a displacement of 20 mm, which protects them in the configuration studied.

The pipes attached to the rotating joint are not designed to take up such a displacement, but it is conceivable that their deformation might not necessarily lead to a complete rupture, taking into account their shape. Such a rupture would in any case only lead to a loss of braking.

18.2.3.3 Displacement of the Bogie

- Mechanical effects

Vertical displacement is viewed as part of normal operations as far as the equipment is concerned (bogie oscillations) and thus has no effect.

A displacement in the horizontal plane is, on the other hand, abnormal. It requires predominance of horizontal loads over vertical loads, which is not the case during the takeoff phase.

- New balance

When the four tyres are correctly inflated, the vertical load transmitted by the bogie beam takes the axle to its upper stop on the bronze bearing of the fork on the shock strut (shock absorber). This generates a camber angle of around 2.5° . The load applied on the two outer tyres (No 1 and 5) is then increased by around 20% whilst the load applied on the two inner tyres (No 2 and 6) being diminished by the same amount.

After the burst of tyre No 2, the load that it was bearing was redistributed between the outer tyres. Consequently, a new equilibrium was generated around its axle on the outer shear ring, the camber angle returning to practically zero.

It is also necessary to consider the possible effect of sideslip. The complete displacement of the shear ring can in fact engender lateral loads as a result of the appearance of a sideslip angle. Studies show that for sideslip angles of less than 5° , the self-aligning moment that appears tends to pull the wheel back towards the running axis.

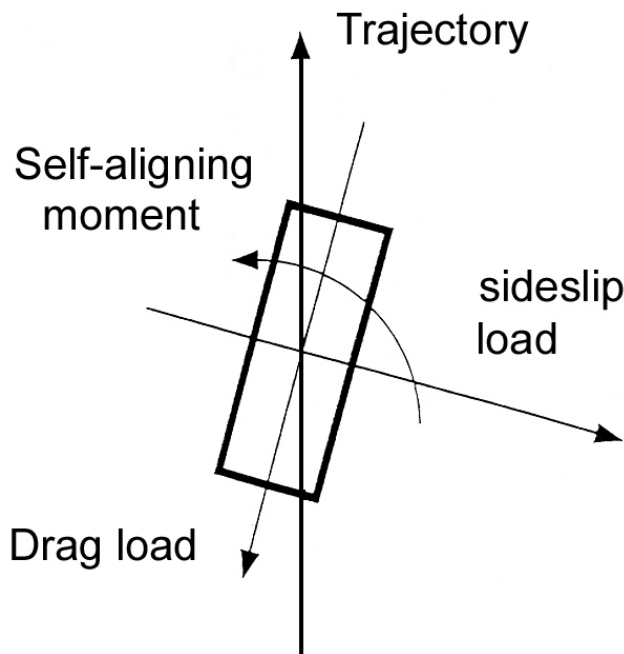


Figure 72: Typical behaviour of tyre under sideslip

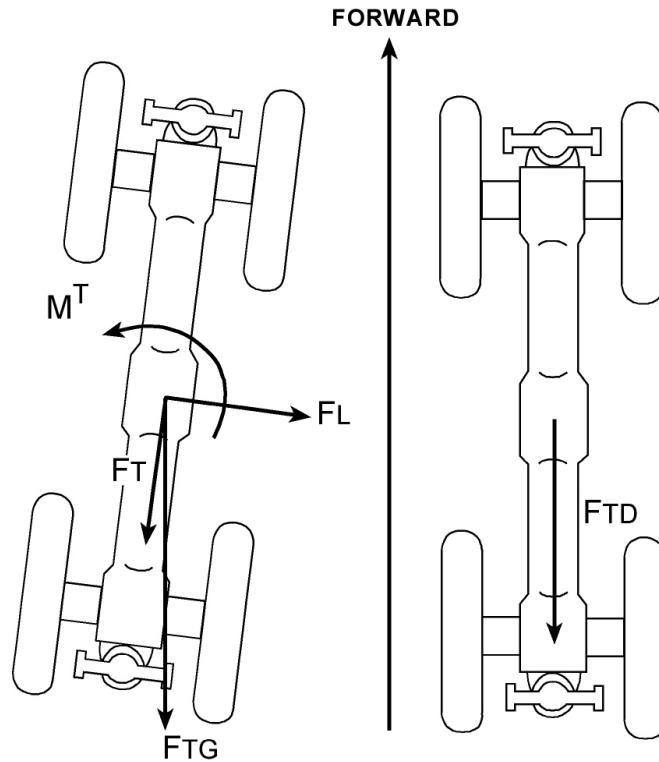


Figure 73: Loads in sideslip situation

Overall, the balance of forces at the centre of the bogie would result in self-aligning moment and two loads whose resultant is increased drag, that is to say a tendency to make the aircraft yaw to the left. The level of this drag would be at most around 1000 daN, very low in relation to the thrust of the engines. The influence of possible sideslip on the trajectory is thus very low or negligible.

- Dynamic behaviour

The Concorde landing gear manufacturer indicated that no cases of landing gear bogie shimmy had been reported. Examination of the parts revealed no such phenomenon. Furthermore, the tyre marks left by tyre No 2 showed no signs of vibration or instability.

1.18.2.4 Examination of the Other Wheels on the left Bogie

Workshop examination of tyres No 5 and 6 showed no evidence of damage before the aircraft crashed. In addition, examination of the wheels, bearings and brakes on tyres No 1, 2, 5 and 6 showed they were in normal condition.

1.18.2.5 Study of the Beginning of the Flight

In theory, the absence of the spacer could have instigated an asymmetrical trajectory, tyre overheating and slower acceleration than normal. Study of the marks on the runway as well as calculations of the trajectory and acceleration made on the basis of the data from the flight recorders show that this was not the case:

- During the takeoff run, the aircraft would have had a tendency to deviate to the left if the left main landing gear had created abnormally high drag. However, its track was straight before the loss of thrust on engines 1 and 2 and there are no observable right rudder inputs. On the contrary, some slight actions to the left are even noticeable before V1.
- Such abnormally high drag could also have led to an abnormal use of the brakes during taxiing to get to the runway. However, the crew performed the pre-takeoff checklist and, in accordance with this, announced the brake temperature, which was 150°C (the temperature must exceed 220°C for there to be an alarm). Furthermore, it was the same for the left and right bogies. The temperature of the brakes was therefore not at all abnormal.
- The acceleration recorded by the flight data recorder is 0.268 G, which is the normal value for the Concorde when it is at its maximum weight. Furthermore, 34 seconds after the beginning of the takeoff run, the aircraft had rolled 1,200 metres and reached a speed of 151 kt. At MTOW, and with conditions as on that day, the Concorde must roll 1.150 metres and reach a speed of 150 kt in 33 seconds. Aircraft performance was thus entirely in accordance with the design values up until the damage to tyre No 2 by the metallic strip. Furthermore, takeoff performance on the flights that preceded the accident (but after the bogie replacement work) was in accordance with published norms. There is no significant difference compared to takeoff performance on other Concorde.
- Up until the time the aircraft ran over the metallic strip, no remarks or reactions by the crew indicate any abnormal aircraft behaviour.

The first tyre marks noted on the runway after the accident were those of tyre No 2 after it was damaged by the metallic strip. There were no identifiable Concorde tyre marks before this point.

In addition, a change in bogie perpendicularity might have occurred, preventing gear retraction. As shown in paragraph 1.16.10, this did not happen.

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In conclusion, nothing in the research undertaken indicates that the absence of the spacer contributed in any way to the accident on 25 July 2000.

1.18.3 Prevention of Debris-related Risks on the Movement Area

1.18.3.1 Current Regulations in France

After the Concorde accident, a review of instructions related to runway inspections at French aerodromes was carried out by the DGAC. This showed that in the absence of national regulations, the ICAO norms and recommendations are generally followed. According to the aerodrome, inspections of the movement area are carried out by various organisations: the runway operations office, the RFFS, the BRIA, the operator. It depends mainly on the terms of the operating contract in force.

The DGAC is currently preparing a draft regulation and an operations manual concerning runway inspections, based on and extending the ICAO's recommendations. A manual on preventing the presence of debris on the movement area is also being prepared.

1.18.3.2 Prevention of debris-related Risks at Paris Charles de Gaulle

1.18.3.2.1 Manoeuvring Area

Safety on the manoeuvring area (runways and taxiways) is the responsibility of the ADP aerial operations division. Apart from checks in case of discovery of debris, the internal regulations specify three daily inspections. Before the accident on 25 July 2000, the real average was two inspections a day, since when it has become three. Sweeping is carried out by agents from the ADP equipment division, under a protocol with the ADP aerial operations division.

Discoveries of debris on the manoeuvring area are reported in the runway operations office duty officer's operations log. Determining the origin of the debris does not systematically lead to an internal investigation. According to the type and size of the object, the BEA is informed, and the pilot or the operator of the aircraft that may have lost the object is alerted.

The instruction lists that are the basis of follow-up for safety on the platform do not contain any data relating to debris. Since May 2001, the presence of debris on the movement area is subject to statistical analysis.

A working group on prevention and safety/feedback was set up in 1999. It is mainly concerned with air traffic aspects but should help identify and analyse events that precede accidents.

Note: a similar working group was created in Nice in 2001.

1.18.3.2.2 The Apron

Prevention of debris on the apron (access and parking areas) is covered by the policy on safety on the apron, which is the responsibility of the ADP operations division. This policy has two parts: one regulatory and the other relating to partnerships.

The regulations for operation of the movement area (that's to say the manoeuvring area and the apron) requires "maintaining the movement area in good condition". It applies to all users of the platform and any breaking of the regulations results in a summons. Application of the regulations is ensured by agents of the state (DGAC and GTA – Gendarmerie des Transports Aériens) with assistance from sworn agents from ADP, the safety inspectors on the movement areas.

In parallel, the partnership element in the safety policy for the apron is organised around two organisations:

- a co-ordination body, the "Area Safety Commission". It includes the representatives of the airport, the airlines, the assistance and service providers on

the apron and various public services. The commission meets three times a year. This body co-ordinates and makes proposals,

- an association governed by the 1901 law, the "Area Safety Charter" created in 1994. Several airlines, ADP and service providers are members. This association makes comments and takes action. Thus, a seminar was held in 2000 on the problem of safety on movement areas. The association also publishes a quarterly bulletin "Safety Info". The association meets frequently and the members are in weekly contact. Nevertheless, ADP's representatives regret that too few airlines participate

and include some training and information events, mainly:

- poster campaigns on specific themes,
- a training project for persons working on the movement area, in co-ordination with their employers,
- an occasional publication "Safety Flash".

Cleaning of the apron is handled by the Equipment Division. Collection of debris is sub-contracted. Both operations are carried out in a preventative and curative manner. In addition, a contract for cleaning small debris calls for the service provider to work on the verges and green spaces bordering the apron.

There is no qualitative or quantitative follow-up system for the presence of debris on the apron.

2 - ANALYSIS

2.1 Accident Scenario

Note: the detailed track of the aircraft from engine power-up until FDR time 97623 is included in appendix 12. All of the distances on the ground are given from the runway threshold. Engine operation is detailed in paragraph 1.16.9.

2.1.1 Flight Preparation

For the flight dispatcher a certain number of problems were posed for the accomplishment of the flight. According to his calculations, taking into account the unavailability of the thrust reverser and with the elements at his disposal, not all of which were in fact correct since the data from the AOG software had not been updated, not all of the passengers and their baggage could be boarded. When they were informed of the situation, the crew took over, wishing to undertake the flight. In fact, after having asked for the faulty thrust reverser to be repaired and before having time to complete the flight preparation that they had decided to take over, they asked the dispatcher to file a direct ATC flight plan. It should however be noted that the Paris - New York flight is undertaken several times a month by each flight crew in the Concorde division and that, consequently, they had very extensive experience with its characteristics.

The investigation showed that the flight was possible without a stop with all of the passengers, after a repair to the thrust reverser, and that the taxiing weight was within the structural limit.

Nevertheless, the investigators were only able to check this by repeating the calculations with the dispatcher since the preparation carried out by the flight crew was not archived, which is not, it should be noted, in accordance with the regulatory requirements. The same remark applies to the load sheet containing the fuel estimate and the Captain's signature. It is, however, noteworthy that the considerable distance between the centralised flight preparation service and the flight preparation cubicles where the crews work does not favour effective synergy.

2.1.2 The Flight until Engine Power-up

When the CVR recording began at 14 h 12 min 23 s, the "flight deck check" check list was under way. This was interrupted to switch the central guidance platform to NAV mode. At the end of the checklist, the following parameters were called out: 95 tons of fuel on board and V2 at 220 kt. It is noticeable that the announcements made in the cabin are no longer heard from that time on. As is common practice, the FE apparently turned off the Public Address since the announcements disturb the smooth running of the checklists.

At 14 h 14 min 04 s, the "pre-startup" check list began. The crew called out the data from the flight preparation. As the checklist was coming to an end, they were informed that the replacement of the pneumatic motor on the thrust reverser was complete. It was 14 h 16 min 11 s.

At 14 h 20 min 06 s, the aircraft manager went into the cockpit and handed over the final load sheet, which was accepted by the Captain. The aircraft manager informed the latter of the resolved problem concerning the identification of certain bags (§ 1.16.2). In addition, he indicated that he planned a fuel allowance of two tons for taxiing. The two tons were included in the load sheet which, in addition, indicated that there were 2.2 tons of baggage. After the departure of the aircraft manager, the crew updated the takeoff weight to 185.1 tonnes and the announced a takeoff CG of 54%, which is in accordance with the CG recommended in the Flight Manual for a takeoff under the conditions on that day. They made a remark about the “tight” quantity of fuel and corrected the centre of gravity without fuel (ZFW CG) to 52.3%. According to the information available to the investigators, it is clear that the quantity of fuel, at 95 tons, was within the regulations and sufficient to carry out the flight.

At 14 h 25 min 54 s the “engine startup” procedure began. Engine 3 and then engine 2 were started up. The aircraft pull forward procedure started and the crew proceeded to start up engines 4 and 1.

At 14 h 34 min 38 s, ATC cleared the aircraft to taxi to runway 26 right via the Romeo taxiway. When the “post engine startup” checklist was complete, the crew began taxiing and started the “taxi” checklist. It was 14 h 37 min 10 s and the Captain was pilot flying. A short time afterwards, the checklist was interrupted by the PFC alarm. The FO stated that the rudder control had already switched from Blue electrical mode to Green electrical mode on two occasions, and he proposed leaving it in the latter mode. Blue electrical mode was nevertheless re-selected - the PFC alarm appeared again at 14 h 38 min 53 s - and the FE indicated that they should expect a switch to Green electrical mode during takeoff. He proposed that in that case they would continue the takeoff, knowing that it was possible to re-arm the Blue electrical mode. The “taxi” checklist was continued and the FE announced at 14 h 38 min 14 s that fuel transfer was under way, which meant that the CG changed from 54,2% to 54%. This transfer was made from tank 11 directly to feeder tanks 1, 2, 3 and 4. When the checklist was again interrupted by the PFC alarm, the crew decided to leave with the rudder in Green electrical mode, which is in accordance with the minimum equipment list.

At 14 h 40 min 01 s, the Concorde was cleared to line up whilst the crew were finishing the “taxi” check list. At the request of the Captain, the FE indicated that eight hundred kilograms of fuel had been consumed, which in fact corresponds to the expected consumption by the engines since startup. Based on the final load sheet handed over by the aircraft manager and knowing that the aircraft took off two minutes later, which corresponds to an additional estimated consumption of two hundred kilograms, it can be deduced that, for the crew, the aircraft weight at which the takeoff was commenced was 185,880 kg, for a MTOW of 185,070 kg. The investigation confirmed these figures and showed that this excess weight had no significant effect on the takeoff and acceleration distances. The “pre-takeoff” check list started at 14 h 40 min 37 and finished about forty seconds later.

At 14 h 41 min 55 s, the FE announced that the CG was 54%. The transfer of fuel was complete.

At 14 h 42 min 17 s, the Concorde was cleared to line up and take off. The controller announced a wind of 090°/8 kt. This announcement did not result in any comment on the part of the crew, even though, with those wind conditions, the takeoff weight should be reduced to 180,300 kg because of the “tyre” speed limit. In reality, the wind was practically zero, as is shown by the Météo France readings and analysis of the track. However, even

if the crew had previously noticed this absence of wind, for example by observing the indication given by the windsock near the threshold of runway 26L around a thousand metres away, it is difficult to understand the absence of any comment on their part.

2.1.3 The Flight up until the Loss of Thrust on Engine 1

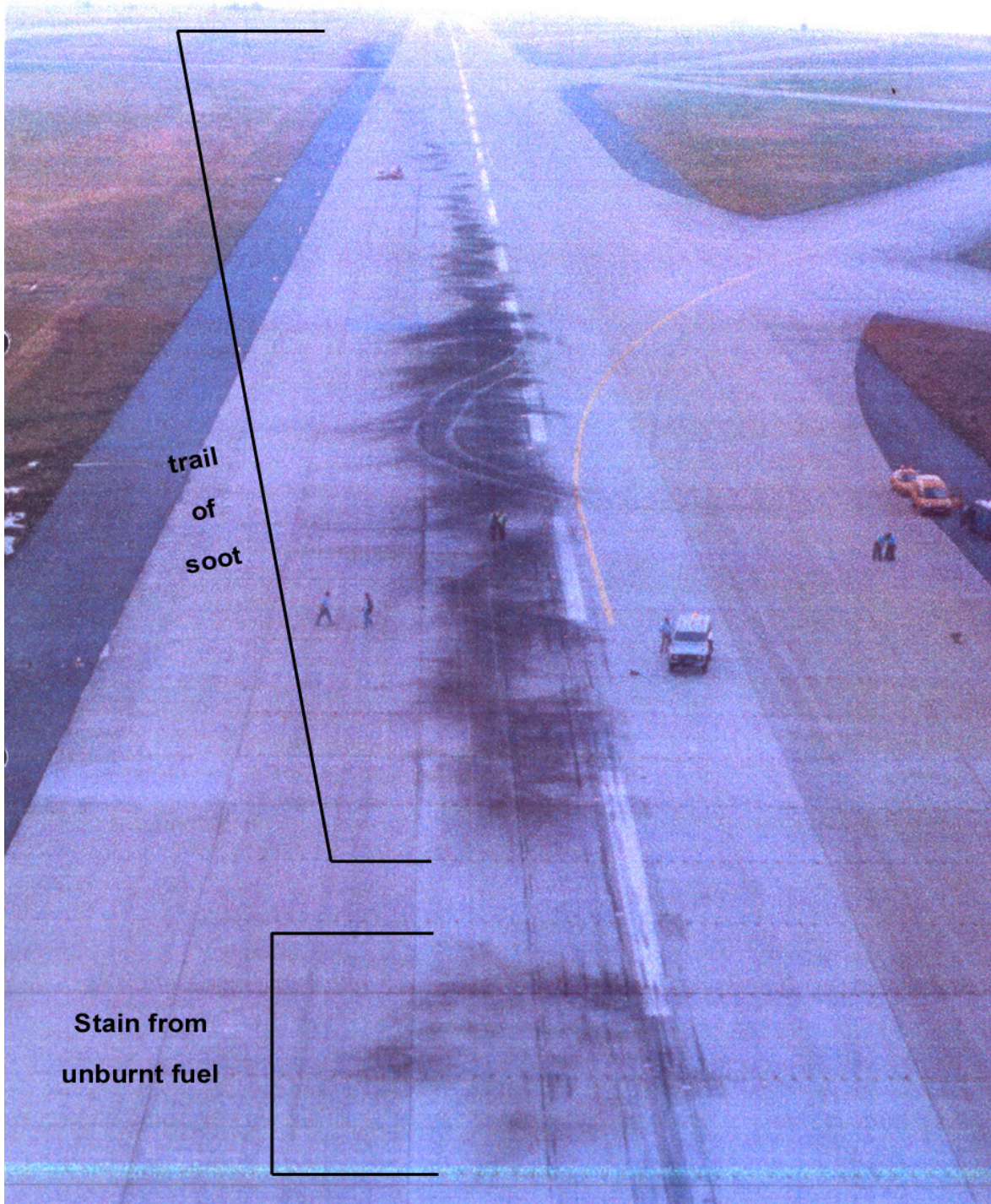


Figure 74: Aircraft track on takeoff

At 14 h 42 min 30.4 s, which is FDR reference time 97560.9, the characteristic clicking of the thrust levers in maximum thrust position is heard. The Captain gave the takeoff “top” one second later. The aircraft’s centre of gravity was around ninety metres from the threshold of the runway.

At 14 h 42 min 54.6 s, in accordance with procedures, the FO announced 100 kt. The recorded airspeed (CAS) was in fact at 100 kt and, as the recorded Nz variation shows, the aircraft had just passed over the asphalt/concrete join on the runway located six hundred metres from the runway threshold. Its track was centred. The FO announced four greens at 14 h 42 min 57 s. This announcement refers to the “GO LIGHTS” and confirms correct engine function, including reheat. The CAS is recorded as 108 kt. The V1 callout was made at 14 h 43 min 03.7 s. The acceleration and the distance run were then entirely in accordance with the simulation calculated for the MTOW, and the value of longitudinal acceleration shows full thrust on all four engines, which is confirmed by the parameters on engines 1 and 2 recorded at 14 h 43 min 08 s and 14 h 43 min 09 s.

At 14 h 43 min 09.5 s (FDR time 97600), a slight variation in Ny, uncommanded by the rudder, is noticeable. The aircraft was then about 1,700 metres from the threshold, in the area where the first parts of the water deflector were found. It was probably at that moment that tyre No 2 ran over the metallic strip. In the following half-second, a clean, short noise is recorded on the CVR. The CAS was 175 kt, the distance from the threshold about 1,720 metres. It is likely that this noise resulted from the damage to the tyre. It was in fact in this area that the metallic strip and the large piece of tyre were found.

At 14 h 43 min 11 s, a very clear change in the background noise is heard, the CAS being 178 kt and the distance run 1,810 metres. The first marks from tyre No 2 were noticeable on the runway. The piece of the lower part of tank 5 then the kerosene stain were found at 1,820 metres. At 1,850 metres, the first marks of very dense soot were noted. These observations allow the conclusion to be drawn that a large quantity of fuel leaked out before the fire broke out and stabilised. With detailed analysis of the sequence, it appears that the change in the background noise resulted from the ignition and the stabilisation of the flame. This is consistent with the controller’s comment which, at 14 h 43 min 13.4 s, indicated extensive flames at the rear of the aircraft. A few tenths of a second after the change in the background noise, the heading began to diminish at a rate of 1°/s, without there being any observable significant variation in longitudinal acceleration, which confirms that the aircraft had not yet suffered any significant loss of thrust. This heading change was probably the result of a combination of the tyre burst and the aerodynamic disturbance due to the fuel leak and the fire.

At 14 h 43 min 11.9 s (FDR time 97602.4), something unintelligible is heard whose origin it has been impossible to identify. The CAS was then 182 kt and the distance from the threshold was 1,885 metres. It was at that moment that the Captain began to deflect the rudder to the right, a slight deflection (8° at first followed by stabilisation at an average value of 5°), in reaction to the aircraft’s slight movement to the left. The last nominal Nx value, at 0.268 g, was recorded at FDR time 97602.5.

Between 14 h 43 min 12 s (97602.5) and 14 h 43 min 13 s (97603.5), engines 1 and 2 suffered their first loss of thrust. This loss of thrust is confirmed by the Nx recording at its minimal value of 0.133 at 97603.5, while the FO said “watch out”. The “GO LIGHTS” for engines 1 and 2 went out. The absence of any significant damage leads to the explanation that the high loss of thrust on engine 2 was due to ingestion of hot gases

whilst the loss of thrust on engine 1 can be explained either by ingestion of debris due to the damage to the tyre or by ingestion of hot gases.

In the same second (the CCLN parameter shows that the column was pulled back at 14 h 43 min 12.2 s at the latest), the Captain began to pull back on the control column in a moderate way while the CAS was 183 kt and the distance from the threshold was 1,915 metres. It was in this area that many people noticed an intense luminous phenomenon accompanied by a strong surge noise.

The sideslip to the left noted at 14 h 43 min 13.4 s, this time at a rate of $2^{\circ}/s$, resulted directly from yaw movement caused by the high loss of thrust from engines 1 and 2. The recorded thrust was then no more than 50% and was mainly delivered by engines 3 and 4. There was no fire alarm in the cockpit at that time. The lift-off of the nose gear, which occurred a few tenths of a second later, when the CAS was 187 kt and the distance from the threshold was 2,045 metres, is entirely consistent with the elevon deflection. This could be the result of the crew taking into account an abnormal unidentified situation. It should be noted that the rate ($1^{\circ}/s$) was lower than normal, which suggests that the crew were conscious of the lack of speed.

At the moment when the sideslip to the left occurred, a further rudder deflection is recorded. It reached 20° to the right at 14 h 43 min 15.7 s, when the sideslip reached its maximum of 5° (heading = 264°), then it decreased towards 10° and stabilised. The simulations described in paragraph 1.16.13 explained this phenomenon as well as why the aircraft continued to deviate from its track. Around the same time engine 1, in a phase of re-acceleration, was producing around 80% of its nominal thrust and an exclamation by the FE can be heard. The CAS was 196 kt.

Thus, during the three seconds when all the events which led to the catastrophe occurred, the crew perceived through a variety of senses a whole group of anomalies: (very) unusual noises, inertial sensations resulting from the violent kick in lateral acceleration associated with the loss of thrust and the sudden loss of longitudinal acceleration and perhaps smells and the luminous flash generated by the ignition and the leak.

Between 14 h 43 min 16.1 s and 14 h 43 min 18.1 s, the engine 1 "GO LIGHT" came back on. This meant that the fuel flow in the engine P7 were, respectively, above 20.5 t/h and 39.1 psi and that it was approaching its nominal thrust. On the other hand, the engine 2 parameters recorded after its loss of thrust show that it was producing thrust hardly any higher than idle, around 3% of its nominal thrust. At 14 h 43 min 20.4 s, the FE announced the failure of engine 2, in accordance with the appropriate procedures, the speed was 203 kt, the distance was 2,745 metres and the pitch attitude was $+9^{\circ}$. In the following second, readout of the parameters shows that engine 2 re-accelerated slightly and delivered thrust of around 15% of nominal thrust. The "GO LIGHTS" on engine 1, then on engines 3 and 4 went out, as a normal reaction to the relaxation of the shock absorber on the left main landing gear.

Between 14 h 43 min 20.9 s and 14 h 43 min 21.9 s, engine 1 suffered a second surge, caused by the ingestion of hot gases and/or kerosene, aided by the change in the aircraft's angle of attack. It was producing thrust that was scarcely above the idle level. As for engine 2, which was re-accelerating, its auxiliary air intake began to re-open, which caused further intake of hot gases and a further surge. The aircraft was again powered mainly by the thrust from engines 3 and 4.

Around the same time, an edge light on the left of the runway was broken by the passage of wheel No 6. The track deviation continued, the aircraft then being about 22.5 metres from the runway centreline. No components from this light were identified in the debris found during disassembly of the engine.

At 14 h 43 min 21.3 s, movement of a selector is heard, identified as being the switching of a TCU, probably that of engine 2, from MAIN to ALTERNATE. This procedure carried out by the FE was intended to regain normal function by switching the computers.

At 14 h 43 min 21.9 s (FDR time 97612.4) aircraft takeoff was effective. The speed was 205 kt, the distance from the threshold was 2,900 metres and the pitch attitude was + 10°. In the following second, the fire alarm was heard, followed by a gong, and the Engine Warning parameter was recorded. On the radio, "(?) it's really burning, eh" is heard, probably coming from a crew in a waiting aircraft, and a few seconds later "(?) it's burning and I'm not sure it's coming from the engine".

The first sample of the parameters on engine 1 after the second surge shows that it was only producing thrust slightly above that corresponding to idle. As for the parameters on engine 2 recorded from 14 h 43 min 24.7 s, they confirm its engine surge and also show that it was at idle.

At 14 h 43 min 24.8 s, the FE said, "shut down engine 2". In the same second, the Captain called for the engine fire procedure. Less than two seconds later, a noise is heard, which spectral analysis and examination of the HP selectors has shown to be the movement of the thrust lever to the stop position. Pulling of the engine 2 fire handle, found in the pulled position in the wreckage, occurred in the following seconds.

A little after 14 h 43 min 27 s, the FO drew attention to the airspeed. The speed was then 200 kt for a V2 of 220 kt (Vzrc on three engines with the gear extended is 205 kt). In the following second, a selector sound is heard, identified as being the fall of the electrical pitch trim compensator switches. This is explained by the fact that, since the aircraft had a high angle of attack, the pitch trim compensator was beyond its normal operating range to counter this angle. A gong, identified as the alarm caused by the fall of the switches, is also heard. Subsequently, there was no further movement of the pitch trim compensators.

The engine 2 N2 went below 58%, leading to automatic switching to CONTINGENCY mode for engines 1, 3 and 4. Engine 1, in a recovery phase after the second surge, only achieved CONTINGENCY rating seven seconds later. The thrust it was then producing was 5% less than nominal thrust with reheat in CONTINGENCY mode. This thrust deficit can be explained by damage resulting from the initial ingestion of solid fragments, since ingestion of hot gases or of kerosene would not have led to the later stability of the engine parameters at a reduced level.

At 14 h 43 min 30 s, the Captain requested gear retraction. The speed was still 200 kt, the radio altimeter indicated 100 feet and the calculated rate of climb was 750 ft/min. In the following seconds, the controller confirmed that there were extensive flames behind the aircraft. Engine 1 was then producing 75% of its nominal thrust and the reheat had just cut in. The FE repeated "the gear" for the FO, who was acknowledging receipt of the transmission from the controller. The aural alarm indicating detection of smoke in the toilets was recorded by the CAM. This alarm can be explained by the fact that the burnt mixture ingested by one of the left engines was used for the air conditioning and circulated to the cabin and the forward toilets, though the possibility of a false alarm cannot be

excluded. The fact that this alarm was recorded by the CAM also shows that the cockpit door was open during the takeoff, which is common practice on Concorde.

At 14 h 43 min 35.5 s, the FE repeated "the gear".

In the following second, a gong is heard which very probably corresponds to the alarm caused by low oil pressure due to the shutdown of engine 2. The Engine Warning parameter appeared again on the FDR.

At 14 h 43 min 37.7 s, the FE repeated "the gear" and the FO answered "no". The red WHEEL light, situated above the landing gear retraction controls probably came on following detection of under-pressure resulting from the damage to tyre No 2 and the procedure requires in this case that the gear not be retracted, except where the needs of safety require it.

At 14 h 43 min 39 s, the Captain ordered "gear retraction" while the FO acknowledged receipt of a message from the control tower. Three seconds later, the engine 2 fire alarm was reactivated with its associated gong. It stopped a few seconds after the FE fired the fire extinguishers (the two extinguishers located in the left wing were found fired in the wreckage).

At 14 h 43 min 45.6 s, the FO probably answered "I'm trying" to the order given by the Captain, which can be interpreted as an attempt to retract the landing gear. At the same time the FE said, "I'm firing". The System parameter overseeing the integrity of the under-pressure system activated, which indicates that the system was functioning up to that moment. In the following second, the Captain asked "(are) you shutting down engine two there" and the FE replied "I've shut it down".

At 14 h 43 min 49.9 s the FO repeated "the airspeed". This warning, repeated again about ten seconds later, is explained by the fact that the speed remained at about 200 kt, lower than the normal climbout speed of 220 kt with a failed engine.

Between 14 h 43 min 49.5 s and 14 h 43 min 54.5 s (FDR time 97640 and 97645), the first differences between the aircraft's attitude and the attitude which should result from inputs on the flight controls can be noted (small roll/pitch and pitch/roll interactions). These differences seem to be explained by the consequences of the fire on the left wing, in particular on the inner elevon. The angle of attack was then 13°.

At 14 h 43 min 56.7 s (FDR time 97647.2), when the CAS was 211 kt, the FO noticed and reported that "the gear isn't retracting". This statement would confirm the interpretation of "I'm trying". Breakdown analysis showed that the non-retraction of the gear was due to the non-opening or non-detection of complete opening of the left main landing gear door (§ 1.16.10).

The flame had then been established for thirty-five seconds. A fluctuation of Nx is observable which might result from a large and brief surge on engine 1, not visible because the parameters were not registered at that moment.

At 14 h 43 min 58.6 s, the engine 2 fire alarm sounded again. It continued to sound until the end of the flight.

In the following second the GPWS “Whoop Whoop Pull Up” warning was heard on three occasions, with the following parameters:

- nose up at 5°,
- radar altimeter at 165 feet,
- rate of descent of about 160 ft/min.

Between 14 h 43 min 59.5 s and 14 h 44 min 11.5 s (FDR time 97650 and 97662), a first disturbance on the engine 1 FF and EGT parameters is noted. A second disturbance was recorded eight seconds later, the CAS being 207 kt. At 14 h 44 min 01 s, the rudder switched to mechanical mode, which led to the loss of yaw auto-stabilisation.

At 14 h 44 min 11.5 s, the engine 1 parameters show a clear deceleration, due to a severe surge. Only engines 3 and 4 remained in operation.

2.1.4 Loss of Control of the Aircraft

The angle of attack changed in twelve seconds from 12° to over 25°, the bank to the left went from 2° to 113° (figure recorded four seconds before the end of the recording) and the magnetic heading decreased from 270° to 115°. Spectral analysis showed that the selector noises which were then heard could be attributed to the movement of the thrust levers to idle stop position. This reduction in thrust on engines 3 and 4 was probably intended to decrease the strong bank to the left caused by the significant thrust asymmetry and by the destruction of vital control surfaces by fire. The decrease in thrust on these two engines was accentuated by a surge due to airflow distortion caused by the angle of attack and the level of yaw reached at that moment.

In these extreme conditions, the combination of lateral and thrust asymmetry and the major thrust/drag imbalance, which could not be compensated for by a descent, led to a loss of control. This loss of control was probably accelerated by the structural damage caused by the fire.

In any event, even if all four engines had been operating, the serious damage caused by the intensity of the fire to the structure of the wing and to some of the flight controls would have led to the rapid loss of the aircraft.

2.2 Crew Actions

During the first thirty-eight seconds of the takeoff, the crew were in a perfectly normal situation. Passage through 100 kt and V1 was announced without any hint of a problem. In the following second, an unusual noise appeared, then almost instantaneously the crew perceived violent lateral and longitudinal accelerations due to the sudden loss of thrust on engines 1 and 2. In the same second, the track deviated towards the left edge of the runway. Forty-one seconds after the takeoff signal and at a speed of 183 kt, that is to say about 15 kt before the planned rotation speed, the Captain began a slow rotation and applied right rudder. At the same time he tilted the wheel slightly to the right. One second later, the FO said “watch out” without any apparent input on the flight controls.

During the takeoff briefing, the crew had pre-activated their mental picture for a normal takeoff and to face the possibility of an engine failure. This called upon all of the

knowledge acquired in training or in simulated flight. They were therefore particularly conscious of the vital importance of speed on Concorde, in particular of Vzrc. They were not, however, prepared for a highly unlikely double engine failure on the takeoff run, which is not taken into account in the certification of the aircraft nor, consequently, covered during type rating and crew training. As a result, they had no points of reference to identify it and consequently no pre-established solution to face it, apart from dealing with the failure of one engine. The FE, who in this phase of flight mainly devotes himself to overseeing the engine parameters in the central position, certainly noticed the loss of thrust on engines 1 and 2. It was probably this which led him to say the word "stop". Then, noting that engine 1 was in a clear recovery phase, he announced the failure with a hesitant verbal communication "failure eng... failure engine two", which is indicative of his state of agitation.

Note: the simulation described in paragraph 1.16.13.4 showed that an aborted takeoff would have led to a high-speed runway excursion. Under these conditions, the landing gear would have collapsed and with the fire that was raging under the left wing, the aircraft would probably have burst into flames immediately.

The double thrust loss occurred after V1, a few seconds before rotation speed. Holding the track became difficult and the control movements required to maintain it were greater than those normally used during training for an engine failure. The background noise was also totally different. The longitudinal and lateral accelerations experienced in the cockpit were also highly abnormal and the overall sensory perceptions in the cockpit at that moment were similar to those of a lateral runway excursion. Furthermore, the study showed that the lateral accelerations in the cockpit were felt earlier by the crew than the accelerations recorded at the aircraft centre of gravity and which modified its track. This resulted in early corrective actions on the controls. The tests carried out in a flight simulator, although not reproducing the accelerations described above, showed that in case of a double engine failure on takeoff, the visual sensation is that of an imminent lateral runway excursion.

The accumulation of all of these sensory inputs in such a short space of time led the crew into a totally unknown highly dynamic situation, with no pre-established solution to face it in a phase of flight where, having passed V1, they were mentally prepared for rotation. In this exceptional and unknown environment, the decision to take off as soon as possible appears to have become compelling. The rate of the rotation also appears to confirm that the pilot was conscious of taking off at a speed below VR.

The shutdown of engine 2 before reaching 400 feet resulted from the Captain and Flight Engineer's analysis of the situation. Indeed, less than three seconds after the failure of engine 2 was announced by the FE and the controller had informed the crew of the presence of flames at the rear of the aircraft, the engine's fire alarm (red alarm) and the associated gong sounded. The exceptional environment described above quite naturally led the FE to ask to shut down the engine. This was immediately confirmed by the Captain's calling for the engine fire procedure. This engine had in fact practically been at idle power for several seconds and the fire alarm was sounding. The engine was therefore shut down following the "engine fire" procedure after having run for twelve seconds at low power. It is important to note that the Concorde Flight Manual requires an immediate reaction by the crew in case of a red alarm.

The crew had no way of grasping the overall reality of the situation. They reacted instinctively when they perceived an extremely serious but unknown situation, which they were evaluating by way of their sensory perceptions. Each time the situation allowed, they applied the established procedure in a professional way.

2.3 Sequence Leading to Ignition of the Kerosene Leak

2.3.1 Destruction of Tyre No 2

Theoretical research and various tests were undertaken in order to understand the process of the destruction of the tyre on F-BTSC. These works all showed the great similarity in the damage, with clean cuts, when the tyre runs over a representative cutting object at various speeds. The tyres were systematically cut right through and burst, releasing pieces of significant weight and size. In particular, the test carried out at the CEAT at a speed similar to that of the Concorde when it ran over the metallic strip (about 75m/s) showed that the pieces released were comparable to those found on the runway.

Although the work undertaken did not deal with the case of objects less sharp than a metallic strip, in-service experience with tyres installed on transport aircraft has shown the scale of damage which these objects can cause and the consequences of possible bursts. On Concorde, nineteen of the fifty-seven known cases of bursts/punctures were caused by foreign objects. All of this clearly shows that in addition to increased surveillance of runways and taxiways, it is becoming necessary to improve the resistance of tyres to damage. It is useful to note that certification imposes no dynamic destructive tests on tyres, which means that there is no indication of burst modes, the weight and size of debris. Nevertheless, with these factors, it would be possible to evaluate the energies released and to deduce the possible consequences on the aircraft's structure.

2.3.2 The Destruction of the Lower Panel of Tank 5

The rupture of tank 5 was caused by a mechanism that had never been seen on civil aircraft before the accident and about which it is difficult to determine the precise process. In addition, the sparse indications from the wreckage, the greater part of the tank having melted, leave uncertainties, in particular in relation to the position and number of impacts and punctures.

However, the studies performed led to determination of the general scenario of the tank rupture which combined the deformation of the lower part of the tank on being struck by a large piece of tyre with the displacement effect linked to the displacement of the fuel engendered by this deformation. Theoretical studies, based on modelling the combination of the structure and the fuel in tank 5 were undertaken, accompanied by firing tests on boxes. Although the tests were not able to reproduce the tank rupture sequence, they nevertheless contributed a great deal to validating the calculations. It should be noted that it is impossible to manufacture a box which is completely representative of tank 5 due to a lack of the raw material, AU2GN, which is no longer made, and that the test equipment makes it impossible to carry out firings with the energy necessary for a rupture.

Studies on the consequences of a puncture of the tanks by a small projectile with speed similar to that of the accident, that's to say relatively low (120 m/s), demonstrated the

possibility of a hydrodynamic pressure surge that could cause the damage to the rib connection areas on the lower lining.

Taking into account the limitations on the studies performed during the investigation, whether on fuel displacement or on the hydrodynamic pressure surge, it would be appropriate to broaden the existing studies to obtain greater knowledge of these phenomena and to use the results for existing or future aircraft. Thus, the investigation was unable to exclude the possibility that the rupture of the tank panel was due to an accumulation of phenomena such as the combination of several impacts by pieces of tyre or even the joint effect of tyre impacts and punctures by small heavy fast objects.

Furthermore, the apparent quantities of fuel which were missing from tanks 6 and 2 could not be explained. This loss of fuel is probably the result of the fire that followed the break-up of tank 5. Indeed, no parts were found on the runway which came from these tanks and the volume of the fuel losses, in particular from tank 6, cannot be attributed to possible simple punctures. These losses may have resulted either from the explosion of the dry bay which might have cracked open the walls of tank 6 or from the intensity of the fire which might equally well have damaged, in flight, the lower part of tank 2 or that of tank 6.

2.3.3 The Fire

Three possible ignition processes were identified and studied. However, bearing in mind the chronology of events, only the hypotheses of ignition by an electrical arc or by the hot parts of the engine and/or the reheat were accepted for the F-BTSC accident, with arguments in favour but also against each hypothesis.

Ignition by an electric arc produced in the main landing gear area through damage to a 115-volt electrical harness is easy to understand. Tests confirmed that the ignition of vaporised kerosene in the area around the gear well was possible with an electric spark of three joules and that the flame was retained and stabilised directly in the re-circulation areas, in contact with the walls of tank 5. However, this hypothesis implies damage to electrical cables partially protected by the landing gear in the case of a tyre burst from the front of the bogie and which, in addition, had been reinforced after the Washington event.

Ignition by the hot parts of the engine and/or the reheat has been explained. However, the tests carried out did not lead to reproduction of the forward propagation of the flame and consequent retention in the slipstream of the landing gear. The partially unrepresentative nature of the test rig available may explain the absence of this extremely complex phenomenon since it is produced in air re-circulation areas. It is difficult to reproduce it on a test rig since it would require a highly detailed replica of the wing, of the fuselage, of the engines and of the landing gear. This phenomenon nevertheless exists and has already been seen with an equivalent rate of leak and higher speed airflow.

In relation to this point, it would be appropriate to continue the studies on fire undertaken in the context of the Concorde accident in order to better comprehend the extremely complex conditions of ignition of the kerosene with forward propagation of the flame that generated such controversy between the experts.

2.4 Runway Surveillance

Study of the arrangements in place at some large airports shows that, as at Paris Charles de Gaulle, measures to combat debris exist in two main categories:

- inspections of the movement area,
- awareness campaigns for users, sometimes accompanied by the setting up of a co-ordination body.

There is often a manual that describes various measures to prevent risks associated with debris.

The accident highlighted the importance that the condition of runways may have. However, in fact, the ICAO standards and recommendations take the place of regulations in France and runway surveillance is left to the initiative of each aerodrome. It is also notable that, as far as Paris Charles de Gaulle is concerned, the daily average was limited to two inspections whereas a service memo specified three, which shows that these inspections are not a priority when faced with operational constraints.

The manner in which the discovery of debris is handled is equally unsatisfactory. Thus, at ADP, items discovered on the manoeuvring area are simply noted in a log and sometimes information is passed on to the operator and the BEA. There is no systematic research to determine the origin of the debris and the indicator boards which are the basis for safety follow-up contain no data on this question. As to the apron, there is no follow-up, either qualitative or quantitative, of the presence of debris though there is a body for co-ordination with airport users, accompanied by awareness and training campaigns.

It is clear that improvements in the prevention of risks associated with the presence of foreign bodies on the movement area, and in particular on runways, requires first of all the establishment of appropriate regulations at the national level and systematic follow-up. This procedure is now under way in France.

The development of a practical manual, of an awareness policy for all participants at airports, as well as the development of information exchange and co-operation at the national and international levels would also help to improve safety in this area.

The investigation did however show the limits of the means currently employed in this area. The metallic strip that led to the destruction of the tyre had been lost from an aircraft that had taken off five minutes before the Concorde. It seems inconceivable, bearing in mind current traffic at large aerodromes, to base a policy on prevention of risks related to debris on inspections alone. To increase their frequency could of course improve the detection of foreign bodies, but that would remain limited to aerodromes with light traffic and appears impractical at aerodromes such as Paris Charles de Gaulle. For the latter, takeoff and landing frequencies are such that there is practically an aircraft permanently on the runway, with a consequent increase in the risk of lost parts, where only a permanent automatic detection system would ensure satisfactory surveillance. Installation of appropriate equipment would, additionally, allow precious information to be made available in case of accidents occurring during takeoff and landing phases.

2.5 Concorde Operations at Air France

The organisation of the units respectively responsible for maintenance and flight operations is different at Air France.

2.5.1 Functioning of the Concorde flight Division

The small size of the Concorde flight division and the specific nature of its activity mean that it operates in a different manner to other divisions. The selection criteria to access Concorde type rating, in particular the experience of the pilots, as well as the aircraft's reputation, confer special prestige on crews both within and outside the airline. This may for example explain why nobody was surprised that the crew, as is their right, took over and completed the preparation of a difficult flight when the agents normally responsible for this task could not manage it.

Carrying a quantity of fuel as a fixed taxiing allowance which was clearly higher than the estimated quantity required for the real taxiing time and the anticipated wait on the ground does not appear to be a satisfactory practice. This does, however, appear to have been a common practice on flights which were critical from the fuel perspective. This excess fuel did not attract any comment from the Captain, apart from his remark that they were going to take off at the aircraft's structural limits. Equally, the controller's announcement of a tailwind did not lead to the slightest comment from the crew, which is, as we have seen, surprising.

Finally, whilst observing that it was only a question of a transitory state in the regulations, the scheduling of a flight crew member whose licence had, for nine days, no longer satisfied the mandatory regulations on medical checks is also surprising.

All of the facts gathered show a firm desire to carry out the flight. It appears that these discrepancies, though they did not contribute to the accident in any way, are a reflection of the particular way in which the Concorde division operated and depend more on a group culture, determined and oriented towards accomplishing the mission, than on the individual and specific behaviour of one crew.

2.5.2 Functioning of Maintenance

Concorde maintenance depends on a common A310/Concorde department whose functioning is comparable to that of the other departments in the Air France Maintenance structure. The technicians possess dual qualifications that allow them to work on both types of aircraft. This structure nevertheless committed a grave error by omitting the bogie spacer. The fact that this oversight did not contribute to the accident does not in any way diminish its seriousness.

The operation was highly unusual. There was no work sheet, which meant the AMM had to be used directly. This did not simplify the technicians' work. In addition, they did not find the extractors available in the store since the Air France reference was different from the one in the AMM and they concluded, in the absence of any previous experience, that the bogie replacement could be carried out without the special tools. This change of bogie on a Concorde was, however, a first for the airline and should have led them to following the

procedures even more rigorously and consulting the documentation scrupulously. Respecting the re-assembly procedure, in particular, would have led to identifying the error committed during disassembly. In aviation, maintenance is a critical element for safety and it is indispensable in case of doubt to complete all the necessary checks, however urgent the operation may be.

In the course of an exceptional event, identifying a serious malfunction with no causal link to the event with which it is associated may lead to a fear that this type of organisational problem is not in itself exceptional. It therefore appears necessary to ensure that the improvisation and lack of method that characterised this operation does not reflect an overall weakness in the organisation of the Concorde fleet's maintenance.

2.6 Maintenance at Continental Airlines

The loss of the wear strip from the thrust reverser door on the Continental Airlines DC-10 originated from lack of rigorous maintenance. In fact, over a period of little more than a month, the part had been replaced during a C check, had become detached and twisted and had again been replaced, this time by a part which was not in accordance with the manufacturer's specifications, this one being the one which fell off on 25 July 2000. Of course, this is not a critical part from the airworthiness perspective, but true safety implies strict respect for procedures, without any personal interpretation.

Facts established concerning the metallic strip and the aircraft reveal inadequate adherence to maintenance procedures by the various workshops that carried out work on the reverser cowl. Thus the engine cowl support was drilled with thirty-seven holes whereas the installation of the strip requires only twelve; equally, a titanium piece was used in Houston along with a mastic which is not normally used for this operation; finally the lower right wear strip was too long compared to the specification, which helps to explain the successive tearing off of the strip located opposite.

It is in fact surprising that nobody noticed the condition of the lower right wear strip nor that on the left fan cowl, if only during the replacement of the lower left wear strip in Houston. It is also surprising that this replacement was not accompanied by any attempt to understand why a part replaced a few days before was so badly damaged, nor by any subsequent check on the condition of the new part.

2.7 Airworthiness Oversight

The investigation showed the complexity of the accident on 25 July 2000. This accident was not predictable, even through deep analysis of all the in-service events. It is nevertheless a fact that failures in many of Concorde systems and equipment, such as the tyres, engines, emergency slides or hydraulics, are relatively more frequent than on other aircraft currently in service. The complexity of Concorde as well as the era in which it was designed may explain this significant difference.

It is clear that the small number of Concordes in service impeded the treatment of problems encountered in operation, as is shown by the numerous points that remained open in the ARM. The absence of serious events - apart from that in 1979 on takeoff from Washington, which led to rapid and effective measures being taken - also explains the

slow rate of evolution of the aircraft. All of the above led to airworthiness oversight which could be considered as less reactive than for other types of aircraft.

It would appear desirable that the continued operation of Concorde be accompanied by strengthening of the means available for analysis of events and of the implementation of any corrective actions.

2.8 Flight Recorders

The inadequacy of some of the information concerning the flight complicated and slowed down the work of the investigation and sometimes limited detailed understanding of what had happened.

Difficulties were also encountered in reconstituting the engines' operations, these difficulties being mainly due to the sampling of parameters. In fact, recording each engine's parameters only every four seconds is wholly inadequate to identify phenomena, such as surges, which can only be identified from fluctuations of very short duration, sometimes of less than a second in certain parameters. This led to long and complex extrapolations from the available parameters. It would not be realistic to expect that as much time and effort would be given over to the examination of all incidents that may occur in the future. In contrast to Air France's Concorde, British Airways aircraft are equipped with recorders that allow all four engine's parameters to be sampled at least every second.

The study of the crew's reactions when faced with an extremely serious situation was limited to the data supplied by the CVR and the FDR. The activity in the cockpit could be deduced in part from the experience of other crews and from analysis of the noises recorded. However, it was not possible to reconstitute everything, whereas a video recording of the instrument panel and of the crew's gestures would have permitted more complete understanding of certain reactions, such as the early rotation. Such recordings are technically possible and are being examined in the context of the ICAO, but the predicted time scale for effective implementation is such that it is important to wait no longer before launching the decision-making process.

Revealing indications of an abnormal situation (noises, engine surges, lateral acceleration, even unusual heat at the rear) were probably perceived by the cabin crew. Currently, however, communications in the passenger cabin are not recorded on any aircraft, although they would sometimes make certain situations clear. In addition, the flight crew turned off reception of the PA in the cockpit, thus cutting out recording via the listening unit.

2.9 Risks associated with the Presence of Asbestos

All of the people involved in this investigation initially worked in the aircraft debris equipped with standard protective clothing. It was only after a few days that the BEA was informed of the presence of asbestos in certain parts of the aircraft. This information led to a halt in work on the site until appropriate means of protection for the personnel were put in place. However, the fact of having worked for several days in a polluted atmosphere will necessitate regular long-term medical follow-up for numerous people.

This is not a new problem. In September 1999, during a meeting of the “Investigation and Prevention of Accidents” (AIG 99) divisional meeting, it was requested that the ICAO gather and distribute information on the dangers of accident sites and determine what training to provide investigators on this point. In the meantime, it seems to be essential to identify, as soon as possible, material used on aircraft which is potentially dangerous in case of an accident and to make this information available to those persons called upon to work on aircraft wreckage.

3 - CONCLUSION

3.1 Findings

- The aircraft possessed a valid certificate of airworthiness.
- The Captain and the Flight Engineer possessed the requisite qualifications and certificates to undertake the flight. In application of a clause in the FCL 1 regulations on the length of validity of medical certificates, subsequently modified, the First Officer's licence was not valid after 18 July 2000.
- The spacer on the left main landing gear bogie had not been re-installed during replacement of the bogie on 17 and 18 July 2000. This omission did not contribute to the accident.
- The aircraft was not subject to acceptable deferred defect limitations on departure from the stand. The electrical system for rudder control had switched to Green during taxiing; departure under these conditions was in accordance with the minimum equipment list.
- Repeating the calculations for the flight preparation showed that the estimated weight of the aircraft on departure was in accordance with operational limits.
- Taking into account the fuel not consumed during taxiing, the aircraft's takeoff weight in fact exceeded the maximum weight by about one ton. Any effect on takeoff performance from this excess weight was negligible.
- During takeoff, after V1, the tyre on wheel No 2 was cut by a metallic strip present on the runway.
- The metallic strip came from the thrust reverser cowl door of engine 3 on a DC 10 that had taken off five minutes before the Concorde.
- This metallic strip had been replaced in Tel Aviv in June 2000 during the aircraft's "C" check, then again in Houston on 9 July.
- The strip installed in Houston had neither been manufactured nor installed in accordance with the procedures as defined by the manufacturer.
- A piece of the tyre from wheel No 2 weighing 4.5 kg was found on the runway, near the metallic strip. Other pieces of this tyre and a few light pieces from the aircraft were also found.
- Rubber marks from the damaged tyre on wheel No 2 then appeared.
- A large part of the underside of tank 5 was found on the runway. It bore no signs of impact and had been ripped away from the inside towards the outside.
- Another part of the underside of tank 5 was found at the accident site. It had a puncture ten millimetres wide and forty millimetres long.

- Research showed that a projectile penetrating tank 5 could have generated a hydrodynamic pressure surge but that this could not have caused the ripping out of the piece of the tank found on the runway.
- A large kerosene mark was found on the runway, immediately after the piece of the tank.
- The fuel that was leaking was ignited; a flame and large quantities of smoke appeared behind and to the left of the aircraft.
- Around ten metres after the unburned kerosene mark, some soot marks on the runway and then some traces of burnt grass on the left edge of the runway were noted over a distance of 1,300 metres.
- After the aircraft's passage over the metallic strip, the rupture of tank 5 and the ignition of the leak, engines 1 and 2 suffered simultaneous surges leading to slight loss of thrust on engine 1 and a severe loss on engine 2.
- The surge on engine 1 was most likely caused by ingestion of hot gases or solid debris, probably pieces of tyre, that on engine 2 resulting from ingestion of hot gases due to the fire.
- The crew began aircraft rotation at the same time, at a speed of 183 kt, 15 kt before VR.
- The marks on the runway show the aircraft deviating to the left of in relation to the runway centreline.
- The crew were advised by the ATC that there were large flames behind them.
- Engine 1 regained almost nominal thrust before suffering, at the moment of takeoff, a second surge leading to a severe loss of thrust; engine 2, in a slight recovery phase, also surged for the second time at that moment.
- The second surge on engine 1 was caused by ingestion of hot gases and/or kerosene, that on engine 2 by ingestion of hot gases through the auxiliary air intake which was beginning to re-open.
- Engine 2's fire alarm was activated.
- The Flight Engineer announced "shut down engine 2" and the Captain called for the engine fire procedure.
- Engine 2's thrust lever was then positioned at idle, the fire handle was subsequently pulled by the Flight Engineer.
- Because of incomplete opening of the left main landing gear door or the absence of detection of opening of these doors, the crew were unable to retract the landing gear.
- Because of the lack of thrust and the impossibility of retracting the landing gear, the aircraft was in a flight configuration which made it impossible to climb or to gain speed.

- Following the third surge due to ingestion of pieces of the aircraft structure, of hot gases and/or of kerosene, engine 1 suffered a final loss of thrust.
- The aircraft then adopted a very pronounced angle of attack and roll attitude.
- The loss of thrust on engines 3 and 4 was caused by a combination of deliberate selection of idle and by a surge due to excessive airflow distortion. This allowed aircraft bank to be reduced.
- The aircraft crashed practically flat, destroying a building and was immediately consumed by a violent fire.
- Many pieces of the aircraft found along the track indicate that severe damage to the aircraft's structure was caused in flight by the fire.
- Even with the engines operating normally, the significant damage caused to the aircraft's structure would have led to the loss of the aircraft.

3.2 Probable Causes

The accident was due to the following causes:

- High-speed passage of a tyre over a part lost by an aircraft that had taken off five minutes earlier and the destruction of the tyre.
- The ripping out of a large piece of tank in a complex process of transmission of the energy produced by the impact of a piece of tyre at another point on the tank, this transmission associating deformation of the tank skin and the movement of the fuel, with perhaps the contributory effect of other more minor shocks and /or a hydrodynamic pressure surge.
- Ignition of the leaking fuel by an electric arc in the landing gear bay or through contact with the hot parts of the engine with forward propagation of the flame causing a very large fire under the aircraft's wing and severe loss of thrust on engine 2 then engine 1.

In addition, the impossibility of retracting the landing gear probably contributed to the retention and stabilisation of the flame throughout the flight.

4 - RECOMMENDATIONS

4.1 Preliminary Recommendation

On the basis of the initial facts established by the investigation, the BEA and the AAIB issued the following safety recommendation concerning the aircraft on 16 August 2000.

"The technical investigation into the accident to Concorde F-BTSC operated by Air France which occurred at Gonesse on 25 July 2000, conducted by the BEA with the participation of representatives of the AAIB, has so far established the following facts:

- *during the take-off run the front right tyre of the left main landing gear was destroyed between V1 and VR, probably after having run over a piece of metal;*
- *the destruction of the tyre caused damage, either directly or indirectly, to the aircraft structure and systems, causing the aircraft to crash less than one minute and thirty seconds after the destruction of the tyre. The damage sequence and the connections between the various events have not yet been fully established. However, the effect of these events was:*
 - *one or more punctures in at least one fuel tank resulting in a major fuel release;*
 - *ignition of the released fuel and an intense fire throughout the remainder of the flight. This fire started a few seconds after the destruction of the tyre;*
 - *a loss of thrust on one, and then two engines.*

The crew had no means of assessing the fire or of taking action to extinguish it.

Further, in-service experience shows that the destruction of a tyre during taxi, takeoff or landing is not an improbable event on Concorde and that such an event may cause damage to the structure and systems. However, such destruction had never caused a fuel fire.

The accident which occurred on July 25 2000 showed that the destruction of a tyre - a simple event which may recur - had catastrophic consequences in a very short time without the crew being able to recover from the situation.

Consequently, without prejudice to further evidence that may come to light in the course of the investigation, the BEA and the AAIB recommend to the Direction Générale de l'Aviation Civile of France and the Civil Aviation Authority of the United Kingdom that:

- ***the Certificates of Airworthiness for Concorde be suspended until appropriate measures have been taken to guarantee a satisfactory level of safety with regard to the risks associated with the destruction of tyres."***

This recommendation was immediately accepted by the airworthiness authorities in France (DGAC) and United Kingdom (CAA) and the Concordes' Certificates of Airworthiness were suspended.

The investigation confirmed the validity of this general recommendation and the reasoning behind it. Elements identified by the investigators during their work were systematically provided to the airworthiness authorities, the manufacturers and the operators, so as to

allow them to define measures to be taken to return the aircraft to service. It was in this context that the airworthiness authorities defined the following measures:

- Installation of flexible linings in tanks 1,4,5,6,7 and 8.
- Reinforcement of the electrical harnesses in the main landing gear bays.
- Modification of Flight Manual procedures so as to inhibit power supply to the brake ventilators during critical phases of flight and revision of the MMEL to ensure that technical operational limitations cannot be applied for the tyre under-pressure detection system.
- Installation of Michelin NZG tyres and modification of the anti-skid computer.
- Modification of the shape of the water deflector and removal of the retaining cable.
- A ban on the use of volatile fuels and an increase in the minimum quantity of fuel required for a go-around.

4.2 Recommendations Specific to Concorde

The investigation did not bring to light the need for any other urgent recommendations. However, on several points, some improvements specifically linked to Concorde seem desirable in the light of information from the investigation. These improvements, which are the subject of the following recommendations, were brought to the attention of the French airworthiness authorities and were taken into account in the context of the aircraft's return to service.

4.2.1

For any transport aircraft, it is essential that feedback, through analysis of in-service incidents, be as effective as possible. Taking into account the small number of aircraft in service and their limited operations, in-service experience on Concorde is particularly limited. It is, however, both an ageing and a complex aircraft. It has been noted that the rate of malfunctions in certain systems or equipment was higher than current rates on other aircraft. Consequently, the BEA recommends that:

- **the airworthiness authorities, the manufacturers and the operators of Concorde reinforce the means available for the analysis of the functioning of aircraft systems and in-service events and for the rapid definition of corrective actions.**

4.2.2

The Concorde Flight Manual stipulates that a red alarm must lead to an immediate reaction by the crew.. In the same manual, dealing with an engine fire is consistent with this general instruction. However, the Air France Operations Manual requires that no action be taken before reaching four hundred feet. Consequently, the BEA recommends that:

- **Air France ensure that the emergency procedures in the section on Concorde utilisation in its Operations Manual be coherent with the Flight Manual.**

4.2.3

Recording the engine parameters which allow engine speed to be determined only every four seconds slowed down and complicated some work essential for the technical investigation. This characteristic also tends to mask certain facts during examination of incidents for which it would not be possible to devote as much time and effort as for the 25 July 2000 accident. In contrast to Air France's Concorde aircraft on the day of the accident, British Airways aircraft are equipped with recorders that allow the parameters from all four engines to be recorded every second. Consequently, the BEA recommends that:

- **Air France equip its Concorde aircraft with recorders capable of sampling at least once a second the parameters that allow engine speed to be determined on all of the engines.**

4.2.4

The technical investigation brought to light various malfunctions relating to the operation of the aircraft, for example the use of non-updated flight preparation data, the absence of archiving of certain documents or incomplete baggage management. Equally, omitting the left bogie spacer was a consequence of non-respect of established procedures and of the failure to use the appropriate tool. Consequently, the BEA recommends that:

- **the DGAC undertake an audit of Concorde operational and maintenance conditions within Air France.**

4.3 General Recommendations

Beyond specific improvements to Concorde, the investigation showed the need for progress in safety in various areas. This general progress is the subject of the following recommendations.

4.3.1

Tests and research undertaken in the context of the investigation confirmed the fragility of tyres against impacts with foreign bodies and the inadequacy of the tests in the context of certification. Recent examples on other aircraft than Concorde have shown that tyre bursts can be the cause of serious damage. Consequently, the BEA recommends that:

- **the DGAC, in liaison with the appropriate regulatory bodies, study the reinforcement of the regulatory requirements and demonstrations of conformity with regard to aviation tyres.**

4.3.2

The investigation showed that a shock or a puncture could cause damage to a tank according to a process of transmission of energy from a projectile. Such indirect processes, though known about, are complex phenomena which had never been identified on civil aircraft. Equally, the ignition of the kerosene leak, the possible forward propagation of the flame, its retention and stabilisation occurred through complex phenomena, which are still not fully understood. Consequently, the BEA recommends:

- **the DGAC, in liaison with the appropriate regulatory bodies, modify the regulatory certification requirements so as to take into account the risks of tank damage and the risk of ignition of fuel leaks.**

4.3.3

In France, airport operations manuals contain instructions based on the ICAO recommendations concerning the inspection of movement areas. However, there are not yet any national regulations concerning their surveillance. The DGAC is currently studying the implementation of such regulations. The accident showed that the presence of objects on this area presented a risk to safety. It also showed that the presence of certain objects on the runway might not be identified by any preventative measures. Consequently, the BEA recommends that:

- **the DGAC ensure the rapid implementation of programmes for the prevention of debris on aerodromes. These programmes should involve all organisations and personnel operating on the movement area,**

the ICAO study the technical feasibility of an automatic detection system for foreign objects on runways.

4.3.4

The loss of a metallic strip by the Continental Airlines DC10 has been identified as resulting from maintenance operations that were not in accordance with the rules of the art. Consequently, the BEA recommends that:

- **the FAA carry out an audit of Continental Airlines maintenance both in the United States and at its foreign sub-contractors.**

4.3.5

The technical investigation again brought to light the current difficulty in identifying and analysing certain crew actions, certain selector noises and visual alarms. On several occasions, the BEA and its fellow agencies abroad have recommended the installation of video recorders inside cockpits. This point was examined in September 1999 at the ICAO during the "Investigation and Prevention of Accidents" divisional meeting (AIG 99) and the meeting formulated recommendation 1.2/4 "Video recordings in the cockpit", requesting that propositions be sent to the flight recorder expert group (FLIREC). Consequently, the BEA recommends that:

- **the ICAO fix a precise timetable for the FLIREC group to establish propositions on the conditions for the installation of video recorders on board aircraft undertaking public transport flights.**

4.3.6

The investigation showed that the cabin crew had certainly perceived significant changes in their environment. It is therefore possible that communications between the cabin crew or attempts to communicate with the cockpit occurred. Exchanges between members of the cabin crew are not, however, recorded and the recording made in the cabin was cut off by the Flight Engineer at 14 h 14 min. Consequently, the BEA recommends that:

- **the ICAO study the procedures for recording specific exchanges between cabin crew members and exchanges between the cockpit and the cabin.**

4.3.7

The investigation showed that the crew were probably never conscious of the origin of the fire nor of its extent. A comparable situation frequently occurs in the case of accidents due to damage to the structure of an aircraft. Consequently, the BEA recommends that:

- **the DGAC, in liaison with the appropriate regulatory bodies, study the possibility of installing devices to visualise parts of the structure hidden from the crew's view or devices to detect damage to those parts of the aircraft.**

4.3.8

The investigation showed that the lateral acceleration suffered by the Concorde crew as a result of the surges on engines 1 and 2 were different from the values recorded at the aircraft's centre of gravity, these values being reproduced on flight simulators. The faithfulness of the simulation is an important part in the quality of training. Consequently, the BEA recommends that:

- **the DGAC, in liaison with the appropriate regulatory bodies, study the possibility of modifying the regulatory requirements relating to new flight simulators so that they accurately reproduce the accelerations really experienced in the cockpit.**

4.3.9

Investigators and their advisers worked on the wreckage for several days without knowing that the accident site was polluted by asbestos used on the aircraft. They were therefore not equipped with special protective clothing, which may have long-term consequences on their health. This type of problem was examined at the ICAO in September 1999 at the "Investigation and Prevention of Accidents" divisional meeting (AIG 99) and the meeting formulated recommendation 8/1 "Information and training on the dangers of accident sites". Consequently, the BEA recommends that:

- **the ICAO put recommendation 8/1 of the AIG 99 meeting into practice in the shortest possible time and, while waiting for the results of this work, that the primary certification authorities ask manufacturers to immediately identify all potentially dangerous substances in case of an accident which are used in the manufacture of aircraft under their responsibility and to mention them in an explicit manner in documentation.**

COMMENTS FROM THE UK ACCREDITED REPRESENTATIVE

The UK Accredited Representative has made the following comments on the investigation conducted by the Bureau Enquêtes Accidents. The section "AAIB Participation in the Investigation" reflects the concerns with the manner in which the French judicial authorities affected the technical investigation. In other areas, whilst the UK Accredited Representative and his Advisors agree with the evidence presented in the BEA report, the comments represent differences in the weighting of the conclusions.

AAIB Participation in the Investigation

Annex 13 to the Convention on International Civil Aviation (The Chicago Convention) sets out *inter alia* the 'International Standards and Recommended Practices' for the conduct of an aircraft accident investigation. The European Council Directive 94 / 56 / EC, which came into force on 21 November 1994, established the fundamental principles governing the investigation of civil aviation accidents and incidents within the European Union States. This Directive embodied the provisions of Annex 13 into European legislation.

The United Kingdom, as the joint State of Design and Manufacture of the Concorde aircraft, had rights of participation in the investigation as laid down in Annex 13 to the Chicago Convention and EU Directive 94 / 56 / EC. The United Kingdom appointed an Accredited Representative and Advisors from the Air Accidents Investigation Branch (AAIB) to participate in the investigation conducted by the Bureau Enquêtes Accidents (BEA) under the provisions of the 'Convention' and the 'Directive'. The UK Accredited Representative also appointed Technical Advisors representing the organisations with design responsibility for airframe, engines and equipment and who were thus the best qualified individuals to assist in the investigation. Co-operation between the BEA and the AAIB enabled the AAIB to make an effective contribution to the investigation.

The French judicial authorities conducted a separate inquiry into the accident in parallel with the BEA investigation. The manner in which the judicial investigation was conducted presented major impediments to the AAIB's participation in the technical investigation. The difficulties encountered are listed below.

The French judicial authorities did not allow the AAIB Investigators to examine all items of the wreckage (Annex 13 Chapter 5. 25b) or to participate in component examinations (Annex 13, Chapter 5. 25g). For example, the judicial authorities:

- a. Did not allow the AAIB investigators to examine the strip of metal which burst the tyre, except very briefly.
- b. Did not allow the AAIB investigators to examine that part of the tank 5 lower skin which was found on the runway, except very briefly.
- c. Did not allow the AAIB investigators to participate in the examination of most of the flight deck controls and instruments.
- d. Did not allow the AAIB investigators to be systematically involved in the examination of evidence.

The French judicial authorities did not allow the AAIB Investigators full access to all relevant evidence as soon as possible. (Annex 13 Chapter 5. 25d). For example, the judicial authorities:

- a. Severely restricted access of Investigators to the crash site.
- b. Withheld photographic evidence of the runway surface for 6 weeks. This evidence later proved valuable in understanding the events on the runway.
- c. Significantly hindered the prompt examination of evidence. This introduced significant delays to necessary safety actions.

The French judicial authorities specifically prohibited Advisors to the UK Accredited Representative from participating in the examination of major components for which the United Kingdom had primary airworthiness responsibility. (Annex 13 Chapter 5. 25). For example,

- a. The judicial authorities prohibited examination by the AAIB Advisors of the engine bays and wing equipment bays (wing dry bays).
- b. The judicial authorities prohibited examination by the AAIB Advisors of the landing gear selector mechanism.
- c. AAIB Investigators and their Advisors were offered access to a limited number of examinations on the condition that they signed a commitment to the judicial investigation. This confidentiality agreement placed unacceptable restrictions on the use of the subsequent evidence and was therefore not signed.

These obstructions to United Kingdom participation were in contravention with the State of Occurrence's obligations under the Chicago Convention (Annex 13). It is also in contravention of the European Council Directive 94 / 56 / EC which states "*investigators should be able to complete their tasks unhindered*". Furthermore, the restrictions and procedural delays imposed by the judicial authorities subverted the Directive requirement that "*air safety requires investigations to be carried out in the shortest possible time*".

BEA Comment: after an aircraft accident in France a judicial inquiry, separate from the technical investigation, is usually conducted by one or more examining magistrates. The constraints of this procedure did not, however, prevent the BEA from carrying out a full investigation, in association with its foreign counterparts. The BEA nevertheless regrets the difficulties encountered by the AAIB investigators and their advisers.

Fuel Tank 5 Rupture Mechanism

There was positive evidence that the rupture of Tyre 2 during the take-off ground roll had been immediately followed by detachment of a portion of the lower skin of Fuel Tank 5 and the resultant massive fuel release. This made it clear that the tank rupture had resulted from the effects of the tyre rupture. The BEA investigation considered the possibility that a tyre explosion or the gas blast from the cut tyre could have contributed to the tank rupture and eliminated this possibility.

The investigation of the reasons for the tank rupture was hampered by the lack of evidence of the damage to the wing lower skin resulting from the effects of the tyre rupture. Only two pieces of the lower skin of the tank were identified: the item from the runway (approximately 32cm by 32cm) and the smaller burnt item from the Gonesse site. The remainder of the lower skin of Tank 5 could not be identified.

This lack of physical evidence led to the innovative use of the RADIOSS computer simulations by EADS and the supporting tank impact tests at CEAT. The scenario in which the 4.5kg piece of tyre struck the underside of the wing, without penetration, and led to the ejection of the portion of lower skin onto the runway appeared to provide a reasonable representation of the general physics of the event but could not be substantiated fully. This scenario did not exclude the possible contribution of other energy inputs. The more limited ONERA study, of the hydrodynamic pressure surge following the penetration of a small projectile showed that structural damage could occur with projectile impact speeds consistent with the circumstances of this accident.

The view of the UK Accredited Representative and his Advisors is that the lack of evidence from the underside of Tank 5 meant that neither scenario could be given precedence over the other. It is possible that the actual failure mechanism in this accident was a combination of both effects.

BEA Comment: the above viewpoint was never expressed by the AAIB's representatives or their advisers in the course of the work with which they were closely associated. Furthermore, this point of view is in contradiction with the results of the studies which were conducted in order to understand the destruction of tank 5 on the basis of the material elements available. The report, and in particular § 2.3.2, has not therefore been modified.

Ignition of Fuel

The evidence presented in the BEA report makes it clear that the fuel release, initiated when Fuel Tank 5 ruptured, had ignited within about 1 second of the rupture.

The Fire Group convened by the BEA, incorporating diverse flammability specialists, considered many possible ignition sources from which the most plausible were selected. These were ignition from an engine surge flame, from electrical arcing and from engine hot surfaces or reheat flames. When it later became clear that the ignition had already occurred before the first engine surge, the possibility of ignition as the result of an engine surge was rejected.

The flame propagation speed of a kerosene fire is generally accepted to be relatively low and even under ideal circumstances does not exceed 6 m/s. Thus the forward propagation of a fire from the reheat area to the area of the landing gear bay could only occur in a continuous region of relatively low speed or reversed airflow relative to the aircraft with its free stream rearward airflow of 90 m/s. No evidence was found that such a region was likely to exist, either in the wake of the landing gear or within the engine bays. Even if instantaneous ignition were postulated rapid propagation would require appreciable localised forward airflows.

Extensive BAE Systems (BAES) testing, conducted on their purpose-built, full-scale fire test rig, found no tendency for a kerosene fire ignited in the reheat nozzle area of the engines to propagate forwards against the airflow. On the other hand, the BAES tests showed that rapid ignition was reliably achieved using electrical arcing sources in the area of the main landing gear bay.

The analysis of the ignition and propagation are complex issues and not amenable to precise calculation. However, the timeframe from fuel release to the initial engine surge, which was due to hot gas ingestion, suggests that the ignition occurred rapidly and that that the ignition source was energetic.

Consideration of the location and installation details of the three-phase power supply cables in the left main landing gear bay for the wheel-brake fans showed that damage to these cables from debris associated with the rupture of Tyre 2 was a clear possibility. The BEA report on the accident to Concorde F-BVFC at Washington DC on 14 June 1979, when Tyres 5 and 6 deflated noted [in translation]: "two electrical connectors of the left gear's electrical harness were torn out." The power supply cables on F-BTSC ran in metallic conduits or, over a short part of their run, were unprotected. The cables were normally powered during take-off and, in the event of appreciable damage, energetic arcing appeared to be possible, either between phases or from one or more phases to earth. It was not possible to determine if these cables had in fact been damaged by debris associated with Tyre 2 rupture, or if arcing had occurred, as the relevant parts of the wreckage were not identified.

EADS ingestion testing conducted on a Concorde aircraft at Istres showed that when fluid was released from the position of the detached portion of wing undersurface appreciable quantities entered the landing gear bay. It was also clear that within the bay extensive reversal, circulation and speed reduction of the airflow occurred.

The view of the UK Accredited Representative and his Advisors is that the elements of the ignition by electrical arcing have been repeatedly demonstrated whereas the forward propagation remains a theoretical case. Thus, in their opinion, the available evidence indicates that arcing of damaged wheel-brake fan power supply cables in the left main landing gear bay was the most probable ignition source.

BEA Comment : the report (in § 1.16.8.3 and § 2.3.3) clearly indicates the existence of divergences between the experts as to the true origin of the ignition of the kerosene. All of the arguments were presented and discussed at great length during the working sessions in which the AAIB's representatives and their advisers participated. The AAIB is restating the point of view it expressed during the investigation, without adding any new factors. Furthermore, aviation safety can only gain through taking into account the various causes considered as possible by the experts. The report's conclusions have thus not been modified, though the AAIB's position has been stated in § 1.16.8.3.

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