MINISTERE DE L'EQUIPEMENT DES TRANSPORTS ET DU LOGEMENT – BUREAU D'ENQUETES ET D'ANALYSES POUR LA SECURITE DE L'AVIATION CIVILE – FRANCE

BEA

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.

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]

Site of accident
La Patte d'Oie in Gonesse (95)

Type of flight
Charter flight
Flight AFR 4590

Aircraft
Concorde
registered F-BTSC

Owner
Air France

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.

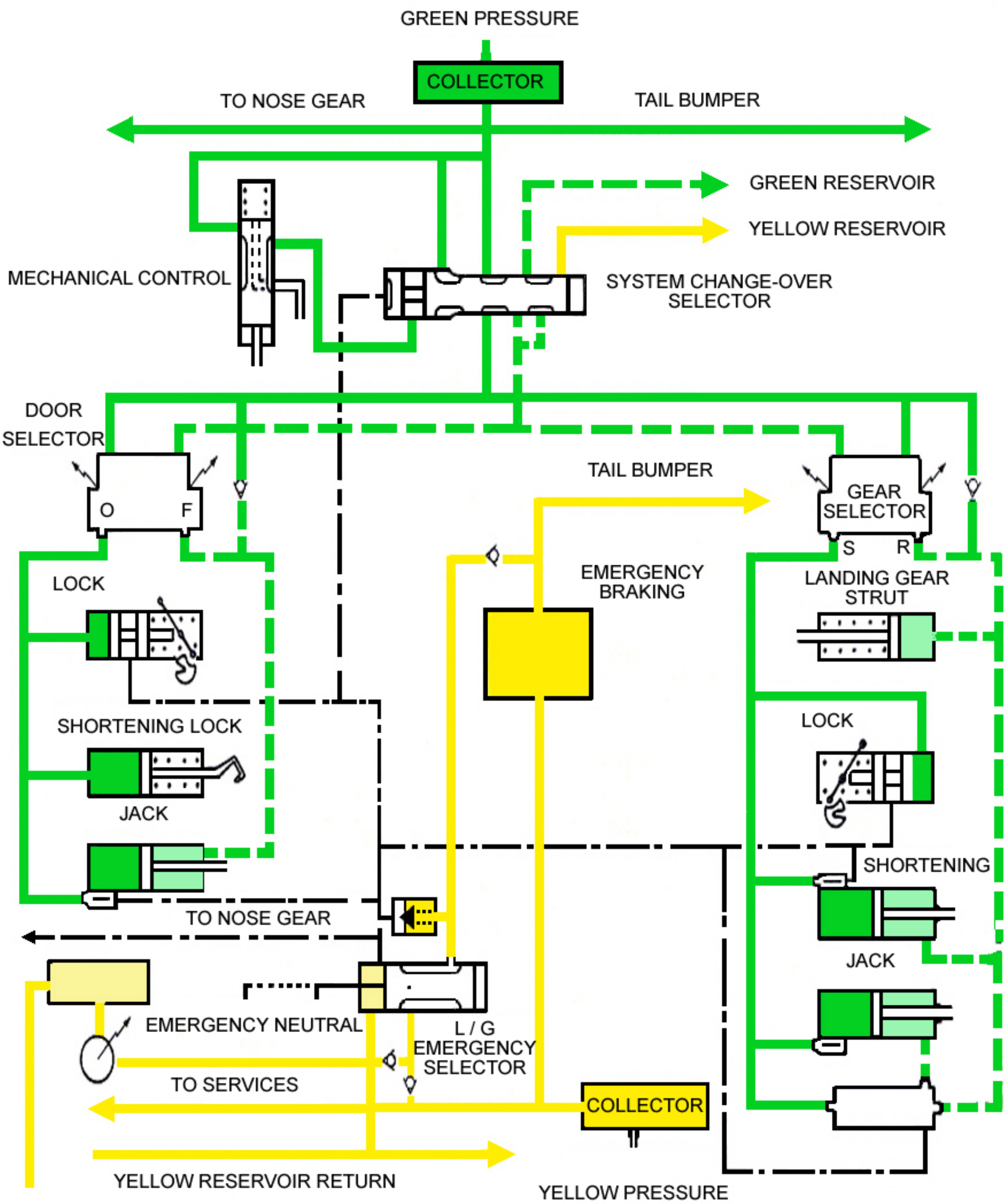

Figure 1: Hydraulic systems for landing gear manoeuvres

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.

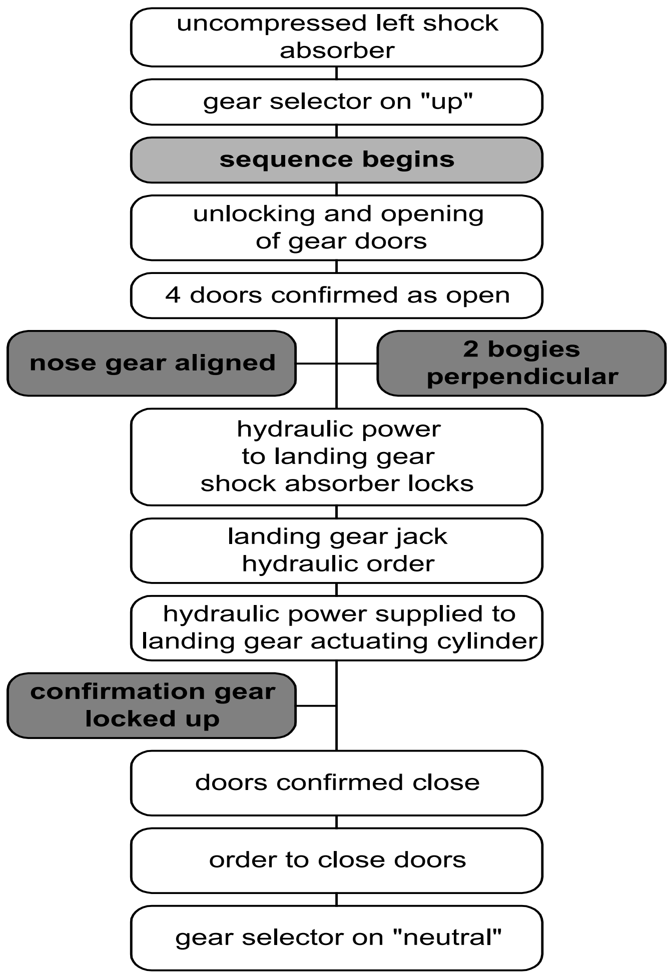

Figure 2: Landing gear retraction sequence

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.

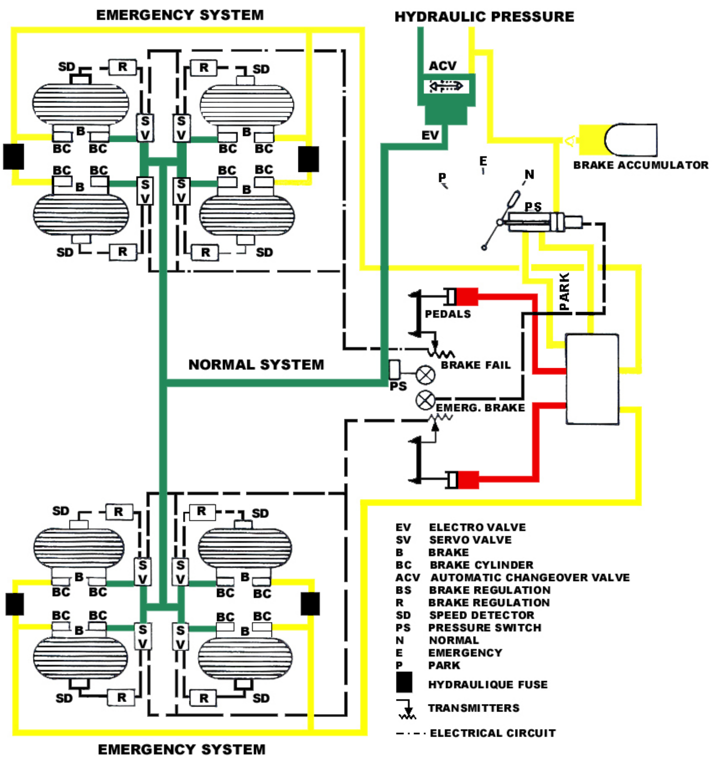

Figure 3: Synoptic diagram of main landing gear braking

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:

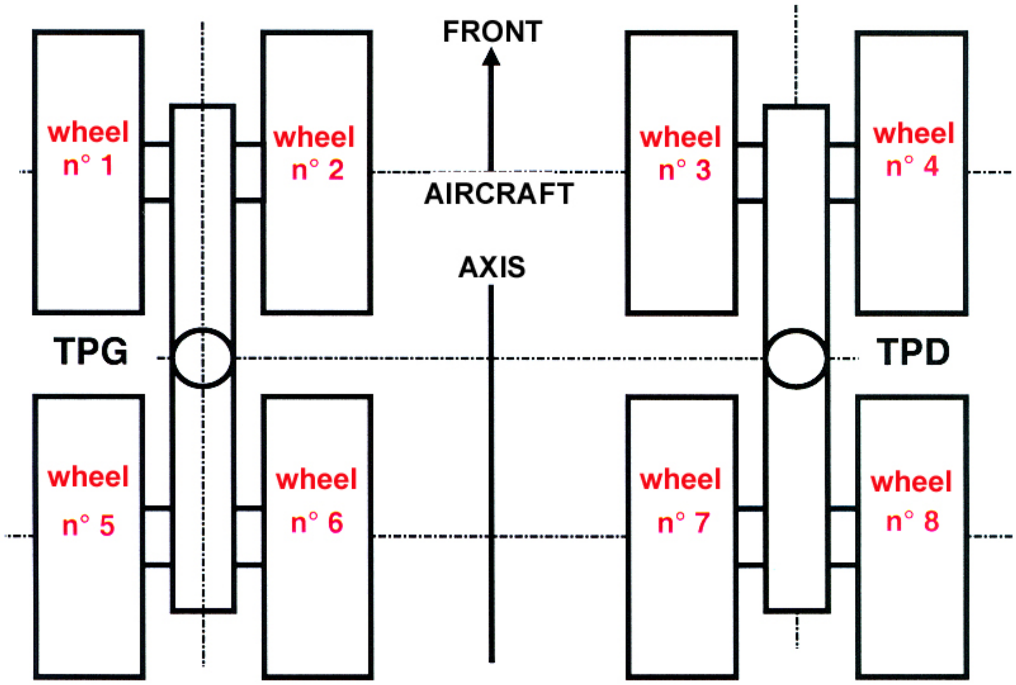

Figure 5: Main gear: view from above

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 2 3 4	5,300 5,770 5,770 5,300	4,198 4,570 4,570 4,198
Main tanks	5 6 7 8	9,090 14,630 9,350 16,210	7,200 11,587 7,405 12,838
Auxiliary tanks	5A 7A	2,810 2,810	2,225 2,225
Transfer tanks (CG)	9 10 11	14,010 15,080 13,150	11,096 11,943 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.

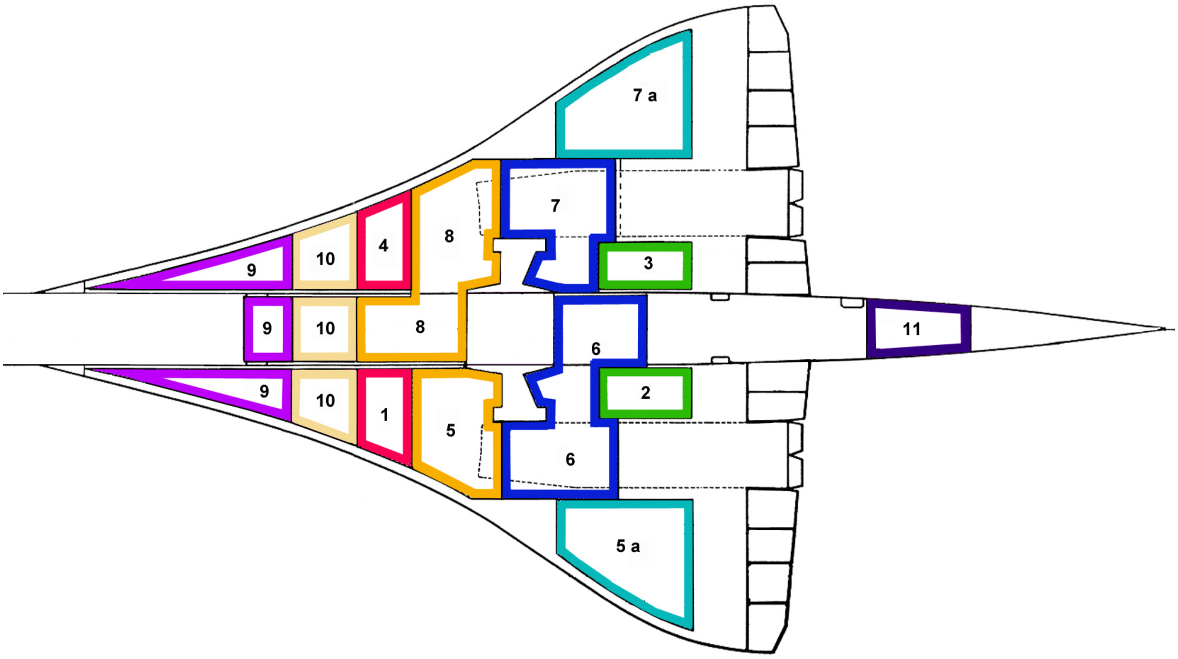

Figure 6: Concorde fuel tanks

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 combustionchamber

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.

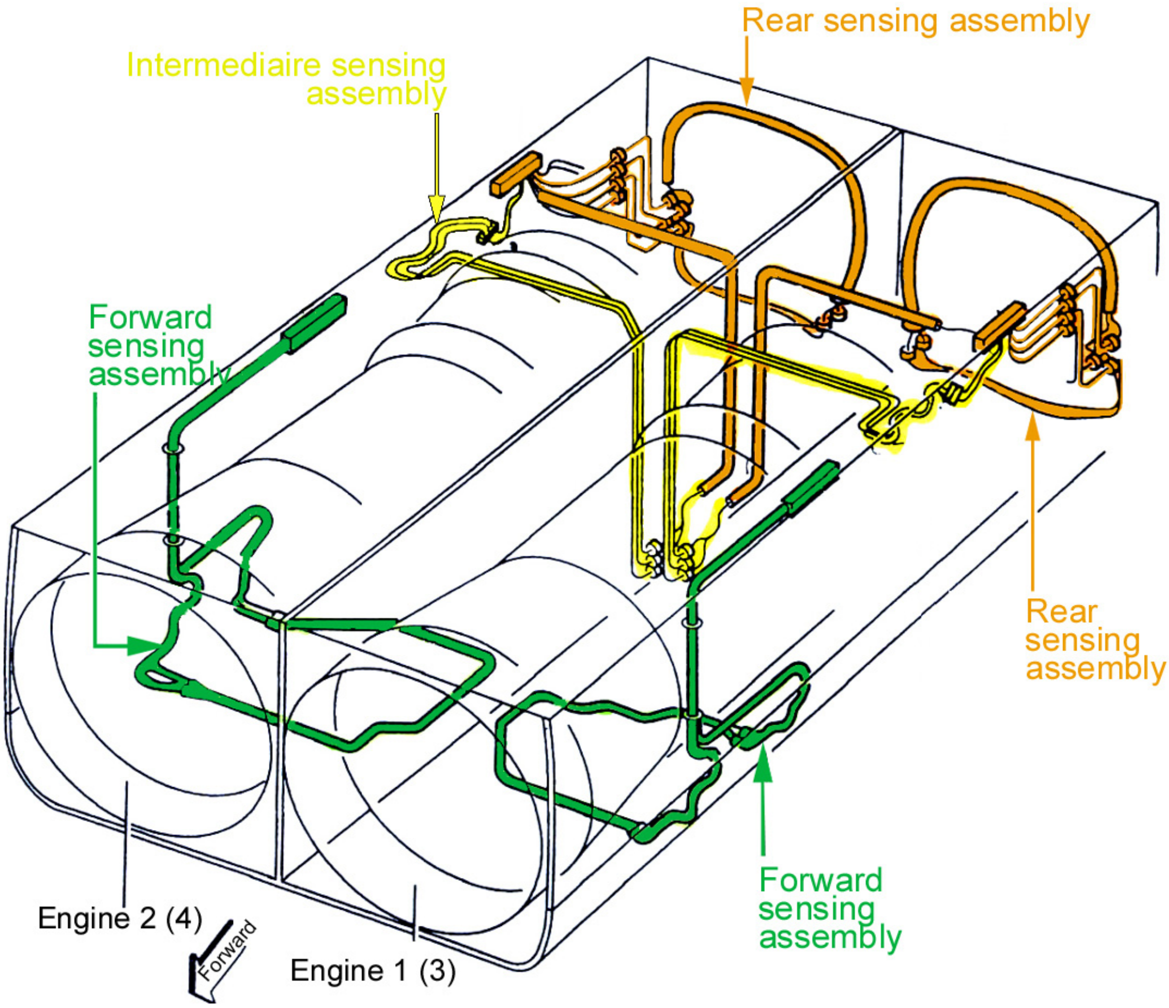

Figure 7: Fire Detection System

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 rudder[9], 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.

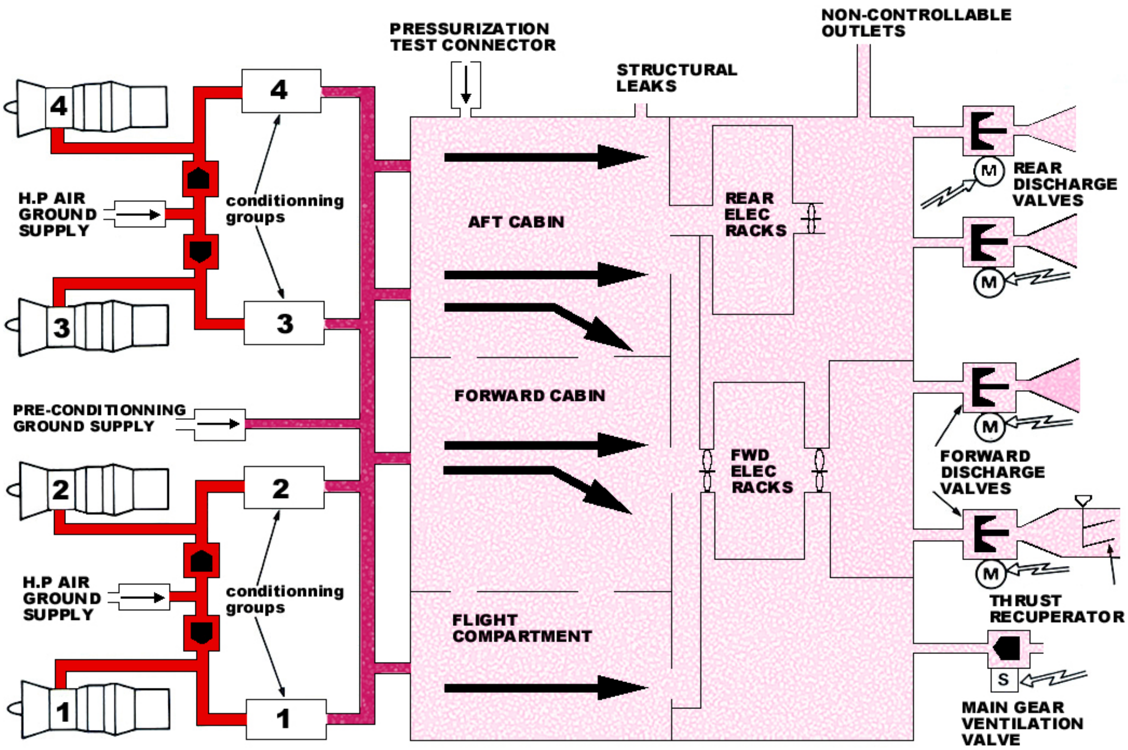

Figure 8: Air Conditioning System

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°,
- 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 °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°/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°/3 kt and 320°/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.

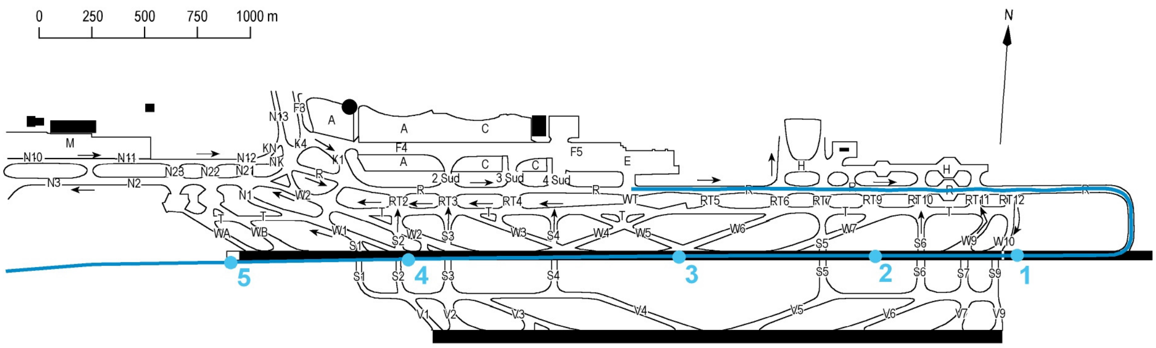

Figure 9: Track of F-BTSC based on AVISO data

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.

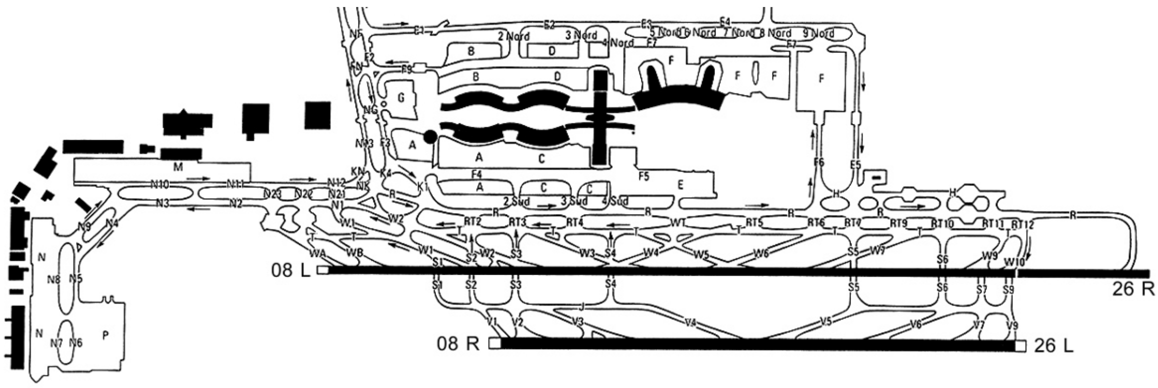

Figure 10: Paris Charles de Gaulle south double runway

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 tandards 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 ndications 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.

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[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 discreet 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 to1 of the discreet on the FDR, and that the end of the communication corresponds to its return to 0.

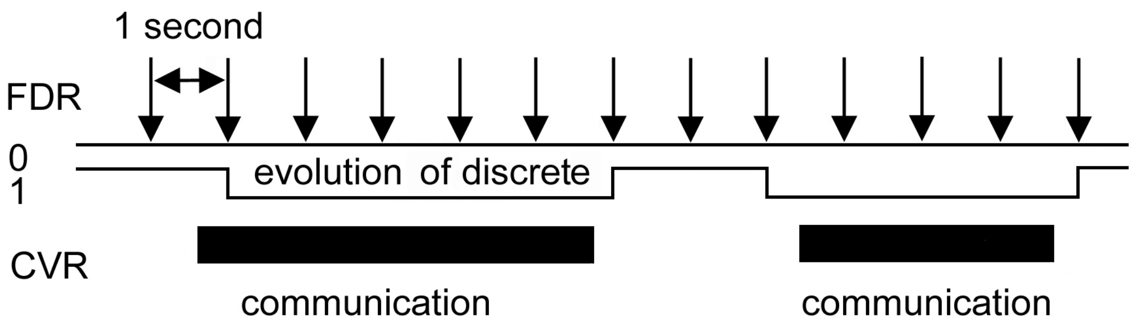

Figure 11: Synchronisation

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.

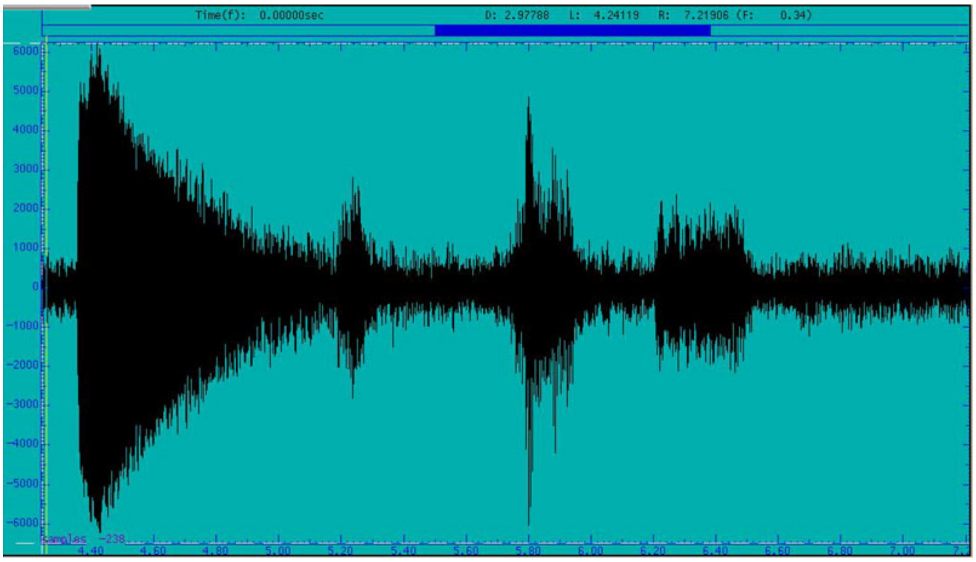

Figure 12: Temporal representation of signal

- 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.

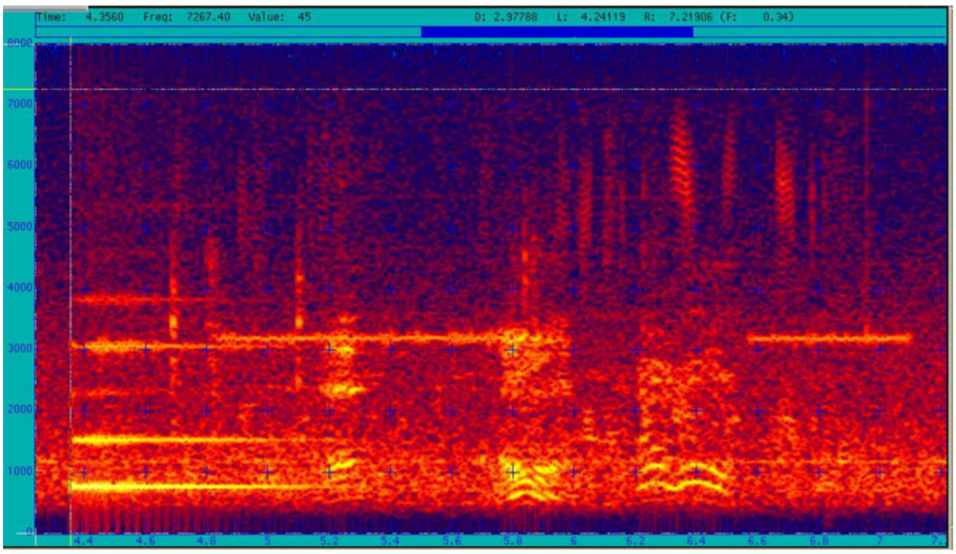

Figure 13: Time-frequency representation of signal

- 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.

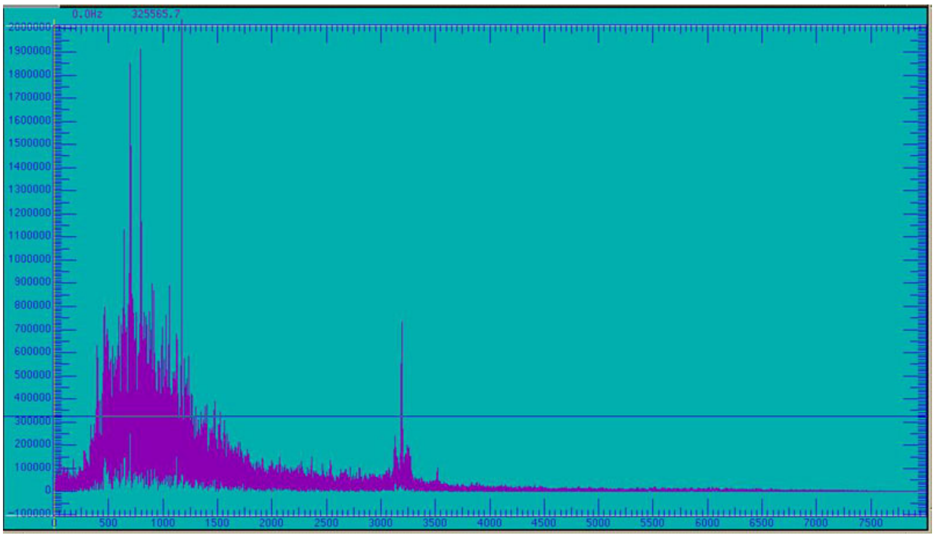

Figure 14: Frequency representation of signal

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.

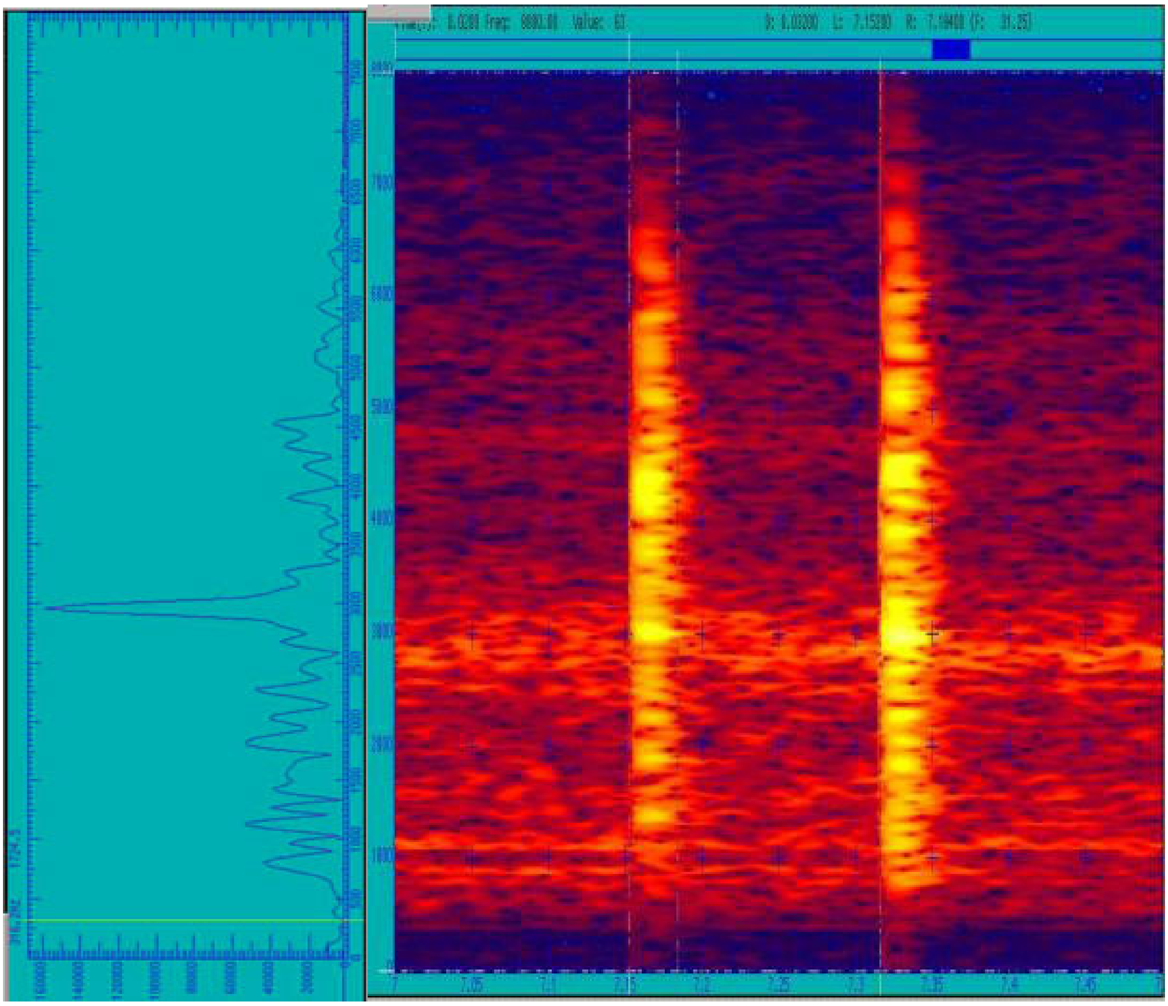

Figure 15: Identification of a selector noise

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.

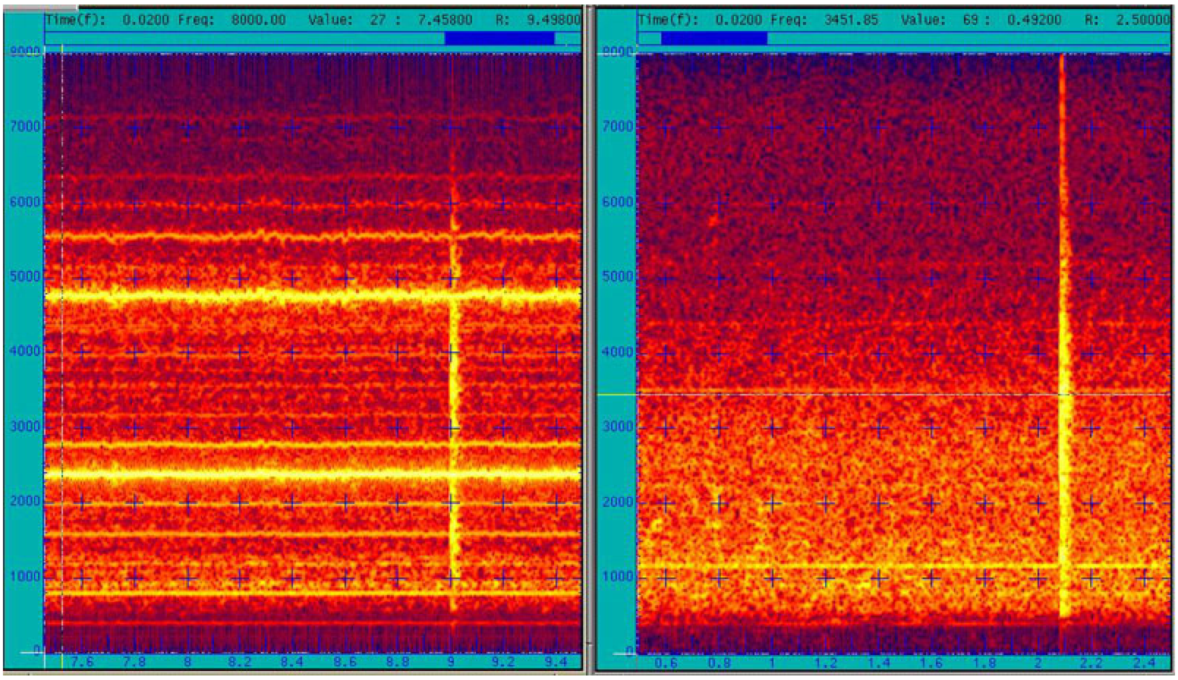

Figure 16: Identical sound with different background noises

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).

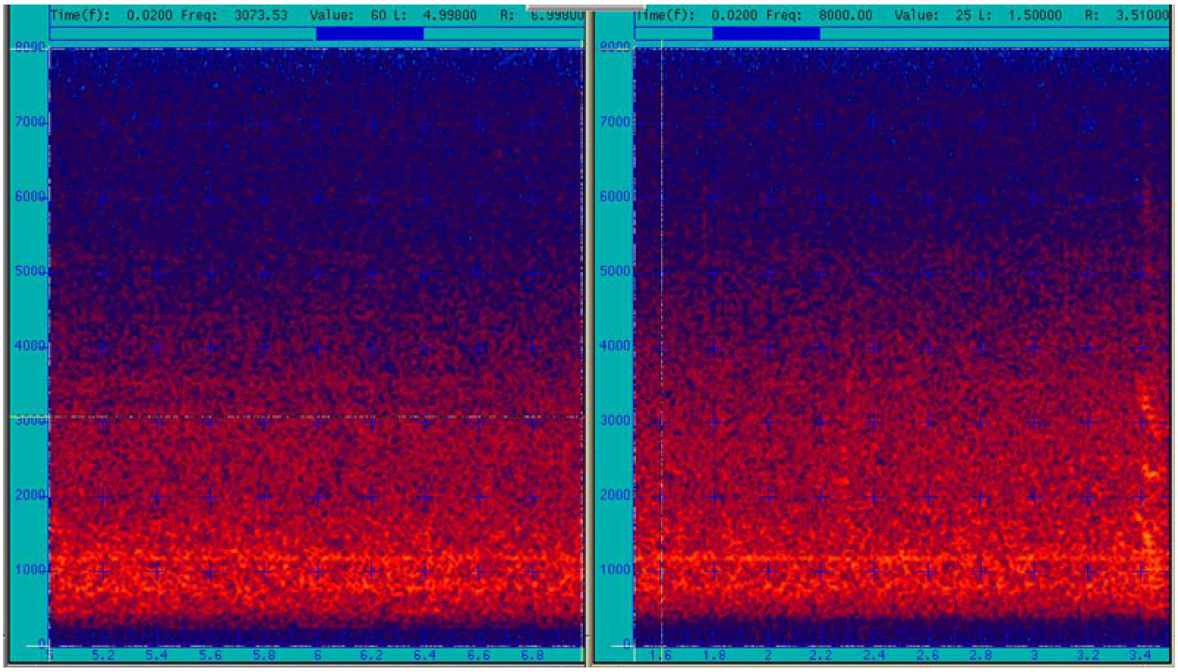

Figure 17: Engine operation: shut down on the left, in flight on the right

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.

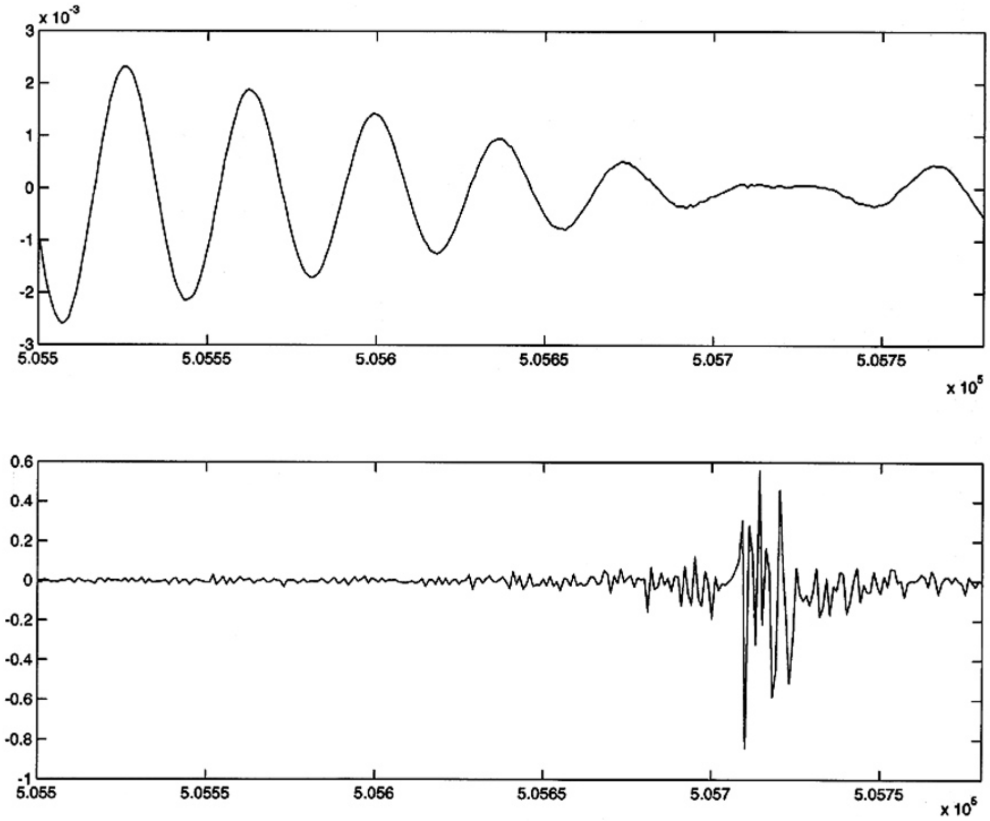

Figure 18: 400 Hz demodulation

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.

    - 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%.

    - 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 ❸

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 ❹

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 ❺

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.

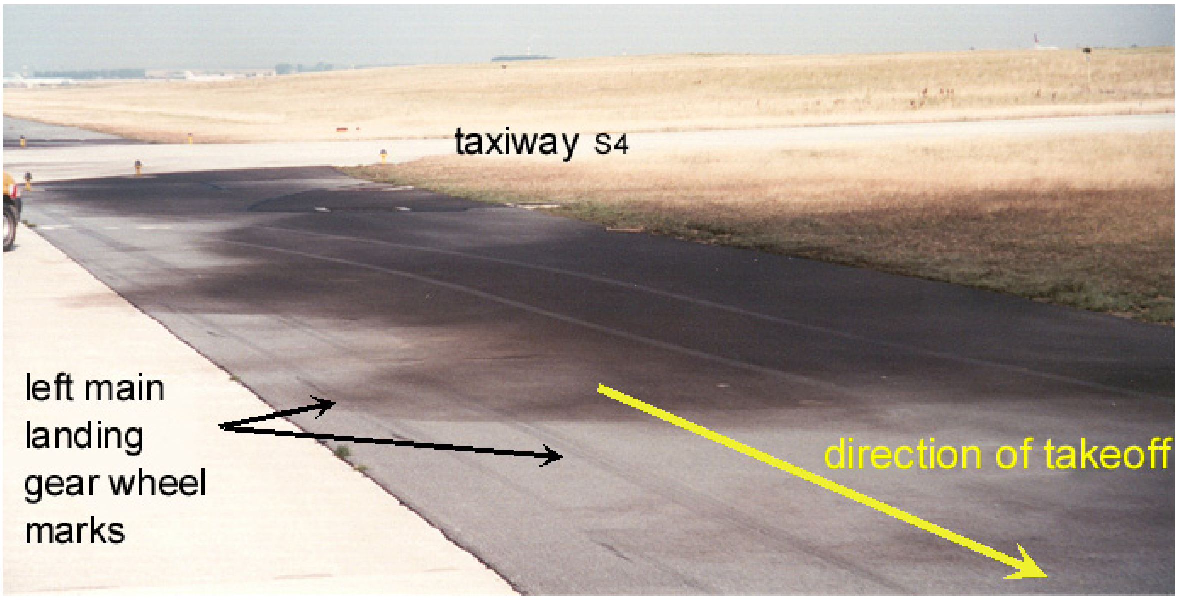

Figure 27: Left main gear wheel marks

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.

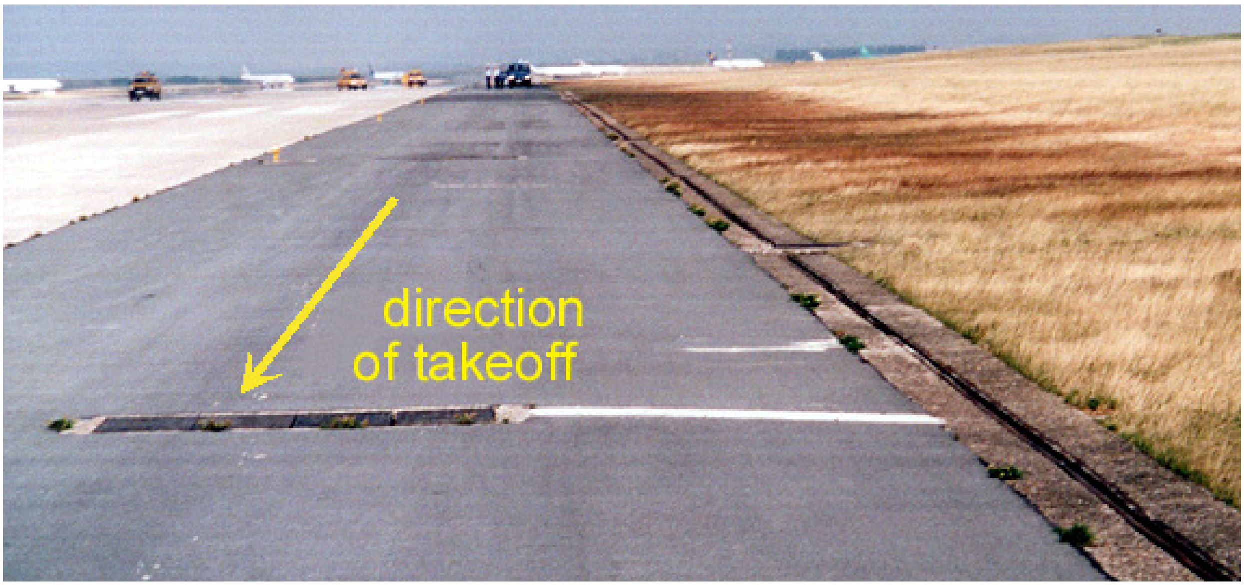

Figure 28: Burnt grass on the edge on the runway

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:
    - a piece identified as coming from a repair on the left inner elevon
    - the tail cone anti-collision light,
    - a severely fire-damaged inspection panel from the wing lower surface,
    - 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:
    - an inspection panel also coming from the upper surface of the left wing dry bay and showing no signs of fire,
    - a fire-damaged piece of duct,
    - 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:
  - two hydraulic shutoff valves, one damaged by fire,
  - two lower inspection panels from the engine nacelle, one melted, the other intact,
  - debris from the wings, in particular fuel tank parts,
  - a fire-damaged hydraulic line,
  - 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.

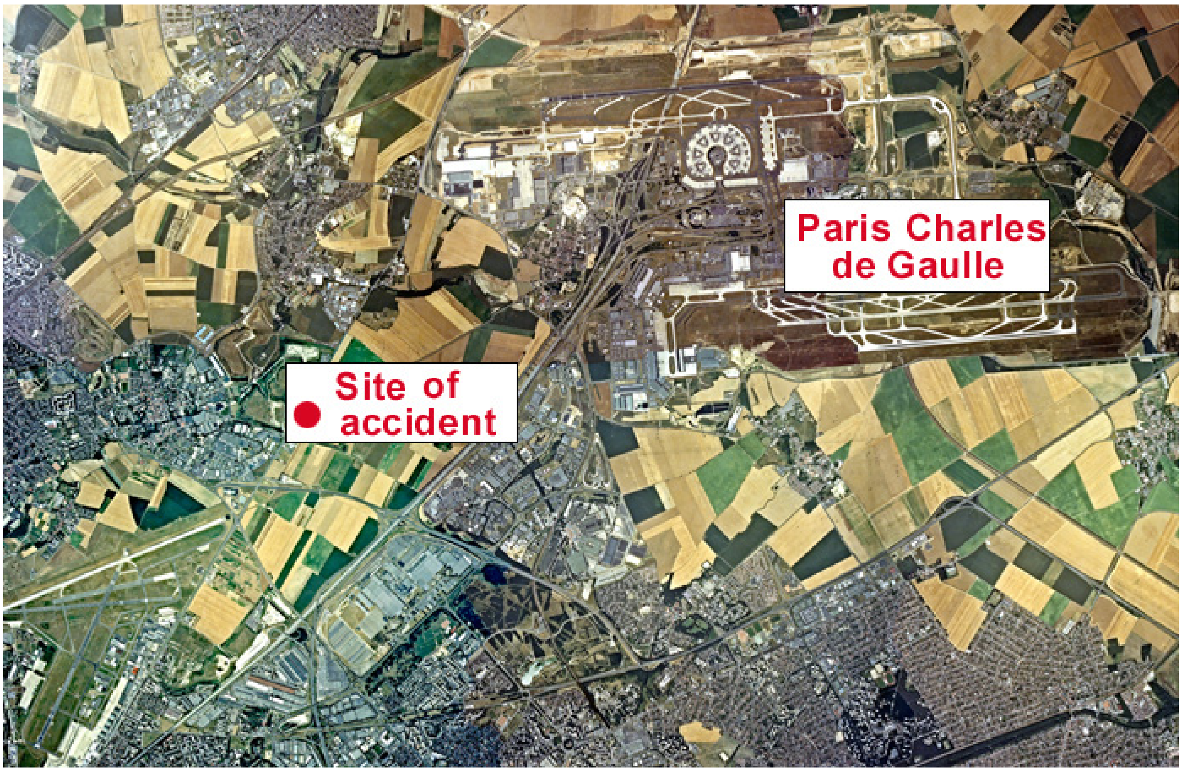

Figure 29: BEA/IGN/FLEXIMAGE image - Aerial photo of the accident site

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

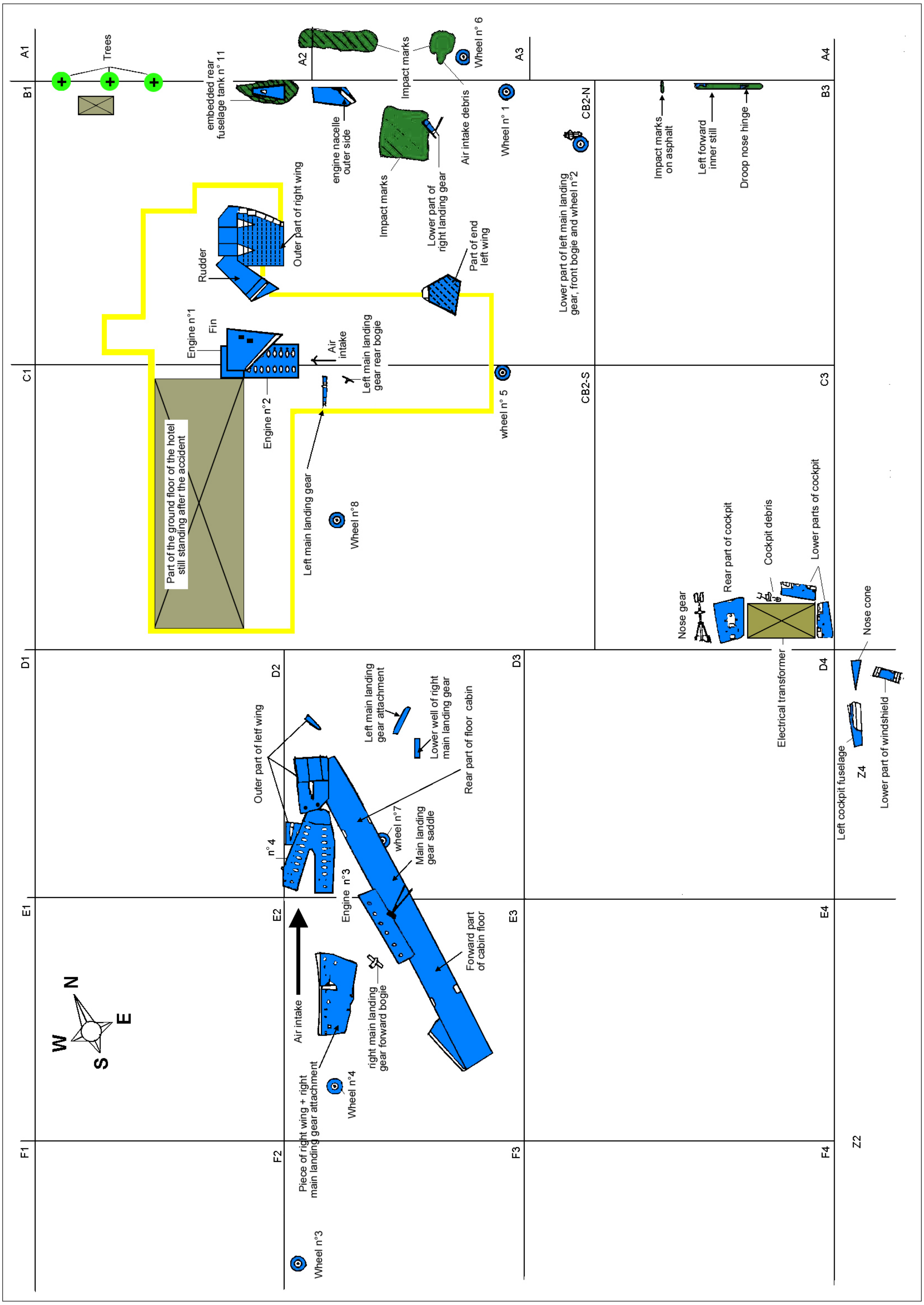

Figure 30: Wreckage distribution plan

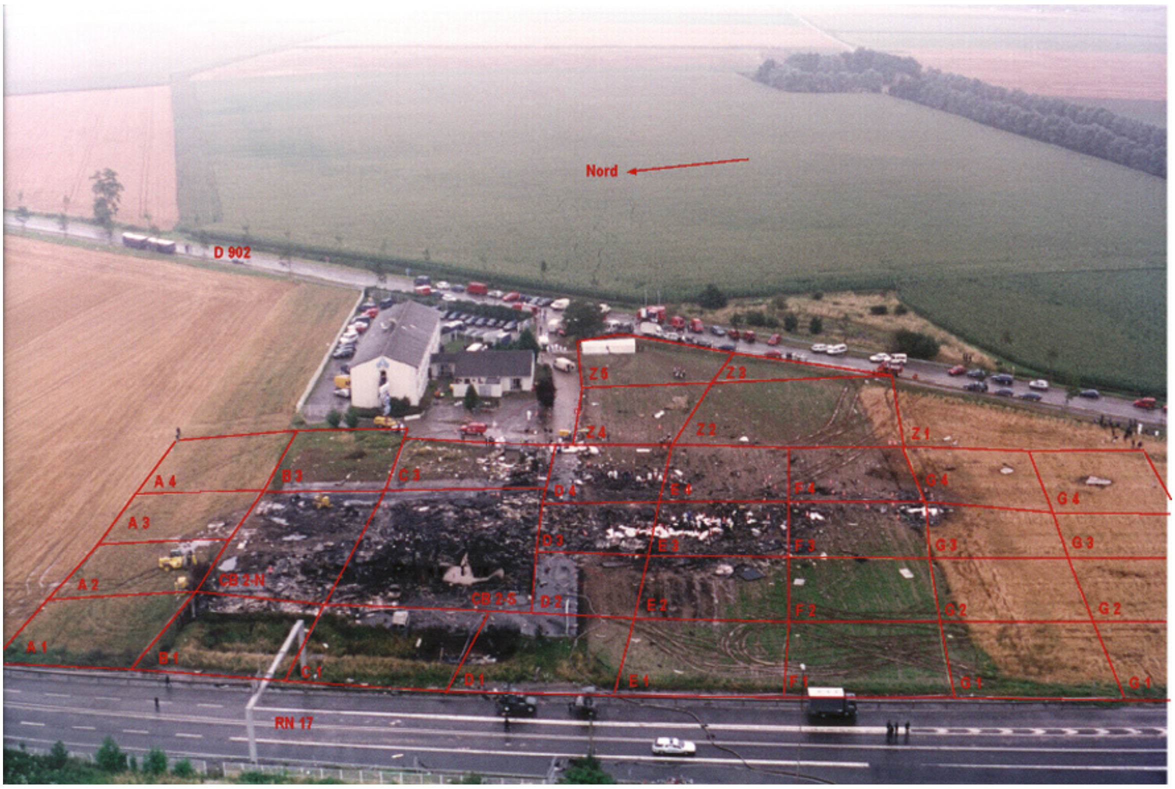

Figure 31: Aerial view with indications of zones

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.

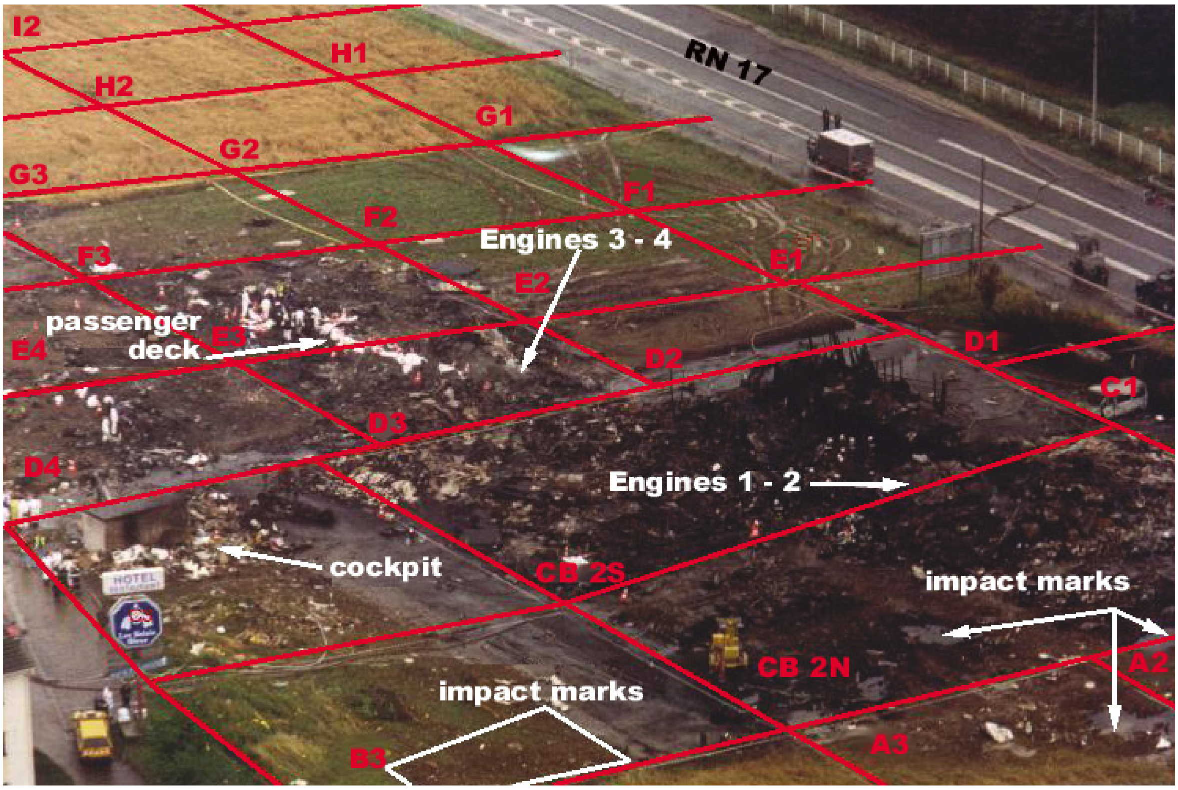

Figure 33: Aerial view with position of main parts

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

Figure 36: Engine 2 exhaust nozzle

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.

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.

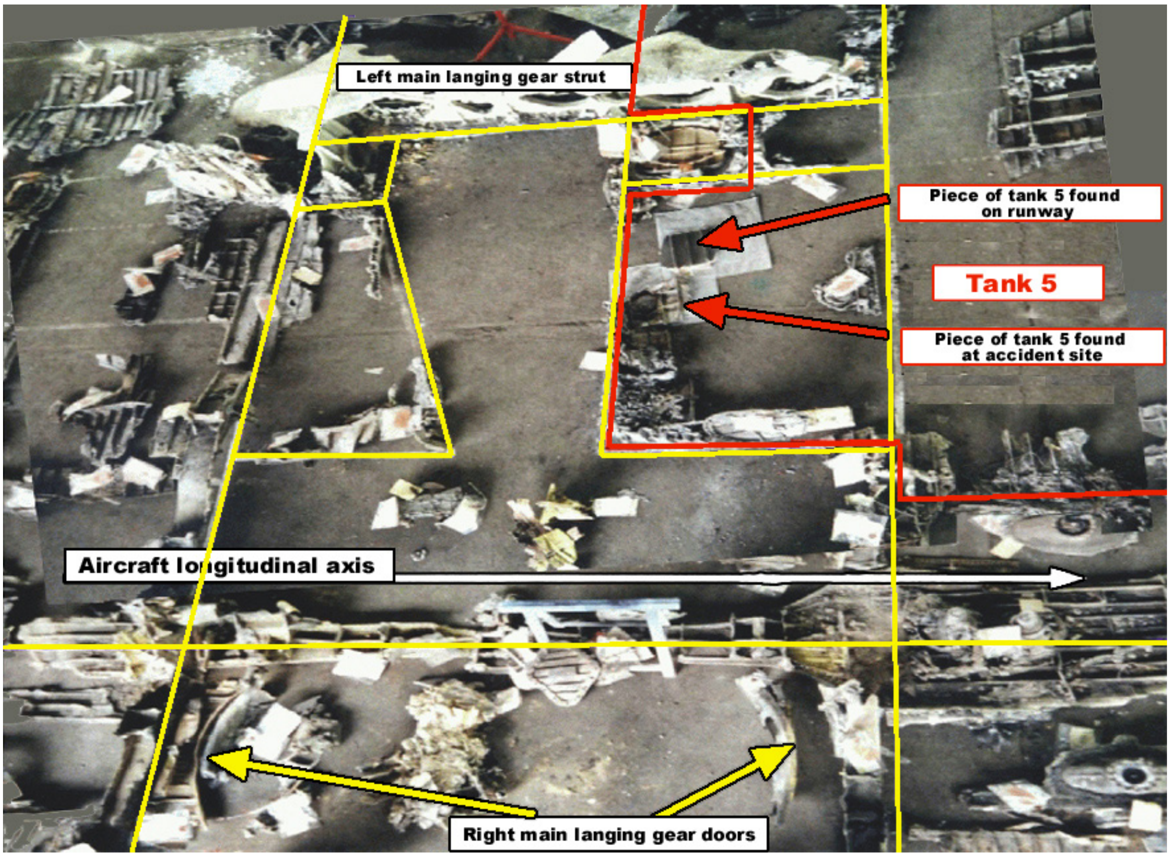

Figure 38: View of wing reconstruction in hangar

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.

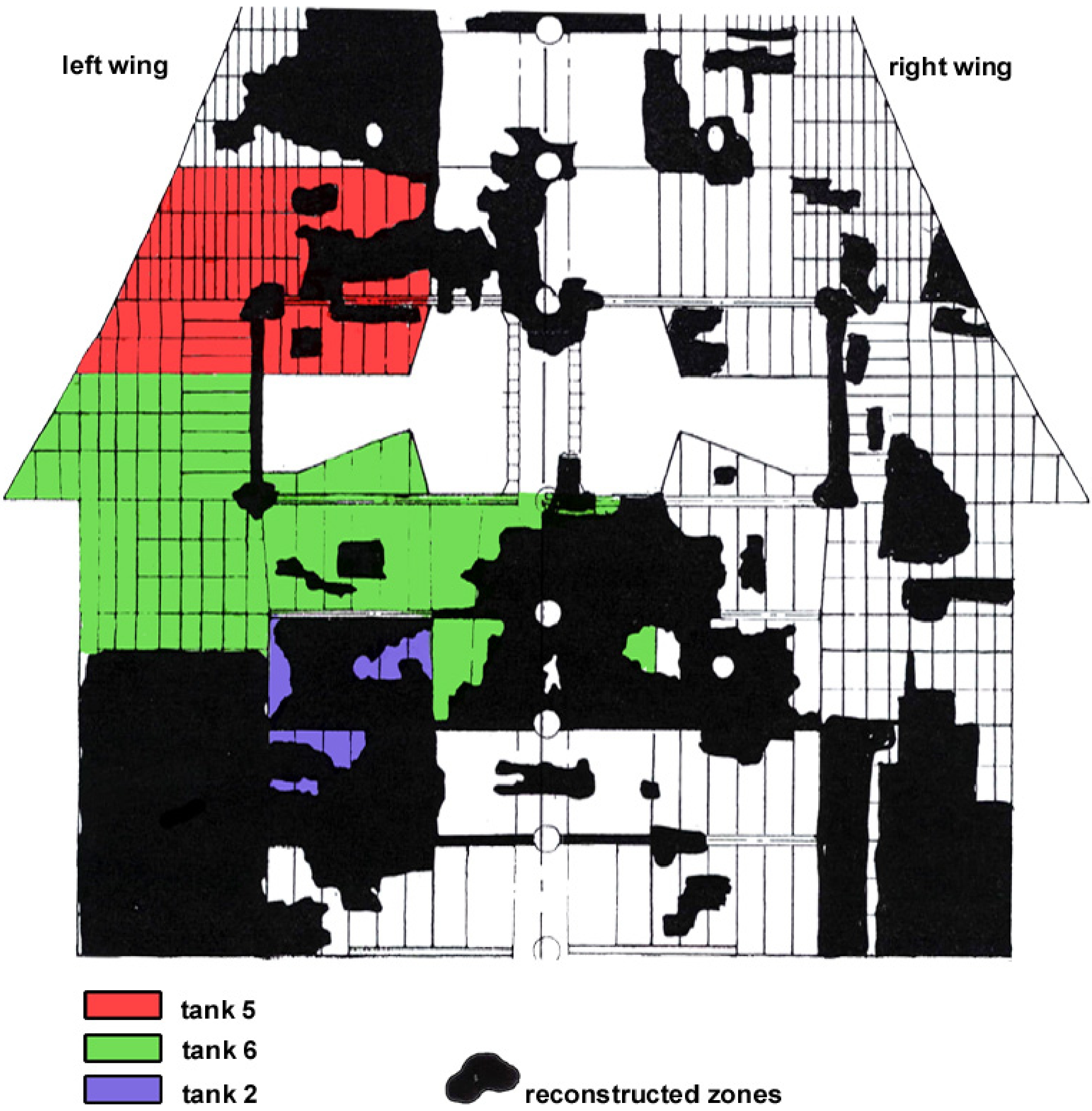

Figure 39: Computer reconstitution of upper wing

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.

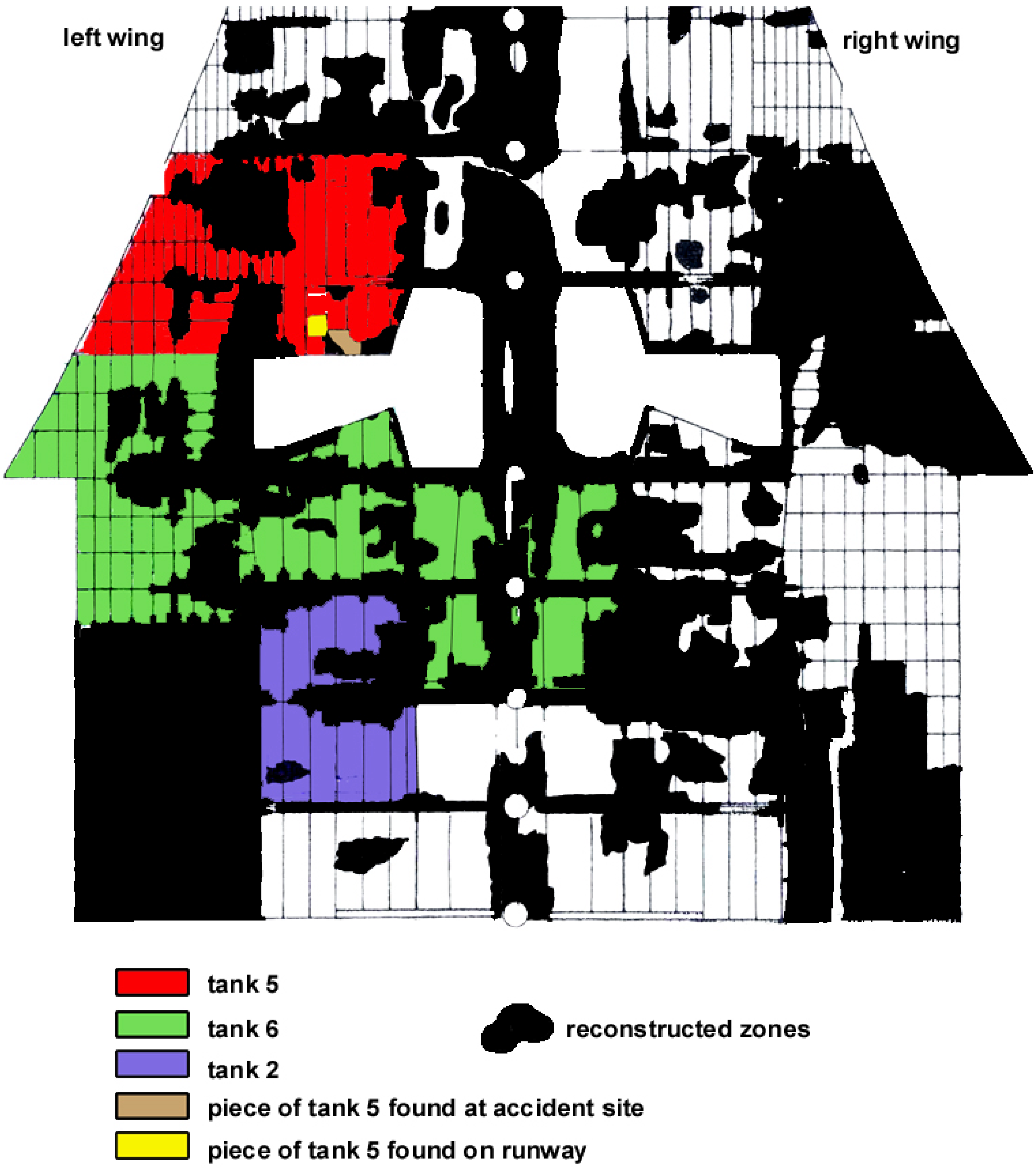

Figure 40: Computer reconstruction of lower wing

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.

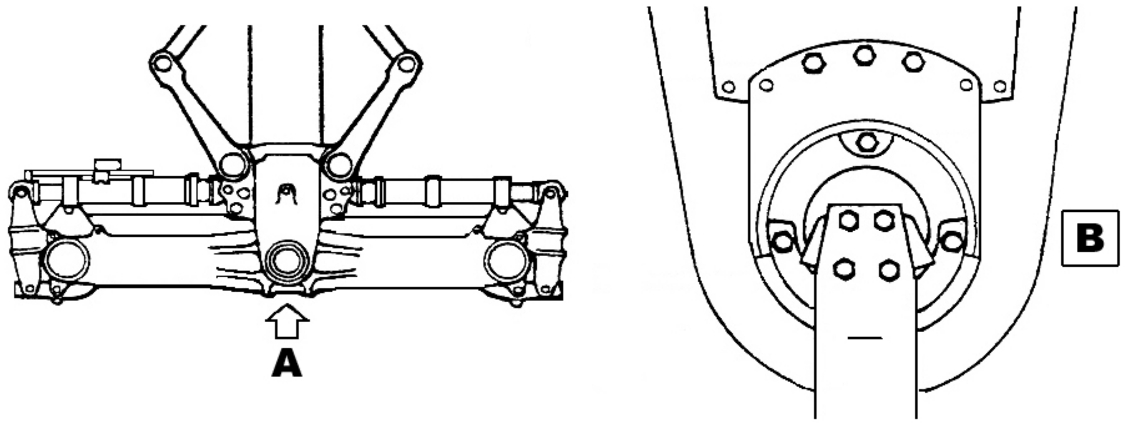

Figure 41: Leg-bogie coupling

- 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.

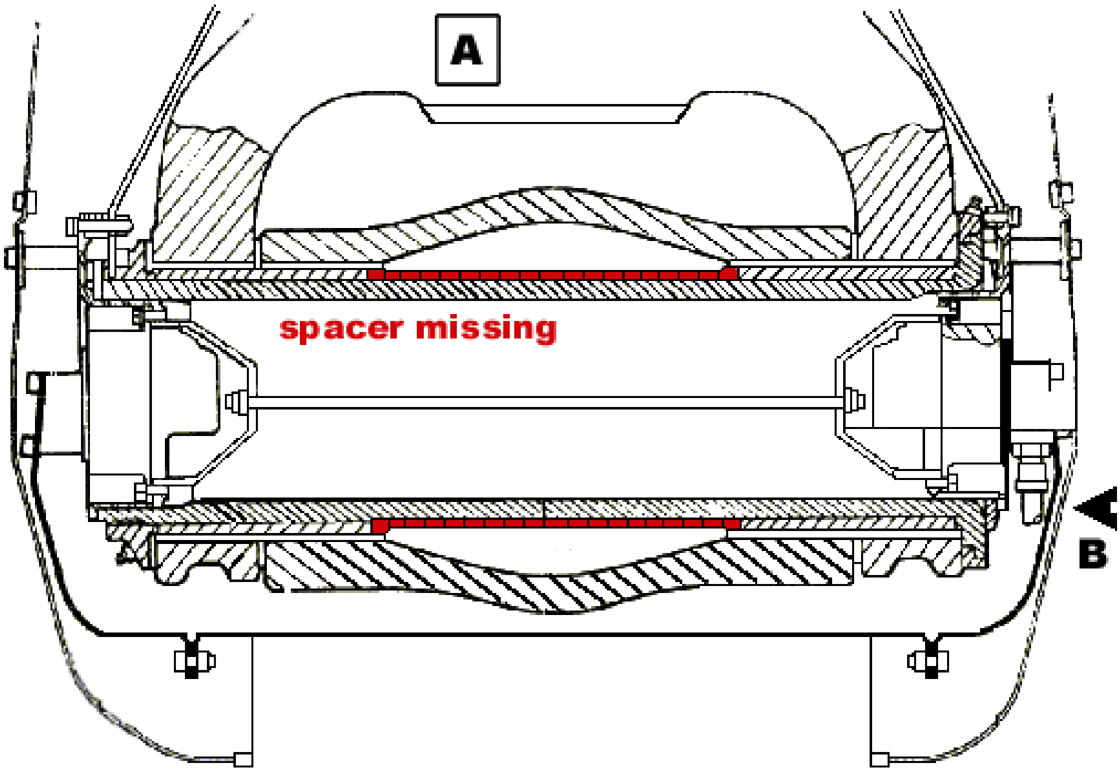

Figure 42: Cross section of leg-bogie coupling

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)].

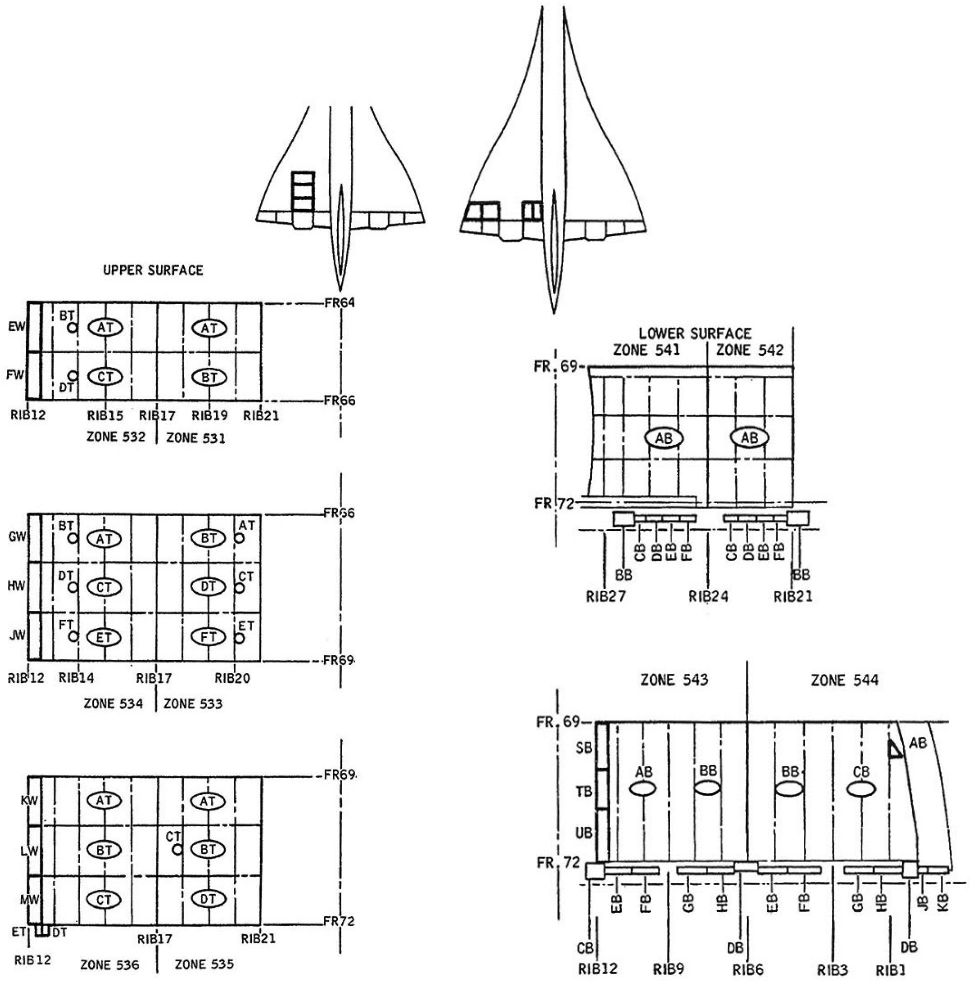

Figure 43: Dry bays

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 mbaron 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 (stoechiometric 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 been[2] 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.

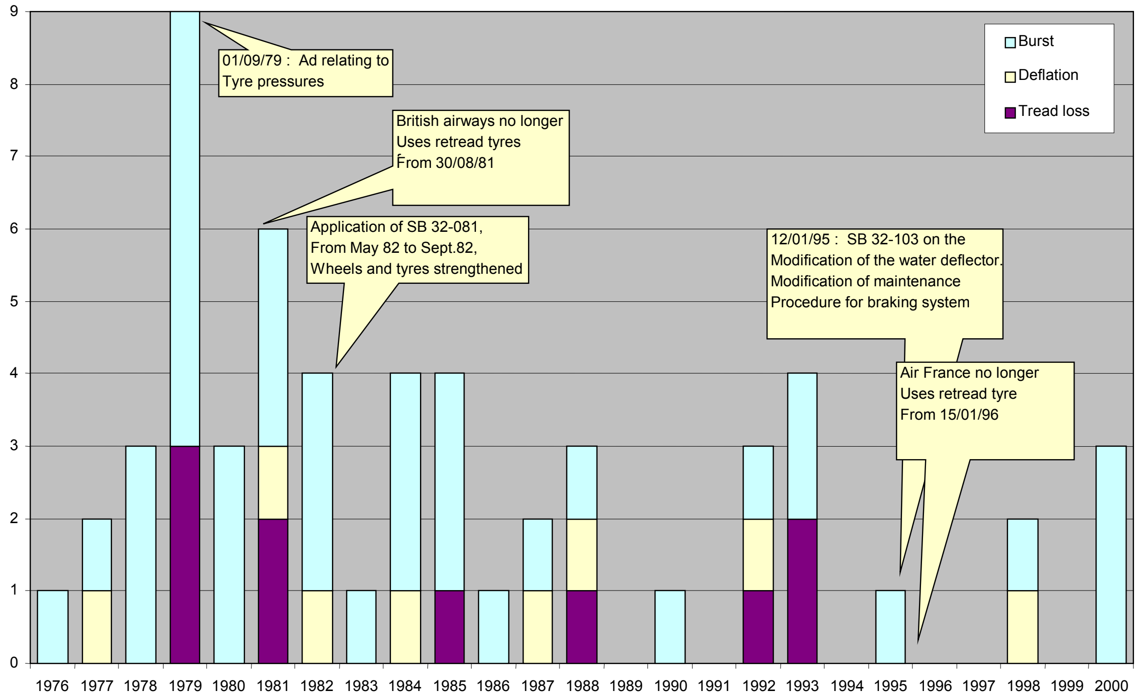

Figure 45: History of Concorde tyre events

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

<u>14 June 1979</u>: 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.

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

<u>5 November 1985</u>: 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.

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

<u>15 July 1993</u>: 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.

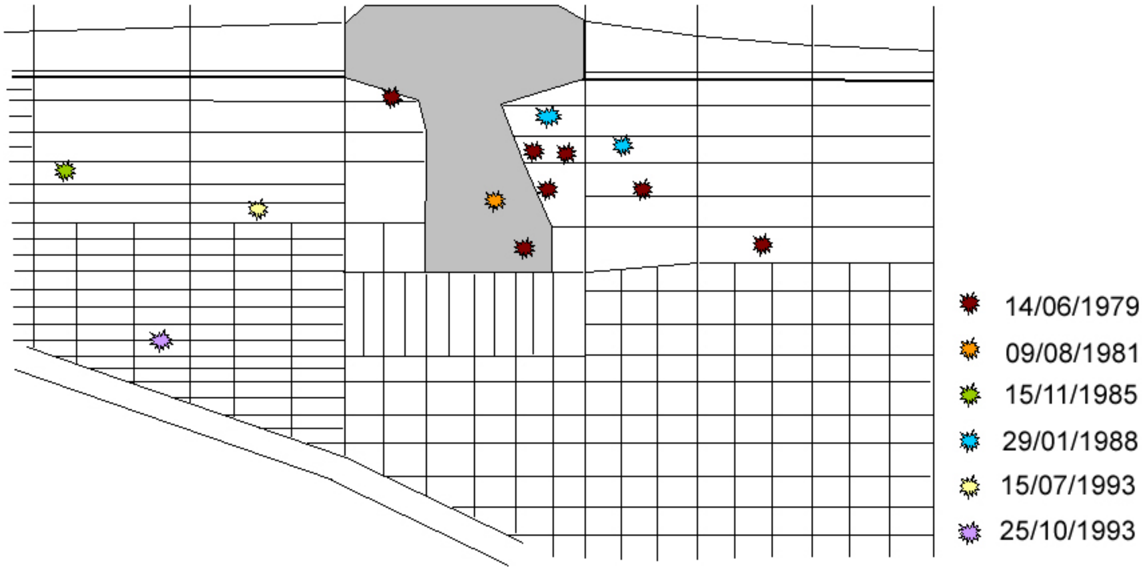

Figure 46: Location of impacts with punctures during various incidents

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:

    - that the size of the penetrations and the rate of flow of the leak are sufficiently low;
    - that ignition cannot be caused by rubber or metal debris penetrating the tank;
    - 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;
    - 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;
    - that ignition of the fuel on contact with hot brakes would not definitely occur, bearing in mind the average temperature reached by the brakes;
    - 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.

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[13] The nominal pressure of Concorde tyres is 16 bars.

1.16.5.3.2 Metallic Strip Dynamic Peneration 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.

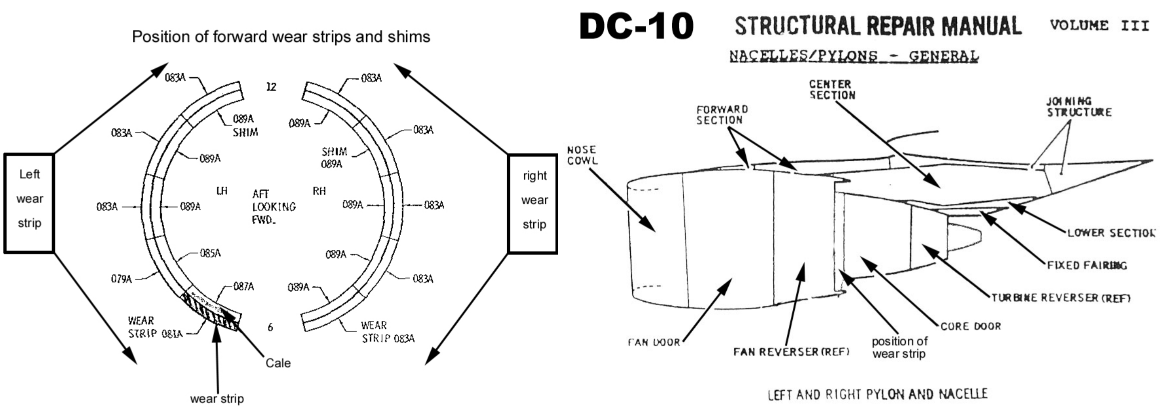


Figure 51: Diagram showing the position of the wear strips

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 forxard part of the core door ususally rests on the wear strip,
- the suport 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

- stripa 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 ± 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.

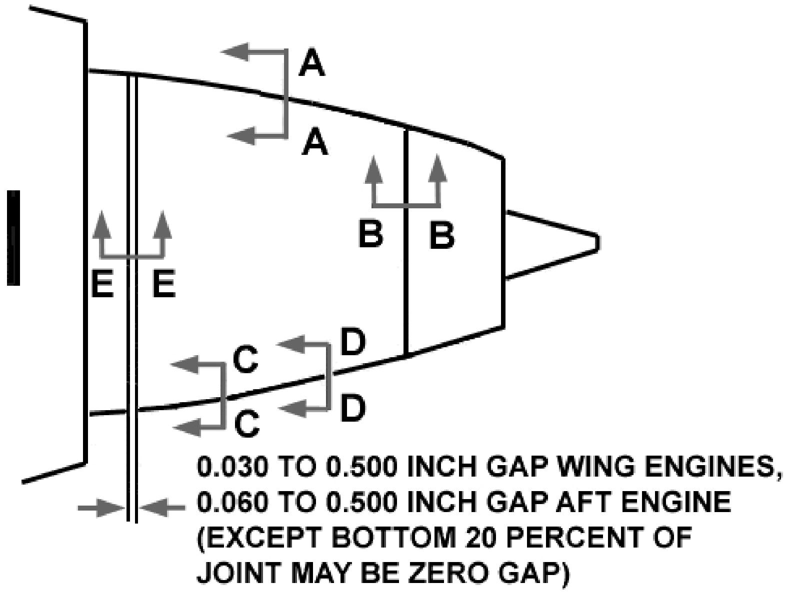


Figure 53: Diagram of cowl

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.

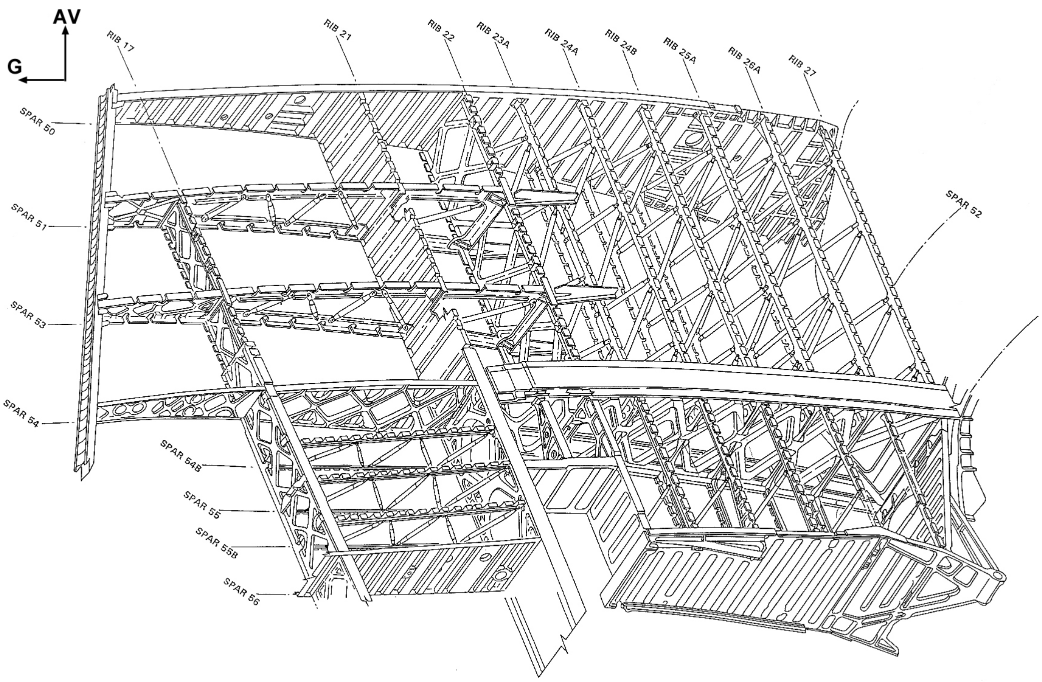


Figure 54: Plan of tank 5

1.16.7.1 Examination of the Pieces of the Tank

1.16.7.1.1 Piece Found on Runway

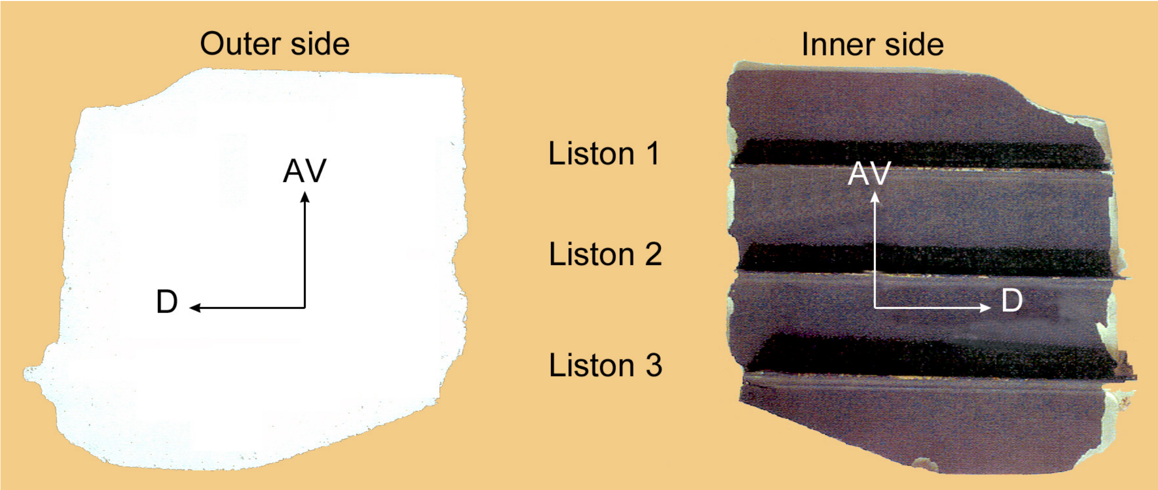


Figure 55: Piece of tank 5 found on the runway

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:

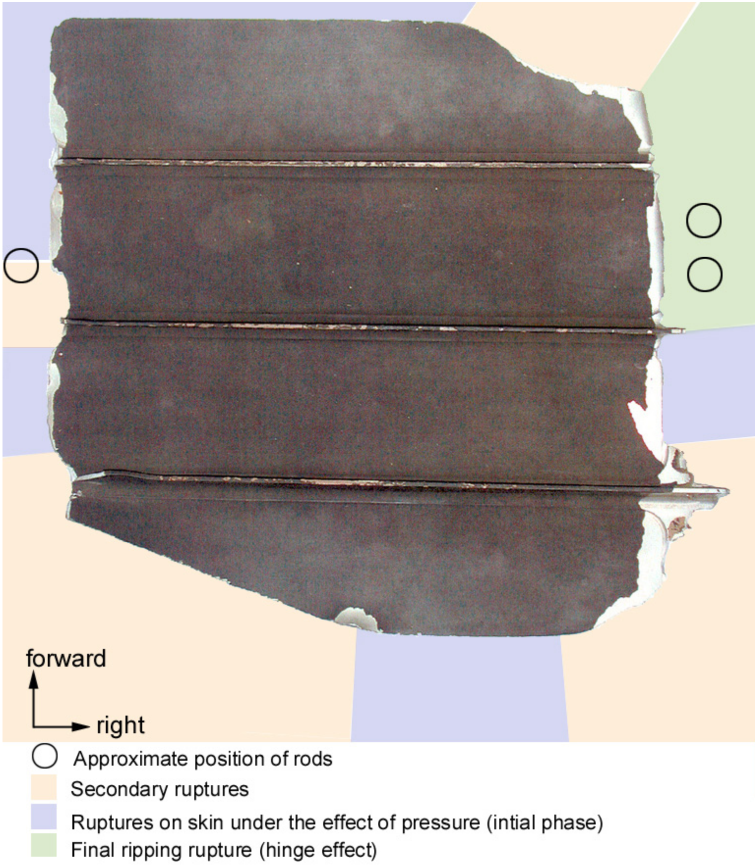


Figure 56: Rupture sequence for piece from tank 5

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.

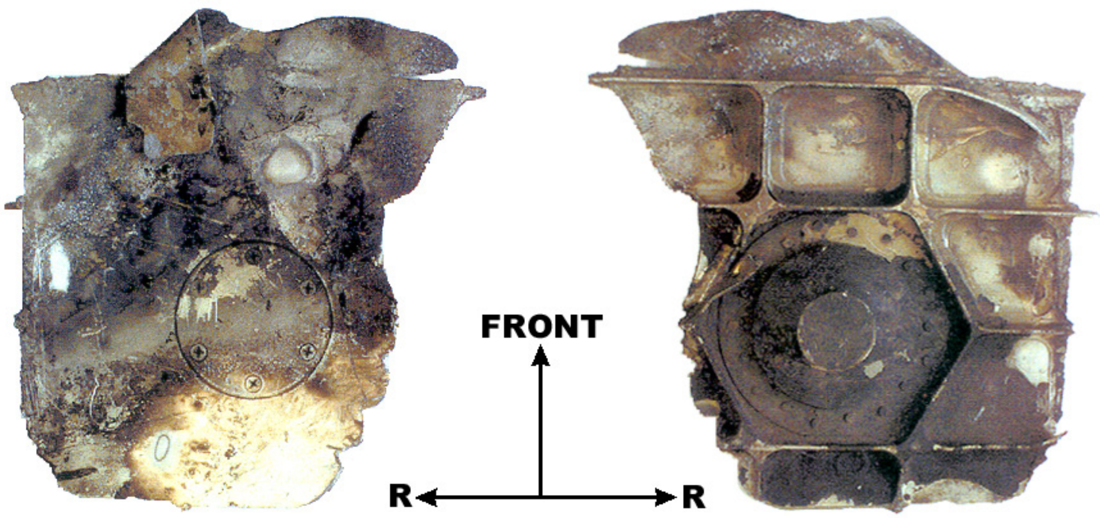


Figure 57: Piece of tank 5 found at site

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.

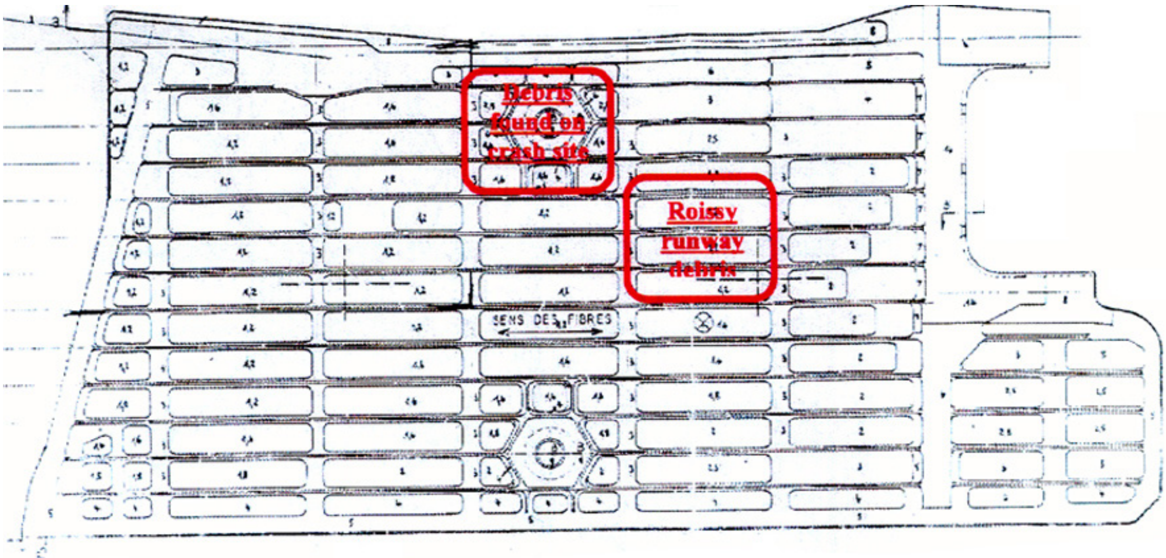


Figure 58: EADS diagram

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.

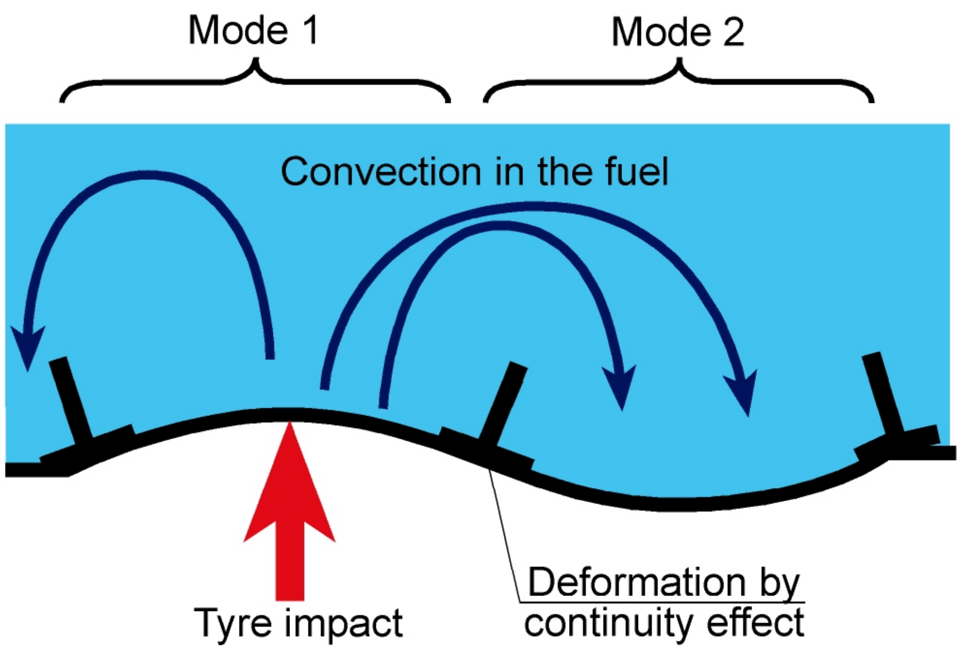


Figure 59: Effect of impact on wing box filled with fuel

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.

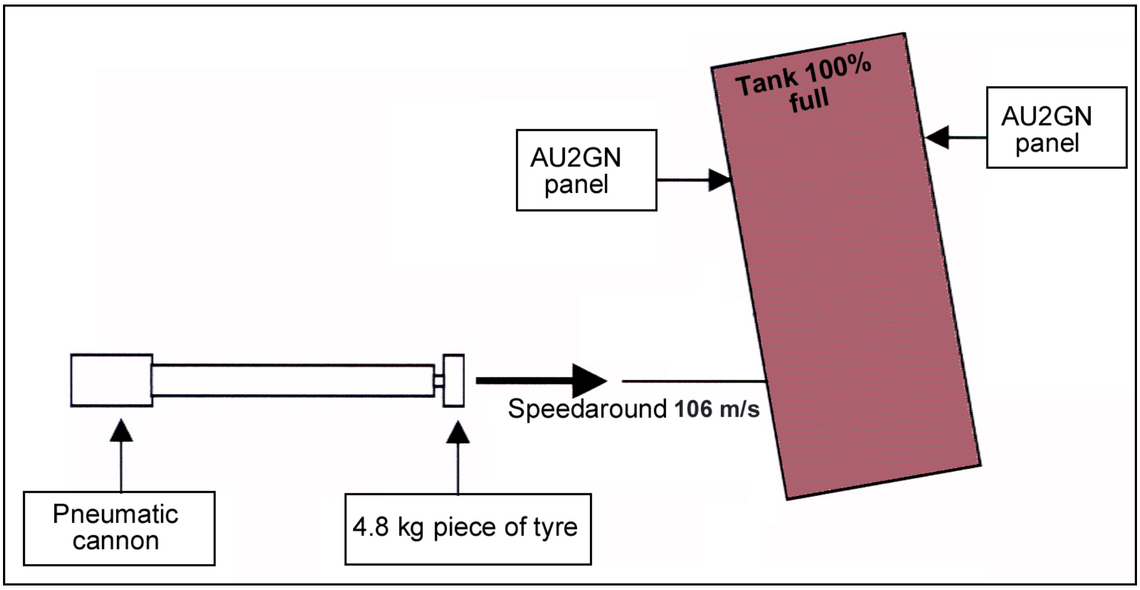


Figure 60: Firing test principle for a piece of tyre

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 surfaces 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.

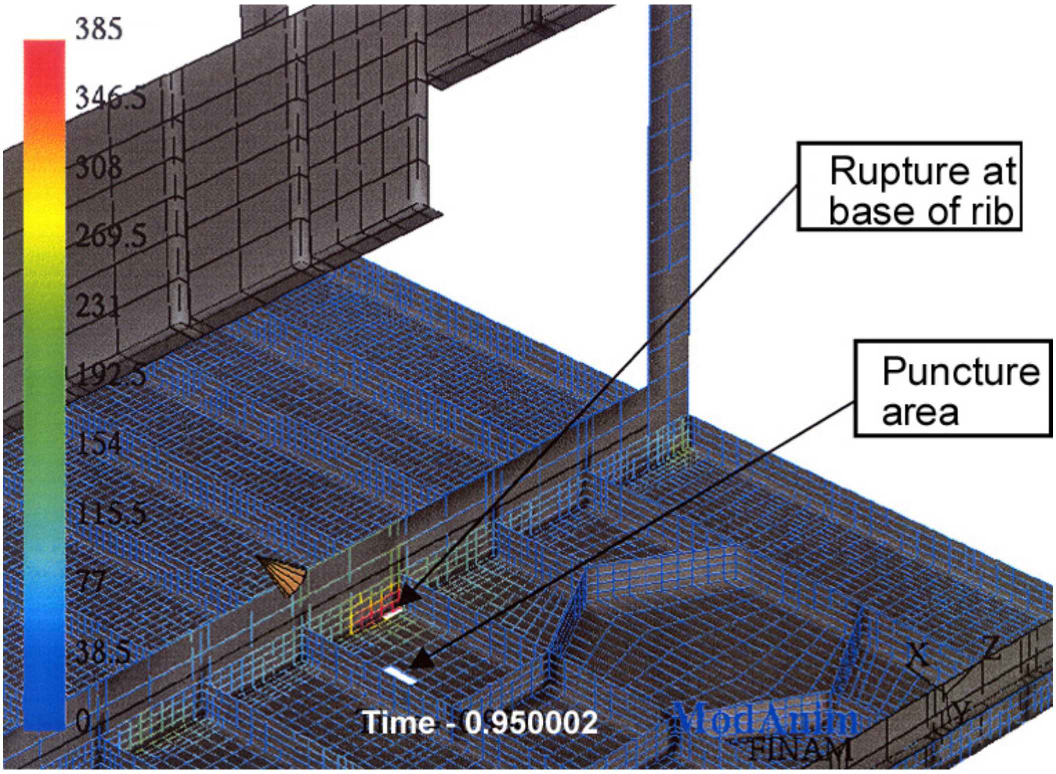


Figure 61: Position of the rupture areas on the lower skin

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 kg – 198 kg = 21 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.

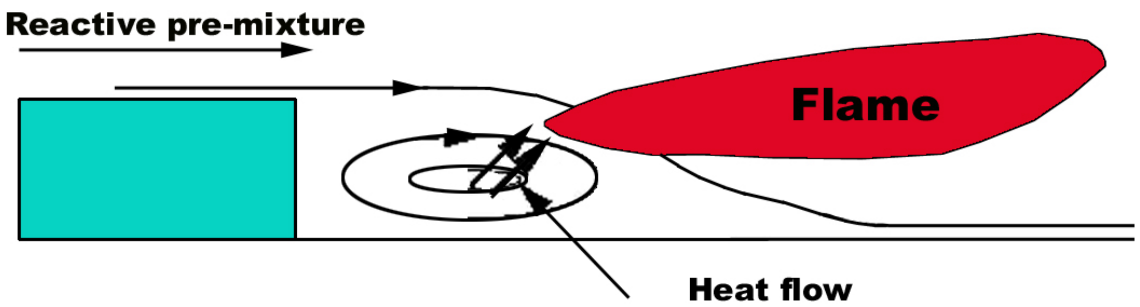


Figure 62: Re-circulation zone

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 stoechiometric 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 situate 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

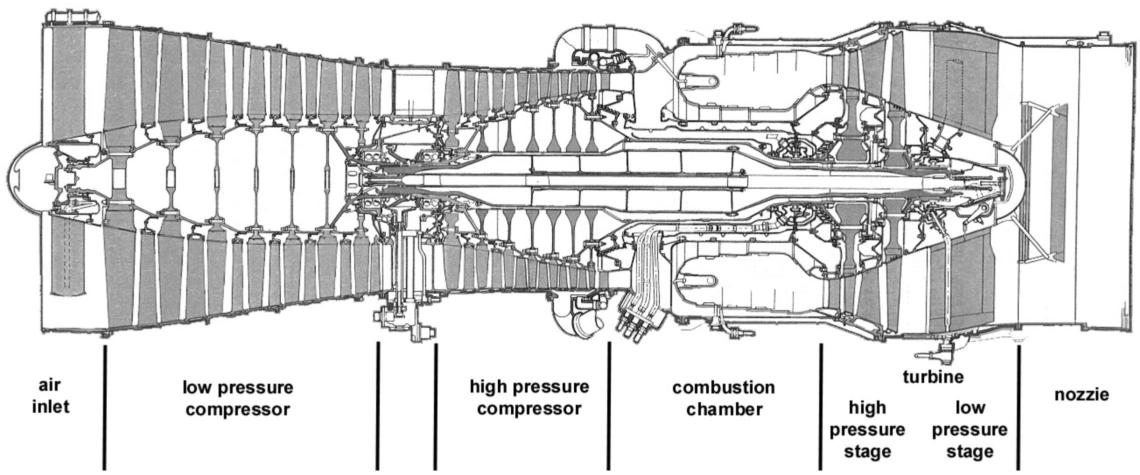


Figure 66: Olympus 593 – Representative diagram of airflow

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 facture 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 damages 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 inn 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 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 filed 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.

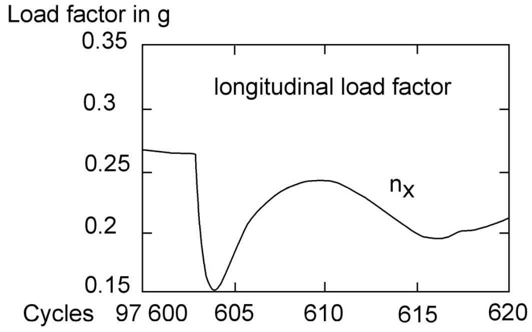
1.16.13.2 Deviation from the Track

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.

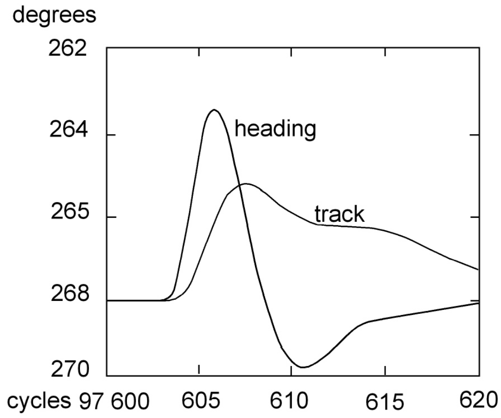
Generally speaking, it was noted that by entering the thrust and control movement parameters recorded on the aircraft into the model, values for acceleration, heading and lateral and longitudinal trim are obtained that are similar to those which were recorded. This confirms that the model was representative 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 (nx)). It was practically at the same moment that the pilot began the rotation.

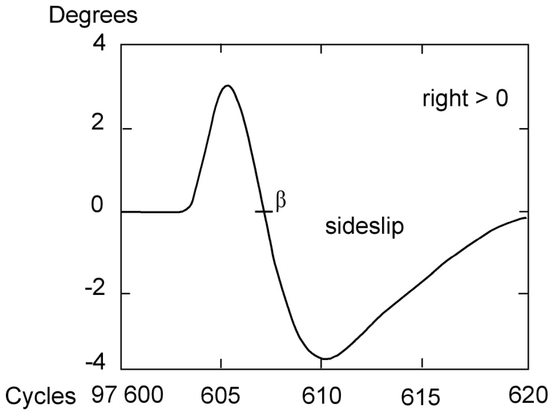
Note: in the figures in this paragraph, the figures on the y-axis correspond to the generated FDR time. For example, for “600”, read “97600”.



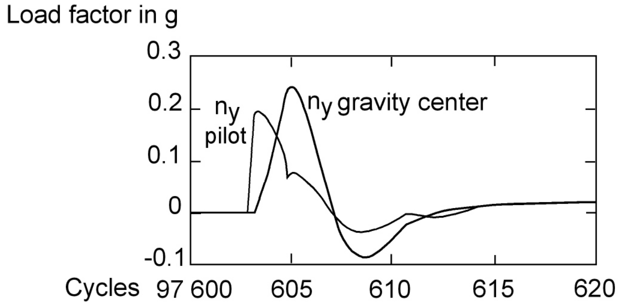
Longitudinal acceleration on Concorde (nx)



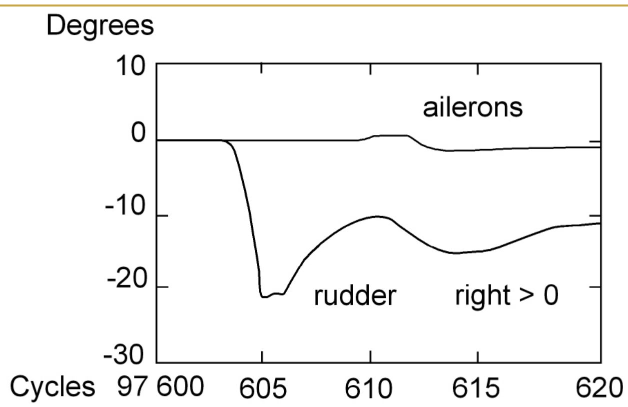
Aircraft heading and route



Aircraft sideslip



Lateral accelerations



Position of rudder

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:

  - All non-inhibited alarms
  - 'Failure' callout by FE
  - TYRE indicator lights up

2) Between 100 kt and V1, the Gong is ignored, takeoff aborted for:

  - 'Failure' callout by FE
  - TYRE indicator lights up
  - 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:

  - significant loss of thrust (- 5% of minimum N2)
  - before 100 kt, loss of a reheat in comparison to the number defined
  - 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	$5{,}4\ 10^{-4}$
1982-1994	42,628	8	$1{,}9\ 10^{-4}$
1995-2000	17,261	1	$0{,}6\ 10^{-4}$
Total	**83,941**	**22**	$\mathbf{2{,}6\ 10^{-4}}$

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.

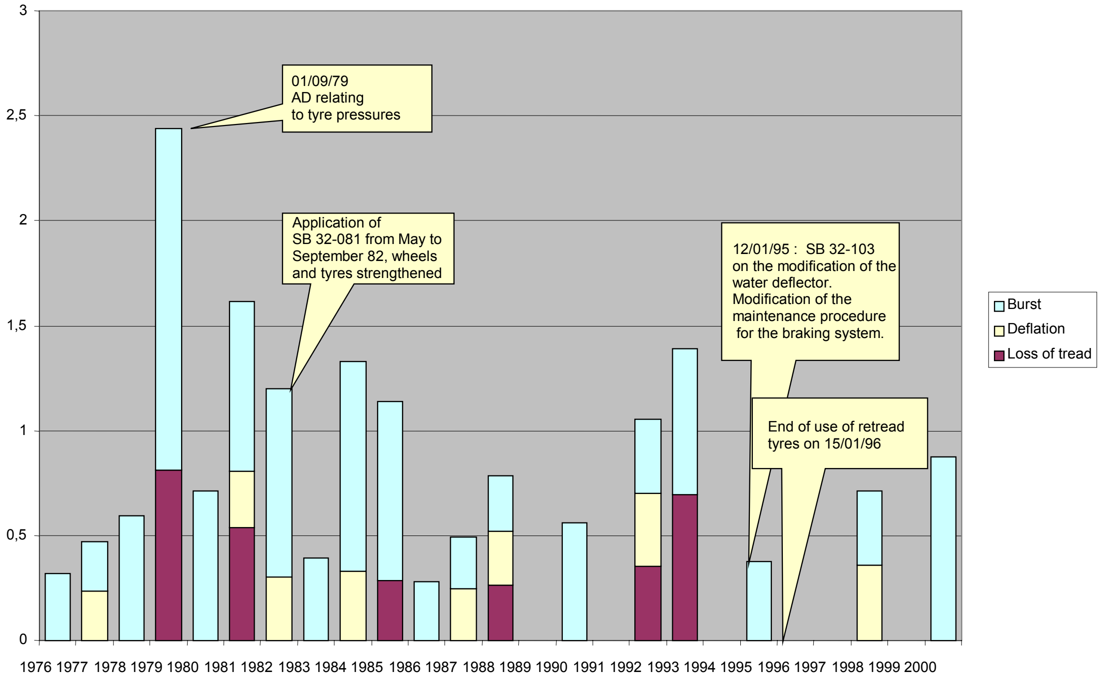


Figure 67: Number of events per thousant cycles

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.

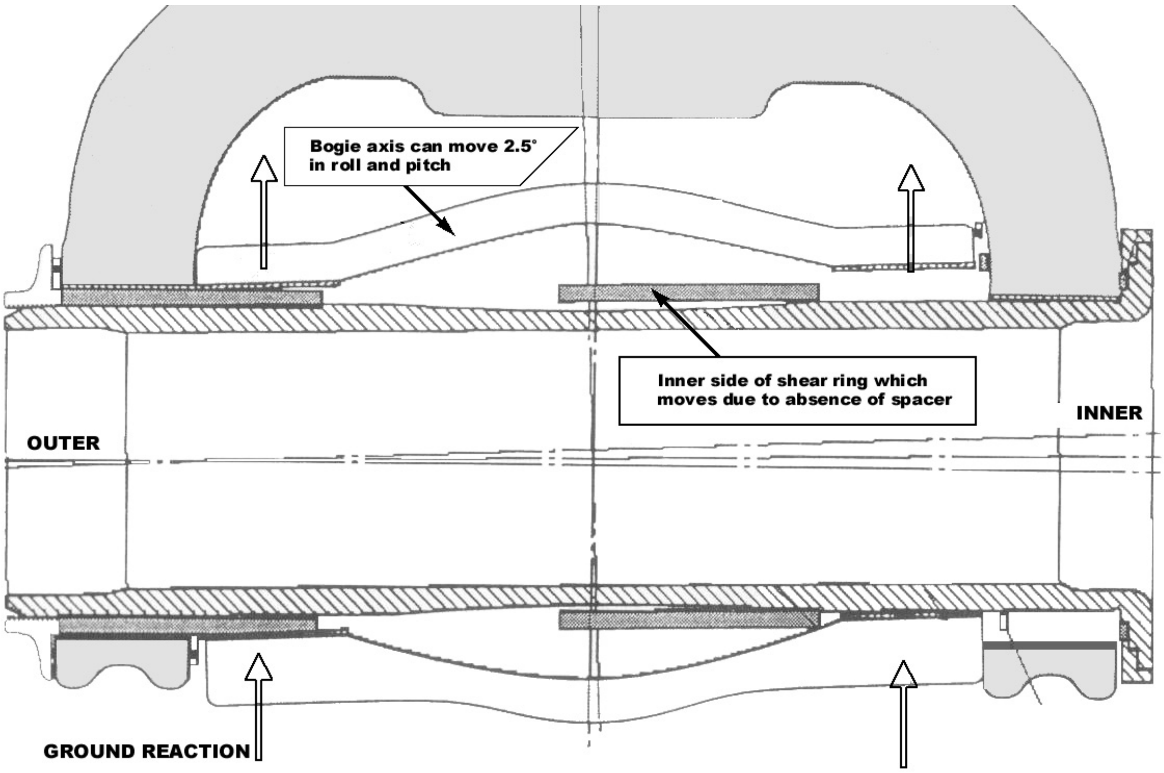


Figure 68: Cross-section of landing gear bogie beam coupling

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.

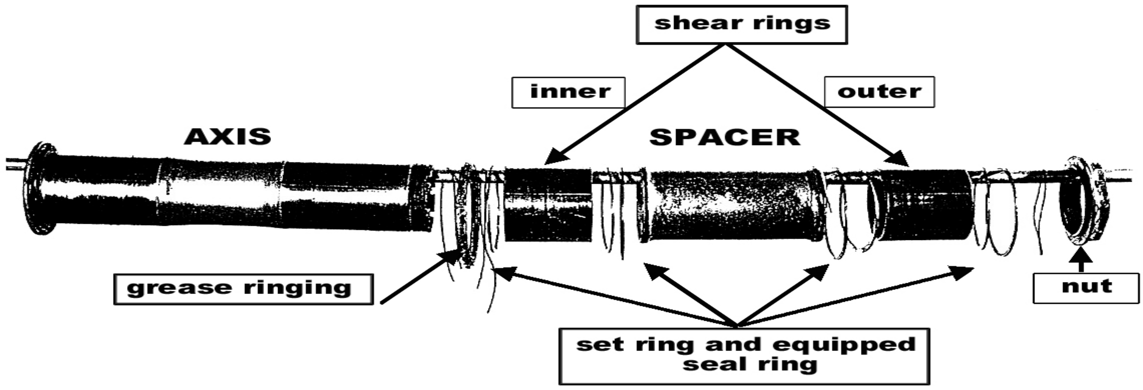


Figure 69: Landing gear, parts of the bogie beam

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.

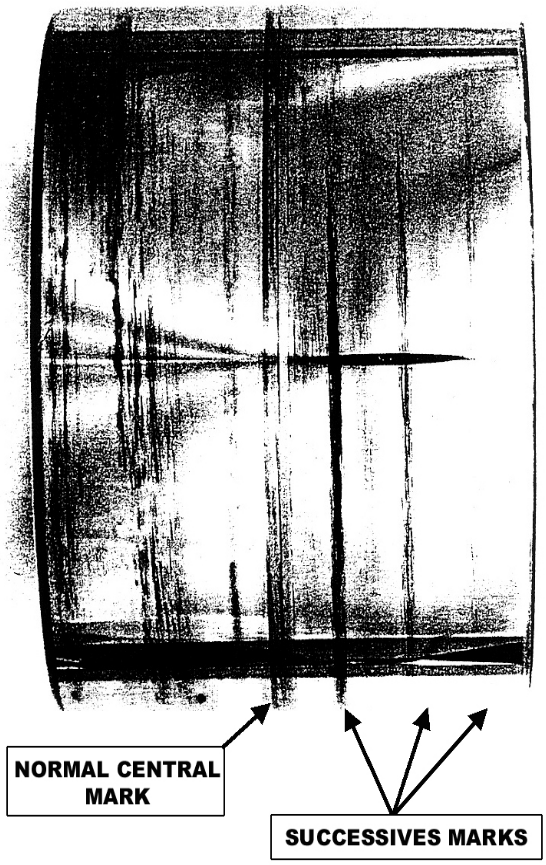


Figure 70: Left landing gear, inner shear ring

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.

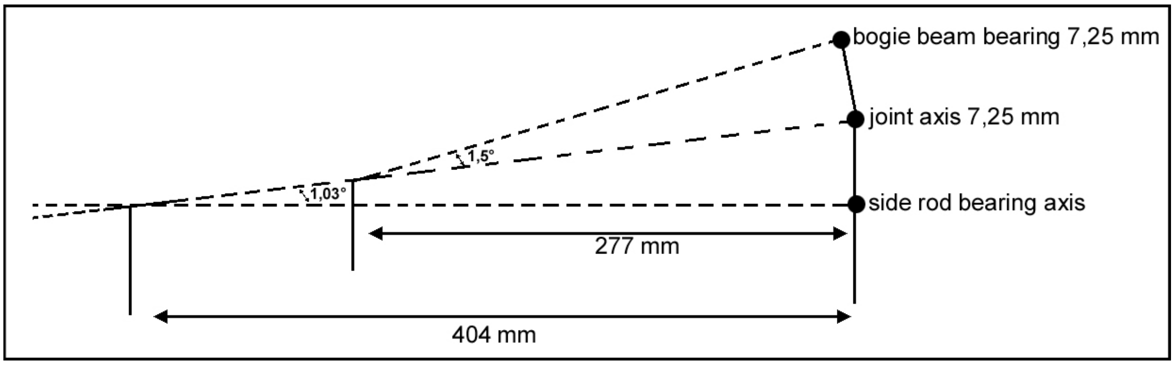


Figure 71: Effect of the lack of ring on the axle geometry

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.

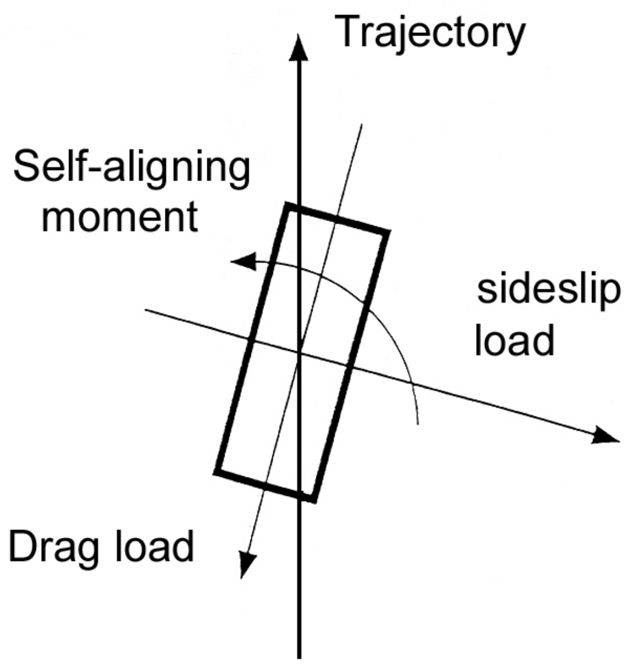


Figure 72: Typical behaviour of tyre under sideslip

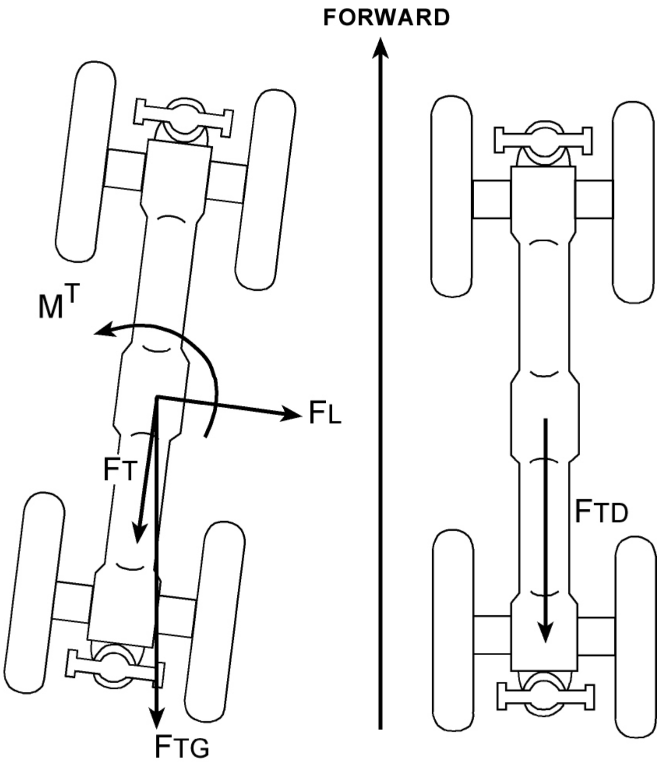


Figure 73: Loads in sideslip situation

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 Concordes.

- 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 AOGE 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

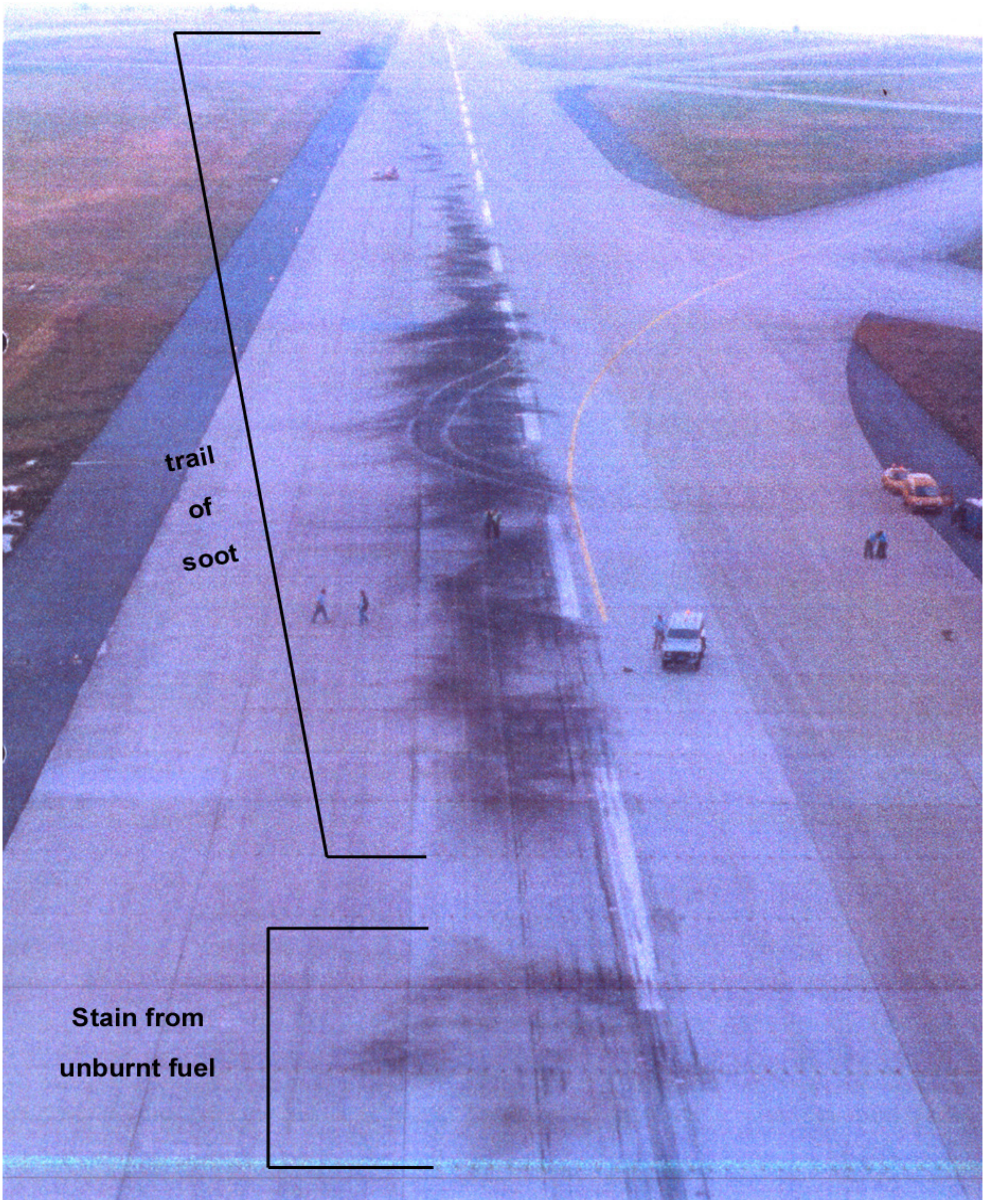


Figure 74: Aircraft track on takeoff

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°/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°/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°. 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 Concordes, 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.

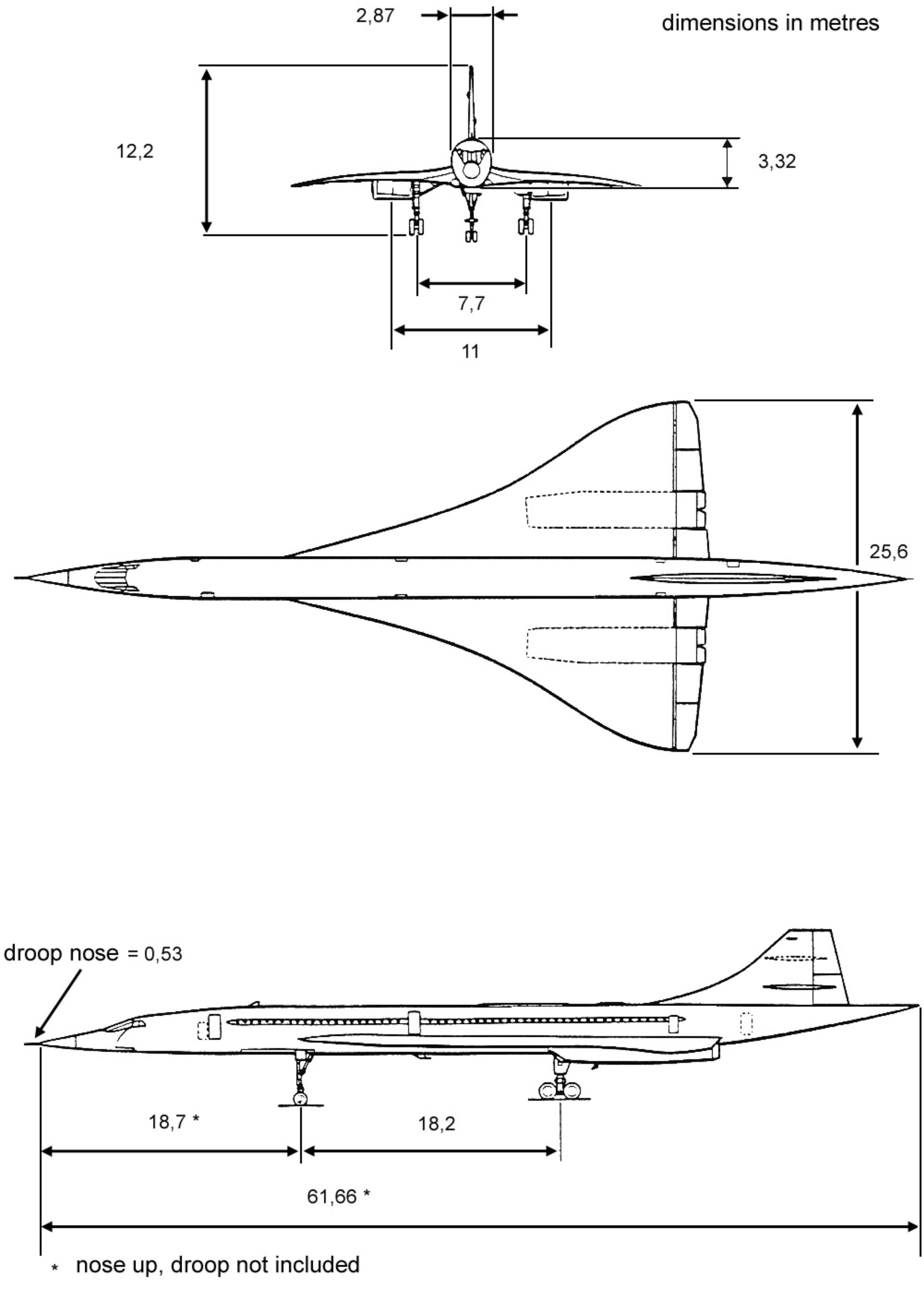
EADS ingestion testing conducted on a Concorde aircraft at Istres showed that when fluid was released from the position of the detached portion of wing undersurface appreciable quantities entered the landing gear bay. It was also clear that within the bay extensive reversal, circulation and speed reduction 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.

List of appendices

APPENDIX 1
Three-angle view of Concorde



CVR TRANSCRIPT

Ce qui suit représente la transcription des éléments qui ont pu être compris au cours de l'exploitation de l'enregistrement phonique (CVR). Cette transcription comprend les échanges entre les membres de l'équipage, les messages de radiotéléphonie et des bruits divers correspondant par exemple à des manœuvres de sélecteurs ou à des alarmes.

L'attention du lecteur est attirée sur le fait que l'enregistrement et la transcription d'un CVR ne constituent qu'un reflet partiel des événements et de l'atmosphère d'un poste de pilotage. En conséquence, l'interprétation d'un tel document requiert la plus extrême prudence.

Les voix des membres d'équipage sont entendues par l'intermédiaire du microphone d'ambiance. Elles sont placées dans des colonnes séparées par souci de clarté. Une colonne est dédiée aux autres voix, bruits et alarmes également entendus par l'intermédiaire du microphone d'ambiance.

FOREWORD

The following is the transcript of the elements which were understood from the work on the CVR recording. This transcript contains conversations between crew members, radiotelephonic messages and various noises corresponding, for example, to the movement of selectors or to alarms.

The reader's attention is drawn to the fact that the recording and transcript of a CVR are only a partial reflection of events and of the atmosphere in a cockpit. Consequently, the utmost care is required in the interpretation of this document.

The voices of crew members are heard via the cockpit area microphone (CAM). They are placed in separate columns for reasons of clarity. Another column is reserved for the voices of others, the noises and alarms also heard via the CAM.

GLOSSARY

UTC	Timings in the transcript in the Preliminary Report were expressed in 25ths of a second. So as to improve readability, the data is now presented in tenths of a second.
FDR	Generated time as recorded by the FDR in seconds and tenths of a second
Ctl	Air traffic control centre on the frequency in use
Co	Dispatcher
Ground	Ground Personnel
FSL	Fire Service Leader
CC	Cabin Crew
SV	Synthetic voice
🡻	Communications with ATC, the ground and the CC by interphone
?	Speaker not identified
( )	Word or group of words in parentheses are doubtful
(…)	Word or group of words with no bearing on the flight
(*)	Word or group of words not understood

CVR UTC	FDR TIME	CAPTAIN	FIRST OFFICER	FLIGHT ENGINEER	COCKPIT AREA MICROPHONE	VHF, INTERPHONE, PA	OBSERVATIONS
14 h 12 min 23 s	**BEGINNING OF RECORDING**						
12 min 24 s		(*)					
12 min 25 s		(*)					
12 min 26 s			(*) the INS is running				
12 min 27 s				Not yet			
12 min 28 s			not yet we can maybe navigate				
12 min 36 s			one hundred fourteen				
12 min 39 s			one hundred fourteen				
12 min 45 s			one hundred fourteen				
12 min 47 s		(*) stab fourteen fourteen					
12 min 50 s			radio altimeter one thousand eight confirmed				

CVR UTC	FDR TIME	CAPTAIN	FIRST OFFICER	FLIGHT ENGINEER	COCKPIT AREA MICROPHONE	VHF, INTERPHONE, PA	OBSERVATIONS
12 min 54 s		One thousand eight twenty-nine seventy-eight three hundred and fifty feet					
12 min 58 s			watches				
12 min 59 s		It's err fourteen					
14 h 13 min 02 s			well and mine isn't quite fourteen err isn't your watch right				
13 min 05 s		I have one thirteen err and twenty seconds					
13 min 09 s		I'm a bit fast	total fuel gauge				
13 min 13 s				So total fuel gauge I have ninety-six four and ninety-six three for ninety-five on board			
13 min 19 s		Ninety-five on board					
13 min 21 s			gear control lights				
13 min 23 s		down four greens					

CVR UTC	FDR TIME	CAPTAIN	FIRST OFFICER	FLIGHT ENGINEER	COCKPIT AREA MICROPHONE	VHF, INTERPHONE, PA	OBSERVATIONS
13 min 25 s			I N S				
13 min 26 s		So the departure position has been entered and checked					
13 min 30 s			man thrust thrust reverser				
13 min 31 s		it's checked idle					
13 min 32 s			radio				
13 min 34 s		set					
13 min 35 s			radar transponder				
13 min 36 s		set stand by pardon					
13 min 38 s			engine debow				
13 min 39 s				Switched on not debow			
13 min 40 s			fire detection				
13 min 42 s				on both			
13 min 43 s			flight recorders with two hundred twenty				

CVR UTC	FDR TIME	CAPTAIN	FIRST OFFICER	FLIGHT ENGINEER	COCKPIT AREA MICROPHONE	VHF, INTERPHONE, PA	OBSERVATIONS
13 min 44 s				two hundred twenty inserted off			
13 min 46 s			fire protection				
13 min 47 s				tested			
13 min 48 s			pressurisation				
13 min 49 s				six thousand			
13 min 50 s			engine control schedule				
13 min 51 s 13 min 53 s 13 min 55 s			 central ventilation batteries	fly over auto four low tested they are on		CC: Ladies and gentlemen, good Day my name is (...) your chief flight attendant in the name of the cap…	
13 min 57 s			I N S				
13 min 58 s				I've released them			
14 h 14 min 00 s		So the programme ten eleven is checked and mode four is on nav					
14 min 04 s			Z F W Z F C G				

CVR UTC	FDR TIME	CAPTAIN	FIRST OFFICER	FLIGHT ENGINEER	COCKPIT AREA MICROPHONE	VHF, INTERPHONE, PA	OBSERVATIONS
14 min 05 s				So I have ninety-one nine and fifty-two two			
14 min 09 s			aircraft weight total fuel				
14 min 10 s				one hundred eighty-six ninety-five			
14 min 12 s			totalizers				
14 min 14 s				At zero			
14 min 15 s			reference speeds				
14 min 23 s		so the reference speeds V1 one hundred fifty V R one hundred ninety-eight V 2 two hundred twenty two one hundred forty-two one hundred eighty it’s displayed on the left			CC: (*)		
14 min 26 s			on the right				
14 min 27 s		and on backup					

CVR UTC	FDR TIME	CAPTAIN	FIRST OFFICER	FLIGHT ENGINEER	COCKPIT AREA MICROPHONE	VHF, INTERPHONE, PA	OBSERVATIONS
14 min 28 s			attitude				
14 min 29 s		it's thirteen degrees					
14 min 30 s			P seven				
14 min 31 s		P seven is thirty-nine point one					
14 min 32 s				I haven't done it			
14 min 33 s				thirty-nine one			
14 min 35 s				thirty-nine one			
14 min 36 s				thirty-nine one			
14 min 38 s			fuel flow	and thirty-nine… five			
14 min 41 s		fuel flow is twenty point three nineteen nine					
14 min 43 s			noise reduction				
14 min 45 s		the reduction is on seventy-three seconds					
14 min 47 s				seventy-three			

CVR UTC	FDR TIME	CAPTAIN	FIRST OFFICER	FLIGHT ENGINEER	COCKPIT AREA MICROPHONE	VHF, INTERPHONE, PA	OBSERVATIONS
14 min 48 s		Gilles is that okay for you?					
14 min 49 s		and minus five		yes			
14 min 53 s		then the thrust lever is at fourteen and you will have N2 of ninety-seven and a bit					
14 min 58 s				ninety-seven			
14 min 59 s			parking brake				
14 h 15 min 00 s		It's on park fifteen hundred in front					
15 min 03 s		three thousand three behind	central alarm system				
15 min 05 s		recall					
15 min 06 s			cancel				
15 min 07 s		inhibit					
15 min 09 s			the window				
15 min 11 s		It's closed locked on the left					
15 min 13 s			on the right				

CVR UTC	FDR TIME	CAPTAIN	FIRST OFFICER	FLIGHT ENGINEER	COCKPIT AREA MICROPHONE	VHF, INTERPHONE, PA	OBSERVATIONS
15 min 14 s			door light				
15 min 16 s				So I still have a cargo I have the forward left door and the aft left door			
15 min 26 s			secondary air doors				
15 min 28 s				auto			
15 min 29 s			feeder pump for three				
15 min 32 s				on			
15 min 33 s			hydraulic alternator for three				
15 min 38 s				off and off			
15 min 40 s			anti collision and seat belts				
15 min 43 s				the seat belts on are on on			
15 min 44 s			that’s it (*)				
15 min 45 s					Cabin gong		
15 min 50 s						CC: yes	

CVR UTC	FDR TIME	CAPTAIN	FIRST OFFICER	FLIGHT ENGINEER	COCKPIT AREA MICROPHONE	VHF, INTERPHONE, PA	OBSERVATIONS
15 min 51 s			➔ yes it's aft no				
15 min 53 s						CC: no forward	
15 min 54 s						CC: Hervé the rear	
15 min 55 s			➔ yes Hervé there's still a door open aft				
15 min 57 s						CC: yeh yeh he's closing it right now	
15 min 59 s			➔ okay				
14 h 16 min 03 s			➔ ground				
16 min 07 s			➔ hello hello				
16 min 08 s						Ground: yes I'm listening	
16 min 10 s			➔ yes that where are we down there				

CVR UTC	FDR TIME	CAPTAIN	FIRST OFFICER	FLIGHT ENGINEER	COCKPIT AREA MICROPHONE	VHF, INTERPHONE, PA	OBSERVATIONS
16 min 11 s						Ground: well the mechanics have finished now they're just getting off the last … the last tool box now but the loading isn't quite finished yet	
16 min 20 s			🡻 the hold there the baggage?				
16 min 22 s						Ground: affirmative there's still a (*) to fill... to completely empty the…	
16 min 26 s			🡻 well it's fortunate that we're three quarters of an hour late otherwise what would it have been like				
16 min 32 s			🡻 that's what ten minutes more at least				
16 min 35 s						Ground: err yes	

CVR UTC	FDR TIME	CAPTAIN	FIRST OFFICER	FLIGHT ENGINEER	COCKPIT AREA MICROPHONE	VHF, INTERPHONE, PA	OBSERVATIONS
16 min 39 s		yes I'm going to see it's because… there was a mechanical problem maybe					
16 min 42 s			oh no				
16 min 43 s				and if if we hadn't been late (*) was late for the fill-up the tankers arrived half an hour before the theoretical departure time so you know (*) sometimes			
16 min 54 s				it's the engine change which			
16 min 57 s				so before staring up we'll do a blue check			
14 h 17 min 01 s			before starting up				
17 min 02 s				yes I prefer before starting up			
17 min 04 s			there are some servos which (*) the flight controls				

CVR UTC	FDR TIME	CAPTAIN	FIRST OFFICER	FLIGHT ENGINEER	COCKPIT AREA MICROPHONE	VHF, INTERPHONE, PA	OBSERVATIONS
17 min 07 s				no it's because we're there's there was a leak on the blue and I had a blockage with a low level blue we filled it up I'm going to press the blue in… the Ground blue pumps are on let's first close the air intakes that are blocked			
17 min 22 s			as soon as they've finished with their mess				
17 min 23 s				yeh			
17 min 26 s				and then after that we're going to start up			
17 min 27 s						Ground: okay in any case for the controls if you like we can do it	
17 min 34 s				➔ okay I'm... I'm applying hydraulic pressure			

CVR UTC	FDR TIME	CAPTAIN	FIRST OFFICER	FLIGHT ENGINEER	COCKPIT AREA MICROPHONE	VHF, INTERPHONE, PA	OBSERVATIONS
17 min 36 s						Ground: okay it's clear you can go	
17 min 40 s				you you have the controls			
17 min 42 s		I've got them					
17 min 44 s			ten minutes				
17 min 45 s					CC: how long		
17 min 46 s			ten minutes				
17 min 47 s					CC: ten minutes... wait here		
17 min 48 s			yeh yeh yeh				
17 min 49 s			it's not it's not the repair to the aircraft it's the baggage which are not loaded				
17 min 53 s					CC: ah okay		
17 min 54 s		but I don't dare tell them that					
17 min 56 s			we think (*)				

CVR UTC	FDR TIME	CAPTAIN	FIRST OFFICER	FLIGHT ENGINEER	COCKPIT AREA MICROPHONE	VHF, INTERPHONE, PA	OBSERVATIONS
17 min 57 s		(*)	to help him to load to speed things up	➔ okay okay I'm closing air intakes three and four			
14 h 18 min 03 s						Ground: okay it's done	
18 min 04 s		how are things in the back?					
18 min 05 s					CC: everything's okay		
18 min 06 s		that's true					
18 min 07 s							
18 min 08 s		well I'll say something just before start-up so as to (*)			CC: yes yes		
18 min 12 s				➔ well the air intakes are okay we can move the flight controls	CC: (*)		
18 min 16 s		(*)				Ground: okay roger it's clear you can go ahead	
18 min 18 s		eh					
18 min 19 s					CC: (*)		

CVR UTC	FDR TIME	CAPTAIN	FIRST OFFICER	FLIGHT ENGINEER	COCKPIT AREA MICROPHONE	VHF, INTERPHONE, PA	OBSERVATIONS
18 min 20 s		what shall I do (*)					
18 min 21 s					CC: (*)		
18 min 22 s		go ahead					
18 min 23 s		shall I do a bit of (*) and I (*)					
18 min 26 s				we're going to be in mechanical but it's not serious but (*)	Gong		
18 min 28 s			You don't need me eh				
18 min 30 s				no no			
18 min 32 s 18 min 34 s			We'll have to ask the dispatcher if he has a weight estimate… at the same time		 Gong		
18 min 35 s 18 min 38 s		I 'm in mechanical maybe that's a problem because it doesn't respond like (*)		 no no it's not a problem			
18 min 41 s			you're bugging me (*)				

CVR UTC	FDR TIME	CAPTAIN	FIRST OFFICER	FLIGHT ENGINEER	COCKPIT AREA MICROPHONE	VHF, INTERPHONE, PA	OBSERVATIONS
18 min 42 s 18 min 44 s				yes you're bugging me if you're not ready (*)	Gong		Joking tone
18 min 49 s 18 min 50 s		well it's making some jumps in mechanical eh but maybe that's normal		yes yes no no but...			
18 min 53 s		so next the rudder					
14 h 19 min 00 s		well that's working eh					
19 min 01 s				okay			
19 min 05 s					Gong		
19 min 06 s				➔ okay so the level has fallen slightly that's normal and it's stabilising the air intakes are closed the flight controls are working correctly I'm cutting hydraulic pressure			
19 min 15 s						Ground: okay thanks	

CVR UTC	FDR TIME	CAPTAIN	FIRST OFFICER	FLIGHT ENGINEER	COCKPIT AREA MICROPHONE	VHF, INTERPHONE, PA	OBSERVATIONS
19 min 20 s				It's going to fall the the controls are going to go forward			
19 min 23 s		okay					
19 min 25 s				yes in mechanical it's going to be a bit hard toy feel it flying on mechanical it's not (...)	Gong		Laughter
19 min 27 s		yes (*)					
19 min 31 s		well I remember					Laughter
19 min 40 s				okay it's dropped I'll deal with it			
14 h 20 min 04 s				there you are we're back on yellow			
20 min 05 s					Co: load sheet sir		
20 min 06 s					Co: good... in fact... there were some bags which were added I have two tons two of baggage		

CVR UTC	FDR TIME	CAPTAIN	FIRST OFFICER	FLIGHT ENGINEER	COCKPIT AREA MICROPHONE	VHF, INTERPHONE, PA	OBSERVATIONS
20 min 14 s					Co: for the BRS security software		
20 min 18 s		yes					
20 min 19 s					Co: there’s a problem we haven’t defined what I called the people who were in the BRS section err the baggage was correctly labelled as four five nine zero but it didn’t go through		
20 min 29 s		hum					

CVR UTC	FDR TIME	CAPTAIN	FIRST OFFICER	FLIGHT ENGINEER	COCKPIT AREA MICROPHONE	VHF, INTERPHONE, PA	OBSERVATIONS
20 min 30 s					Co: so we tried to do a few things to call to ring a few bells but in the end we have two tons two of bags they are labelled but I can't read all the baggage to be loaded so I'll have to see with the people concerned to do that I'll warn the DO for me it's clear for security I have no no-shows and I have no extra bags		
20 min 56 s					Co: and all the bags have been through the x-ray according to the required random procedure		
14 h 21 min 03 s		okay			Co: I reckon that it's the monitor that's not working		

CVR UTC	FDR TIME	CAPTAIN	FIRST OFFICER	FLIGHT ENGINEER	COCKPIT AREA MICROPHONE	VHF, INTERPHONE, PA	OBSERVATIONS
21 min 08 s		okay			Co: I've adjusted the fuel to maximum for taxi because it's increased by two hundred kilos of baggage		
21 min 18 s		In any case it's what you told us eh ninety-one nine we were basing ourselves on that					
21 min 21 s					Co: okay		
21 min 22 s		So we're okay eh					
21 min 24 s		So because there you've put taxiing a bit high eh…					
21 min 28 s					Co: I've put two two tons		
21 min 29 s		We'll be taking off with a bit more than that in fact eh					
21 min 31 s					Co: yes		
21 min 32 s		But that's okay it's not important					

CVR UTC	FDR TIME	CAPTAIN	FIRST OFFICER	FLIGHT ENGINEER	COCKPIT AREA MICROPHONE	VHF, INTERPHONE, PA	OBSERVATIONS
21 min 34 s					Co: does that suit you?		
21 min 35 s		So zero fuel is fifty-two three Gilles eh in fact					
21 min 37 s				yes I've corrected it			
21 min 38 s		You've corrected it eh		(*)			
21 min 41 s					Co: otherwise for loading we'll close the hold and we're ready		
21 min 45 s		So that's okay					
21 min 47 s		So here there's six and six twelve twelve and five ten seven					
21 min 50 s		right					
21 min 52 s		Four hundred well that's perfect					

CVR UTC	FDR TIME	CAPTAIN	FIRST OFFICER	FLIGHT ENGINEER	COCKPIT AREA MICROPHONE	VHF, INTERPHONE, PA	OBSERVATIONS
21 min 53 s				From the mechanical viewpoint the mechanical viewpoint it’s over since			
21 min 57 s				(*)	Co: yes but err the baggage came came came and well it reset on the D but… problem		
14 h 22 min 05 s					Co: that’s it		
14 h 22 min 05 s					Co: that’s it		
22 min 06 s		thanks					
22 min 07 s		Well sir till next time					
22 min 08 s					Co: goodbye gentlemen		
22 min 09 s		goodbye	goodbye				
22 min 11 s					Co: see you soon		
22 min 12 s		See you soon	See you soon				

CVR UTC	FDR TIME	CAPTAIN	FIRST OFFICER	FLIGHT ENGINEER	COCKPIT AREA MICROPHONE	VHF, INTERPHONE, PA	OBSERVATIONS
22 min 14 s		Fifty-two three well that's what he said it's forty kilos over but anyway	…				
22 min 17 s 22 min 19 s		 (*)		And we have I've… I've taken the takeoff weight as one hundred and eighty-five tons			
22 min 22 s 22 min 24 s		Well we'll take one hundred eighty-five one hundred that's to say we'll be at the structural … limits		 With fifty-two two			
22 min 29 s		Structural err fifty-four for one hundred CG (*) see					
22 min 38 s		And we're really at the minimum					
22 min 42 s				fuel			
22 min 43 s		fuel yes					
22 min 44 s		good					
22 min 45 s				go			

CVR UTC	FDR TIME	CAPTAIN	FIRST OFFICER	FLIGHT ENGINEER	COCKPIT AREA MICROPHONE	VHF, INTERPHONE, PA	OBSERVATIONS
22 min 50 s				Did you have time to do the certificates, Christian			
22 min 53 s		partially					
22 min 54 s		Two thirds					
22 min 55 s		I … each time that I have some spare time I do some I have some now I'll go on					
22 min 59 s		I'm not far from the end I think		yes, I'll leave it to you			
14 h 23 min 00 s				I'll leave it to you			
23 min 01 s		But anyway I'll only pass over when we've passed the sound barrier eh because					
23 min 07 s		(…)		(*)			
23 min 10 s à 23 min 32 s		(…)					

CVR UTC	FDR TIME	CAPTAIN	FIRST OFFICER	FLIGHT ENGINEER	COCKPIT AREA MICROPHONE	VHF, INTERPHONE, PA	OBSERVATIONS
23 min 34 s			pardon				
23 min 35 s		I'm bothering you					
23 min 36 s			no no (*)				
23 min 41 s				so			
23 min 42 s				I just have the cargo open			
23 min 46 s			They're closing it				
14 h 24 min 02 s				To tell you the truth we have corrected the CG to fifty-two three instead of fifty-two two			
24 min 06 s			fine				
24 min 07 s		He made a mistake in the CG					
24 min 10 s			Unless it isn't him				Jokey tone
24 min 12 s		(*)					
24 min 31 s						Ground: Ground station are you receiving	
24 min 35 s		➔ yes					

CVR UTC	FDR TIME	CAPTAIN	FIRST OFFICER	FLIGHT ENGINEER	COCKPIT AREA MICROPHONE	VHF, INTERPHONE, PA	OBSERVATIONS
24 min 37 s						Ground: Well we've just locked the rear hold loading door the handle is in its recess	
24 min 44 s		🡻 Well great so err if I understand the aircraft is clear there					
24 min 49 s						Ground: the aircraft cleared we're ready for start-up	
24 min 52 s			Go ahead pull				
24 min 55 s		🡻 Fine so we'll start in normal sequence and then we will be pulled back err forwards so we'll start up the three first so otherwise the chocks … nose gear are in position eh					
14 h 25 min 04 s						Ground: the nose gear chocks are not in position	

CVR UTC	FDR TIME	CAPTAIN	FIRST OFFICER	FLIGHT ENGINEER	COCKPIT AREA MICROPHONE	VHF, INTERPHONE, PA	OBSERVATIONS
25 min 08 s		➔ Okay and you confirm that all doors are checked eh					
25 min 12 s						Ground: the doors are checked yes	
25 min 13 s			Is there a tractor?				
25 min 14 s		➔ Okay so err... yes good question is there an extinguisher in the corner there?					
25 min 20 s			A tractor				
25 min 21 s		➔ A tractor I mean is it there?					
25 min 23 s 25 min 27 s			I haven't seen it no			Ground: the tractor is in position with the bar locked yes the lockpin is on the nose gear	
25 min 29 s		➔ Well err so we I'm reminding you about start-up on three					

CVR UTC	FDR TIME	CAPTAIN	FIRST OFFICER	FLIGHT ENGINEER	COCKPIT AREA MICROPHONE	VHF, INTERPHONE, PA	OBSERVATIONS
25 min 34 s				The pre-startup check-list has been done has been done		Ground: okay roger	
25 min 36 s			yes yes we’re ready				
25 min 37 s		➔ Is air pressure established?					
25 min 39 s						Ground: no not yet but it won’t be long	
25 min 41 s		➔ So call me back when air pressure is established					
25 min 45 s		➔ Ladies and gentlemen all is in order and we are starting up our engines					
25 min 51 s						Ground: air pressure established	
25 min 54 s		➔ Perfect start up three					
25 min 57 s				The three			

CVR UTC	FDR TIME	CAPTAIN	FIRST OFFICER	FLIGHT ENGINEER	COCKPIT AREA MICROPHONE	VHF, INTERPHONE, PA	OBSERVATIONS
25 min 58 s			(...)	Held			Song
14 h 26 min 00 s				Open			
26 min 01 s				start pump			
26 min 06 s		I'm passing over the lever Jean					
26 min 07 s			top				
		ten for one hundred					
26 min 08 s		top					
26 min 11 s			ignition				
26 min 12 s		ignition					
26 min 14 s		N1					
26 min 25 s		Twenty-five percent					
26 min 27 s				returned			
26 min 28 s				closed			
26 min 29 s		Closed okay					
26 min 30 s			Shall I take the lever?				

CVR UTC	FDR TIME	CAPTAIN	FIRST OFFICER	FLIGHT ENGINEER	COCKPIT AREA MICROPHONE	VHF, INTERPHONE, PA	OBSERVATIONS
26 min 32 s		If you like okay thanks fine					
26 min 35 s		stabilised debow					
26 min 37 s		Normal on three					
26 min 38 s				normal			
26 min 39 s		Released at sixty-seven					
26 min 53 s		Two hundred and ninety it's dropping					
26 min 58 s		Okay rotating stall		(*)			
14 h 27 min 01 s				Ready hydraulics			
27 min 02 s			Held	Ready hydraulics?			
27 min 03 s				hydraulics			
27 min 05 s			➔ Concorde four five nine zero good evening on Echo twenty-six we will be ready to pull in two minutes				
27 min 14 s		➔ Ready for two?					

CVR UTC	FDR TIME	CAPTAIN	FIRST OFFICER	FLIGHT ENGINEER	COCKPIT AREA MICROPHONE	VHF, INTERPHONE, PA	OBSERVATIONS
27 min 15 s 27 min 21 s 27 min 23 s				 Two		Ctl: Air France Four five nine zero good day err you're pushing back facing the west well are you ready to push back?	Ground: no no not for the moment Ground: okay ready for two
27 min 25 s 27 min 26 s 27 min 27 s 27 min 28 s 27 min 29 s		➔ okay start up two N2	➔ yeh in two minutes or err no not pushed back but pulled facing west	 Held open start pump			
27 min 31 s						Ctl: To be pulled back facing west so you get pulled back facing west and call back to taxi	
27 min 35 s		ten percent					
27 min 36 s		fuel	➔ roger				
27 min 37 s		top					
27 min 41 s		N1					
27 min 42 s		And ignition					

CVR UTC	FDR TIME	CAPTAIN	FIRST OFFICER	FLIGHT ENGINEER	COCKPIT AREA MICROPHONE	VHF, INTERPHONE, PA	OBSERVATIONS
27 min 48 s					cabin gong		
27 min 53 s		Twenty-five percent					
27 min 55 s				returned			
27 min 56 s				closed			
27 min 57 s		closed					
14 h 28 min 02 s		stabilised debow normal on two					
28 min 05 s				normal			
28 min 21 s					Noise		Increase in engine RPM
28 min 22 s		Two sixty-eight					
28 min 25 s		falling and rotating stall					
28 min 28 s		➔ Fine two is running so we can disconnect the units and call me back when the aircraft is away		We can disconnect the units			
28 min 35 s						Ground: okay roger	

CVR UTC	FDR TIME	CAPTAIN	FIRST OFFICER	FLIGHT ENGINEER	COCKPIT AREA MICROPHONE	VHF, INTERPHONE, PA	OBSERVATIONS
28 min 40 s			We are cleared to pull				
14 h 29 min 11 s					Noise		Similar to seat movement
29 min 15 s					Noise		Similar to seat movement
29 min 45 s						Ground: Ground station	
29 min 47 s			They're calling us				
29 min 49 s		➔ yes?					
29 min 50 s						Ground: So for the departure direction we haven't got much choice it's going to be westwards	
29 min 53 s		(...)					Laughter
29 min 54 s			no you say east				In a jokey manner
29 min 56 s		➔ yes that yes in fact I think that I don't see any other solution err … I don't see any other solution yes					

CVR UTC	FDR TIME	CAPTAIN	FIRST OFFICER	FLIGHT ENGINEER	COCKPIT AREA MICROPHONE	VHF, INTERPHONE, PA	OBSERVATIONS
14 h 30 min 02 s						Ground: okay aircraft cleared ready to taxi	
30 min 05 s		➔ So we have clearance the brake is released we can go back …					
30 min 11 s		➔ And we can put a block on … sorry we can go on yes a block on thirty one	Go on go on				
30 min 13 s						Ground: thirty one okay roger	
30 min 30 s			(the barrier didn't see)				
30 min 54 s					Cabin gong		
14 h 31 min 27 s						Ground: you can start the other engines	
31 min 31 s		➔ okay so ready for four?					
31 min 33 s						Ground: ready all four	
31 min 35 s		➔ start-up four					

CVR UTC	FDR TIME	CAPTAIN	FIRST OFFICER	FLIGHT ENGINEER	COCKPIT AREA MICROPHONE	VHF, INTERPHONE, PA	OBSERVATIONS
31 min 36 s				held			
31 min 39 s				open			
31 min 40 s		N2					
31 min 41 s				start pump			
31 min 48 s		ten percent					
31 min 49 s		fuel					
31 min 50 s		top					
31 min 51 s		N1					
31 min 54 s		ignition					
14 h 32 min 04 s		Twenty-five percent					
32 min 05 s				returned			
32 min 06 s				closed			
32 min 07 s						Ground: push complete can you put on the parking brake please	
32 min 08 s		➔ Yes parking brake on can we disconnect the yoke ready for one?					

CVR UTC	FDR TIME	CAPTAIN	FIRST OFFICER	FLIGHT ENGINEER	COCKPIT AREA MICROPHONE	VHF, INTERPHONE, PA	OBSERVATIONS
32 min 11 s						Ground: ready for one	
32 min 17 s		➔ start-up one					
32 min 18 s		so stabilised debow thanks					
32 min 19 s				held			
32 min 23 s				open			
32 min 25 s				start pump			
32 min 26 s		N2					
32 min 37 s		ten percent					
32 min 38 s		fuel					
32 min 40 s		top N1					
32 min 42 s		ignition					
32 min 55 s		twenty-five percent					
32 min 57 s				returned			
32 min 58 s				closed			
32 min 59 s		Valves closed					
14 h 33 min 02 s		stabilised debow					

CVR UTC	FDR TIME	CAPTAIN	FIRST OFFICER	FLIGHT ENGINEER	COCKPIT AREA MICROPHONE	VHF, INTERPHONE, PA	OBSERVATIONS
33 min 04 s		normal on four					
33 min 05 s				normal four			
33 min 17 s		So three hundred and ten it's dropping					
33 min 22 s		and rotating stall normal on one					
33 min 25 s				normal on one			
33 min 37 s 33 min 40 s		 Three hundred and four	➔ Concorde four five nine zero we will be ready to taxi in one minute				
33 min 42 s 33 min 44 s		It's falling Rotating stall				Ctl: roger four five nine zero for taxi contact Ground one twenty one ninety seven goodbye	
33 min 47 s			➔ goodbye				

CVR UTC	FDR TIME	CAPTAIN	FIRST OFFICER	FLIGHT ENGINEER	COCKPIT AREA MICROPHONE	VHF, INTERPHONE, PA	OBSERVATIONS
33 min 48 s		➜ fine start-up complete so err you can stop listening in and make a sign on the left showing the hydraulic pin goodbye thanks for everything have a good day					
33 min 55 s						Ground: I'll make a sign to the right	
33 min 56 s					Two gongs		
33 min 57 s		➜ make a sign to the right okay goodbye					
33 min 59 s					Gong		
14 h 34 min 00 s						Ground: goodbye	
34 min 01 s		T C U test			Gong		
34 min 03 s				yes	Gong		
34 min 05 s					Gong		
34 min 08 s				they've changed	Gong		
34 min 10 s			yes				

CVR UTC	FDR TIME	CAPTAIN	FIRST OFFICER	FLIGHT ENGINEER	COCKPIT AREA MICROPHONE	VHF, INTERPHONE, PA	OBSERVATIONS
34 min 17 s					Gong		
34 min 23 s				so			
34 min 24 s				(*) departure on			
34 min 33 s			➔ Concorde four five nine zero to taxi next to five south we are				
34 min 38 s 34 min 39 s			 stab feel and trim (*)			Ctl: Air France four five nine zero good day taxi to holding point twenty-six right via Romeo	
34 min 44 s			➔ via Romeo twenty-six right				
34 min 45 s		post start-up check-list					
34 min 46 s			stab feel and trim is engaged				
34 min 48 s		engaged					
34 min 49 s			flight controls I've checked				
34 min 50 s		clear on the right	clear on the right it's clear				

CVR UTC	FDR TIME	CAPTAIN	FIRST OFFICER	FLIGHT ENGINEER	COCKPIT AREA MICROPHONE	VHF, INTERPHONE, PA	OBSERVATIONS
34 min 51 s			he's indicating you can taxi to Romeo it's the… it's the				
34 min 55 s		first left					
34 min 56 s			first left				
14 h 35 min 03 s			T C U				
35 min 04 s		tested					
35 min 05 s				Tested			
35 min 06 s			engine de-icing				
35 min 07 s				off			
35 min 08 s			door lights				
35 min 09 s				Lights off			
35 min 10 s			central system recalled				
35 min 12 s			ramp and spill				
35 min 13 s				They are on auto and at zero			
35 min 15 s			secondary nozzle				
35 min 17 s		(*)					Gap in the recording due to tape splice

CVR UTC	FDR TIME	CAPTAIN	FIRST OFFICER	FLIGHT ENGINEER	COCKPIT AREA MICROPHONE	VHF, INTERPHONE, PA	OBSERVATIONS
35 min 18 s			Engine idle				
35 min 20 s				low			
35 min 21 s			Feeder pumps				
35 min 22 s				All on on			
35 min 32 s						Ctl: Air France four five nine zero Do you want Whisky ten or err Romeo taxiway?	
35 min 37 s			➔ err I need all the runway eh				
35 min 38 s						Ctl: okay So you taxi for Romeo Air France four five nine zero	
35 min 41 s			➔ fine roger four five nine zero via Romeo				
35 min 46 s			feeder pumps				
35 min 48 s				All on on			
35 min 49 s			hydraulics electrics				
35 min 50 s				checked			

CVR UTC	FDR TIME	CAPTAIN	FIRST OFFICER	FLIGHT ENGINEER	COCKPIT AREA MICROPHONE	VHF, INTERPHONE, PA	OBSERVATIONS
35 min 53 s			Backup alternator				
35 min 54 s				checked			
35 min 55 s			engine overheat				
35 min 57 s				tested			
35 min 58 s			Front wheel steering apparently there isn't any				
14 h 36 min 00 s		well...					
36 min 01 s		It's working					
36 min 03 s		I'm managing to control the aircraft					
36 min 05 s			taxi turn are on "on"				
36 min 07 s			Aircraft clear signal received				
36 min 10 s		yes					
36 min 11 s			Nose droop at five				
36 min 27 s		I'll get up a bit of speed before trying the brakes					

CVR UTC	FDR TIME	CAPTAIN	FIRST OFFICER	FLIGHT ENGINEER	COCKPIT AREA MICROPHONE	VHF, INTERPHONE, PA	OBSERVATIONS
36 min 29 s			Be careful it's going fast				
36 min 31 s		I mean that...					
36 min 32 s			yes (*)				
36 min 33 s		I'll let it go eh…					
36 min 34 s			yes yes let it go on the contrary				
36 min 36 s		That's what I meant					
36 min 43 s			So we have to continue on the taxiway to get to the end eh				
36 min 47 s		Yes fine okay					
36 min 49 s			(shouldn't) take Tango Tango we don't go to the end				
36 min 53 s		Emergency brake test					
36 min 57 s			not good				
14 h 37 min 03 s		Normal braking					

CVR UTC	FDR TIME	CAPTAIN	FIRST OFFICER	FLIGHT ENGINEER	COCKPIT AREA MICROPHONE	VHF, INTERPHONE, PA	OBSERVATIONS
37 min 07 s		No pressure, no jumping, no release					
37 min 10 s		Taxiing check-list					
37 min 11 s				yes			
37 min 18 s			(*)	So the brake fan light is on on			
37 min 19 s		eh?					
37 min 20 s				auto ignition...			
37 min 21 s			(*) as long as possible				
37 min 22 s				on			
37 min 23 s				Reheat A D S drain static and ice			
37 min 25 s		Four on two low	two	(*)			
37 min 27 s				And on and total inhibit			
37 min 28 s					Gong		
37 min 29 s		P F C					

CVR UTC	FDR TIME	CAPTAIN	FIRST OFFICER	FLIGHT ENGINEER	COCKPIT AREA MICROPHONE	VHF, INTERPHONE, PA	OBSERVATIONS
37 min 32 s 37 min 38 s			Ah you've got the rudders going to green all the time I think that we'll leave it that's the second time it's done it during the tests		 Gong		
37 min 39 s			Shall I reset or not?				
37 min 43 s			I don't see which one (*)				
37 min 45 s				Reset - we'll see			
37 min 46 s			no no				
37 min 47 s				If it sounds during takeoff we touch nothing while we (start) it			
37 min 51 s			It's already done it to me twice				
37 min 54 s				twice... so the brakes			

CVR UTC	FDR TIME	CAPTAIN	FIRST OFFICER	FLIGHT ENGINEER	COCKPIT AREA MICROPHONE	VHF, INTERPHONE, PA	OBSERVATIONS
37 min 56 s		emerg tested normal no pressure no jumping no release					
14 h 38 min 00 s				the trims for fifty-four percent			
38 min 02 s		Actually zero zero for fifty-four I see two and a half checked ico flight					
38 min 08 s				Pressurisation and air conditioning checked			
38 min 14 s				Fuel transfer is under way pipe safeties			
38 min 21 s				Fine on arrival			
38 min 22 s			yes				
38 min 26 s		yes					
38 min 27 s 38 min 29 s		 off attached		Seats and harness over-pull off and anti-skid off and de-icing and takeoff briefing			

CVR UTC	FDR TIME	CAPTAIN	FIRST OFFICER	FLIGHT ENGINEER	COCKPIT AREA MICROPHONE	VHF, INTERPHONE, PA	OBSERVATIONS
38 min 33 s		re...			Gong		
38 min 34 s				Ah it's dropped again			
38 min 35 s			That's it it's dropped				
38 min 36 s				You're right let's stay in yell in green			
38 min 40 s			We're staying in green eh				
38 min 43 s		Both rudders or the upper					
38 min 44 s				yes both yes			
38 min 45 s		Both eh					
38 min 46 s		(*)	oh yes yes yes oh well you have to... they're always together aren't they?				

CVR UTC	FDR TIME	CAPTAIN	FIRST OFFICER	FLIGHT ENGINEER	COCKPIT AREA MICROPHONE	VHF, INTERPHONE, PA	OBSERVATIONS
38 min 49 s				Yes no but when you press you switch to the green system but the the … was the drop on both of them…or on just one?			
38 min 56 s			On both of course no? no?				
38 min 59 s				I don’t think no you can only have one maybe			
14 h 39 min 00 s			ah I don’t know well err...				
14 h 39 min 04 s		So the takeoff is … at maximum takeoff weight one hundred eighty tons one hundred which means four reheats with a minimum failure N2 of ninety eight					

CVR UTC	FDR TIME	CAPTAIN	FIRST OFFICER	FLIGHT ENGINEER	COCKPIT AREA MICROPHONE	VHF, INTERPHONE, PA	OBSERVATIONS
39 min 21 s 39 min 25 s		between zero and one hundred knots I stop for any aural warning the tyre flash				(Ctl) Air France four five nine zero contact the Tower on one hundred twenty decimal nine	
39 min 29 s			➔ one hundred twenty-nine four five nine zero good afternoon				
39 min 35 s		tyre flash and failure callout from you right					
39 min 38 s		between one hundred knots and V1 I ignore the gong I stop for an engine fire a tyre flash and the failure callout					
39 min 45 s				yes			
39 min 46 s		after V1 we continue on the SID we just talked about we land back on runway twenty-six right					

CVR UTC	FDR TIME	CAPTAIN	FIRST OFFICER	FLIGHT ENGINEER	COCKPIT AREA MICROPHONE	VHF, INTERPHONE, PA	OBSERVATIONS
39 min 51 s		and the quick reference handbook is ready for an overweight landing					
39 min 56 s						(Ctl) Air France four five nine zero hello	
39 min 58 s			➔ hello threshold twenty-six right four five nine zero				
14 h 40 min 01 s						(Ctl) (*) four five nine zero line up on runway twenty-six right	
40 min 04 s			➔ we line up and hold on twenty-six right four five nine zero				
40 min 07 s		Ready in the back?					
40 min 10 s			Let's go				
40 min 11 s		➔ CC prepare for takeoff					
40 min 16 s		pre-takeoff check-list					

CVR UTC	FDR TIME	CAPTAIN	FIRST OFFICER	FLIGHT ENGINEER	COCKPIT AREA MICROPHONE	VHF, INTERPHONE, PA	OBSERVATIONS
40 min 19 s		How much fuel have we used?					
40 min 23 s				We've got eight hundred kilos there			
40 min 24 s		eight hundred kilos?					
40 min 28 s		right	No difference on the second segment				
40 min 31 s		We haven't left yet, have we (*)					
40 min 35 s		Err brakes one hundred degrees					
40 min 37 s				Before takeoff Takeoff monitor			
40 min 39 s			armed				
40 min 40 s		armed					
40 min 41 s 40 min 43 s 40 min 44 s				The parameters for take... Takeoff parameters	 (CC) cabin ready		

CVR UTC	FDR TIME	CAPTAIN	FIRST OFFICER	FLIGHT ENGINEER	COCKPIT AREA MICROPHONE	VHF, INTERPHONE, PA	OBSERVATIONS
40 min 45 s		Well they're confirmed, nothing has changed					
40 min 47 s				Noise reduction parameters confirmed engine rating light on take-off			
40 min 55 s				N1 limiter four ninety eight eighty idle on high			
14 h 41 min 00 s				Central alarm system			
41 min 01 s 41 min 02 s 41 min 03 s		 recall inhibit				(Ctl) Air France four five nine zero so I will call you back as soon as it's free in front	
41 min 04 s			➔ holding position four five nine zero				
41 min 05 s				The transponder			
41 min 08 s				I'm putting it on			

CVR UTC	FDR TIME	CAPTAIN	FIRST OFFICER	FLIGHT ENGINEER	COCKPIT AREA MICROPHONE	VHF, INTERPHONE, PA	OBSERVATIONS
41 min 09 s				Brake temperatures checked one hundred fifty the CG is at fifty …. Four two			
41 min 17 s				Reheat four whites de-icing			
41 min 19 s		okay					
41 min 20 s		Is it hotter on the left or the right there?					
41 min 28 s				It's about the same you know			
41 min 30 s			What's the max ?				
41 min 32 s				There we're at one hundred fifty			
41 min 33 s			Yeah it goes up fast on this taxiway we'll have to watch out				
41 min 45 s 41 min 47 s		So um depart on the centreline to one hundred	On the centreline level one hundred				
41 min 55 s				CG fifty four			

CVR UTC	FDR TIME	CAPTAIN	FIRST OFFICER	FLIGHT ENGINEER	COCKPIT AREA MICROPHONE	VHF, INTERPHONE, PA	OBSERVATIONS
14 h 42 min 08 s				(*)			
42 min 17.0 s	97547.5					(Ctl) Air France four five nine zero runway twenty-six right wind zero ninety eight knots cleared for takeoff	
42 min 21.6 s 42 min 23.3 s	97552.1 97553.7		➪ Four five nine zero takeoff twenty-six right		Noise of selector		
42 min 24.8 s	97555.3	Is everybody ready					
42 min 25.8 s	97556.3		yes				
42 min 26 s	97556.5			yes			
42 min 26.6 s	97557.1	To one hundred V1 one hundred fifty					
42 min 28.8 s	97559.3	(*)					
42 min 30.4 s	97560.9				Noise of selector		Clicking of thrust levers
42 min 31 s	97561.5	top					
42 min 31.3 s	97561.8				Change in background noise		Increase in the airflow in the air conditioning and an increase in engine speed

CVR UTC	FDR TIME	CAPTAIN	FIRST OFFICER	FLIGHT ENGINEER	COCKPIT AREA MICROPHONE	VHF, INTERPHONE, PA	OBSERVATIONS
42 min 35.3 s	97565.8					(?) go Christian	
42 min 37.4 s	97567.9					Two transmission clicks	
42 min 43.3 s	97573.8			We have four reheats			
42 min 47.5 s	97578				Noise of selector		Movement of automatic selector on passing 60 kt
42 min 54.6 s	97585.1		one hundred knots				
42 min 55.1 s	97585.5				Noise		
42 min 55.5 s	97586	checked					
42 min 57 s	97587.5			Four greens			
14 h 43 min 03.7 s	97594.2		V 1				
43 min 10.1 s	97600.6				Noise		
43 min 11 s 43 min 11.9 s	97601.5 97602.4				Change in background noise (*)		Unintelligible noise
43 min 13 s	97603.5		watch out				

CVR UTC	FDR TIME	CAPTAIN	FIRST OFFICER	FLIGHT ENGINEER	COCKPIT AREA MICROPHONE	VHF, INTERPHONE, PA	OBSERVATIONS
43 min 13.4 s 43 min 13.8 s 43 min 16.1 s 43 min 16.4 s	97603.9 97604.3 97606.6 97606.9			(stop)	End of change in background noise Noise of selector	(Ctl) Concorde zero... four five nine zero you have flames (*) you have flames behind you	(?) (*) right SIMULTANEOUS BROADCASTS
43 min 18.8 s	97609.3		➔ roger				
43 min 20.4 s	97610.9			Failure eng… failure engine two			
43 min 21.3 s	97611.8				2 selector noises		TCU movement passing from main to alternate
43 min 22.8 s	97613.3				Bell		Fire alarm
						(?) it's really burning eh	
43 min 23.5 s	97614				Gong		
43 min 24.8 s	97615.3			Shut down engine two			
43 min 25.8 s	97616.3	Engine fire procedure					
43 min 26.2 s	97616.7				Noise of selector		Thrust lever reduction or HP shutoff
43 min 26.8 s	97617.3				End of bell		

CVR UTC	FDR TIME	CAPTAIN	FIRST OFFICER	FLIGHT ENGINEER	COCKPIT AREA MICROPHONE	VHF, INTERPHONE, PA	OBSERVATIONS
43 min 27.2 s 43 min 27.5 s 43 min 28.2 s	97617.7 97617.9 97618.7		Watch the airspeed the airspeed the airspeed		Noise of selector Gong		Automatic trim selector
43 min 28.7 s 43 min 29.3 s 43 min 30 s	97619.2 97619.8 97620.5	Gear on retract			Noise of selector	(?) it's really burning and I'm not sure it's coming from the engines	Fire handle being pulled
43 min 31.6 s 43 min 32 s 43 min 32.6 s	97622.1 97622.5 97623.1			The gear	Toilet smoke detection alarm	(Ctl) four five nine zero you have strong flames behind you	
43 min 34.5 s	97624.5					Beginning of reception of a Middle Marker	
43 min 34.7 s	97625.2		➔ yes roger				
43 min 35.5 s	97626			The gear (Jean)			
43 min 37 s	97627.5				Gong		
43 min 37.3 s 43 min 37.7 s 43 min 38.4 s	97627.8 97628.2 97628.9		no	gear	Noise Noise	(Ctl) so do as you wish you have priority for a return to the field	
43 min 39 s	97629.5	(gear) retract					

CVR UTC	FDR TIME	CAPTAIN	FIRST OFFICER	FLIGHT ENGINEER	COCKPIT AREA MICROPHONE	VHF, INTERPHONE, PA	OBSERVATIONS
43 min 41.2 s	97631.7		➔ roger				
43 min 42.3 s	97632.8				Bell		Fire alarm
43 min 43 s	97633.5				Gong		
43 min 44.7 s	97635.2				3 selector noises		Fire extinguisher fired with first shot
43 min 45.6 s	97636.1		(I'm trying)	I'm firing it			
43 min 46.3 s	97636.8	(are you) shutting down engine two there			End of toilet smoke detection alarm		
43 min 4.28 s	97638.7			I've shut it down			
43 min 49.3 s	97639.8					End of reception of Middle Marker	
43 min 49.9 s	97640.4		The airspeed				
43 min 53 s	97643.5				Noise		
43 min 54.8 s	97645.3				End of bell		
43 min 56.7 s	97647.2		The gear isn't retracting				
43 min 58.6 s	97649.1				Bell		Fire alarm
43 min 59.1 s	97649.6				(SV) whoop whoop pull up		GPWS warning
43 min 59.4 s	97649.9				Gong		

CVR UTC	FDR TIME	CAPTAIN	FIRST OFFICER	FLIGHT ENGINEER	COCKPIT AREA MICROPHONE	VHF, INTERPHONE, PA	OBSERVATIONS
14 h 44 min 00.6 s	97651.1				(SV) whoop whoop pull up		GPWS warning
44 min 00.7 s	97651.2		The airspeed				
44 min 02 s	97652.5				(VS) whoop whoop pull up		GPWS warning
44 min 03 s	97653.5					(FSL) De Gaulle tower from fire service leader	
44 min 05.2 s	97655.7					(Ctl) fire service leader err... the Concorde I don't know his intentions get into position near the southern double runway	
44 min 10.5 s	97661				Noise of selector		
44 min 12 s	97662.5	(*)					
44 min 13.2 s 44 min 14.6 s 44 min 16.5 s	97663.7 97665.1 97666.7	(too late)	Le Bourget Le Bourget			(FSL) De Gaulle tower from fire service leader authorisation to enter twenty-six right	

CVR UTC	FDR TIME	CAPTAIN	FIRST OFFICER	FLIGHT ENGINEER	COCKPIT AREA MICROPHONE	VHF, INTERPHONE, PA	OBSERVATIONS
44 min 18.1 s 44 min 19.8 s	97668.6 97670.3	 (no time no)				(Ctl) Fire service leader correction the Concorde is returning on runway zero nine in the opposite direction	
44 min 22.8 s	97673.2		➔ negative we're trying for Le Bourget				
44 min 24.7 s	97675.2				Noise of selector		
44 min 25.1 s	97675.6				Noise of selector		
44 min 25.4 s	97675.9				Noise of selector		
44 min 26.2 s	97676.7				Noise of selector		
44 min 26.4 s 44 min 26.6 s 44 min 27 s	97676.9 97677.1 97677.5		(no)		 Gong Gong and noise of selector	(FSL) De Gaulle tower from fire service leader can you give me the situation of the Concorde now	
44 min 27.5 s	97678				Noise of selector and beginning of movement of objects in cockpit		
44 min 29 s	97679.5	(*)					Noises of effort

CVR UTC	FDR TIME	CAPTAIN	FIRST OFFICER	FLIGHT ENGINEER	COCKPIT AREA MICROPHONE	VHF, INTERPHONE, PA	OBSERVATIONS
44 min 30 s	97680.5	(*)					
44 min 30.7 s	97681.2	(*)					
14 h 44 min 31.6 s	**97682.1**	**END OF RECORDING**					

ANALYSIS OF ALARMS AND NOISES RECORDED ON THE CVR

1 - ALARMS

Toilet smoke

Tests confirmed that the alarm heard at 14 h 43 min 32.6 s was in fact a toilet smoke detection alarm. This alarm can be recorded by the CVR when the cockpit door is open.

Fire alarm

The bell heard three times after 14 h 43 min 22.8 s was identified as a fire alarm. This alarm, well known to aircrew, also includes a gong.

Gongs

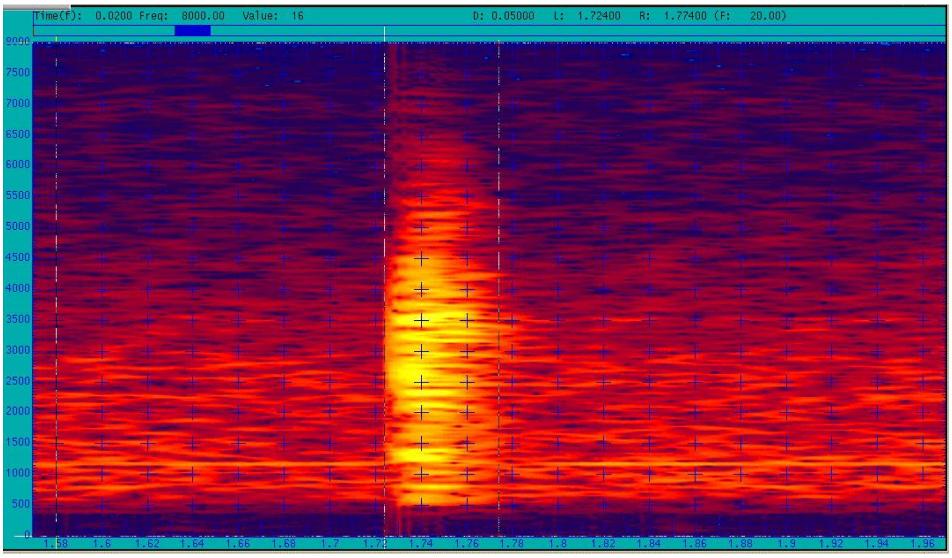
- 14 h 43 min 23.5 s: this gong, which appears 0.7 s after the first ring of the bell, is part of the aural fire alarm.
- 14 h 43 min 28.2 s: this gong corresponds to the automatic switching of the electric pitch trim actuators.
- 14 h 43 min 37 s: this gong is probably related to the engine 2 alarm following the drop in oil pressure due to engine 2 shutdown. On the FDR the engine warning parameter appears again.
- 14 h 43 min 43 s: this gong, which appears 0.7 s after the first ring of the bell, is part of the aural fire alarm.
- 14 h 43 min 59.4 s: this gong, which appears 0.7 s after the first ring of the bell, is part of the aural fire alarm.
- 14 h 44 min 26.6 s: no explanation found.
- 14 h 44 min 27 s: no explanation found.

Note: two gongs generated by two different systems but separated by less than twenty milliseconds cannot be distinguished by spectral analysis.

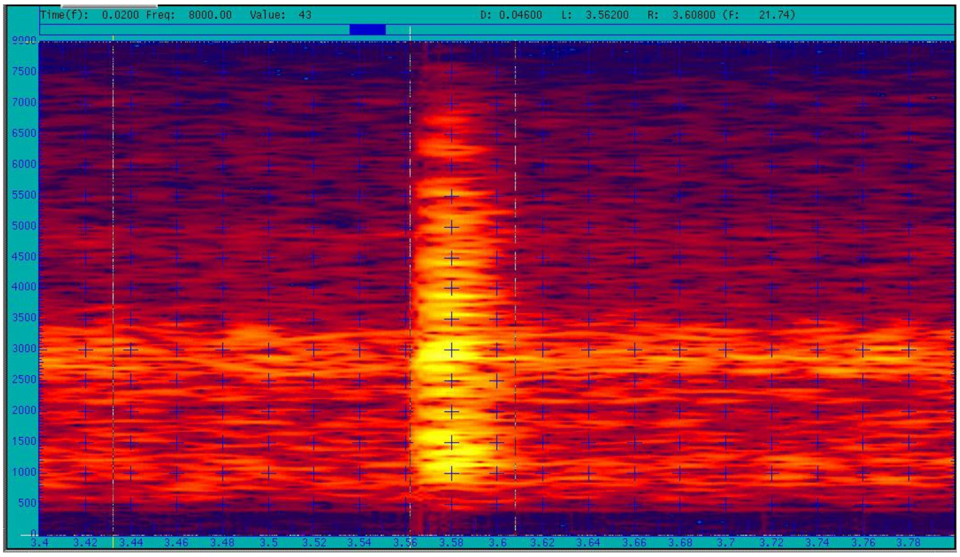
2 - NOISES

➥ Noise at 14 h 42 min 30.4 s

This noise is identified as the "clicking" of the thrust levers. The normal procedure, during power up, is to advance the levers to their stop. This interpretation is consistent with the results from the FDR. The comparison of the time-frequency representations recorded on F-BTSC and of that recorded on F-BTSD are shown hereafter.



Noise on F-BTSC



Clicking of thrust levers during power up on F-BTSD

Change in background noise at 14 h 42 min 31.3 s

After the clicking of the thrust levers, there is an increase in the noise from the air conditioning, associated with the increase in engine noise. It is not possible to determine the rotation speed of the rotating parts of the engine.

➥ Noise of selector at 14 h 42 min 47.5 s

When passing through sixty knots. The “engine 4 take off N1 limiter” changes position automatically. Synchronisation with the FDR confirms this selector movement since the aircraft was passing through sixty knots when this noise was made.

➥ Noise at 14 h 42 min 55.1 s

The origin of this noise was not identified.

➥ Noise at 14 h 43 min 10.1 s

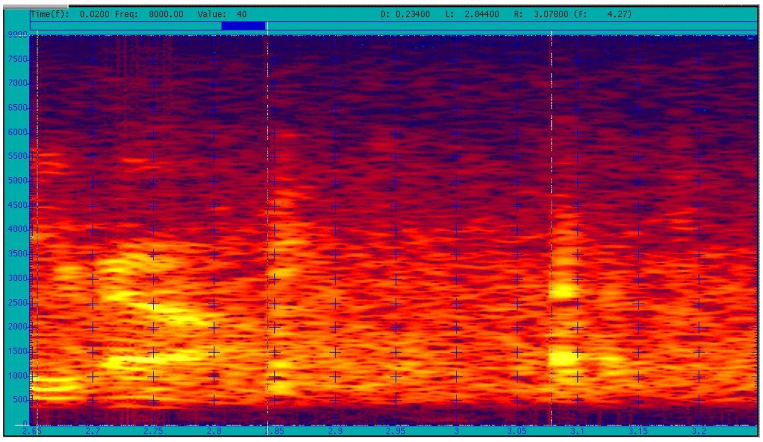
The origin of this noise was not identified. It is followed by a change in the background noise which couldn’t be interpreted either.

➥ Noise at 14 h 43 min 16.1 s

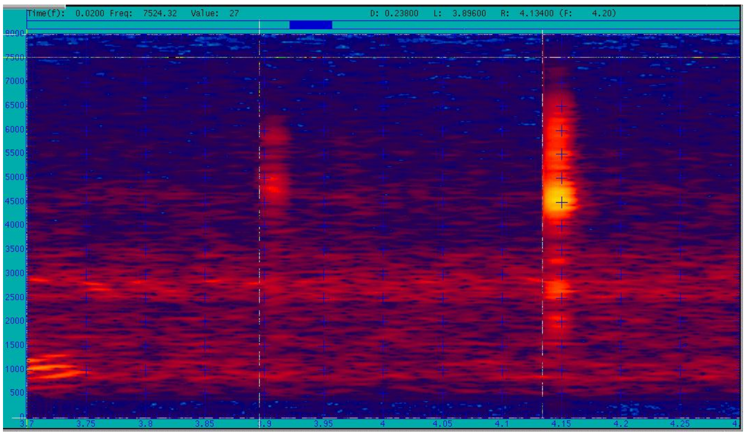
The origin of this noise was not identified.

➥ Noise of selector at 14 h 43 min 21.3 s

The rate and auditory perception, as well as application of procedures, enabled this noise to be identified as being that of the movement of the TCU selector from “main” to “alternate”. The time-frequency analyses of the noise on F-BTSC and on F-BTSD are shown hereafter.



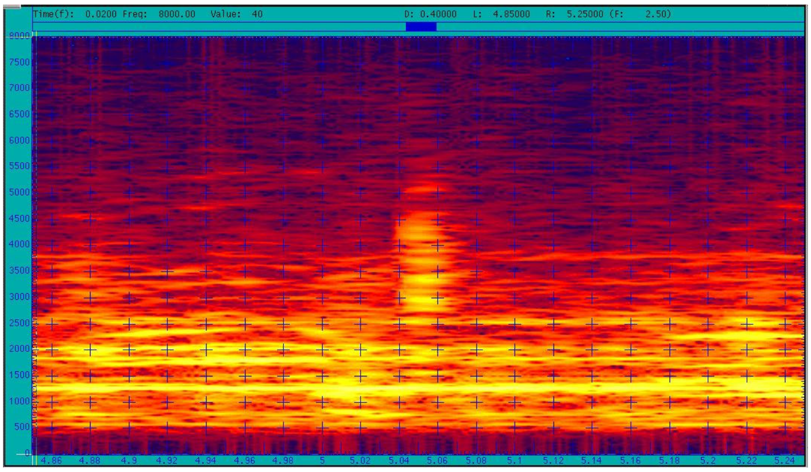
Noise of selector on F-BTSC (234 ms)



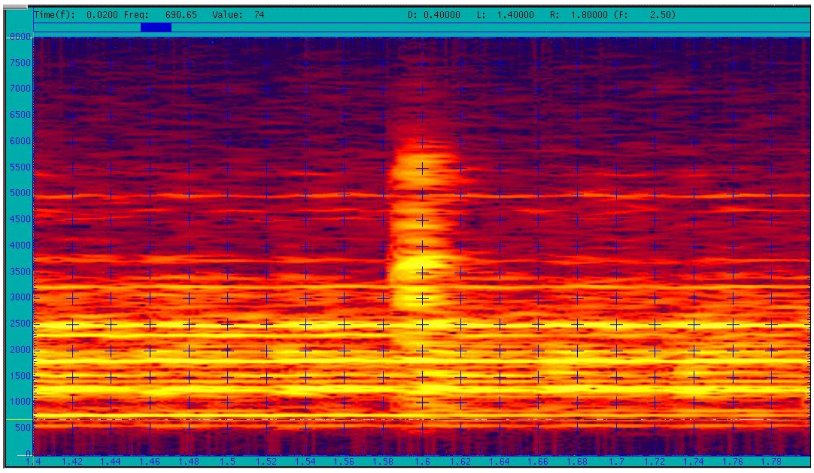
Noise of selector on F-BTSD (238 ms)

➥ Noise of selector at 14 h 43 min 26.2 s

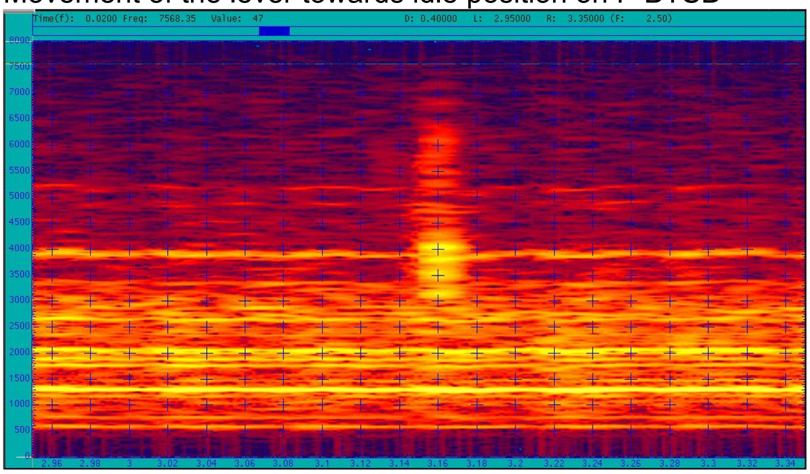
On the FDR a decrease in engine speed is noted after this selector noise. There were four hypotheses to explain this decrease in speed. The first was independent of crew action in the cockpit, the three others were respectively an action on the thrust lever, a cut through movement of the HP fuel cock or a de-selection of auto-thrust. The spectral representation is very close to that of a thrust lever reduction or a HP fuel cock shutoff, though it is impossible to distinguish between them. The time-frequency analyses of the noise on F-BTSC and on F-BTSD are shown hereafter.



Noise of selector on F-BTSC



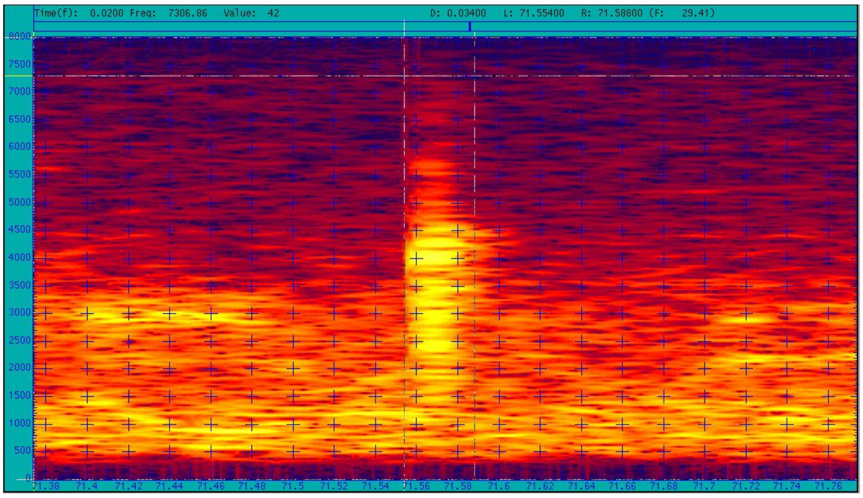
Movement of the lever towards idle position on F-BTSD



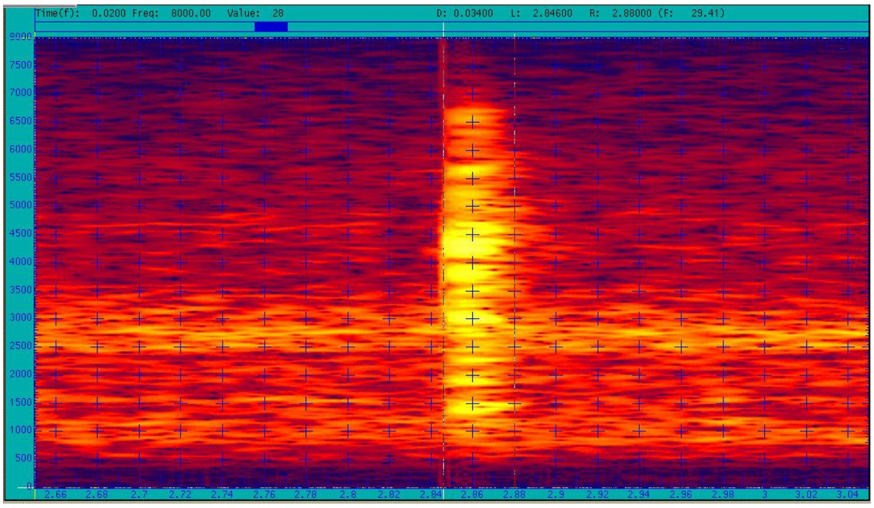
HP fuel cock shutoff on F-BTSD

- Noise of selector at 14 h 43 min 27.5 s

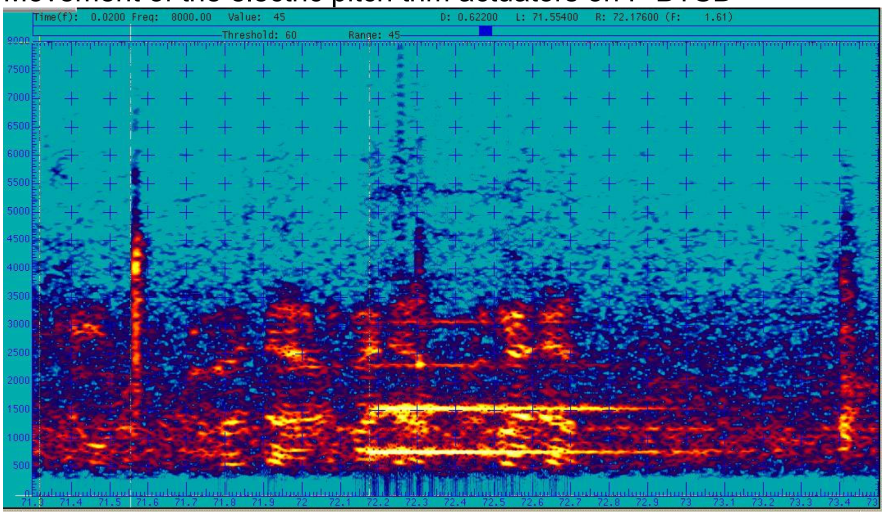
  Several elements enabled identification of the electric pitch trim actuators: energy peaks at approximately frequencies, the duration of the signal and the time between the selector noise and the appearance of the gong 0.7 to 0.8 s later. The time-frequency analyses of the noise on F-BTSC and on F-BTSD are shown hereafter.



Noise on F-BTSC



Movement of the electric pitch trim actuators on F-BTSD



Distance between the selector noise and the appearance of the sound of the gong

➥ Noise of selector at 14 h 43 min 29.3 s

The spectral representation closest to this noise corresponds to pulling the fire handle. The noise at 14 h 43 min 44.7 s confirms this action.

➥ Noise at 14 h 43 min 37.3 s

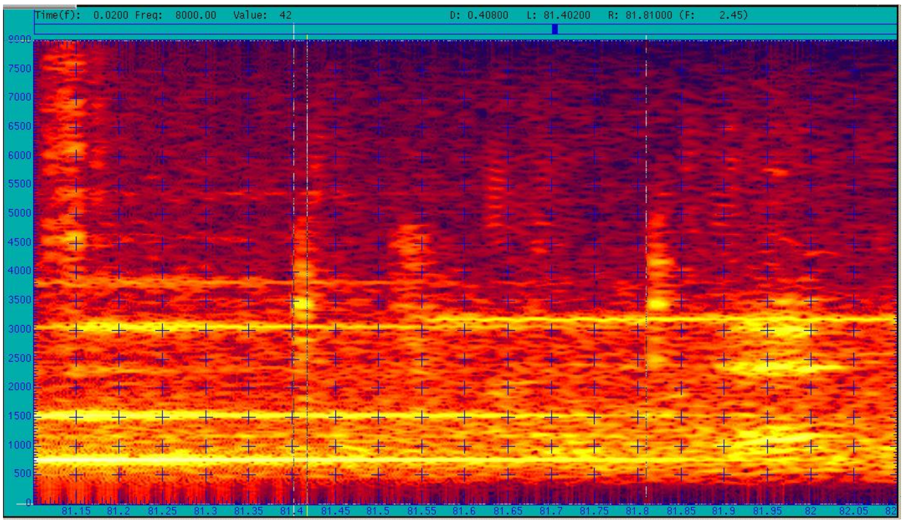
The origin of this noise was not identified.

➥ Noise at 14 h 43 min 38.4 s

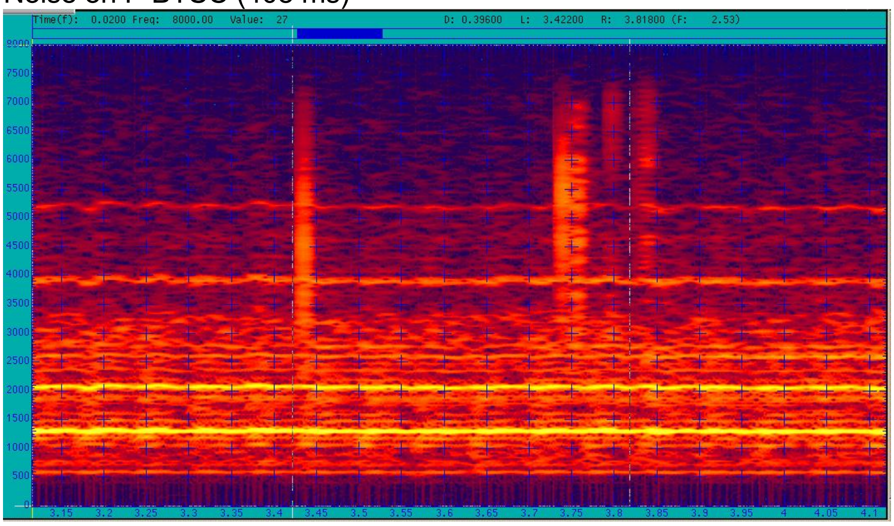
The origin of this noise was not identified.

➥ Noise of selector at 14 h 43 min 44.7 s

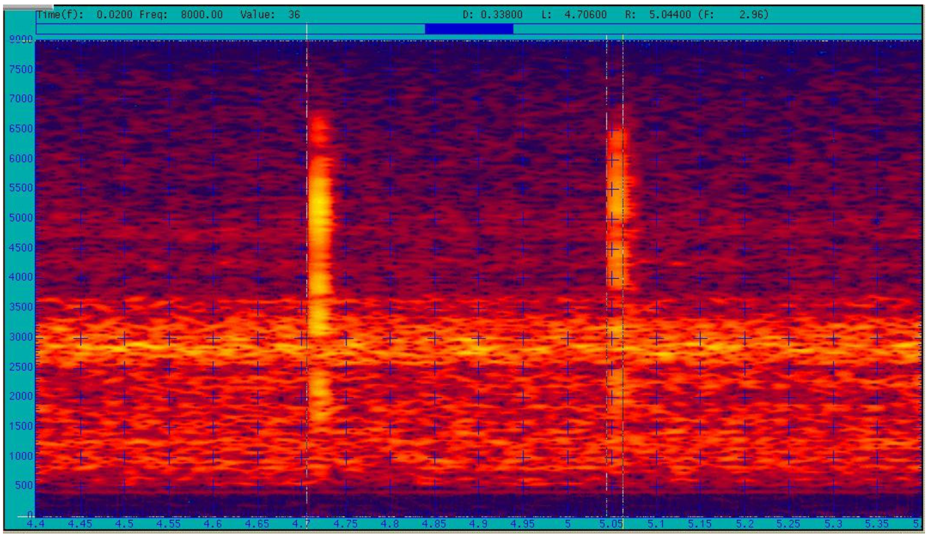
This noise is similar to activation of the “first shot” pushbutton which corresponds to the firing of the extinguishers in the engines. This action can only be taken if the fire handle has been pulled. The rate between the two energy peaks which make up this noise is characteristic of action on this button or, more exactly, of the destruction of the glass which covers this button. In the three time-frequency analyses that are shown hereafter, this time is between 0.35 and 0.4 s.



Noise on F-BTSC (408 ms)



First shot activated on F-BTSD with fire alarm (396 ms)



First shot activated on F-BTSD without fire alarm (338 ms)

➥ Noise at 14 h 43 min 53.0 s

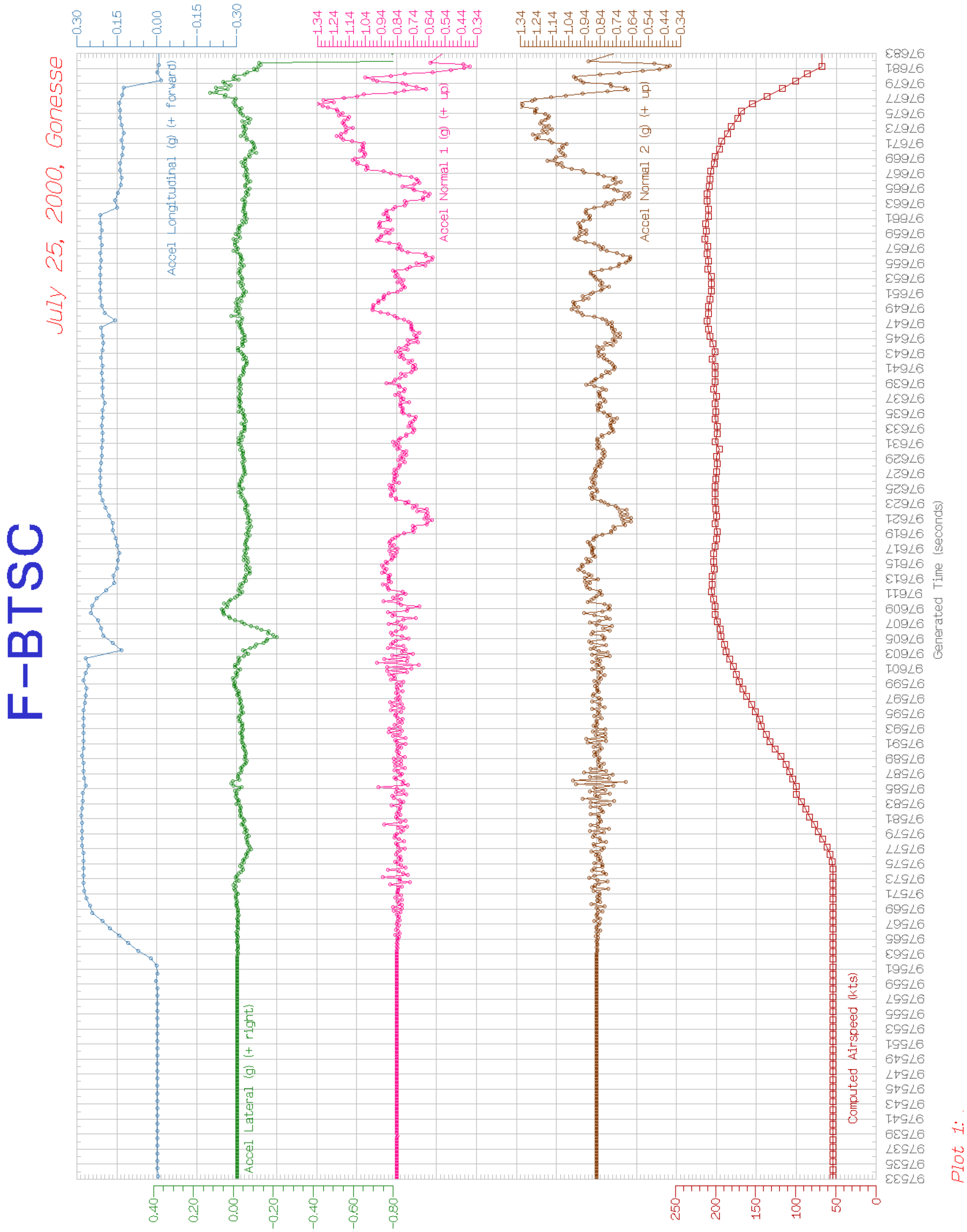
The origin of this noise was not identified.

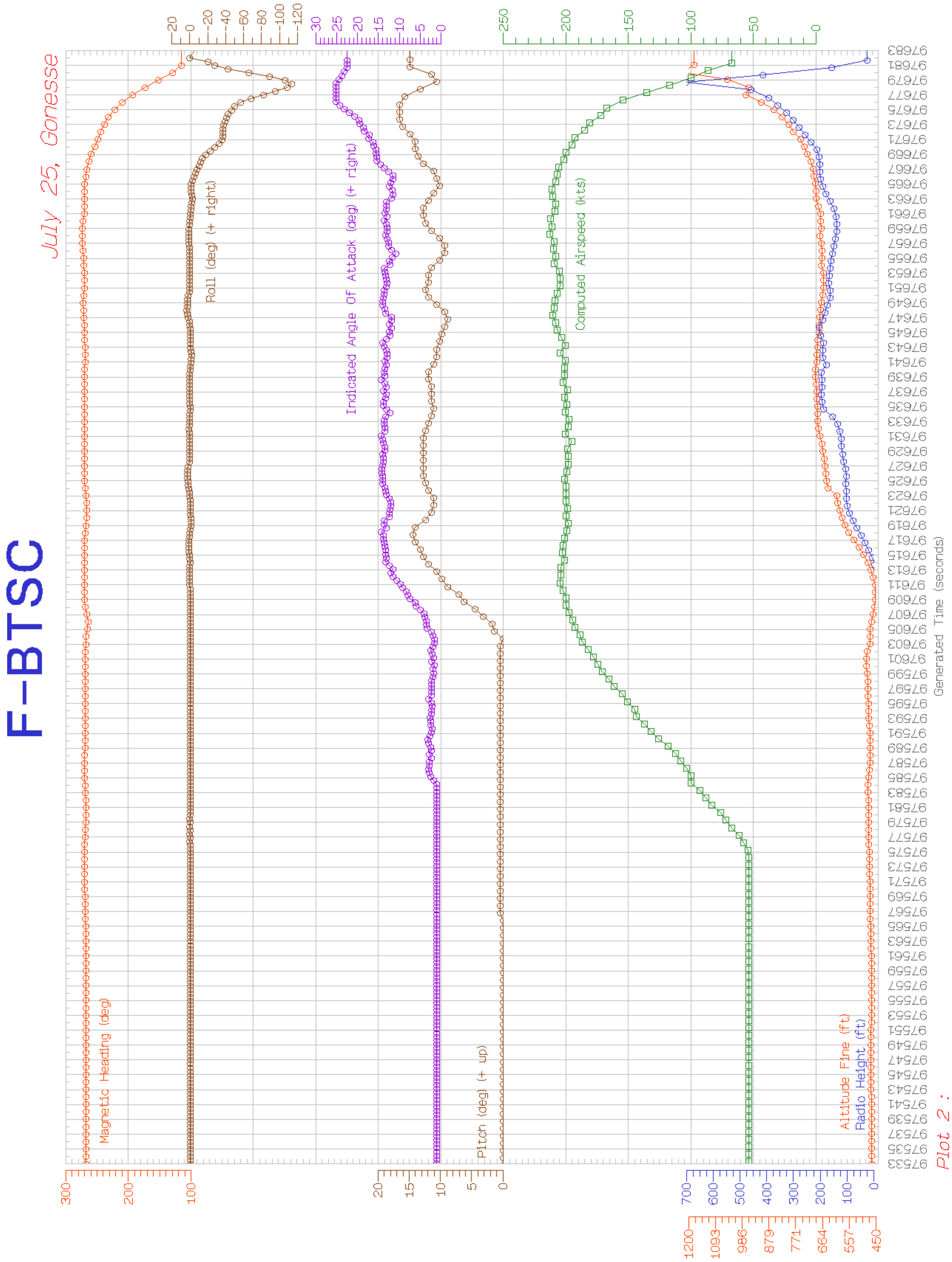
➥ Noise at 14 h 44 min 10.5 s

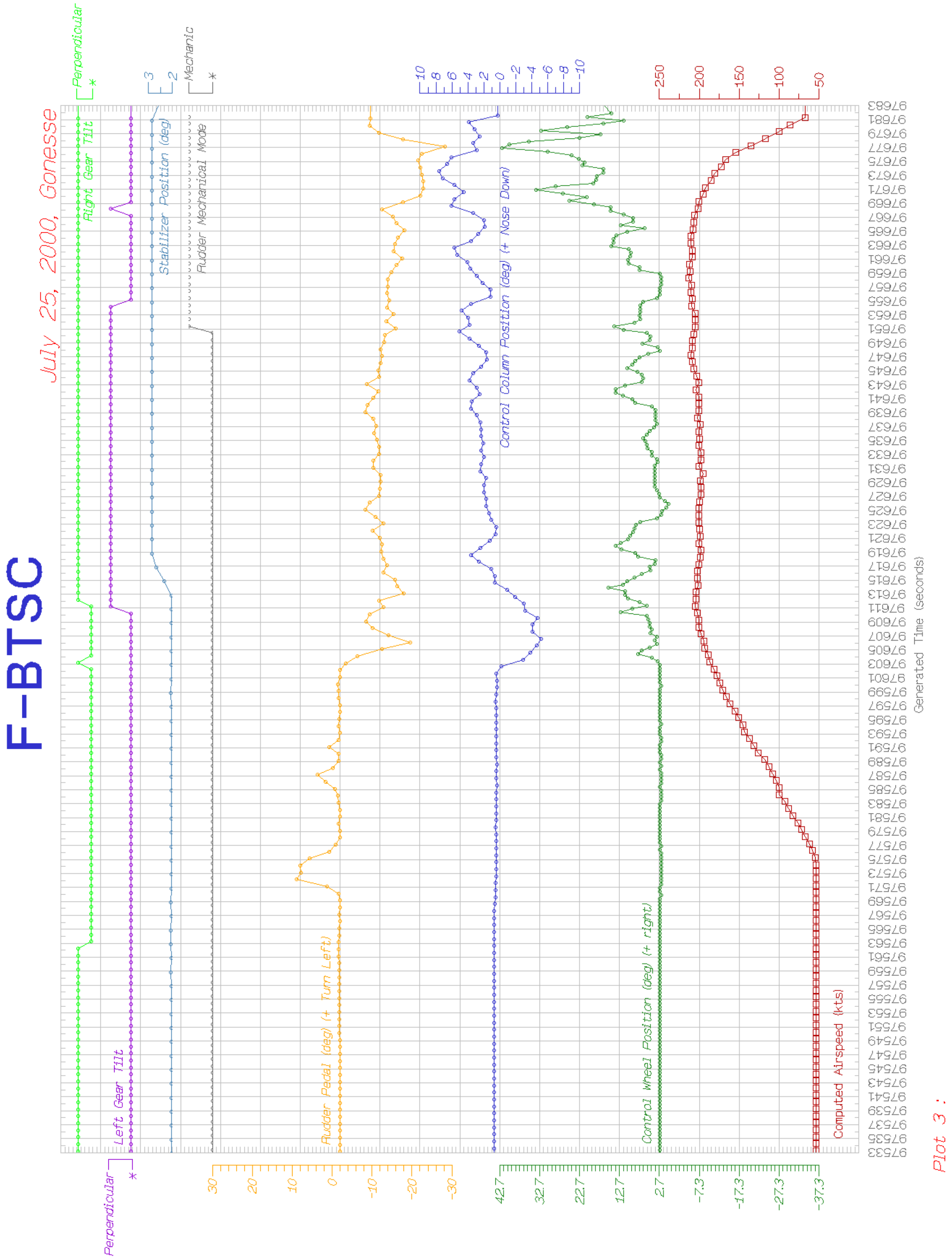
The origin of this noise was not identified.

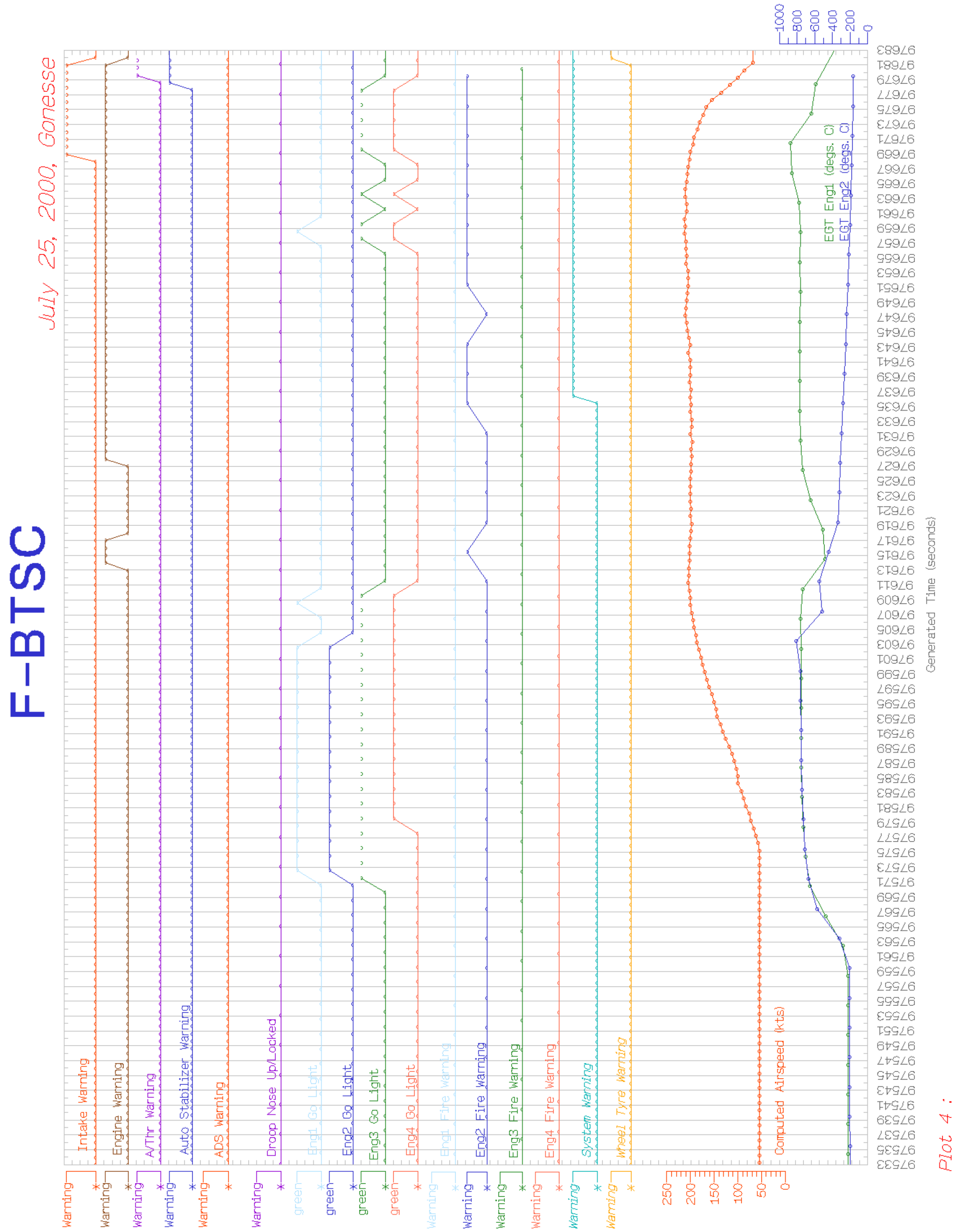
➥ Noises of selectors between 14 h 44 min 24 s and 14 h 44 min 27.5 s

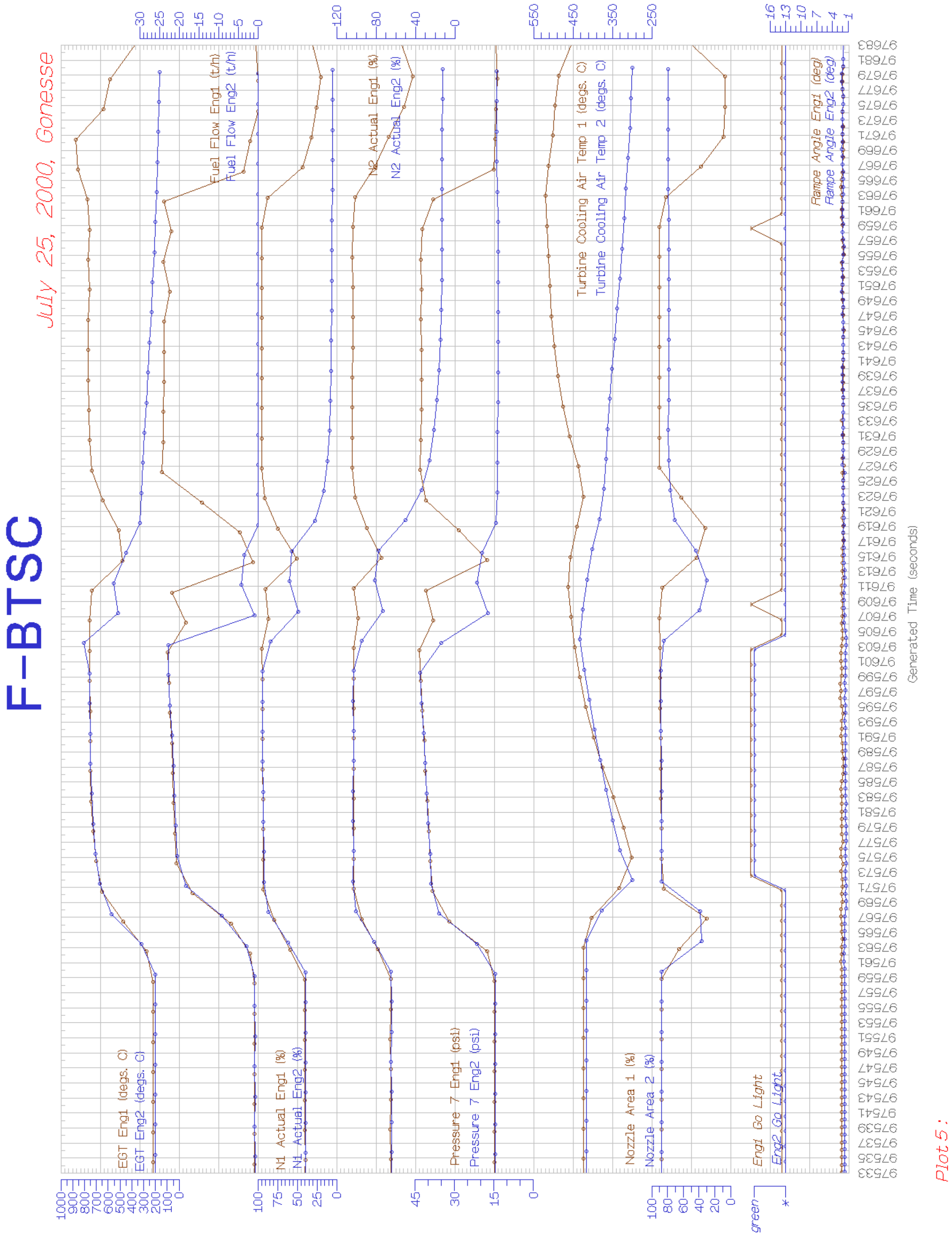
Six selector movement noises are perceptible. None could be identified. However, two or three appear to be movements of engine thrust levers or HP fuel cock cut-offs.

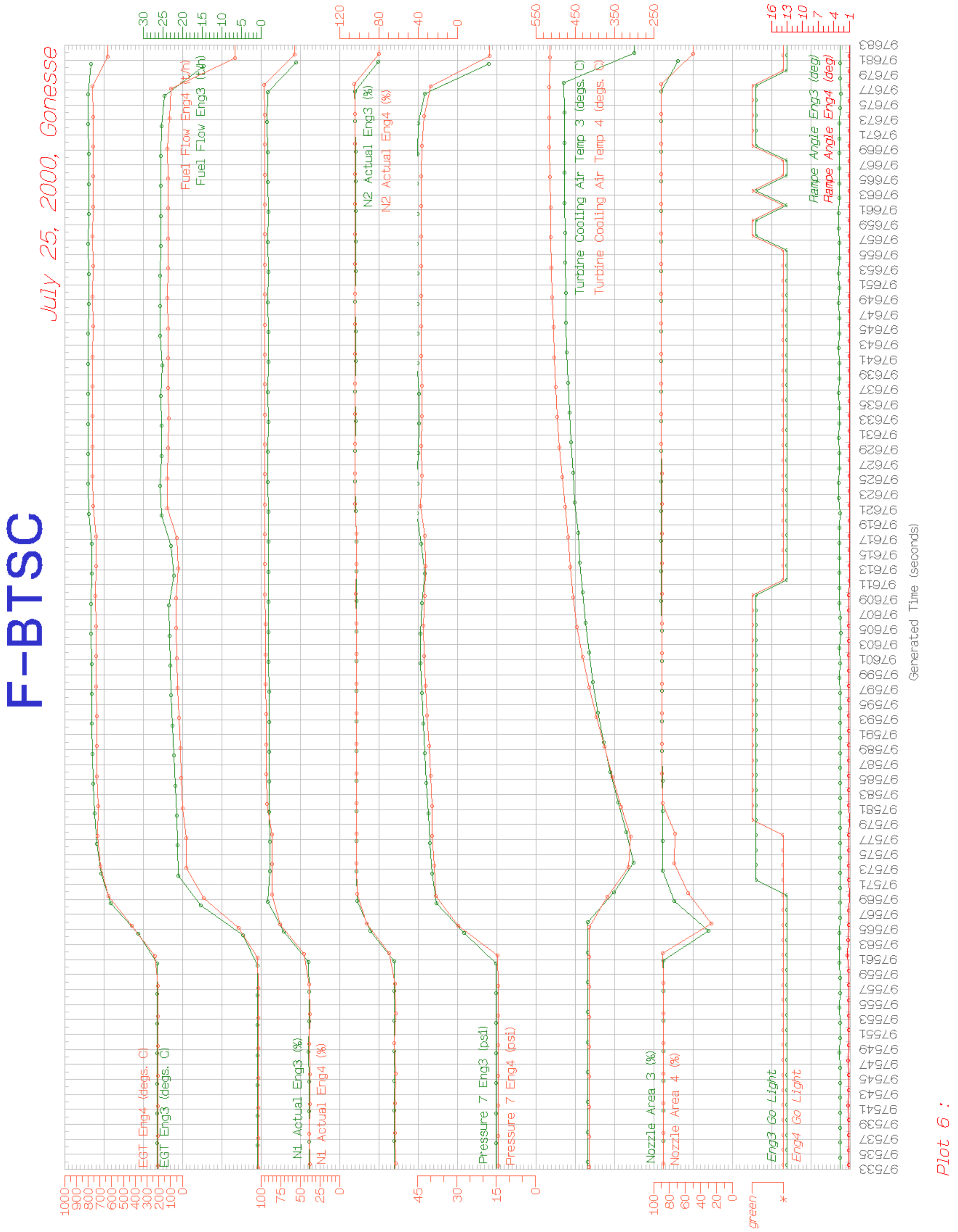

F-BTSC
July 25, 2000, Gonesse
Accel Longitudinal (g) (+ forward)
Accel Lateral (g) (+ right)
Accel Normal 1 (g) (+ up)
Accel Normal 2 (g) (+ up)
Computed Airspeed (kts)
Generated Time (seconds)
Plot 1:


F-BTSC
July 25, Gonesse
Plot 2 :
Magnetic Heading (deg)
Roll (deg) (+ right)
Indicated Angle Of Attack (deg) (+ right)
Pitch (deg) (+ up)
Computed Airspeed (kts)
Altitude Fine (ft)
Radio Height (ft)
Generated Time (seconds)


F-BTSC
July 25, 2000, Gonesse
Plot 3 :
Right Gear Tilt
Left Gear Tilt
Perpendicular
Stabilizer Position (deg)
Rudder Mechanical Mode
Mechanic
Rudder Pedal (deg) (+ Turn Left)
Control Column Position (deg) (+ Nose Down)
Control Wheel Position (deg) (+ right)
Computed Airspeed (kts)
Generated Time (seconds)


F-BTSC
July 25, 2000, Gonesse
Plot 4 :
Intake Warning
Engine Warning
A/Thr Warning
Auto Stabilizer Warning
ADS Warning
Droop Nose Up/Locked
Eng1 Go Light
Eng2 Go Light
Eng3 Go Light
Eng4 Go Light
Eng1 Fire Warning
Eng2 Fire Warning
Eng3 Fire Warning
Eng4 Fire Warning
System Warning
Wheel Tyre Warning
Computed Airspeed (kts)
EGT Eng1 (degs. C)
EGT Eng2 (degs. C)
Generated Time (seconds)


F-BTSC
July 25, 2000, Gonesse
EGT Eng1 (degs. C)
EGT Eng2 (degs. C)
Fuel Flow Eng1 (t/h)
Fuel Flow Eng2 (t/h)
N1 Actual Eng1 (%)
N1 Actual Eng2 (%)
N2 Actual Eng1 (%)
N2 Actual Eng2 (%)
Pressure 7 Eng1 (psi)
Pressure 7 Eng2 (psi)
Turbine Cooling Air Temp 1 (degs. C)
Turbine Cooling Air Temp 2 (degs. C)
Nozzle Area 1 (%)
Nozzle Area 2 (%)
Eng1 Go Light
Eng2 Go Light
Rampe Angle Eng1 (deg)
Rampe Angle Eng2 (deg)
Generated Time (seconds)
Plot 5 :


F-BTSC
July 25, 2000, Gonesse
Plot 6 :
Generated Time (seconds)
EGT Eng4 (degs. C)
EGT Eng3 (degs. C)
Fuel Flow Eng4 (t/h)
Fuel Flow Eng3 (t/h)
N1 Actual Eng3 (%)
N1 Actual Eng4 (%)
N2 Actual Eng3 (%)
N2 Actual Eng4 (%)
Pressure 7 Eng3 (psi)
Pressure 7 Eng4 (psi)
Turbine Cooling Air Temp 3 (degs. C)
Turbine Cooling Air Temp 4 (degs. C)
Nozzle Area 3 (%)
Nozzle Area 4 (%)
Eng3 Go Light
Eng4 Go Light
Rampe Angle Eng3 (deg)
Rampe Angle Eng4 (deg)

PREVIOUS EVENTS

Year	Date	Registr.	Place	Circumstances	Event	Cause	Phase	Damage
1976	15/12/76	F-BVFB	Paris	Burst tyre 2	Burst		Taxi	No other damage
1977	22/07/77	F-BVFA	Washington	Burst tyres 1 and 2	Burst	FOD	Taxi	Deflector
1977	19/12/77			Deflation tyre 4	Deflation		Landing	Slight loss of tread
1978	02/08/78	G-BOAD		Burst tyre 2	Burst		Landing	Hydraulic leak Deflector
1978	10/12/78	F-BVFA		Burst tyre 7	Burst		Taxi	
1978	12/12/78	F-BVFA		Burst tyre 1	Burst		Taxi	
1979	04/02/79	F-BVFC	Washington	Burst tyre 2	Burst		Taxi	
1979	15/03/79	F-BVFC	Dakar	Burst tyres 5 and 6	Burst	FOD	Takeoff	Engines 1 & 2 replaced Wheel and brake damage gear locking hydraulics
1979	02/06/79	F-BVFC	New York	Loss of tread tyre 6	Loss of tread		Takeoff	Impact on wing Hydraulic servovalve fairing Damage to gear
1979	14/06/79	F-BVFC	Washington	Loss of tread tyre 6 Burst tyre 5	Loss of tread and burst	Deflation	Takeoff	Destruction of wheel, damage to left gear, hydraulic and electrical circuits, wing skin Tanks 2, 5 and 6 penetrated Engine 2
1979	21/07/79	F-BVFD	Washington	Burst tyre 6	Burst		Takeoff	Engine 2 Engine 2 air intake Traces of rubber observed on the wing just above the burst tyre
1979	23/09/79	F-BVFB	Dakar	Loss of tread tyre 3	Loss of tread		Takeoff	Engine 3 replaced Left gear damaged
1979	06/10/79	G-BOAA	London	Burst tyre 4	Burst	FOD	Takeoff	Wheels n° 7 and 8 Engines 3/4
1979	31/10/79	F-BVFD		Loss of tread tyre 7	Loss of tread	FOD	Takeoff	
1979	21/12/79	G-BOAB	London	Burst tyres 5, 6, 7, 8	Burst	Electrical failure	Landing	Engine 3 deflector
1980	05/02/80	G-BOAD	London	Burst tyre 8	Burst	Braking system jam	Landing	Green/yellow hydraulics Brakes Deflector
1980	16/07/80	F-BVFC		Burst tyre 3	Burst		Taxi	
1980	16/09/80	G-BOAF	London	Burst tyre 8	Burst		Takeoff	Engine 3 Gear door Deflector
1981	19/02/81	F-BTSD	Washington	Burst tyre 2	Burst	FOD	Takeoff	Engine 1 & 2 replaced

Year	Date	Registr.	Place	Circumstances	Event	Cause	Phase	Damage
1981	13/07/81	F-BVFF	Paris	Loss of tread tyre 5	Loss of tread	FOD	Takeoff	Engine 2 and gear
1981	09/08/81	G-BOAG	New York	Burst tyres 1 and 2	Burst		Takeoff	Impacts on wing Tank 5 penetrated Hydraulics Elevon Engines 1/2/3
1981	20/09/81	G-BOAD	New York	Burst tyre 6	Burst		Takeoff	Impacts on fuselage Engine 2 Brake servovalve damaged Deflector
1981	14/12/81	G-BOAC	London	Burst tyres 1 and 2	Burst		Takeoff	Yellow hydraulics Engines 1/2 Deflector
1981	26/12/81	G-BOAE	New York	Deflation tyre 2	Deflation		Taxi	No other damage
1982	30/04/82	G-BOAF	London	Deflation tyre 4	Deflation		Taxi	No other damage
1982	03/06/82	F-BVFB	Paris	Burst tyre 6	Burst		Landing	Hydraulics and gear
1982	04/08/82	F-BVFB		Burst tyre 4	Burst		Taxi	
1982	19/09/82	F-BTSC		Burst tyre 4	Burst		Taxi	
1983	09/05/83	F-BVFB	New York	Burst tyre 1 or 2?	Burst	FOD	Taxi	2 wheels replaced
1984	08/03/84	G-BOAC	New York	Burst tyre 2	Burst		Takeoff	Impacts on wing Engine 2 Deflector
1984	29/04/84	G-BOAE	London	Deflation tyre 8	Deflation	Wear to braking system	Landing	No other damage
1984	11/07/84	G-BOAD	London	Burst tyre 1	Burst		Landing	Brakes Deflector
1984	14/08/84	G-BOAA	London	Burst tyre 4	Burst		Taxi	Deflector
1985	20/02/85	F-BVFF	New York	Burst tyre 8	Burst	Servovalve	Landing	Wheel and gear hydraulics
1985	27/02/85	G-BOAE	New York	Loss of tread tyre 4 and 8	Loss of tread		Taxi	
1985	14/11/85	G-BOAE	London	Burst tyre 7	Burst		Landing	Hydraulic fire
1985	15/11/85	G-BOAB	London	Burst tyre 5	Burst	FOD	Takeoff	Impacts on fuselage, damage to brake door Tank 5 penetrated Engines 1 and 2 Deflector+I67
1986	18/05/86	F-BVFB	Paris	Burst tyre 5	Burst	FOD	Taxi	No other damage
1987	11/08/87	G-BOAC	New York	Burst tyres 1,2,4,5,6 and 8	Burst	Braking system	Landing	Impacts on wing Engine 3 Gear doors Deflector Brake fan
1987	10/09/87	F-BTSD	New York	Deflation tyre 8	Deflation	FOD	Takeoff	No other damage
1988	29/01/88	G-BOAF	London	Deflation tyre 3	Deflation		Takeoff	Loss of wheel bolts. Impacts on wing Tank 7 damaged

Year	Date	Registr.	Place	Circumstances	Event	Cause	Phase	Damage
1988	09/03/88	G-BOAC	London	Burst tyre 1	Burst	Braking system	Landing	Hydraulics
1988	10/04/88	F-BTSD	New York	Loss of tread tyre 7	Loss of tread	FOD	Takeoff	Brake hydraulics
1990	14/08/90	F-BVFA	Paris	Burst tyre 5	Burst	FOD	Taxi	No other damage
1992	13/02/92	G-BOAG	London	Loss of tread tyre 7	Loss of tread		Takeoff	Deflector
1992	27/03/92	F-BTSC	New York	Burst tyre 1	Burst	FOD	Takeoff	No other damage
1992	04/09/92	F-BVFF	New York	Deflation tyre 4	Deflation	FOD	Taxi	Wheel
1993	16/01/93	F-BVFF	Paris	Loss of tread tyre 7 and 8	Loss of tread	FOD	Takeoff	SV fairing, right MLG, right gear strut, actuator, Tyre mark air intake 3 Engine 3 Deflector wheel 8 Wing root fairing
1993	15/07/93	G-BOAF	London	Burst tyre 4	Burst	Braking system jam	Landing	Impacts on wing Tank 8 penetrated Green hydraulics Engine 3 Deflector
1993	28/07/93	F-BVFC	New York	Loss of tread tyre 2	Loss of tread	Servovalve	Landing	Brake 2 piping
1993	25/10/93	G-BOAB	London	Burst tyre 2	Burst	Braking system jam	Taxi	Impacts on wing Deflector Tank 1 penetrated
1995	21/07/95	G-BOAB	London	Burst tyre 2	Burst		Taxi	Hydraulic leak
1998	22/07/98	F-BVFF	Paris	Burst tyre 8	Burst	Servovalve	Taxi	No other damage
1998	28/08/98	G-BOAE	New York	Deflation tyre 3	Deflation	FOD	Taxi	No other damage
2000	22/01/00	F-BVFF	New York	Burst tyre 4	Burst	Servovalve	Landing	No other damage
2000	13/06/00	G-BOAF	London	Burst tyre 6	Burst		Landing	No other damage
2000	14/07/00	G-BOAB	London	Burst tyre 1	Burst	FOD	Takeoff	Deflector

Analyse de la combustion observée sous l'aile gauche du Concorde F-BTSC accidenté à Gonesse le 25 juillet 2000

Rapport final

Mai 2001

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Résumé

Cette note analyse les mécanismes d'allumage et de stabilisation de la flamme turbulente observée sous l'aile gauche du Concorde F-BTSC accidenté à Gonesse le 25 juillet 2000. Cette étude s'appuie notamment sur les faits relatés dans les rapports du Bureau-Enquêtes-Accidents (*Accident survenu le 25 juillet 2000 au lieu-dit La Patte d'Oie de Gonesse (95) au Concorde immatriculé F-BTSC exploité par Air-France*, rapport préliminaire d'août 2000 et rapport d'étape de janvier 2001), sur des informations communiquées par le BEA, sur l'interrogation de quelques témoins privilégiés de l'accident et sur les propriétés connues des flammes turbulentes.

Trois points sont essentiellement discutés ici :

- Les mécanismes de stabilisation de la flamme turbulente accrochée sous l'aile de l'avion et nettement visible sur les photographies de l'avion lors de l'accident.
- L'estimation, au vu des caractéristiques de la flamme, du débit de combustible s'échappant par la fuite du réservoir No 5.
- Les mécanismes d'inflammation du kérosène, et plus particulièrement celui qui nous semble le plus plausible : l'inflammation au contact des gaz brûlés issus de la post-combustion des moteurs puis remontée de la flamme sous l'aile le long de la nacelle.

Certaines des données numériques utilisées sont extraites des rapports du BEA, tandis que d'autres ont dû être approximées afin de compléter l'analyse. Dans ce cas, les valeurs choisies sont toujours précisées pour permettre leur analyse critique. Les résultats numériques doivent donc être considérés avec beaucoup de précautions et donnent essentiellement des ordres de grandeur. Ils permettent toutefois de conclure sur la possibilité d'observer, en cas de fuite de kérosène sous l'aile delta du Concorde, les faits suivants :

1. L'ingestion de kérosène par les prises d'air secondaires de la nacelle moteurs, principalement celle qui alimente l'échangeur du climatiseur d'air de la cabine.
2. L'inflammation de ce kérosène à l'intérieur de la nacelle, au voisinage de la tuyère primaire du moteur, soit au contact des parois chaudes, soit par mélange avec les gaz issus de la réchauffe. Cette inflammation supprime le flux froid entourant en fonctionnement normal le jet chaud issu de la réchauffe.
3. Inflammation au niveau des paupières du kérosène s'écoulant à l'extérieur de la nacelle.
4. La remontée de la flamme dans les couches limites sous l'aile et le long de la nacelle, essentiellement dans les turbulences générées par le sillage du train d'atterrissage.
5. La stabilisation d'une flamme au niveau du puits et des fûts de train qui jouent alors le rôle d'un accroche-flamme.

Quelques variantes de ce scénario sont également brièvement discutées, en particulier la cause et le rôle possible du pompage du moteur 2. Enfin, une comparaison est effectuée avec l'accident survenu à Washington le 14 juin 1979 au Concorde F-BVFC. Dans ce dernier cas, où l'avion a pu revenir malgré les dommages subis, le débit de fuite de kérosène est connu mais s'avère de 10 à 20 fois inférieur à la situation de l'accident de Gonesse, ce qui explique qu'une grande flamme ne se soit pas développée.

Sommaire

1 Stabilisation et accrochage de la flamme

Lors de l'accident du Concorde F-BTSC le 25 juillet dernier, une énorme flamme turbulente stable était accrochée sous l'aile de l'avion. Les mécanismes qui permettent l'accrochage et la stabilisation d'une telle flamme sont discutés ici en s'appuyant sur les photographies disponibles de l'événement. Cette discussion ne concerne que la situation de l'avion à ce moment là, c'est à dire depuis peu après le décollage et jusqu'au crash, sans préjuger des scénarii possibles pour expliquer l'initiation et le développement de la combustion qui seront discutés ultérieurement.

1.1 Stabilisation d'une flamme dans un écoulement

La stabilisation d'une flamme dans un écoulement n'est possible que selon certains mécanismes :

- *Propagation de la flamme vers l'amont d'un écoulement libre.* Dans le cas du Concorde, la vitesse relative de l'écoulement d'air est d'environ 100 m/s. La vitesse de propagation S_T d'une flamme turbulente parfaitement prémélangée (hypothèse permettant la meilleure propagation) peut, en première approximation, être estimée par :

$$\frac{S_T}{S_L} \approx 1 + \frac{u'}{S_L} \tag{1}$$

  où S_L est la vitesse de flamme laminaire, au maximum d'environ $S_L \approx 0.5\, m/s$ pour du kérosène parfaitement mélangé à de l'air en proportions stœchiométriques. u' mesure les fluctuations turbulentes de vitesse, dont l'ordre de grandeur est le dixième de la vitesse de l'écoulement ($u' \approx 10\, m/s$). Dans le cas le plus favorable, la vitesse de flamme turbulente S_T ne peut guère dépasser 10 m/s et ne permet pas à la flamme de soutenir un écoulement de 100 m/s.

- *Autoinflammation des réactifs.*[1] Ce mécanisme, rencontré dans le cas où l'un au moins des réactifs est chaud (plusieurs centaines de degrés Celsius) est sans objet ici car la température d'autoallumage du kérosène est de l'ordre de 240 ^oC.[2]

- *Stabilisation par point chaud ou "flamme-pilote".* Dans ce cas, les gaz frais sont continuellement allumés par une source de chaleur qui maintient ainsi la combustion. Si ce mécanisme aurait pu être évoqué dans le cas d'une flamme stabilisée accrochée au voisinage des tuyères des moteurs 1 et 2, il ne parait pas être en jeu pour la flamme stabilisée sous l'aile du Concorde.

- *Stabilisation en aval d'un obstacle.* Quand un obstacle est placé dans un écoulement, on observe le développement de turbulences avec des zones de recirculation. Dans cette configuration, l'écoulement peut localement avoir une direction opposée à celle de l'écoulement principal. Cette zone de recirculation permet l'accrochage d'une zone de combustion à travers deux mécanismes (figure 1) :

  - La recirculation génère une région de faibles vitesses. Quand ces vitesses sont de l'ordre de la vitesse de propagation d'une flamme turbulente, la flamme peut se propager en amont de l'écoulement vers l'obstacle et ainsi stabiliser la combustion.

[1] L'auto-inflammation doit être comprise ici comme un mécanisme de stabilisation de flamme où les réactifs sont continuellement allumés par un apport d'énergie provenant en général d'un des réactifs introduit chaud dans la zone de réaction. Elle ne préjuge évidemment pas du fait que la flamme ait pu être initiée par auto-inflammation avant de se stabiliser par un autre mécanisme (voir sections 3 et 4).

[2] Cette température d'autoinflammation correspond à la température à laquelle il faut porter un mélange stœchiométrique kérosène/air pour provoquer spontanément la combustion (voir Annexe A).

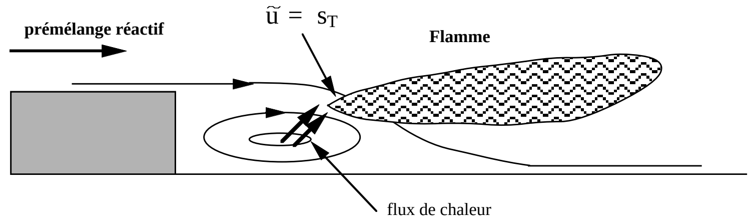


Figure 1: Stabilisation d'une flamme par une zone de recirculation.

– La zone de recirculation contient des gaz brûlés, elle agit donc comme un réservoir de gaz chauds, contribuant à l'allumage, légèrement en aval, du mélange combustible/comburant.

Ces deux mécanismes nous paraissent clairement en jeu dans l'accident de Gonesse, comme nous allons maintenant l'expliciter.

1.2 L'accident de Gonesse

Au vu des photographies de l'avion en feu (photographies Sygma, Fig. 2), de la géométrie du train principal du Concorde et de sa position sous l'aile, notamment au voisinage immédiat de la nacelle moteurs (Fig. 3 et photographies 37 et 38, § D.3), il nous parait évident que la flamme est accrochée dans le sillage des fûts du train d'atterrissage gauche, de part et d'autre du puits de logement du train et peut être même dans son voisinage. En effet, les fûts de train sont susceptibles de créer des zones de recirculation, surtout au voisinage du puits de train où ces fûts sont renforcés (environ 0.50 m de diamètre). Dans ces régions, les zones de vitesse lentes sont également favorisées par la présence de l'aile et du carénage des moteurs, générateurs de couches limites (zone de vitesse lente au voisinage des parois, Annexe D). La taille des zones de recirculation en aval d'un obstacle stabilisant une flamme peut atteindre 5 à 10 fois le diamètre de l'obstacle, c'est à dire ici jusqu'à environ 3 m.

Remarquons que des traces de stabilisation de la flamme ne sont pas nécessairement apparentes sur les fûts de train, d'une part car la flamme est stabilisée légèrement en aval, d'autre part car ils sont continuellement refroidis par l'écoulement amont. Il est, par contre, probable que si la rentrée du train avait été possible, la flamme aurait été soufflée, pour éventuellement se stabiliser plus en aval dans l'écoulement au voisinage des paupières du moteur. Ce point, spéculatif, est discuté plus en détail au paragraphe 6.4.1.

Un schéma illustrant la stabilisation de la flamme est proposé sur la figure 4.

Figure 2: Photographie de l'avion après le décollage. La flamme semble accrochée dans le sillage des fûts du train d'atterrissage gauche. Source : Agence Sygma.

Figure 3: Photographie d'un Concorde au décollage illustrant la géométrie des trains d'atterrissage. Source : http://www.airliners.net.

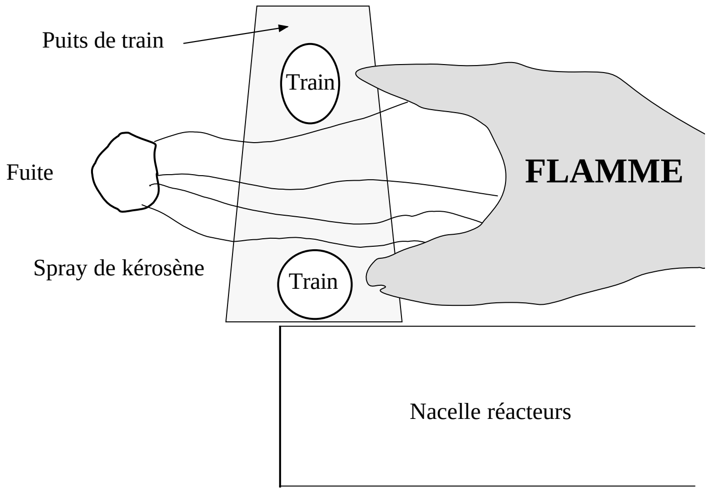


Figure 4: Schéma illustrant les mécanismes proposés pour expliquer la stabilisation d'une flamme turbulente sous l'aile du Concorde.

2 Estimation du débit de fuite du kérosène

L'objectif est ici d'estimer l'ordre de grandeur du débit de combustible nécessaire à l'alimentation de la flamme accrochée à l'avion lors de l'accident. Cette estimation ne peut être, bien sûr, que très approximative dans la mesure où un certain nombre de paramètres restent inconnus et qu'au vu de la très forte émission de suies constatée (flamme très jaune, fortes traces de suies sur la piste), la combustion du kérosène n'est clairement pas complète. L'estimation est conduite ici en utilisant plusieurs approches qui conduisent finalement à des résultats similaires. Les hypothèses faites sont à chaque fois précisées.

2.1 Modèle de Magnussen

Ce modèle est le plus simple développé pour décrire les taux de réaction pour les flammes turbulentes non-prémélangées, c'est à dire où les réactifs sont injectés séparément dans la zone de réaction. Le taux de réaction volumique du combustible est écrit :

$$\dot{m}_F = \alpha \overline{\rho} \frac{1}{\tau_t} \min \left(\widetilde{Y}_F, \frac{\widetilde{Y}_O}{s}, \beta \frac{\widetilde{Y}_P}{1+s} \right) \tag{2}$$

où α est une constante de l'ordre de l'unité, $\overline{\rho}$ la masse volumique moyenne des gaz, $\widetilde{Y}_F$, $\widetilde{Y}_O$ et $\widetilde{Y}_P$ sont respectivement les fractions massiques du combustible, de l'oxydant et des produits de combustion. β est une constante destinée à prendre en compte la nécessité de la présence de gaz brûlés pour apporter l'énergie nécessaire au maintien de la flamme. Le taux de réaction moyen est inversement proportionnel au temps caractéristique de la turbulence τ_t.

La combustion a lieu essentiellement au voisinage des valeurs stœchiométriques des fractions massiques de combustible et d'oxydant, soit environ $\widetilde{Y}_F \approx z_{st} = 0.063$ (Annexe A). Le taux de réaction maximal est donc :

$$\dot{m}_F^{max} \approx \alpha \overline{\rho} \frac{z_{st}}{\tau_t} \tag{3}$$

Le temps caractéristique de la turbulence τ_t peut être estimé à partir de $\tau_t \approx l_t/u'$ où u' correspond aux fluctuations de vitesse dues à la turbulence, considérées de l'ordre de 10 % de la vitesse de l'écoulement d'environ 100 m/s (vitesse de l'avion de 200 kt ou 360 km/h). L'échelle caractéristique l_t de l'écoulement est de l'ordre de 0.5 m à 1 m en se basant sur le diamètre du fût du train d'atterrissage ou la taille du carénage des moteurs. Pour

$$u' = 10\, m/s \quad ; \quad l_t = 0.5\, m \quad ; \quad \tau_t = 1/20\, s \quad ; \quad \alpha = 1 \quad ; \quad \overline{\rho} = 1\, kg/m^3 \tag{4}$$

Le taux de réaction maximal vaut $\dot{m}_F^{max} = 1.26\, kg/s/m^3$ (par unité de volume de flamme). Il faut maintenant estimer le volume de la flamme. Celle-ci est globalement conique, mais l'expérience montre que le taux de réaction total varie assez peu d'une section à l'autre. En effet, au fur et à mesure que la flamme se développe vers l'aval et s'agrandit, le temps caractéristique de la turbulence diminue. Le volume de flamme augmente mais correspond à un taux de réaction volumique plus faible. Si on considére une flamme de diamètre $D = 3\, m$, de longueur $L = 50\, m$ et d'épaisseur $e = 0.1\, m$, le taux de réaction total de combustible devient :

$$\boxed{\dot{m}_F^{tot} = \pi D L e \dot{m}_F^{max} \approx 60\, kg/s} \tag{5}$$

2.2 Modèle de Flamme Cohérente

Le principe de ce modèle est d'assimiler la flamme à une surface et d'écrire le taux de réaction total comme le produit de la surface de flamme S par le taux de réaction par unité de surface $\dot{\Omega}_F$:

$$\dot{m}_F^{tot} = \dot{\Omega}_F\, S \tag{6}$$

Le taux de réaction $\dot{\Omega}_F$ est estimé à partir du taux de réaction pour une flamme de diffusion laminaire plane étirée (Poinsot and Veynante 2001) :

$$\dot{\Omega}_F = \rho \frac{Y_F^0}{1 - z_{st}} \sqrt{\frac{\varepsilon_s \mathcal{D}}{2\pi}} \exp\left[- \left(\mathrm{erf}^{-1} \left(\frac{\phi - 1}{\phi + 1} \right) \right)^2 \right] \tag{7}$$

où $\mathcal{D}$ désigne le coefficient de diffusion moléculaire, qui controle l'apport des réactifs à la zone de réaction pour une flamme de diffusion et ϕ le rapport stœchiométrique du mélange kérosène/air, défini à l'annexe A (Eq. 11 ; $\phi \approx 14.8$). erf^{-1} désigne la réciproque de la fonction d'erreur exponentielle erf.[3] ε_s est le taux d'étirement des éléments de flamme, c'est à dire le gradient de vitesse dans le plan de la flamme. L'estimation de cet étirement reste un point délicat faute d'informations précises. Il peut être pris égal à l'inverse du temps caractéristique de la turbulence τ_t ($\varepsilon_s \approx 1/\tau_t \approx 20\, s^{-1}$) ou estimé à partir du gradient de vitesse induit par l'écoulement sous l'aile : $\Delta U \approx 100\, m/s$ (écart de vitesse entre l'air et le kérosène s'écoulant de la fuite) pour une taille caractéristique $l_t \approx 0.5\, m$ ($\varepsilon_s \approx \Delta U / l_t \approx 200\, s^{-1}$), soit une fourchette :

$$20\, s^{-1} \leq \varepsilon_s \leq 200\, s^{-1} \tag{8}$$

Le facteur 10 entre les extrémités de la fourchette deviendra un facteur 3 sur le taux de réaction total (racine carrée dans l'expression 7).

La surface totale d'une flamme laminaire (c'est à dire plane et non-plissée) ayant le même encombrement que la flamme observée est estimée avec les mêmes valeurs que précédemment (3 m de diamètre, 50 m de long). La surface totale de flamme turbulente sera alors donnée par :

$$S = \pi D L \Xi = 470 \Xi\, m^2 \tag{9}$$

où Ξ est le plissement de la flamme, c'est à dire le rapport de la surface réelle de flamme à la surface de flamme laminaire. Ce plissement est également difficile à estimer. Les valeurs observées dans les flammes turbulentes sont généralement de l'ordre de 5 à 10. Le tableau 1 résume les différents résultats pour le taux de réaction total $\dot{m}_F^{tot}$ selon les paramètres retenus.

La variation de $\dot{m}_F^{tot}$ est grande ($4.2 \leq \dot{m}_F^{tot} \leq 200\, kg/s$), mais en se basant sur un plissement $\Xi = 5$ ($\Xi = 1$ est nettement sous estimé car il est clair que la flamme n'a pas la forme d'un cône lisse), valeur minimale raisonnable, le taux de réaction, et le débit de fuite du kérosène, est de l'ordre de plusieurs dizaines de kilogrammes par seconde.

[3] La fonction d'erreur exponentielle est définie par :

$$\mathrm{erf}(\eta) = \frac{2}{\sqrt{\pi}} \int_0^\eta e^{-x^2}\, dx$$

Cette fonction est tabulée et figure dans les bibliothèques scientifiques des ordinateurs. Elle vérifie, en particulier :

$$\mathrm{erf}(0) = 0 \quad ; \quad \mathrm{erf}(+\infty) = 1 \quad ; \quad \mathrm{erf}(-x) = -\mathrm{erf}(x)$$

ε_s (s^{-1})	$\dot{\Omega}_F$ $(g/s/m^2)$	$\Xi = 1$	$\Xi = 5$	$\Xi = 10$	$\Xi = 15$
20	8.9	4.2 kg/s	21. kg/s	42. kg/s	63. kg/s
200	28.3	13. kg/s	66. kg/s	130. kg/s	200. kg/s

Tableau 1: Estimation du taux de réaction total $\dot{m}_F^{tot}$ selon les valeurs retenues pour l'étirement ε_s et le plissement Ξ. Le coefficient de diffusion moléculaire, identifié à celui de l'air est pris égal à $\mathcal{D} = 2.10^{-5}\, m^2/s$; $\rho \approx 1\, kg/m^3$; $Y_F^0 = 1$; $\mathrm{erf}^{-1}[(\phi - 1)/(\phi + 1)] \approx 1$.

2.3 Estimation de la fuite à partir de la capacité du réservoir n^o 5

Lors de l'accident de Gonesse, le réservoir n^o 5 contenait au départ 7.2 tonnes de kérosène. En admettant que ce réservoir n'ait servi qu'à l'alimentation de la fuite et que l'indication de la jauge après l'accident (2 tonnes) est fiable, la fuite constatée serait de l'ordre de 5 tonnes. Cette hypothèse est confortée par le fait que le réservoir "symétrique" du réservoir n^o 5, le réservoir n^o 8, semble plein au moment de l'impact à Gonesse (jauge indiquant 12.8 tonnes, correspondant à la capacité maximale du réservoir). En situant le début de la fuite au voisinage de "V1" (temps 97595), le temps total de fuite est donc de 97681 - 97595 = 86 s et correspond à une fuite moyenne de l'ordre de 60 kg/s, compatible avec les estimations ci-dessus.

Cette estimation est évidemment à prendre avec précaution dans la mesure où les réservoirs de l'avion communiquent entre eux et que des dégats structurels ont pu affecter aussi d'autres réservoirs de l'avion (réservoir 6 notamment).

2.4 Commentaire : comparaison avec l'accident de Washington

Nous retiendrons pour l'accident de Gonesse un débit de fuite de kérosène de l'ordre de $\dot{m}_F^{tot} = 50\, kg/s$. En admettant que ce kérosène se mélange avec l'air passant à travers une section de $S = 6\, m^2$ (ordre de grandeur de la section de passage de l'air sous l'aile au voisinage de la fuite) à la vitesse $V = 100\, m/s$ (vitesse de l'avion), le débit d'air disponible est d'environ $\dot{m}_O^{tot} = \rho S V \approx 600\, kg/s$. Parfaitement mélangés, ces débits correspondraient à un mélange de richesse $\Phi = s_a \dot{m}_F^{tot}/\dot{m}_O^{tot} \approx 1.2$ où $s_a = 14.8$ (car 14.8 kg d'air sont nécessaires pour brûler 1 kg de combustible dans les conditions stœchiométriques, annexe A). Cette condition de mélange combustible/comburant correspond à un mélange riche, puisqu'il contiendrait environ 20 % de combustible en sus de la stœchiométrie. Un tel mélange est parfaitement inflammable (voir Annexe A). Même si le mélange n'est pas uniforme, cette valeur de Φ laisse supposer qu'il existe suffisamment de zones comprises entre les limites d'inflammabilité pauvre et riche pour permettre la propagation d'une flamme turbulente.

En revanche, dans le cas de l'accident de Washington en 1979, le débit de fuite était de l'ordre de $\dot{m}_F^{tot} = 5\, kg/s$. Tous paramètres étant égaux par ailleurs, ce qui n'est qu'une hypothèse simplificatrice, la richesse du mélange serait dix fois plus faible ($\Phi \approx 0.1$). Une flamme ne peut se propager dans un mélange aussi pauvre qui contient dix fois moins de combustible qu'à la stœchiométrie (la richesse minimale d'inflammabilité est de l'ordre de $\Phi = 0.5$ à $\Phi = 0.6$ dans les conditions normales). Par contre, ce combustible peut localement brûler au voisinage d'une source de chaleur intense, sans pour autant permettre le développement d'une flamme. Cette estimation permettrait d'expliquer ce qui semble être une petite flamme au voisinage des réacteurs dans le cas de l'accident de Washington (voir Annexe G), sans que celle-ci puisse se développer ni en aval, ni en amont. A contrario, si cette analyse est fondée, elle valide, indirectement, l'estimation du débit de fuite de kérosène pour le cas de Gonesse. En résumé, la fuite de kérosène était probablement insuffisante à Washington pour conduire au développement d'une flamme similaire à celle observée à Gonesse.

2.5 Conclusion

Il est difficile d'estimer précisément a posteriori le débit de la fuite de kérosène, faute d'éléments précis. Néanmoins, vu la longueur de la flamme accrochée à l'arrière de l'avion et le fort dégagement de suies observé traduisant une combustion incomplète du kérosène, il est raisonnable de penser que **le débit de combustible nécessaire est de l'ordre de plusieurs dizaines de kilogrammes par seconde**, typiquement de 50 à 100 kg/s. Cette estimation semble en outre compatible avec l'estimation faite à partir du temps de vol et des indications retrouvées à Gonesse et le fait que l'accident de 1979 à Washington n'ait pas donné lieu au développement d'une flamme similaire.

Signalons que des mesures effectuées depuis par EADS avec un réservoir de Concorde ont confirmé nos estimations et semblent montrer que le débit de fuite est probablement compris entre 50 et 180 kg/s.

La combustion de 50 kg de kérosène par seconde permet de libérer une puissance de $50\,kg/s \times 42.5\,MJ \approx 2\,GW$. Une partie de cette puissance (au minimun 10 %) est dégagée au voisinage immédiat de l'avion (aile et réservoirs 2 et 6, moteurs gauches,...) qu'elle contribue à chauffer par convection et rayonnement.

Il faut prendre conscience du fait que **la fuite de kérosène est considérable dans le cas de l'accident de Gonesse**. Un débit de 50 à 100 kg/s correspond à 10 à 20 fois la consommation nominale, à pleine puissance, d'un des moteurs Olympus de l'avion (environ 5 kg/s). **Ce débit est très au delà des valeurs retenues pour les tests de certification et l'étude du développement éventuel d'une flamme** lors de l'analyse de l'accident de Washington (Rapport No 408.251/79 et son annexe 9 "Evaluation du risque incendie", SDF/B87/K/32/0040, 1979). Il avait été en particulier précisé que

- Une fuite de kérosène du réservoir 5 ne pourrait excéder 0.1 kg/s :

  "Une fuite de carburant dans le réservoir 5 ou 8 devant les entrées d'air est peu vraisemblable. On pense que les seules perforations possibles dans cette zone seraient dues à l'impact de débris de faible dimension suite à la rupture d'une roue et qu'elles ne dépasseraient pas en section de fuite celle d'un trou de diamètre ∅ 10 mm et en débit de fuite 0.1 kg/s."

  Dans ces conditions, l'inflammation est effectivement quasiment impossible. Avec les mêmes paramètres que ceux utilisés pour nos estimations, une fuite de 0.1 kg/s correspondrait à une richesse moyenne $\Phi \approx 0.002$. Pour des valeurs aussi faibles, il n'y a aucun espoir d'observer une inflammation.[4]

- Peu de données sont disponibles sur l'ingestion de kérosène par le moteur. Le rapport déjà cité précise :

  "The effect upon the engine would depend upon the quantity of fuel entering the engine and the power settings at the time. No relevant data is available at any condition, other than at idle, where it is common practice to use 1 % fuel/water insertion to wash compressors. However it can be said that at higher flows and settings there may be surge, accompagnied by loss of power and possibly some internal engine damage."

  Des tests de pompage du moteur sur ingestion de kérosène ont, semble t-il, été effectués au banc lors des procédures de certification, mais avec des débits considérablement plus faibles

[4] Remarquons que l'estimation d'un débit de fuite de 0.1 kg/s pour une perforation de 10 mm confirme indirectement nos estimations : pour une perforation de 0.30×0.30 m, comme lors de l'accident de Gonesse, une simple régle de trois donne un débit de 115 kg/s.

que celui rencontré à Gonesse. Il n'y a apparemment pas de pompage moteur lorsque celui-ci ingère moins de 0.1 kg/s de kérosène.

3 Causes possibles d'initiation et développement de la flamme

La stabilisation de la flamme dans le sillage du train d'atterrissage principal gauche, au moins après le décollage de l'avion, est une certitude au vue des photographies de l'évenement. L'ordre de grandeur du débit de fuite de kérosène, plusieurs dizaines de kilogrammes par seconde, est quasiment certain compte tenu de la taille de la flamme observée et est corroboré par plusieurs recoupements (jauge du réservoir 5, pas de flammes développée lors de l'accident de Washington, mesures effectuées par EADS...). Il s'agit maintenant de comprendre comment une telle flamme a pu s'initier et se développer.

L'analyse est ici plus spéculative dans la mesure où nous ne disposons que de peu d'informations (dispositions des éléments retrouvés sur la piste essentiellement) et de quelques témoignages, heureusement précis (voir annexe F). En effet, la plupart des témoignages, comme les photographies et le film vidéo, éléments très précieux, concerne essentiellement l'avion après son décollage alors que la flamme accrochée sous l'aile est déjà établie.

3.1 Les scénarii d'inflammation possibles

Au début de l'enquête, le "groupe feu" mis en place par le BEA et chargé d'expliquer l'inflammation de l'avion a élaboré 17 scénarii possibles. Sept scénarii, considéré comme les plus plausibles, avaient été classés, a priori, par ordre de probabilité décroissante (voir table 2).

Ces propositions invoquent plusieurs mécanismes possibles :

- **Inflammation par arc électrique** (scénarii 1, 2, et 5, le cas 4 pouvant éventuellement en faire partie). Dans cette situation, l'inflammation serait due à une étincelle électrique consécutive à la rupture mécanique d'un faisceau électrique par des débris. Dans cette hypothèse, le cas 1 (inflammation dans le puits de train) est nettement le plus favorable.

- **Inflammation par le moteur** (scénario 6). Les moteurs du Concorde, et particulièrement la post-combustion (ou réchauffe) dégagent une puissance unitaire d'environ 240 MW (voir annexe A). Les parties chaudes du moteur et/ou les gaz brûlés chauds (environ 1400 K) sont susceptibles de provoquer l'inflammation du kérosène s'échappant par la fuite. Deux exemples de cette situation, l'un accidentel, l'autre voulu, sont données à l'Annexe H.

- **Inflammation suite à pompage moteur** (scénario 3). Lors d'un pompage moteur (désamorçage du compresseur), l'écoulement dans le moteur peut s'inverser et provoquer une remontée de flamme. Un tel pompage peut être dû à l'ingestion de débris et/ou de kérosène par le moteur.

- **Inflammation par conduction thermique sur le train** (scénario 7). Ce mécanisme suppose une température suffisante des éléments du train d'atterrissage ou des roues (disque de frein, par exemple), pour provoquer l'inflammation du kérosène.

L'objectif premier de ce rapport est d'analyser la possibilité du scénario 6 où le kérosène issu de la fuite du réservoir aurait été enflammé par le moteur. Ce scénario nécessite deux étapes : inflammation du kérosène par le moteur, probablement par les gaz chauds issus du moteur et/ou les parties chaudes du moteur au voisinage des tuyères de sortie, puis remontée de la flamme vers l'amont de l'avion pour s'accrocher dans le sillage du train d'atterrissage comme semblent le montrer les photographies ultérieures de l'événement (voir § 1). La possibilité d'un tel scénario n'est pas en soit évidente compte tenu, notamment, de la vitesse des écoulements en jeu. La vitesse de l'avion est d'environ 100 m/s, soit très au delà des vitesses que peut soutenir une flamme turbulente dont l'expression (1) donne un ordre de grandeur.

Avant d'analyser plus en détail ce scénario (voir § 4), nous voudrions faire quelques commentaires sur les scénarii possibles.

3.2 Allumage par étincelle

L'inflammation par étincelle électrique est évoquée plus ou moins directement dans les scénarii 1, 2, 4 et 5 de la table 2. Cette étincelle serait due à la rupture d'un faisceau électrique par des débris de pneumatique. Des cables 115 V - 400 Hz destinés à l'alimentation des ventilateurs de frein traversent le puits de train et descendent le long de la jambe de train. Leur rupture, à notre connaissance non prouvée lors de l'accident, est évidemment susceptible de provoquer des étincelles agissant comme une bougie automobile pour enflammer le mélange air/kérosène.[5] Plausible, ce scénario est à notre sens très peu probable comme le montre la discussion de l'annexe B :

- L'allumage par étincelle d'un mélange combustible/comburant est très délicat. Il n'est possible que pour un mélange aux proportions bien définies, avec des gouttelettes de kérosène suffisamment fines. L'étincelle doit aussi avoir une taille adéquate (l'écart entre les électrodes est un paramètre important) et délivrer une énergie suffisante (voir § B.1).

- Le kérosène est, par nature, un combustible relativement difficile à enflammer. Il est, par exemple, possible d'éteindre une allumette ou une cigarette en la plongeant dans un bac de kérosène. De même, un collègue du CNRS, étudiant les feux de nappe de kérosène, a été obligé de recourir à des dispositifs d'allumage pyrotechniques. Ces difficultés d'inflammation ont d'ailleurs conduit à utiliser des injecteurs spéciaux dans les phases d'allumage des moteurs du Concorde (§ B.2 et figure 21).

- La géométrie de l'avion et de son train d'atterrissage principal, les circuits électriques et le pneu incriminé dans l'accident (roue No 2) rendent très peu probable la génération d'une étincelle dans une zone adéquate en termes de mélange air / gouttelettes de kérosène (voir § B.2).

3.3 Allumage sur pompage moteur

Un pompage moteur, provoqué par l'ingestion de débris et/ou de kérosène , outre un "bang" caractéristique, peut provoquer une remontée de flamme vers l'amont du moteur et le développement d'une flamme importante à l'aval. Ces flammes auraient donc pu enflammer le kérosène s'échappant du réservoir 5.

Nous ne sommes pas spécialistes des phénomènes de pompage mais ce scénario nous parait peu crédible en raison de la chronologie des événements :

- Le premier pompage,"pompage léger" du moteur 1, est situé aux environs du temps 97602.8, soit 1930 m après le début de la piste, dalle 178.

- Le second pompage, "pompage lourd" du moteur 2 est plus tardif : temps 97603.2, 1970 m après le début de la piste, dalle 183.

- Les traces de suies sur la piste, résidus de combustion, commencent à la dalle 168 soit 1850 m après le début de la piste.

Même compte tenu des incertitudes sur la localisation précise de l'avion, les traces de suies (et donc la combustion) commencent sensiblement avant les pompages. En outre, les témoignages font

[5] Des test de rupture de cables sont prévus au CEAT dans le cadre de l'enquête.

état d'une inflammation en deux temps : première flamme accrochée à la sortie des réacteurs puis expansion soudaine (voir annexe F). La première flamme, relativement localisée, n'a probablement pas laissé de traces de suies sur la piste et était donc allumée avant la dalle 168.

Le pompage du moteur 1 est probablement du à l'ingestion de débris[6] : relativement loin de la fuite, il est peu vraisemblable qu'il ait pu ingérer du combustible liquide et/ou des produits de combustion. Inversement, même si ce pompage a pu engendrer une remontée de flamme, il y a peu de chances que celle-ci ait pu enflammer un mélange combustible kérosène/air, produit trop loin du moteur.

Le moteur 2 aurait pu ingérer du kérosène liquide provenant de la fuite, au moins par les prises d'air secondaires.[7] Néanmoins, son pompage est trop tardif pour expliquer l'inflammation du kérosène s'échappant par la fuite du réservoir. En revanche, ce pompage aurait éventuellement pu contribuer à la remontée de la flamme vers l'amont et à son accrochage dans le sillage du train principal gauche (§ 5).

3.4 Inflammation par conduction thermique

L'inflammation sur le train ou les roues par conduction thermique est l'hypothèse retenue pour le dernier scénario classé (scénario 7 de la table 2). Ce scénario a été étudié puis rejetté lors de l'étude des possibilités d'incendie conduite après l'accident de 1979 à Washington (rapport 408.251/79, Aerospatiale/BAE). Il nous parait également peu crédible car les parties les plus chaudes (roues, disques de frein) ne sont pas dans une zone où il y a des chances de trouver un mélange kérosène/air dans des proportions combustibles (Annexe A) et sont constamment refroidies par l'écoulement d'air.

3.5 Inflammation par les moteurs (réchauffe).

Les moteurs Olympus du Concorde dégagent une puissance unitaire d'environ 240 MW (Annexe A) et constituent donc une source d'énergie suffisante pour enflammer le kérosène s'échappant par la fuite. La température des gaz brûlés issus de la post-combustion (ou réchauffe), en fonctionnement au décollage, est d'environ 1400 K (1100 °C), largement suffisante pour enflammer du kérosène. L'allumage sur les parois externes de la nacelle est, a priori, impossible car les températures de ces parois sont insuffisantes (typiquement entre 50 et 150 °C, d'après la note SDF/B87/K/32/0040). Ce scénario soulève quelques questions analysées plus loin (section 4) :

- Mise en contact du mélange kérosène/air avec des gaz chauds issus du moteur.
- Inflammation du mélange kérosène/air.
- Propagation de la flamme vers l'amont de l'avion pour s'accrocher dans le sillage du train d'atterrissage.

[6] L'ingestion de corps durs par le moteur 1 a été prouvée par les expertises (voir rapport d'étape, janvier 2001).

[7] Les expertises ont montré que le moteur 2 avait ingéré des "corps mous", ce qui inclut les morceaux de pneumatique.

Classement	Hypothèses	Points favorables	Points défavorables
1	Inflammation à l'intérieur du puits de train	- Accroche flamme - Stabilité - Temps de séjour - Mélange air / carburant - Source d'inflammation - Nébulisation - Fuite probable du réservoir 5 dans le puits de train	
2	Inflammation par arc sur les circuits électriques au niveau du train	- Vulnérabilité - Proximité du réservoir 5 - Energie électrique présente	
3	Inflammation consécutive à la flamme amont provoquée par un pompage	- Dommage aux moteurs - Deux "bang" entendus - Energie suffisante	Pas d'évidence de flammes
4	Inflammation proche de la fuite de carburant des réservoirs 5 et/ou 6	- Stabilité - Proximité - Temps de séjour	Pas d'évidence de flammes
5	Inflammation par arc sur les circuits électriques au niveau des karman	- Vulnérabilité - Présence d'énergie électrique importante	En dehors du cône de probabilité d'impact de morceau de roue
6	Inflammation par conduction thermique sur les moteurs ou par la réchauffe	- Haute température	- Propagation des flammes - Nombre de cas reportés - Témoignages
7	Inflammation sur le train ou les roues par conduction thermique	- Fragment de pneu calciné	

Tableau 2: Scénarii possibles d'évolution du feu tels qu'ils ont été identifiés et classés a priori selon une probabilité décroissante au début de l'enquête . Ce classement et les points favorables et défavorables sont ceux attribués à ce moment là par le "groupe feu" et ne correspondent pas nécessairement à nos analyses actuelles.

4 Inflammation par le jet de gaz brûlés issus de la réchauffe

L'objectif de ce paragraphe est d'analyser en détail les mécanismes qui ont probablement conduit à l'inflammation du kérosène fuyant du réservoir 5, puis à l'expansion de la flamme.

4.1 Introduction

Lors de la rupture du réservoir, une très forte quantité de kérosène a probablement été projetée sous l'aile de l'avion en direction du sol. Cette supposition est confortée par les mécanismes de rupture du réservoir (cisaillement de l'intérieur vers l'extérieur du réservoir), le fort débit moyen de la fuite (voir § 2) et la nappe de kérosène liquide retrouvée sur la piste aux dalles 163, 164 et 165 (nappe d'environ 15 m $\times$ 10 m). Le cisaillement du jet de kérosène liquide s'échappant du réservoir par un écoulement d'air externe à 100 m/s (vitesse de l'avion) a ensuite assuré la vidange du réservoir. Dans ces conditions, des paquets de liquide se désagrègent rapidement en gouttes puis en gouttelettes pour former un brouillard (spray) de kérosène, très vite bien mélangé avec l'air ambiant. Cette situation est d'ailleurs clairement visible sur les photographies prises lors de l'accident de Washington en 1979 (Annexe G). L'espace compris entre l'aile, la nacelle des moteurs et le sol était ainsi saturé d'un mélange kérosène-air, avec une quantité importante de kérosène liquide ruisselant sur les parois.

Le kérosène liquide ruisselant sous l'aile et le long de la paroi de la nacelle coté cellule et le mélange kérosène/air rencontrent les gaz brûlés issus des moteurs en aval des tuyères. Cette mise en contact est similaire à la configuration dite de la "flamme-pilote" étudiée par P. Moreau à l'ONERA (voir Annexe C) et peut provoquer l'inflammation du kérosène s'échappant du réservoir au voisinage des tuyères. Si ce mécanisme est plausible, il n'est probablement pas le plus favorable. En effet, les gaz chauds sortant de la réchauffe sont "isolés" par de l'air froid arrivant le long du moteur et destiné à favoriser la tenue des matériaux. La mise en contact gaz brûlés chauds - mélange froid kérosène/air n'est donc certainement pas optimale, surtout vu les vitesses élevées des écoulements (gaz brulés à environ 600 m/s ; mélange kérosène/air à 100 m/s). Il est toutefois vrai que l'angle des paupières (tuyères secondaires orientables) au décollage (voir figure 5) peut favoriser la mise en contact du kérosène et des gaz brûlés provenant du moteur. L'absence de paroi en aval des paupières, pour créer des zones de faibles vitesses, rend la propagation de la flamme vers l'amont très difficile voire impossible par des mécanismes de déflagration, ce qui n'exclut pas complètement les possibilités de remontée par détonation, même si ce scénario nous semble peu vraisemblable.[8]

4.2 Ingestion de kérosène par l'ensemble nacelle-moteur et inflammation

L'hypothèse la plus vraisemblable est, pour nous, l'ingestion de kérosène par l'ensemble nacelle-moteur puis son inflammation au contact des gaz sortant de la réchauffe au voisinage de la tuyère primaire. Cette ingestion peut se faire par plusieurs orifices :

[8] La propagation d'une flamme dans les conditions normales correspond à un régime dit de *déflagration* : la vitesse caractéristique de la flamme reste faible, typiquement quelques mètres par seconde pour les combustibles usuels. Dans certaines conditions, une transition vers la *détonation* peut se produire. La flamme se propage alors à vitesse supersonique et accompagne une onde de choc correspondant à un saut de pression qui peut atteindre plusieurs dizaines de bars et s'avérer extrèmement destructif (la destruction d'un immeuble par une explosion due au gaz est en fait une détonation). Peu probable, la transition vers la détonation est relativement mal connue pour les brouillards de gouttes de kérosène et dépend fortement des caractéristiques de ces brouillards. En outre, une propagation détonante aurait certainement occasionné des dommages structuraux supplémentaires à l'avion conduisant à retrouver plus d'éléments matériels sur la piste.

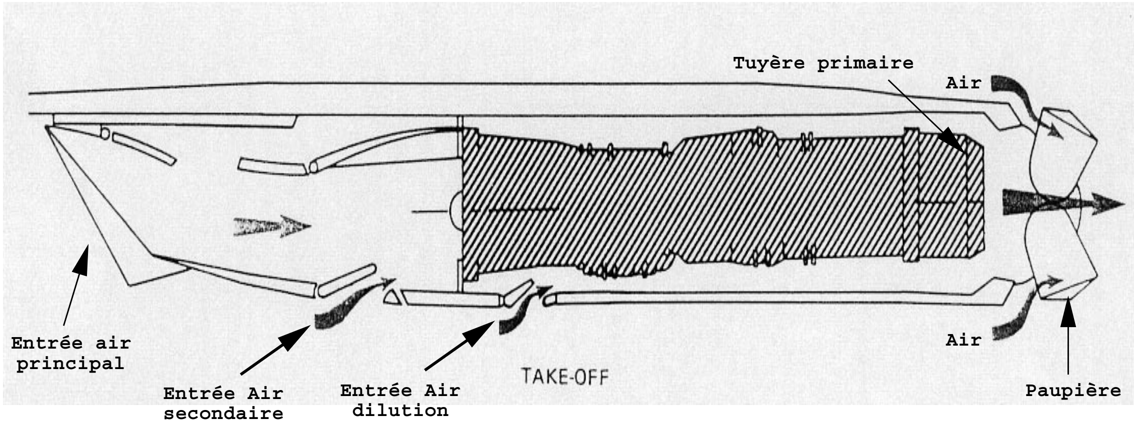


Figure 5: Implantation du moteur Olympus dans la nacelle du Concorde. Les alimentations d'air et des paupières sont ici dans la configuration au moment du décollage.

- par les prises d'air secondaire du moteur, situées sous la nacelle moteur. Ces prises d'air, schématisées sur la figure 5 sont ouvertes au décollage et clairement visibles sur la photographie de la figure 3.
- par la prise d'air de la climatisation. Cette prise d'air est située sur la nacelle moteur, côté cellule de l'avion, au voisinage du raccord avec l'aile. Elle est visible sur la photographie 40 de l'Annexe D.3.

Au décollage les entrées d'air secondaires des réacteurs, situées sous la nacelle, sont grandes ouvertes (Fig. 5). La première entrée apporte un complèment d'air au système propulsif et sert notamment à prévenir un pompage du moteur lorsque l'avion se cabre. La seconde trappe, plus en aval, assure un écoulement d'air longeant les parties chaudes de la réchauffe (refroidissement) qui débouche peu avant les paupières, le long de la tuyère primaire. Cet écoulement a une vitesse faible, de l'ordre de 20 m/s, et une température modérée comparée à celle des gaz de réchauffe, qui eux ont une température de l'ordre de 1400 K. L'écoulement provenant de cette deuxième trappe apporte un surplus d'air à la réchauffe, pour être ensuite mélangé à l'écoulement provenant de l'entrainement d'air entre l'arrière corps du moteur et les paupières dont l'angle est de 25^o au décollage (voir Fig. 5).

La trappe située sur le flanc intérieur de la nacelle est aussi ouverte lors du décollage. Elle sert à aspirer l'air de refroidissement de l'échangeur de la climatisation de la cabine. Après la traversée des échangeurs, cet air est réinjecté sur la partie supérieure du système de propulsion, à l'intérieur de la nacelle (Fig. 6).

Après rupture du réservoir, toutes ces prises d'air ont très certainement absorbé de grandes quantités de kérosène. La prise d'air du climatiseur est clairement la plus exposée : elle est située sur la face intérieure de la nacelle (i.e. côté cellule), au voisinage de sa jonction avec l'aile, à un endroit où beaucoup de kérosène est susceptible d'avoir ruisselé. Les autres prises d'air sont plus grandes mais, situées sur la face inférieure de la nacelle, sont moins exposées.

L'écoulement de combustible pénétrant dans la nacelle, qu'il soit issu de la deuxième trappe située sous la carène moteur ou du système de climatisation, a pu s'enflammer soit au contact des parois chaudes du moteur, soit lorsqu'il arrive au contact des gaz issus de la réchauffe au niveau de la tuyère primaire du moteur. Dans cette région, de nombreux obstacles, essentiellement constitués par le système hydraulique de manœuvre de la tuyère, permettent le développement de zones de recirculation et assurent l'accrochage de la flamme (Fig. 7). Cette analyse est confirmée par une

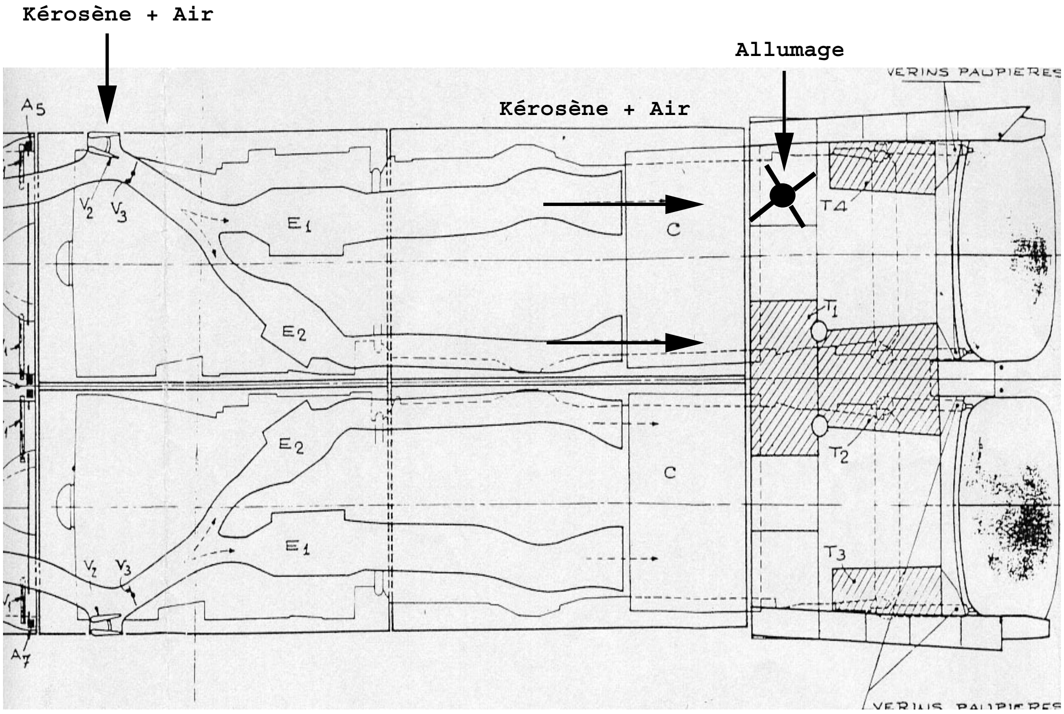


Figure 6: Schéma des prises d'air de la climatisation au niveau moteur. Un mélange kérosène-air ingéré au niveau de la trappe coté interne de la nacelle sera, après traversée des échangeurs, injecté sur la partie supérieure du système propulsif.

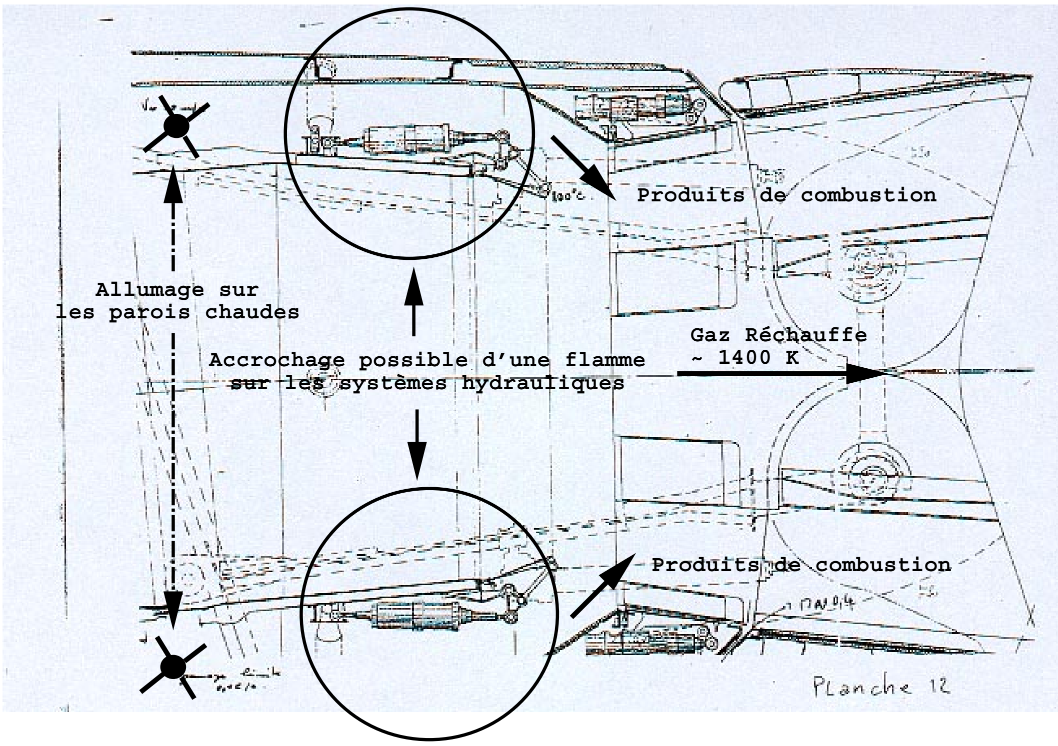


Figure 7: Schéma de la partie arrière du moteur (les paupières sont ici en position vol). Après allumage sur les parois chaudes, une zone de combustion trouvera de nombreux points d'accrochages sur les systèmes hydrauliques.

étude sur les risques d'incendie consécutifs à une fuite de kérosène après perforation d'un réservoir conduite après l'accident de Washington en 1979 (Note Aérospatiale-BAE No 408.251/79 et son annexe 9, "Evaluation du risque incendie" SDF/B87/K/32/0040) :

"Below 0.26M/220 knots there would be a real risk of fuel being sucked into a 4 inch by 6 inch inlet on the side of the nacelle which admits cooling air to the air conditioning system heat exchanger located in the engine bay. After passing through the heat exchanger it would exhaust onto the jet pipe. There is, therefore, a possibility of ignition and a fire within the ducting and between the jet pipe and heat shield. The fire would not propagate forward since the heat exchanger matrix would be a flame trap and would be a contained situation."

Cette étude montre donc clairement les risques d'inflammation de kérosène ingéré par la prise d'air de refroidissement de l'échangeur de la climatisation. Les risques sont évidemment les mêmes pour du kérosène ingéré par la seconde prise d'air secondaire sous la nacelle (Fig. 8). En revanche, l'étude souligne qu'une flamme allumée dans ces conditions est incapable de se propager vers l'amont. En effet, même si la flamme est susceptible de trouver des vitesses d'écoulement suffisamment faibles pour progresser, elle ne peut en aucun cas traverser l'échangeur : ses mailles sont trop fines pour permettre le passage d'une flamme (notion de "distance de coincement", voir par exemple De Soete 1976).

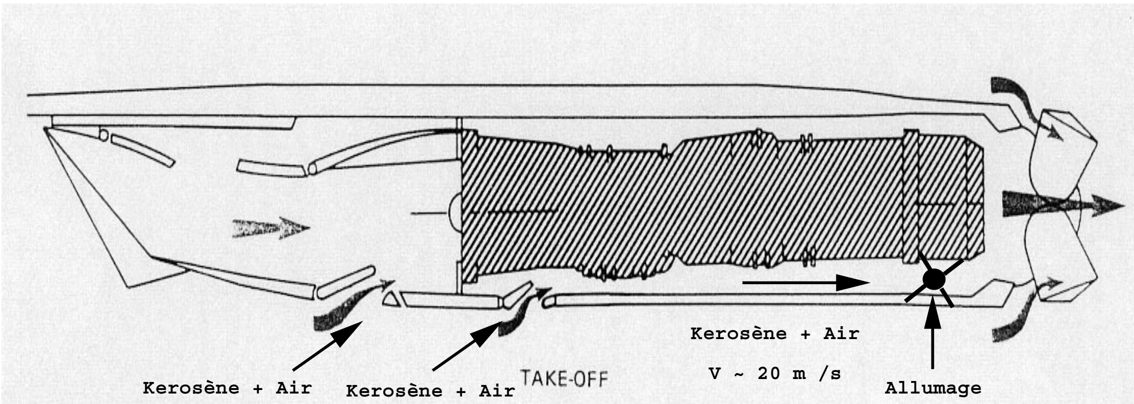
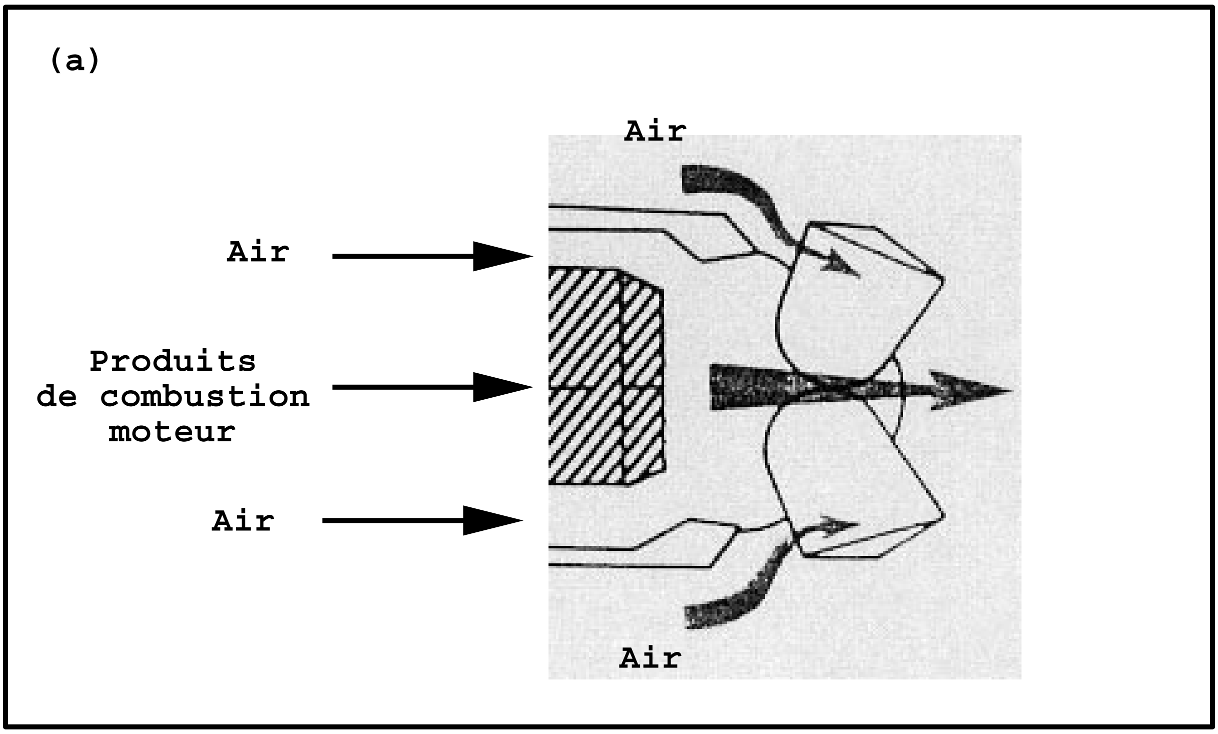


Figure 8: Schéma de l'Olympus avec ses entrées d'air secondaires. Un mélange kérosène-air ingéré par la seconde trappe est convecté vers les parties chaudes du moteur pour éventuellement s'auto-inflammer.

L'inflammation du kérosène est donc parfaitement possible à l'intérieur de la nacelle, au voisinage de la tuyère primaire du moteur 2. Cette inflammation conduit alors à l'existence d'une flamme accrochée derrière le moteur mais différente de la flamme de réchauffe observée en fonctionnement normal. Cette flamme est alimentée par le combustible ingéré par l'ensemble nacelle-moteur et peut brûler une partie du mélange kérosène/air qui s'écoule sous l'aile et le long de la nacelle. L'écoulement des gaz en amont des paupières est alors sensiblement modifié. En effet, comme l'illustre la figure 9, le jet froid entourant le jet de réchauffe au niveau de l'arrière corps a disparu et n'assure plus son rôle de bouclier thermique. En particulier, le kérosène s'écoulant à l'extérieur de la nacelle et débouchant entre l'arrière corps et la paupière rencontre maintenant directement des produits de combustion. L'inflammation du kérosène en écoulement le long de la nacelle et dans les couches limites turbulentes est alors inévitable (Fig. 10).

Cette analyse correspond clairement à la première étape de l'inflammation décrite par deux pompiers témoins des événements (Annexes F.3.1 et F.3.3) et à ce que décrit le commandant



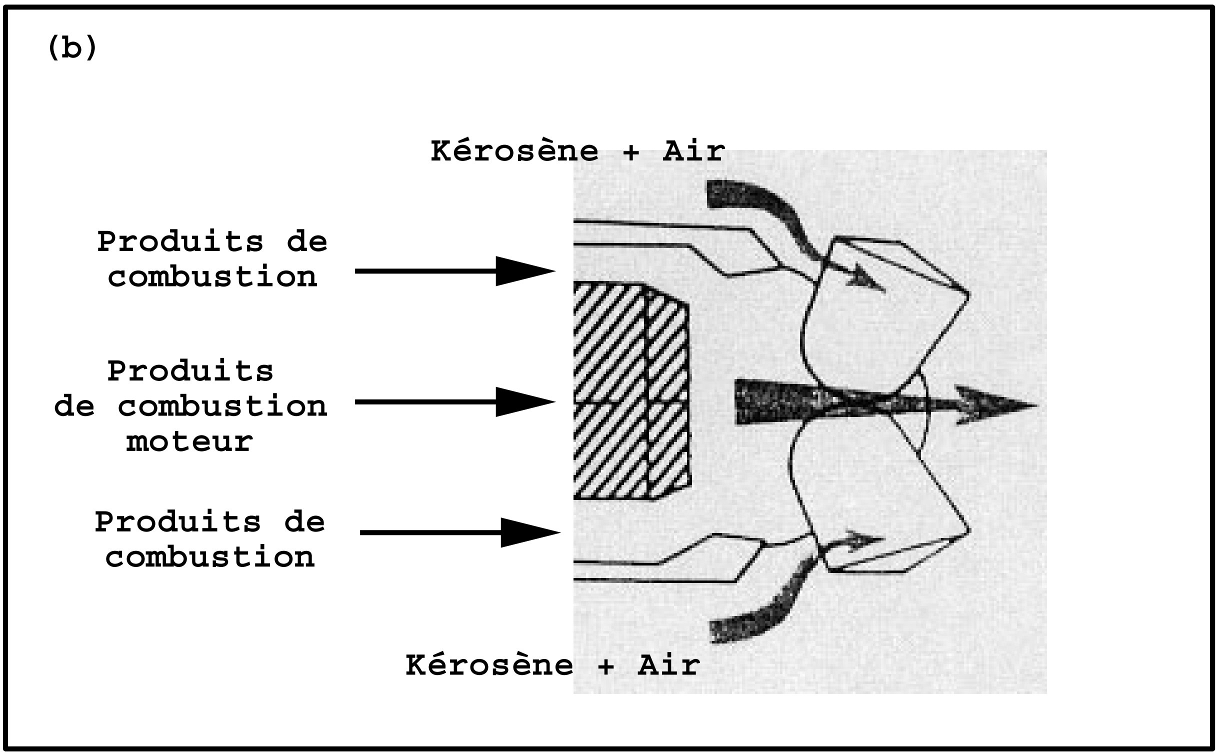


Figure 9: Schéma de l'arrière corps. (a) Fonctionnement normal au décollage : l'air moteur est utilisé pour canaliser le jet de la réchauffe. (b) Dans le cas d'un feu à l'intérieur de la nacelle, l'écoulement d'air entourant le jet de réchauffe est remplacé par un écoulement de gaz brûlés qui va entrer en contact avec le kérosène ruisselant le long de la nacelle.

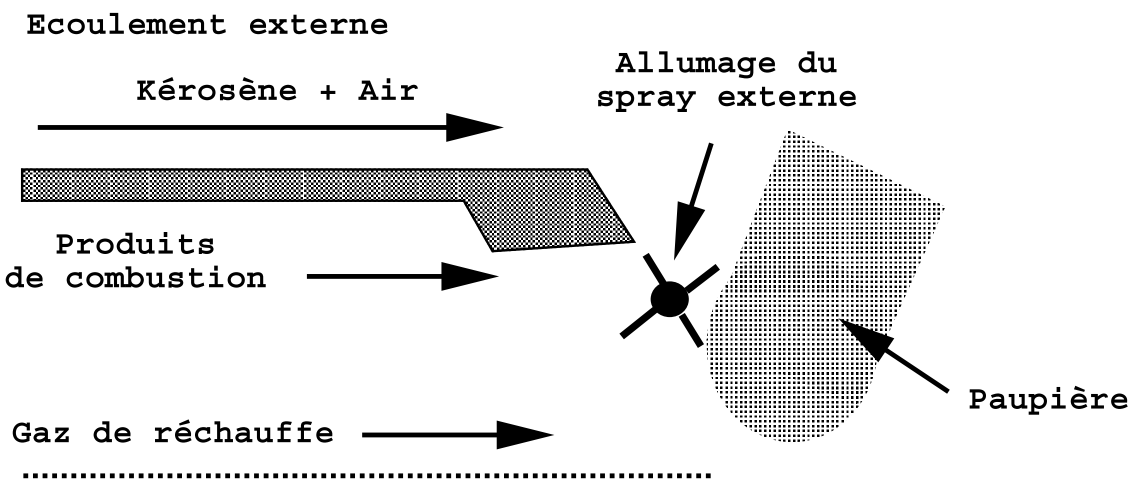


Figure 10: L'écoulement d'air autour des gaz de réchauffe est remplacé par un écoulement de gaz brûlés au contact duquel le spray ruisselant sur la nacelle va s'enflammer.

de bord d'un appareil en attente de décollage (Annexe F.3.4).[9] Il s'agit maintenant d'expliquer comment la flamme a pu remonter vers l'avant de l'avion pour venir s'accrocher dans le sillage du train d'atterrissage comme le montre les photographies ultérieures de l'événement (§ 1).

4.3 Remontée de la flamme vers l'avant de l'avion

4.3.1 Introduction

Une fois acquise la possible inflammation, au voisinage de la tuyère primaire du moteur 2, du kérosène s'échappant par la fuite du réservoir 5, il faut analyser les possibilités de remontée de la flamme vers l'amont. Plusieurs mécanismes de remontée de flamme sont a priori possibles :

- **A l'extérieur de la nacelle**, le long de la nacelle et sous l'aile de l'avion.
- **A l'intérieur de la nacelle**, entre les parois de la nacelle et le moteur. Cette remontée est impossible par le circuit de climatisation car l'échangeur empêche le passage de la flamme (voir § 4.2). Elle est, en revanche, possible en direction de la seconde prise d'air secondaire, comme le montre la figure 11.
- **Pompage moteur**. Un pompage moteur peut occasionner une inversion de l'écoulement à l'intérieur du moteur et provoquer une remontée de la flamme à travers le compresseur (phénomène dit de "flamme-amont").

Ces explications sont toutes trois plausibles et aucune ne peut être complétement exclue. La propagation à l'extérieur de la nacelle, dans les couches limites, nous semble toutefois la plus probable. Examinons maintenant successivement chacune de ces hypothèses.

4.3.2 Remontée de flamme le long de la face externe de la nacelle

A première vue, une telle remontée est impossible : la vitesse de propagation d'une flamme turbulente peut difficilement excéder quelques mètres par seconde alors que l'écoulement sous l'aile de l'avion est à environ 100 m/s.

[9] Contrairement aux pompiers, nous n'avons pas interrogé personnellement ce commandant de bord et nous ne lui avons donc pas fait préciser la localisation exacte de la première inflammation dont il témoigne.

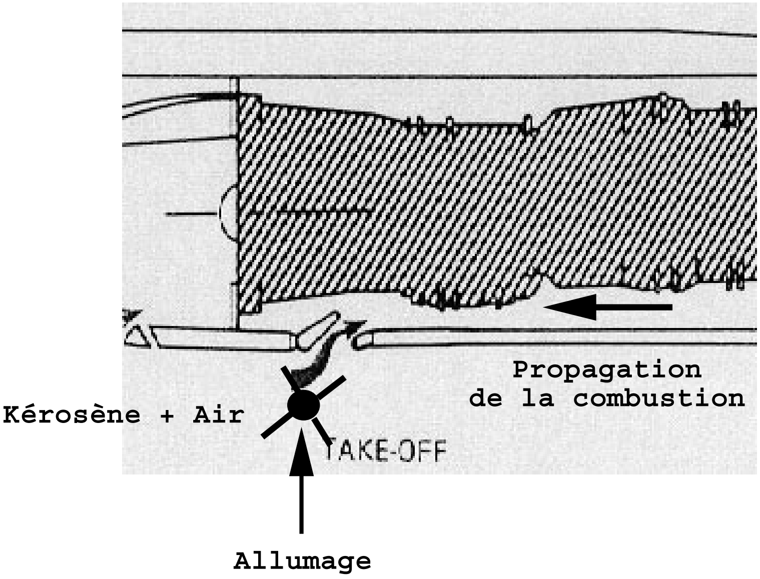


Figure 11: Allumage du spray ruisselant sur la nacelle par remontée de flamme dans l'écoulement d'air interne moteur.

Cette analyse est beaucoup trop simpliste car la propagation d'une flamme est un phénomène local et instantané : il suffit que localement la flamme rencontre à un instant donné un écoulement à vitesse suffisamment faible. Des expériences récentes (voir Annexe E) montrent qu'une flamme est capable de se propager de proche en proche dans des zones qui ont, à cet instant, des faibles vitesses. Une flamme est alors capable de soutenir des vitesses moyennes largement supérieures à sa vitesse de propagation. En fait, la vitesse moyenne, et plus généralement les grandeurs statistiques, d'un écoulement ne sont pas représentative de sa structure locale instantanée, seule significative en terme de propagation de flamme.[10]

Dans le cas du Concorde, la géométrie est compliquée (Annexe D) : couches limites (et donc zones à faibles vitesses où l'écoulement est très perturbé) sous l'aile et le long de la nacelle, "coin" nacelle/aile, présence de la jambe de train et des contrefiches, génératrices de sillages importants, combustible ruisselant sur les parois, aile et nacelle,... Dans cette situation, une flamme peut trouver localement et instantanément des zones à vitesses suffisamment faibles pour se propager vers l'amont jusque dans le sillage du train d'atterrissage, sans compter qu'elle perturbe elle même l'écoulement. En revanche, la flamme ne pourra pas dépasser le train. En amont de celui-ci, l'écoulement est nettement moins perturbé (absence de sillage, couches limites réduites), sans oublier que la fuite de combustible ne se situe que 25 cm en amont du puits de train et que les contrefiches de celui-ci contribuent certainement à l'homogénéisation du mélange kérosène/air.

Pour nous, comme le discute l'Annexe D, la remontée d'une flamme le long de la nacelle dans les couches limites et dans le sillage du train est clairement possible. Cette analyse correspond aussi au témoignage d'un des pompiers interrogés (Annexe F.3.3) qui décrit la flamme comme aspirée vers l'avant de l'avion. Elle est aussi compatible avec le développement en deux temps décrits par les autres témoins (Annexe F).

[10] Ce phénomène rend d'ailleurs impossible une simulation numérique fiable de la remontée de la flamme dans le cas de l'accident du Concorde qui ne peut être décrite en terme de grandeurs statistiques. En fait, une telle propagation est chaotique : il suffit qu'à un seul instant la vitesse ait été suffisamment faible pour permettre la remontée de la flamme. De plus, les modèles utilisés pour décrire la combustion turbulente sont actuellement trop grossiers pour prédire de manière fiable les phénomènes de stabilisation de flammes dans une géométrie aussi complexe.

4.3.3 Remontée de la flamme entre nacelle et moteur

La remontée de la flamme à l'intérieur de la nacelle entre les parois de celle-ci et le moteur (Fig. 11) est probablement plus facile qu'à l'extérieur : vitesses plus faibles des écoulements (environ 20 m/s), obstacles divers,... Dans cette situation, la flamme arriverait au niveau de la seconde prise d'air secondaire sous la nacelle, au voisinage de la zone de recirculation qui se développe derrière la jambe de train.

En revanche, il n'est pas clair que cette flamme puisse sortir de la nacelle au niveau de la prise d'air (vitesse de l'air de l'ordre de 20 m/s, couches limites quasi-inexistantes à cet endroit,. . .), ni que le ruissellement de kérosène à ce niveau ait pu être suffisant. Remarquons toutefois qu'une flamme sortant par la prise d'air secondaire correspondrait au témoignage d'un des pompiers (Annexe F.3.2). Il est néanmoins le seul témoin à décrire cette situation et a plus probablement vu la flamme alors qu'elle était en train de remonter vers l'amont de l'avion (voir Annexe F.4).

4.3.4 Remontée de la flamme sur pompage moteur

La première flamme, accrochée aux tuyères, n'a probablement pas laissée de traces de suies sur la piste et celles-ci correspondent plus vraisemblablement au développement de la flamme stabilisée. La remontée aurait alors commencé avant les pompages mais pourrait ne s'être achevée qu'après. Remarquons qu'à l'inverse, le pompage du moteur 2 aurait pu être provoqué par l'aspiration de gaz brûlés provenant de la flamme se développant dans le sillage du train.

5 Scénario probable de l'inflammation de l'avion

L'objectif est ici de résumer nos conclusions en proposant le scénario qui nous semble le plus probable pour expliquer l'inflammation du kérosène et la stabilisation de la flamme lors de l'accident de Gonesse. Ce scénario est construit à partir des analyses effectuées précédemment et utilise les discussions conduites en annexe.

5.1 Scénario de l'inflammation

Les témoignages décrivent précisément une inflammation en deux temps de l'avion : première flamme au voisinage des tuyères des moteurs gauches puis expansion (Annexe F). Par ailleurs, l'inflammation par étincelle suite à la rupture d'un cable électrique, si elle n'est pas complétement impossible, nous parait très improbable (Annexe B). L'allumage direct du kérosène liquide ruisselant le long de la nacelle et sous l'aile au contact des gaz chauds issus du moteur est théoriquement possible mais cette situation semble peu favorable (vitesses d'éjection des gaz, gaine d'air frais protégeant la sortie du moteur, absence de parois et de zones à vitesse lente en aval des paupières pour permettre la remontée ultérieure de la flamme,...). Le scénario le plus vraisemblable nous paraît alors être :

1. Ingestion de kérosène par les entrées d'air secondaires ou, plus probablement, par la prise d'air du climatiseur (§ 4.2).

2. Allumage sur les parties chaudes du moteur et/ou les gaz issus de la réchauffe au voisinage de la tuyère primaire du moteur. La conséquence directe de la présence d'une flamme et de gaz brûlés dans cette partie du moteur est la suppression du confinement du jet de réchauffe et de la protection thermique des parois normalement assurée par l'écoulement d'air qui entoure le moteur (§ 4.2).

3. Inflammation au niveau des paupières du kérosène s'écoulant à l'extérieur de la nacelle, au contact de la flamme-pilote accrochée au voisinage de la tuyère primaire du moteur.

4. Remontée de la flamme vers le train principal gauche, jouant le rôle d'accroche-flamme par les couches limites et le sillage du train, le long de la paroi externe de la nacelle et sous l'aile (§ 4.3).

Ce scénario nous semble aujourd'hui le plus crédible, tant au vu des témoignages (Annexe F), que des éléments matériels réunis et de nos connaissances en combustion. Il n'exclut néanmoins pas complétement quelques variantes et laisse quelques interrogations résumées ici.

Deux autres scénarios peuvent être évoqués pour expliquer la remontée de la flamme, comme nous l'avons déjà signalé. La flamme peut se propager entre moteur et nacelle puis sortir par la seconde prise d'air sous la nacelle (figure 11). Possible, ce mécanisme semble peu favorable (sortie au niveau de la prise d'air dans une ambiance où la quantité de kérosène n'est probablement pas maximale, voir § 4.3). La flamme aurait aussi pu remonter suite à un des pompages moteur. Au contraire, le pompage du moteur 2 pourrait être dû à la remontée de la flamme et à l'ingestion de gaz brûlés par le moteur par les entrées d'air secondaires.

Un autre point concerne l'explosion de la dalle 181. Cette dalle présente apparemment les traces d'une explosion : traces de suies qui semblent montrer un violent écoulement en direction du sol, arrachage d'un élément de béton à la piste (photographie 12). Cette explosion pourrait s'expliquer par la remontée de la zone de combustion.

Figure 12: Photographie de la dalle 181 de la piste, montrant les traces de ce qui semble être une explosion avec arrachement d'un morceau de béton (10 cm de large, 25 à 30 cm de long, 1 cm d'épaisseur).

La détonation (combustion en régime supersonique avec formation d'ondes de choc) est connue pour être très difficile avec les mélanges kérosène / air. Néanmoins, l'inflammation brutale d'un prémélange quasi-stœchiométrique dans un milieu (relativement) confiné peut conduire à une surpression non négligeable, éventuellement destructrice, et ce, même en régime dit de déflagration (propagation subsonique d'une flamme). Cette situation aurait pu se produire soit dans les zones de recirculation en aval du train, soit plus probablement dans le puits de logement du train, lors de la remontée de la flamme. La zone de recirculation turbulente apparaissant dans ce type de cavité a pu conduire au remplissage du puits de train d'un mélange kérosène / air.

La combustion d'un prémélange air / kérosène dans un puits de train d'environ $2 \times 1 \times 0.5\,m$ avec une vitesse de flamme turbulente de l'ordre de $S_T = 5$ à $10\,m/s$ peut être réalisée en un temps de l'ordre d'un dixième de seconde (correspondant au temps de parcours d'une dalle par l'avion) et induire une surpression locale. Suivant la position des éléments mécaniques, hydrauliques et électriques autour du puits de train, cette surpression a pu engendrer quelques dégats : dégats à l'intérieur du puits de logement du train, détérioration de la piste... En admettant que le puits ait entièrement été rempli d'un mélange stœchiométrique kérosène / air à pression atmosphérique, cas le plus défavorable, elle aurait contenue $1000/22.4 \approx 45$ moles d'air (le volume de kérosène, supposé sous forme liquide, est négligeable), soit 0.5 moles ou 84 g de kérosène dont la combustion aurait libérée une énergie de 3.5 MJ (ou, en 0.1 s, une puissance crête de 35 MW).

Cette “explosion” pourrait aussi être la conséquence d'un pompage moteur (remontée de flamme vers l'amont, réinflammation brutale dans le réacteur,...), le “bang” sonore caractéristique du pompage et mentionné par les témoins correspondant à une surpression.

Les éléments concernant l'explosion observée à la dalle 181 restent toutefois assez flous. Ces commentaires doivent donc être pris avec beaucoup de réserve.

5.2 Enchainement et localisation des événements

Après avoir analysé le scénario probable de l'inflammation du kérosène s'échappant du réservoir numéro 5, il s'agit maintenant de tenter de dater la succession des événements au vu des éléments trouvés sur la piste et des enregistrements disponibles.

La première flamme, accrochée à l'arrière des moteurs et signalée par les témoins (voir Annexe F), s'est probablement allumée très rapidement après le début de la fuite (environ quelques dixièmes de seconde après, temps nécessaire au transport du kérosène vers la tuyère primaire du moteur).

Si le début de la fuite de kérosène correspond au moment du changement de bruit de fond (temps 97601.5), l'apparition de cette petite flamme se situe probablement lorsque les paupières sont au niveau de la nappe de kérosène imbrûlé observée sur la piste (dalles 163 à 165).[11] La quantité de kérosène liquide retrouvé laisse supposer que l'espace entre sol et aile du Concorde était rempli d'un brouillard de kérosène. Cette flamme n'est probablement pas encore assez étendue pour laisser des traces de suies sur la piste et enflammer le kérosène répandu.

Il est plus difficile de dater la remontée et l'accrochage de la flamme dans le sillage du train d'atterrissage gauche. En effet, rien ne permet d'affirmer que cette remontée était achevée avant la levée de la roue avant ou même le décollage. Les photographies disponibles (voir, par exemple, les photographies 2 ou 14) qui montrent clairement la stabilisation de la flamme dans le sillage du train ont été prises alors que l'avion était déjà en vol.

La première flamme stabilisée au voisinage des tuyères joue le rôle de flamme pilote (voir § 1.1). La flamme prend alors de l'expansion et s'étend vers l'amont et vers l'aval en brûlant le kérosène s'écoulant sous l'aile de l'avion. L'expansion vers l'aval peut être très rapide et correspond probablement aux premières traces de suies sur la piste.[12] Au contraire, la combustion vers l'amont est plus lente et laisse au troisième pompier le temps de voir une flamme comme aspirée vers l'avant de l'avion (Annexe F.3.3).

Trois évenements particuliers peuvent correspondrent à l'accrochage de la flamme dans le sillage du train d'atterrissage : l'explosion de la dalle 181, le pompage lourd du moteur 2 et la levée de la roue avant. Explosion et pompage sont relativement voisins en temps, soit environ 1.5 s après l'inflammation supposée. Ce temps correspondrait à une remontée plutôt rapide de la flamme mais possible. La levée de la roue avant et le cabrage de l'avion sont sensiblement plus tardifs (environ 3 secondes après l'allumage supposé), ce qui laisse le temps à la flamme de remonter vers le train, surtout que l'écoulement sous l'avion est modifié à ce moment là (§ 6.1). Signalons que l'un des témoins (troisième pompier, Annexe F.3.3) décrit la remontée de la flamme comme s'étant produite après la levée de la roue avant.

[11] Il faut noter que les quatres témoins qui ont vu l'avion quasiment par son travers au moment de l'inflammation, trois pompiers en service au poste de secours SISS2 et un commandant de bord en attente de décollage sur la bretelle E5, situent cette inflammation beaucoup plus tôt (voir Annexe F). Pour les pompiers, elle s'est produite peu après le travers de la bretelle S5 tandis que le commandant la localise à plus ou moins 100 m de la bretelle W7.

[12] Remarquons que ces traces ont pu être laissées par l'extrémité de la flamme qui peut déjà se situer quelques dizaines de mètres derrière l'avion.

6 Remarques complémentaires

Les remarques présentées ici visent à compléter le scénario précédent (§ 5), notamment sur les conséquences de la présence de la flamme accrochée sous l'avion.

6.1 Traces de suies sur la piste

Les traces de suies retrouvées sur la piste 26 R présentent une discontinuité : traces continues de la dalle 169 à la dalle 226, traces discontinues ensuite, traces intenses au voisinage de la bretelle S4 et enfin herbe brûlée avec fortes traces de suies au bord de la piste après la dalle 307. Comme nous l'avons déjà dit, l'apparition des suies (dalle 169) correspond probablement au moment où la flamme prend de l'ampleur. En effet, la petite flamme "chalumeau" initialement décrite par les témoins n'a propablement pas laissée de traces sur la piste, faute d'une ampleur suffisante.

La disparition des suies à la dalle 226 est probablement liée au fort cabrage de l'avion avant le décollage. Dans ces conditions, l'écoulement sous l'aile est fortement modifié : plus d'air passe sous l'avion et est accéléré par le convergent que repésente l'avion par rapport à la piste (Fig. 13). On peut alors penser que la combustion s'effectue dans des meilleures conditions, conduisant à la formation de beaucoup moins de suies.

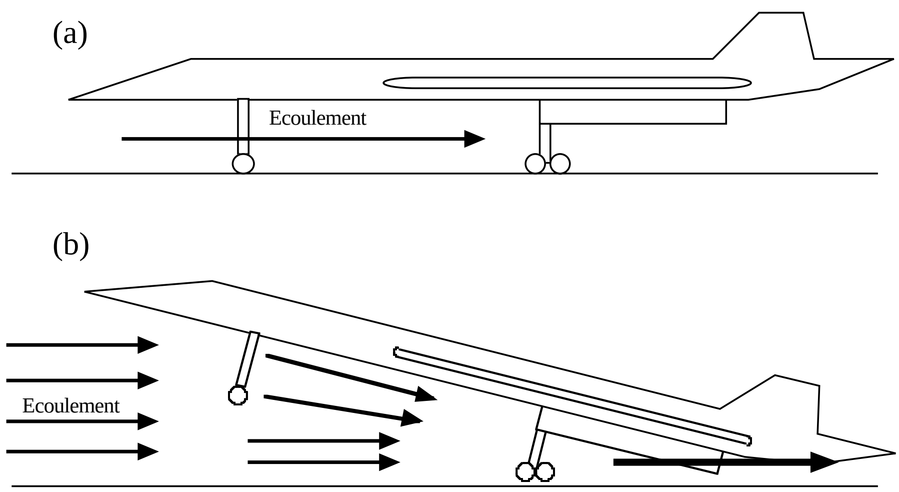


Figure 13: Schématisation de la modification de l'écoulement sous l'avion lors du cabrage. (a) avion au roulage ; (b) avion cabré. Cette modification peut expliquer la disparition des suies observées sur la piste vers la dalle 226.

Une fois que l'avion a décollé, après la dalle 306, l'écoulement est encore une fois modifié. De nouveau, moins d'air alimente la flamme et la combustion peut redevenir incomplète donnant lieu à la formation de beaucoup de suies (Photographie 14).

Ces explications sont parfaitement plausibles. Néanmoins, il ne faut pas perdre de vue que d'autres sont possibles. En effet, la combustion est dans ces conditions fortement instationnaire. Le débit de fuite de kérosène a aussi pu varier au cours du temps, notamment avec l'assiette et les accélérations de l'avion.

6.2 Dégats structuraux dus à la flamme

Comme mentionné à la section 2, la flamme accrochée sous l'avion dégageait une puissance de l'ordre de 2 GW, dont 10 à 20 % l'était au voisinage immédiat de l'aile, de la cellule et de la nacelle

Figure 14: Photographie de l'avion après le décollage. La combustion, clairement incomplète, donne lieu à la formation de beaucoup de suies (particules de carbone imbrûlées) d'où sa couleur jaune. Le panache de suies noires est particulièrement visible derrière la flamme. Photographie prise par un touriste japonais depuis un avion en attente de traversée de la piste 26 R.

gauche. Un tel dégagement a pu occasionner des dégats structuraux non négligeable (fusion des panneaux de l'aile et/ou de la nacelle) et chauffer les réservoirs 2 et 6. D'après les cadrans des jauges retrouvés à Gonesse, le réservoir 2 pourrait être vide au moment de l'impact alors que son symétrique, coté droit de l'appareil, était pratiquement plein. L'apport éventuel du combustible du réservoir 2 aurait pu se traduire par une modification de la flamme, variable selon la durée de cet apport, instantanée ou non.

6.3 Ingestion de gaz brûlés par le moteur

L'ingestion de gaz brûlés provenant de la flamme accrochée sous l'aile par les prises d'air des moteurs gauches a déjà été évoquée. Outre la discussion déjà conduite (§ 5), l'ingestion de gaz brûlés pourrait être la cause du pompage lourd du moteur 1 entre les instants 97612.1 et 97613.1. A ce moment, l'avion quitte le sol, ce qui entraine une modification de l'écoulement autour de celui-ci et a pu favoriser une telle ingestion. Les traces de suies retrouvées sur la piste semblent d'ailleurs montrer une modification de la combustion (voir ci-dessus).

6.4 Et si...

L'objectif est ici d'envisager, d'un point de vue purement combustion, deux événements possibles qui auraient pu se produire lors de l'accident de Gonesse : la rentrée du train d'atterrissage principal gauche et un arrêt de l'avion sur la piste au lieu de décoller. Ces analyses sont évidemment purement spéculatives mais montrent que ces alternatives n'auraient probablement pas changé grand chose.

6.4.1 Rentrée du train d'atterrissage

Comme nous l'avons dit à la section 1.2 de ce rapport, la flamme turbulente accrochée sous l'aile du Concorde lors de l'accident de Gonesse était stabilisée par le sillage du train d'atterrissage principal gauche. La remontée de la flamme depuis l'arrière corps des moteurs vers l'avant de l'appareil n'a, de plus, été possible qu'en raison des perturbations aérodynamiques engendrées par le train (§ 4.3). Si le train avait pu être rentré, la flamme aurait probablement été soufflée pour venir se stabiliser au voisinage de la sortie des réacteurs.[13]

Dès que la flamme est soufflée, les mécanismes ayant conduit à son allumage (ingestion de kérosène par la trappe du climatiseur et/ou les prises d'air secondaires du moteur, mise en contact de ce kérosène avec les parties chaudes du moteur,...) réapparaissent. Dans ce cas, une flamme entretenue aurait probablement subsisté à l'intérieur de la nacelle, au voisinage de la tuyère primaire du moteur. Cette flamme ne pourrait alors plus remonter le long de la nacelle (absence du sillage du train) mais contribuerait à l'accrochage d'une flamme principale au voisinage des paupières, se développant vers l'arrière de l'avion.

6.4.2 Arrêt de l'avion avant décollage

Lors de l'accident de Gonesse, l'avion a décollé avec les conséquences que l'on connait. Une alternative était que le pilote décide d'interrompre le décollage et de tenter d'arréter l'appareil sur la piste. Il ne nous appartient pas de juger de la faisabilité et de l'opportunité d'une telle tentative, en admettant que le pilote ait pu avoir les éléments d'informations pouvant le pousser à une telle décision. Néanmoins, toujours d'un point de vue "combustion" nous pouvons examiner les conséquences prévisibles de l'arrêt de l'appareil, en supposant qu'il fût possible sans dégats annexes (sortie de piste, etc...).

En admettant que l'avion ait pu s'arrêter et compte tenu du débit de la fuite de kérosène, de l'ordre de 50 à 100 kg/s (voir § 2), il aurait été immédiatement entouré d'une mare de kérosène en feu (il restait encore environ 2 tonnes de kérosène dans le réservoir N^o 5 à Gonesse, probablement plus en cas d'arrêt sur la piste). Le feu serait en outre remonté vers le réservoir et aurait éventuellement pu déclencher une explosion. Il ne faut pas non plus oublier que le feu aurait aussi provoqué des dommages aux autres réservoirs dont la plupart sont encore pleins à ce moment là. Même en l'absence d'explosion et malgré leur indéniable rapidité d'intervention, les pompiers se seraient retrouvés en face d'un gigantesque brasier probablement très difficile et très long à maîtriser, laissant très peu de chances aux passagers et à l'équipage de l'avion.

[13]Cette remarque ne considère évidemment qu'un point de vue "combustion." Vu la situation de l'avion, la rentrée du train endommagé n'était pas souhaitable (risque de ne pouvoir le ressortir ou de créer une combustion résiduelle de pneus dans le puits de train,...).

ANNEXES

A Caractéristiques chimiques du kérosène

Le kérosène est un hydrocarbure assimilé ici à $C_{12}H_{24}$. Le kérosène est en fait un mélange de différents hydrocarbures et plusieurs formules chimiques globales sont utilisées dans la littérature ($C_{10}H_{20}$, $C_{10}H_{18}$,...). Pour notre utilisation, seul compte le rapport du nombre d'atomes d'hydrogène et de carbone, voisin de 2.

A.1 Réaction chimique

La réaction chimique globale est :

$$C_{12}H_{24} + 18O_2 \longrightarrow 12CO_2 + 12H_2O \tag{10}$$

La combustion stœchiométrique de 168 kg de kérosène nécessite donc 576 kg d'oxygène soit environ 2485 kg d'air. Pour 1 kg de kérosène, il faut 3.4 kg d'oxygène ou 14.8 kg d'air. Le rapport stœchiométrique massique (rapports des masses d'oxygène et de combustible nécessaires dans les proportions stœchiométriques) vaut donc $s = 3.4$. De même, une mole de kérosène nécessite pour brûler 18 moles d'oxygène et $18 \times (1 + 3.76) = 85.7$ moles d'air. Rappellons qu'une mole de gaz occupe, dans les conditions normales, un volume de 22.4 litres.

Le rapport stœchiométrique ϕ qui compare les caractéristiques chimiques d'un écoulement pur de kérosène (fraction massique de kérosène $Y_F^0 = 1$) et d'air (fraction massique d'oxygène $Y_O^0 = 0.23$) vaut :

$$\phi = \frac{sY_F^0}{Y_O^0} \approx 14.8 \tag{11}$$

Le rapport de mélange stœchiométrique Z_{st}, caractérisant le mélange stœchiométrique kérosène / air en terme d'une variable de mélange Z ($Z = 0$ dans l'air pur et $Z = 1$ dans le combustible pur), est donné par :

$$Z_{st} = \frac{1}{\phi + 1} \approx 0.063 \tag{12}$$

A.2 Energie dégagée par la réaction

Le pouvoir calorifique inférieur (PCI) du kérosène est d'environ $PCI = 42.5$ MJ/kg. Ce pouvoir calorifique mesure l'énergie dégagée par la combustion d'un kilogramme de combustible. L'eau formée par la réaction est supposée rester à l'état vapeur, c'est à dire que la chaleur latente de vaporisation de celle-ci, a priori récupérable, n'est pas prise en compte, d'où l'adjectif "inférieur".

A titre d'illustration, le moteur Olympus du Concorde brûle environ 20 tonnes de kérosène par heure à pleine puissance, soit 5.6 kg/s. Cette combustion produit une puissance de $5.6 \times 42.5 \approx 240$ MW. La puissance cumulée des quatre réacteurs est donc comparable à celle d'une centrale nucléaire.

A.3 Limites d'inflammabilité

La combustion d'un mélange kérosène/air n'est possible que pour certaines proportions du mélange, décrites par les limites d'inflammabilité. La proportion de kérosène dans l'air, en volume, doit être au minimum de 0.6 % (limite pauvre) et au maximum de 4.7 % (limite riche). Les proportions stœchiométriques correspondent à une mole de kérosène pour 85.7 moles d'air, soit environ 1.2 % en volume. La combustion du kérosène dans l'air n'est donc possible que pour des mélanges dont la richesse[14] Φ vérifie :

$$0.5 \leq \Phi \leq 4 \tag{13}$$

Remarque : Un mélange kérosène/air ne peut donc brûler que si les réactifs sont dans des proportions convenables, c'est à dire s'il y a suffisamment de kérosène mais pas trop. Il serait tentant d'extrapoler ce résultat en terme de débit maximal de fuite d'un réservoir du Concorde pour éviter l'inflammation. Malheureusement, cette extrapolation n'est pas immédiate car la combustion est controlée par la *richesse locale et instantanée* du mélange, c'est à dire par la richesse en un point donné à un instant donné. Seule une estimation de la *richesse moyenne*, comparant les débits globaux de combustible et d'air, est, a priori, possible comme nous l'avons fait au paragraphe 2.4 pour comparer les accidents de Gonesse et de Washington.

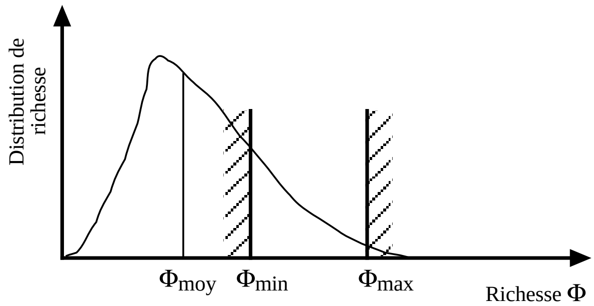


Figure 15: Distribution de la richesse locale dans un mélange turbulent combustible/air imparfait. Le mélange ne peut brûler que s'il se situe dans les limites d'inflammabilité (richesse locale Φ telle que $\Phi_{min} \leq \Phi \leq \Phi_{max}$). La richesse moyenne du mélange Φ_{moy} peut facilement être estimée à partir des débits globaux d'air et de combustible mais n'est pas forcément représentative du mélange local. Ici, $\Phi_{moy} < \Phi_{min}$ mais une partie du mélange peut bûler.

Pour aller plus loin, il faudrait pouvoir estimer une distribution de richesse et déterminer la part du mélange se trouvant dans les limites d'inflammabilité (Fig. 15), ce qui suppose une description précise du mélange turbulent dans les conditions de roulage du Concorde. Le seul point sûr est qu'une richesse moyenne très faible correspond à une fraction importante du mélange se situant en dessous de la limite d'extinction pauvre (richesse minimale Φ_{min}), comme pour l'accident de Washington (voir § 2.4). Au contraire, une richesse moyenne au delà des limites d'inflammabilité traduirait probablement une large distribution de richesse du mélange dont une part non négligeable serait comprise entre les limites Φ_{min} et Φ_{max}. Il est certain qu'un débit de kérosène faible ne permettrait pas son inflammation mais il est difficile de fixer une limite en terme de richesse moyenne, surtout compte tenu des incertitudes, notamment dans l'estimation du débit d'air qu'il faut considérer et la description de son mélange turbulent avec le kérosène.

A.4 Vitesse de flamme

Une flamme est capable de se propager dans un mélange combustible / oxydant au repos. La vitesse de propagation est appelée vitesse de flamme laminaire. Elle caractérise, en partie, la combustion et mesure le taux de dégagement de chaleur d'une flamme laminaire. Cette vitesse est

[14]La richesse Φ compare la proportion de combustible dans un mélange combustible / comburant à celle que devrait avoir ce combustible pour que le mélange soit stœchiométrique. Ainsi, une richesse $\Phi = 1$ signifie que le mélange est en proportion stœchiométrique tandis que $\Phi = 0.5$ indique qu'il contient moitié moins de combustible que le comburant disponible permettrait d'en brûler (mélange pauvre). Lorsque $\Phi > 1$, le combustible est en excès et le mélange est alors dit "riche".

maximale aux voisinages des proportions stœchiométriques, environ 0.5 m/s pour le kérosène, et tombe à zéro (pas de combustion) aux limites d'inflammabilité.

A.5 Auto-inflammation

La température d'auto-inflammation T_i correspond à la température à laquelle il faut porter un mélange combustible / comburant stœchiométrique pour assister au développement spontané d'une flamme.[15] Pour le kérosène, cette température d'auto-inflammation vaut environ[16] :

$$T_i \approx 240^oC \approx 513\,K \tag{14}$$

Cette donnée n'est toutefois pas suffisante car l'inflammation d'un mélange combustible n'est pas instantanée. En fait, la combustion résulte de réactions chimiques plus ou moins complexes. Par exemple, la combustion d'un hydrocarbure fait intervenir quelques centaines d'espèces chimiques et quelques milliers de réactions élémentaires. Ces réactions sont généralement classées en quatre groupes qui interviennent successivement :

- *les réactions d'initiation* permettent de briser les molécules initiales (combustible, comburant). Elles sont généralement fortement endothermiques, raison pour laquelle il faut apporter de l'énergie (étincelle, source de chaleur,...) pour initier la combustion.

- *les réactions de ramification* produisent les radicaux chimiques, intermédiaires de réaction.

- *les réactions de propagation* constituent le coeur même de la combustion. Fortement exothermiques, elles fournissent la chaleur dégagée par la combustion et assurent son entretien.

- *les réactions de terminaison* interviennent en fin de processus et conduisent à l'équilibre final.

Le développement de ces processus demande un certain temps quantifié en terme de temps d'auto-inflammation et fonction de la température initiale du mélange. Comme le montre la figure 16, plus la température initiale est élevée, plus ce délai est court. En dessous de la température d'autoinflammation, la combustion n'est plus possible. Ce délai dépend aussi fortement de la richesse du mélange réactif, c'est à dire de la proportion combustible/air, comme le montre la figure 17. Pour des températures initiales de l'ordre de 1100 K, seuls les mélanges prochent des conditions stœchiométriques ($Z \approx 0.063$) peuvent s'enflammer avec un délai de l'ordre de quelques dizaines de millisecondes. Un contact direct avec les gaz de réchauffe du moteur Olympus du Concorde ($1400\,K$) conduirait à des délais d'inflammation beaucoup plus courts, de l'ordre de 0.1 m/s pour les conditions stœchiometriques. L'augmentation de la température initiale des gaz permet d'envisager l'inflammation de mélanges contenant une proportion plus importante de kérosène que les conditions stœchiométriques.

Dans le cas du Concorde, pour un mélange combustible porté à 800 °C par mélange avec les gaz chauds issus du réacteur (environ 1000 °C), le délai serait $\tau_i \approx 40$ ms. Pour un écoulement de gaz frais à 100 m/s, il faudrait donc environ 4 m pour que la réaction se développe, ce qui semble exclure une flamme accrochée à l'arrière de l'avion. Cette analyse est toutefois beaucoup trop grossière :

[15] Les taux de réaction chimiques dépendent exponentiellement de la température à travers les lois d'Arrhénius qui régissent les cinétiques chimiques. Au delà de la température d'auto-inflammation, les réactions chimiques s'emballent et la combustion se développe.

[16] La correspondance entre degrés Celsius (^oC) et Kelvin (K), référencés respectivement au point de congélation de l'eau et au zéro absolu, est donnée par la relation $1^oC = 273.15\,K$

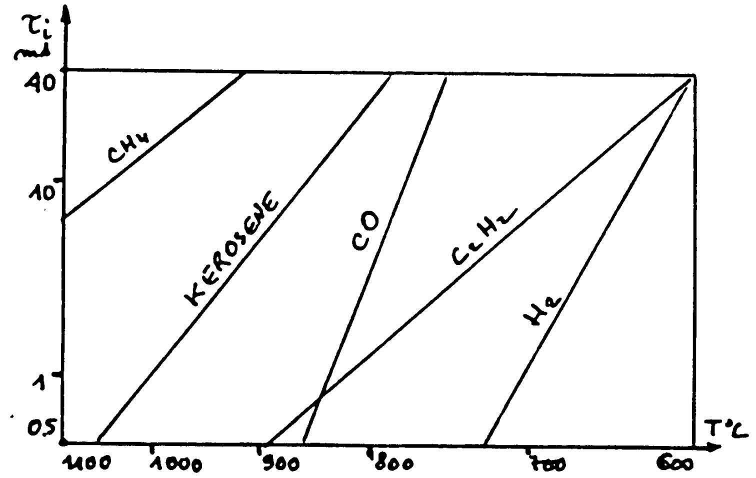


Figure 16: Délais d'autoinflammation τ_i (ms) donnés en fonction de la température initiale du mélange (^{o}C) pour différents combustibles. E. Esposito, cours de combustion, Ecole Centrale Paris

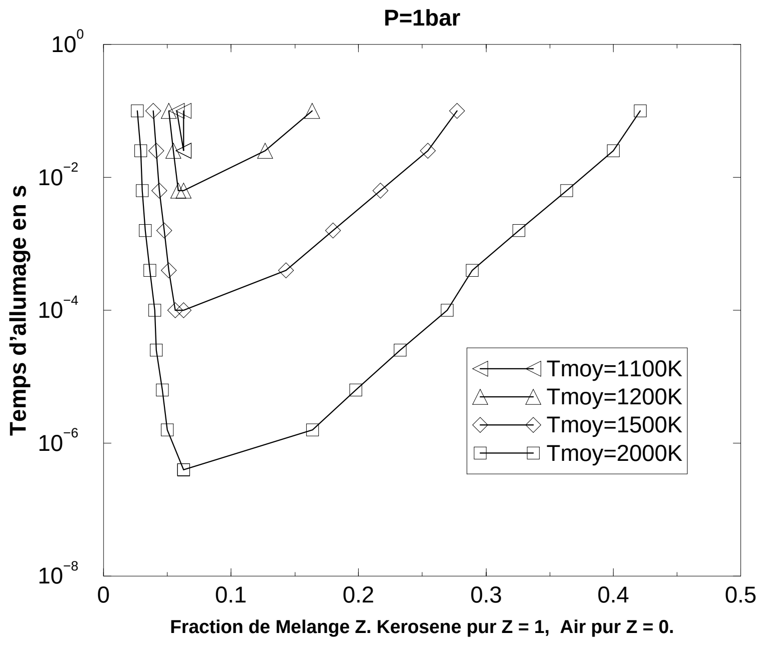


Figure 17: Délais d'auto-allumage d'un mélange kérosène/air en fonction des proportions de combustible et d'air exprimées en terme de variable de mélange Z ($Z = 0$: air pur ; $Z = 1$: kérosène pur ; $Z = Z_{st} = 0.063$: proportions stœchiométriques) pour différentes températures initiales. Simulations numériques réalisés avec une description détaillée de la cinétique du kérosène par C. François et L. Vervisch, LMFN/CORIA, INSA de Rouen.

- Elle exclut l'existence de zones de recirculation où l'inflammation a le temps de se développer : voisinage des paupières, raccordement des flux froid et chaud au niveau de la tuyère interne dans l'hypothèse d'ingestion de combustible par la prise d'air climatisation (voir § 4),...
- Les délais d'auto-inflammation sont mesurés pour un mélange air/combustible au repos porté à une température donnée. La situation lors de l'accident du Concorde est sensiblement différente puisque les gaz frais sont mélangés avec des gaz chauds issus de deux combustion successives (chambre principale, post-combustion). En outre :
  - Le mélange gaz frais / gaz chauds est turbulent. Ce mélange est alors nettemment augmenté par la turbulence et les délais d'inflammation raccourcis.
  - Les gaz chauds contiennent des produits de combustion et des radicaux. Les réactions d'initiation et de ramification, très favorisés, sont alors plus rapides, réduisant considérablement les délais d'inflammation.

B Inflammation d'un mélange kérosène/air par arc électrique

B.1 Généralités

L'énergie minimale nécessaire pour l'inflammation d'un mélange kérosène-air est de l'ordre de 0.2 mJ. Cette énergie n'est pas très élevée et est, a priori, largement disponible dans les faisceaux électriques traversant le puits de train. Cette valeur n'est toutefois réaliste que dans des conditions idéales : mélange stœchiométrique vapeur de kérosène - air, écoulement au repos, caractéristiques adéquates de l'arc,... certainement plus proches des conditions de l'inflammation dans le réservoir du vol TWA 800 que dans celles de l'accident du Concorde à Gonesse. A titre de comparaison, l'énergie d'une bougie automobile est de l'ordre de 20 mJ, pour une durée d'étincelle de 1 ms.

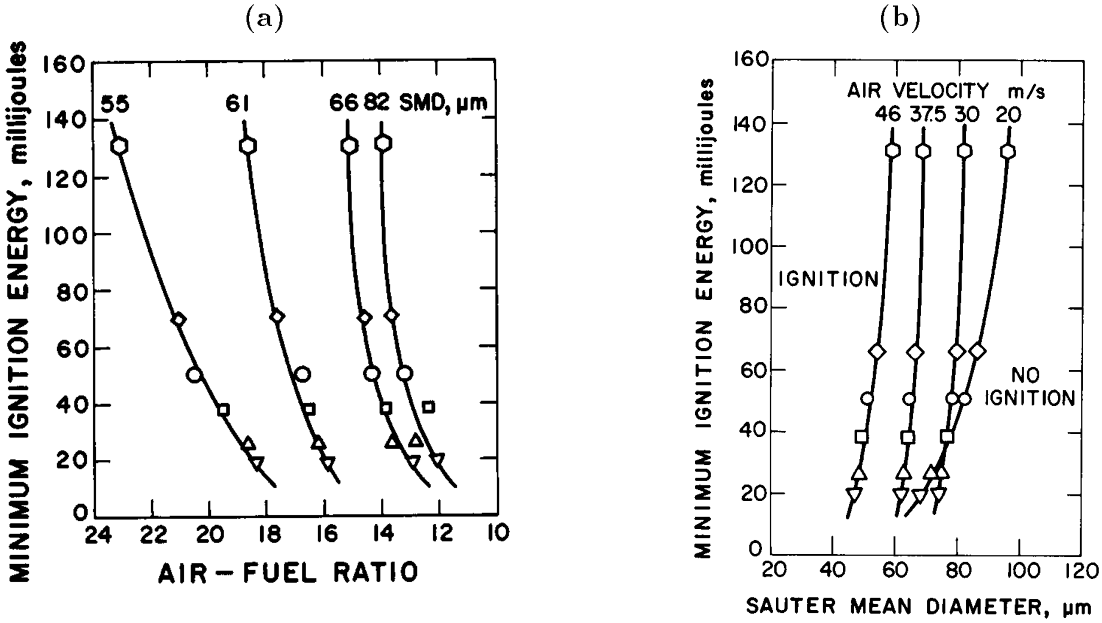


Figure 18: Energie minimale nécessaire à l'inflammation par étincelle d'un mélange gouttes de kérosène / air. (a) pour un écoulement d'air à 37.5 m/s en fonction du rapport de masse air/combustible (rapport stœchiométrique : 14.8) et de la taille moyenne des gouttes (diamètre moyen de Sauter, SMD) ; (b) pour un mélange stœchiométrique gouttes de kérosène / air, en fonction de la taille moyenne des gouttes (diamètre moyen de Sauter, SMD) pour différentes vitesses de l'écoulement d'air. Données extraites des travaux de Subba Rao et Lefebvre (1973), cités par Kuo (1986).

L'énergie nécessaire à une bougie pour enflammer un mélange gouttes de combustible / air dépend fortement d'un certain nombre de paramètres : richesse du mélange air / combustible, tailles des gouttes de kérosène, vitesse et turbulence de l'écoulement. La figure 18(a) montre l'énergie minimale nécessaire à l'allumage en fonction du rapport de masse air/combustible (le mélange stœchiométrique correspond à 14.8, voir § A) et de la taille moyenne des gouttes. L'énergie minimale est d'autant plus élevée que le rapport de masse air/combustible est élevée (les mélanges très riches ne sont pas considérés ici) et que le diamètre des gouttes est grand. Il faut noter que plus les gouttes sont grosses, plus le domaine où l'inflammation est possible est limité. Ainsi, pour des gouttes de diamètre moyen 82 μm, il est quasiment impossible d'allumer pour un rapport air/combustible supérieur à 14 (richesse inférieure à $\Phi = 1.06$) quelle que soit l'énergie disponible. Ces résultats sont confirmés par la figure 18(b) qui montre l'influence de la vitesse de l'écoulement : plus cette vitesse est élevée, plus l'allumage est difficile. Ce résultat est confirmée par la figure 19. Pour un rapport air / combustible donnée et une énergie donnée, la taille moyenne des gouttes qu'il est possible d'enflammer diminue lorsque la vitesse de l'écoulement augmente.

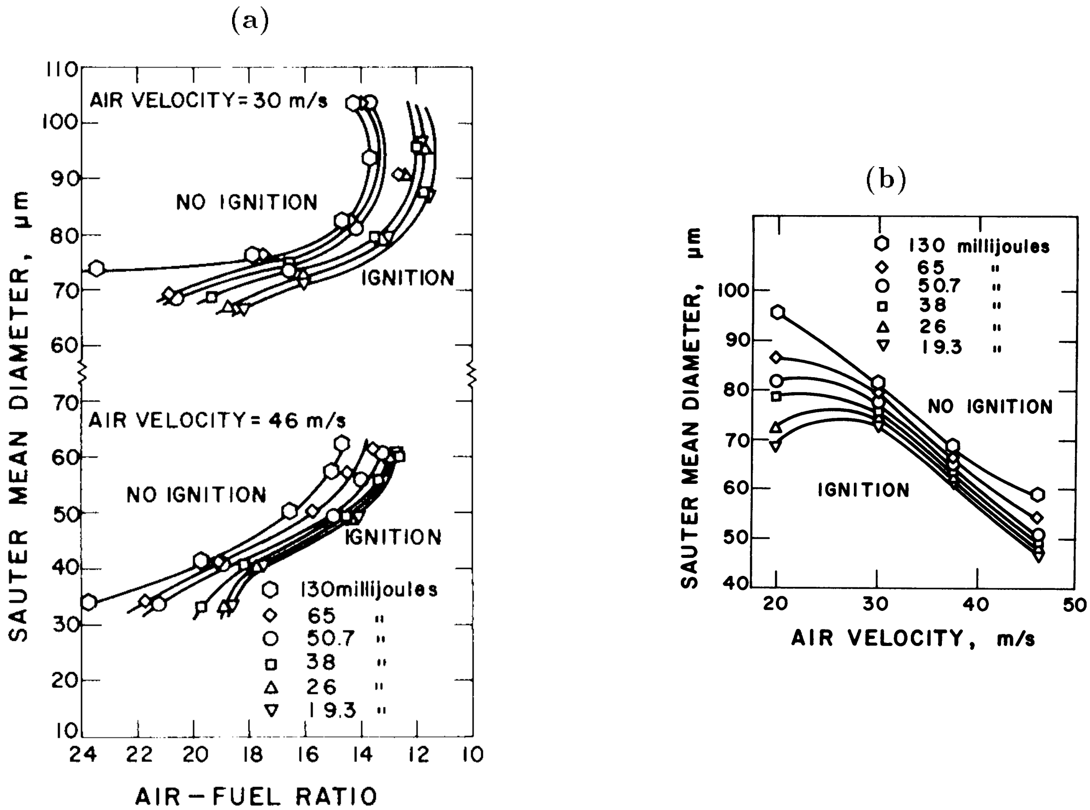


Figure 19: Limite d'inflammation d'un mélange gouttes de kérosène / air en fonction de la taille moyenne des gouttes (diamètre moyen de Sauter, SMD) et pour différents niveaux d'énergie de l'étincelle. (a) en fonction du rapport de masse air / combustible (rapport stœchiométrique : 14.8) ; (b) en fonction de la vitesse de l'écoulement pour un mélange stœchiométrique. Données extraites des travaux de Subba Rao et Lefebvre (1973), cités par Kuo (1986).

L'énergie disponible à l'étincelle n'est pas un paramètre suffisant. En effet, l'énergie requise dépend aussi sensiblement de l'écart entre les électrodes, comme le montre la figure 20. Il existe une distance optimale entre les électrodes. Une trop courte distance réclame une énergie élevée.[17] La figure 20 montre aussi que l'énergie minimale dépend également de la turbulence de l'écoulement. Plus l'écoulement est turbulent, plus les fluctuations de vitesse sont élevées et plus l'énergie nécessaire à l'inflammation est importante.

Ces résultats montrent clairement que l'inflammation par étincelle d'un mélange de kérosène et d'air est possible mais réclame des conditions très favorables : mélange quasiment stœchiométrique, faible vitesse d'écoulement, peu de turbulence, gouttes aussi fines que possible, énergie suffisante de l'arc électrique, bonne configuration de l'arc,... Cet allumage est, en pratique, délicat et requiert des précautions particulières. C'est pourquoi, en général, dans les foyers aéronautiques, comme dans d'autres systèmes, des injecteurs spéciaux sont utilisés au moment du démarrage pour assurer une pulvérisation suffisamment fine du kérosène au voisinage de (ou des) bougie(s) d'allumage, comme le montre la figure 21.

[17] Ce résultat, a priori surprenant, est dû au fait qu'il existe une taille minimale en deçà de laquelle un noyau de flamme ne peut pas se développer. il faut alors que l'énergie de l'étincelle soit suffisante pour permettre à la flamme d'atteindre cette taille.

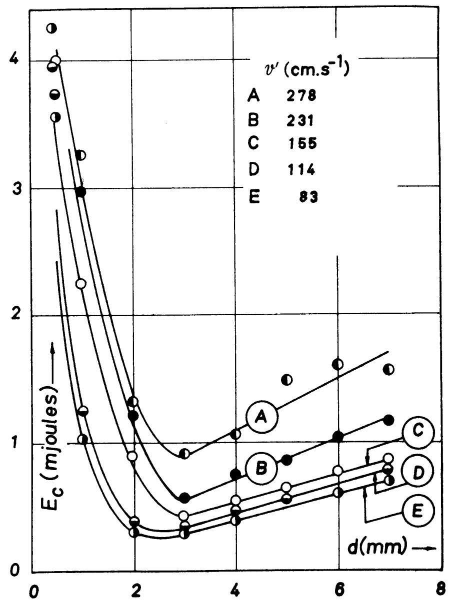


Figure 20: Influence de la distance entre les électrodes sur l'énergie minimale d'allumage par étincelle d'un mélange propane / air de richesse $\Phi = 0.8$ pour différents niveaux de turbulence. Données extraites des travaux de De Soete (1971), cités par De Soete (1976).

B.2 Commentaires relatifs à l'accident de Gonesse

Le paragraphe précédent (§ B.1) montre clairement que l'inflammation d'un mélange kérosène/air par un arc électrique, par exemple dû au sectionnement d'un faisceau électrique, est, a priori, difficile. En effet, il faut réunir des conditions extrèmement favorables tant en terme de mélange, de pulvérisation du kérosène liquide, de vitesse de l'écoulement, d'énergie et de morphologie de l'étincelle qui rendent peu probable cette situation. Rappelons que la conception du système d'allumage du kérosène dans un moteur aéronautique est, en elle-même, un challenge pour les ingénieurs qui recourent souvent à des dispositifs spécifiques (injecteurs supplémentaires dédiés).

Dans le cas de l'accident de Gonesse, vu la conception du Concorde et la nécessité d'un écoulement à faible vitesse, l'allumage par étincelle n'est sérieusement envisageable que dans le puits de train (passage de cables électriques, écoulements recirculants à faible vitesse) ou, éventuellement, dans le sillage de la jambe de train (zone de recirculation, cable alimentant les ventilateurs de frein descendant le long de la jambe). La photographie 22 présente la configuration du train principal gauche du Concorde. Elle montre, en particulier, les positions relatives des roues, du puits et de la jambe de train, ainsi que des contrefiches.

La configuration du Concorde montre que les faisceaux sont plutôt protégés d'un éclatement du pneu de la roue numéro 2. Les cables d'alimentation des ventilateurs de roues descendent le long de la face arrière de la jambe de train et donc à l'opposé de la roue 2 (photographie 23). Les cables 115 V alimentant les ventilateurs de freins sont situés au fond du puits de train et principalement vers l'avant de l'avion. Ils ne paraissent véritablement accessibles à des impacts d'objets que vers les extrémités latérales du puits. Ils semblent en outre protégés de débris issus de la roue 2 par les contrefiches et l'extrémité de la jambe de train (photographie 24). Rien ne semble aujourd'hui indiquer qu'ils aient été sectionnés lors de l'éclatement du pneu. La situation était différente lors de l'accident de Washington (14 juin 1979) puisque la roue 6 est directement à l'aplomb du puits de train et n'est pas séparée de celui-ci par les contrefiches. Des débris avaient d'ailleurs traversé complétement le puits de train.

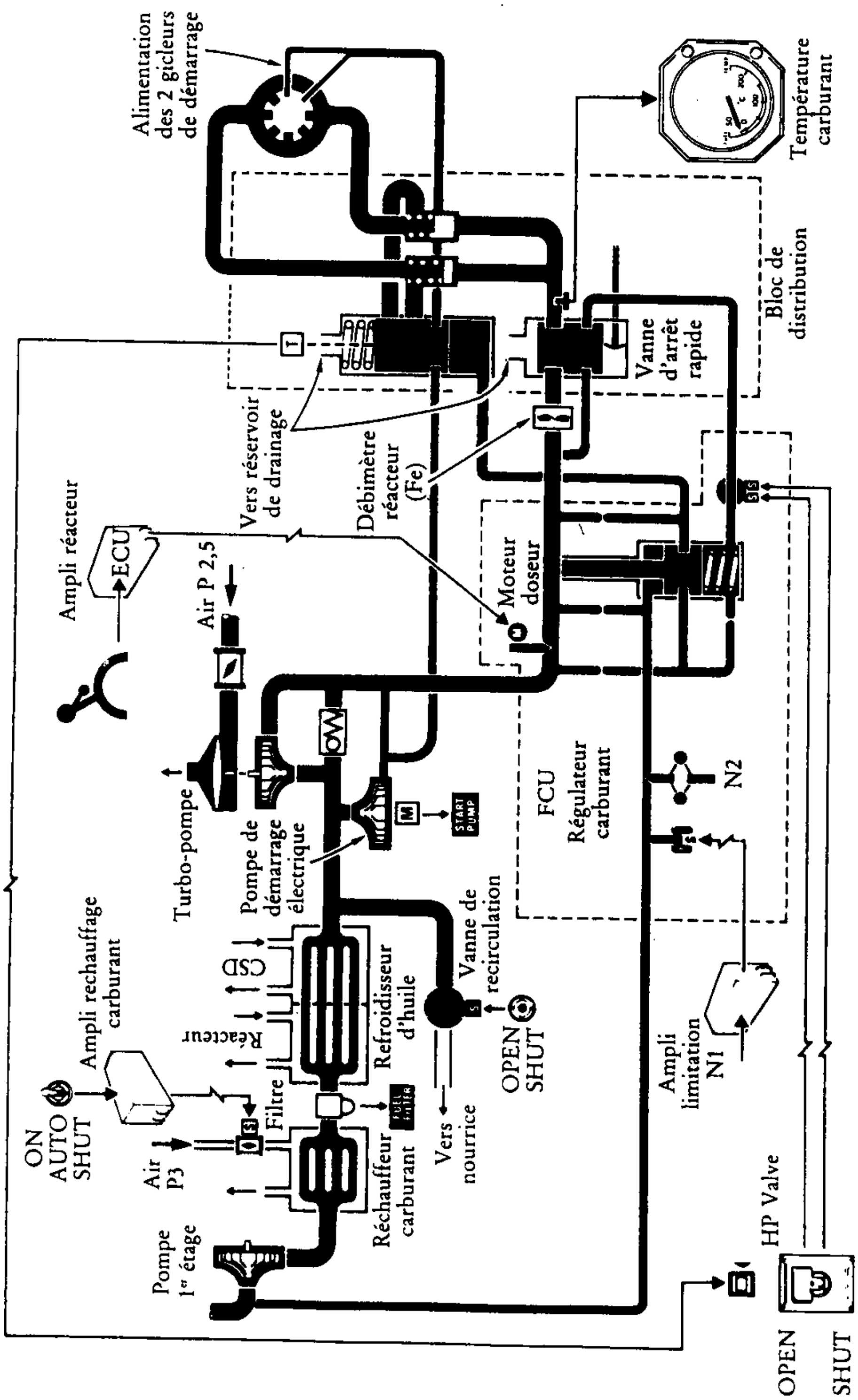


Figure 21: Schéma de principe de la distribution de combustible dans les moteurs Olympus du Concorde. Ce schéma montre en particulier le dispositif d'injection spécial destiné à l'allumage du moteur. Extrait de la documentation Air France relative au Concorde (Référence DT.NT 20/7/99 10h20 GM, I-18.00.1).

Figure 22: Photographie du train principal gauche d'un Concorde vu vers la gauche de l'appareil. La roue numéro 2, incriminée dans l'accident de Gonesse est la roue au premier plan à droite. Les roues en cause dans l'accident de Washington (14 juin 1979) sont les deux roues arrières du train (5 et 6). Photographie BEA prise sur un Concorde d'Air France à Roissy le 8/12/2000.

Figure 23: Photographie de la jambe du train principal gauche d'un Concorde. L'avant de l'appareil est vers la gauche de l'image. Les cables d'alimentation des ventilateurs de roues descendent le long de la face arrière de la jambe. Photographie BEA prise sur un Concorde d'Air France à Roissy le 8/12/2000.

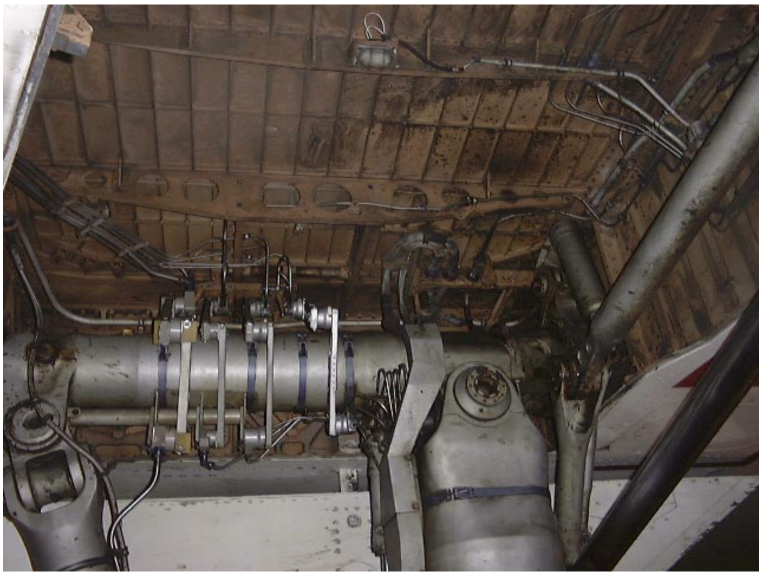


Figure 24: Photographie du puits du train principal gauche d'un Concorde. L'avant de l'appareil se trouve vers la droite de l'image. Les cables électriques sont essentiellement situés au fond du puits et paraissent protégés d'impacts de débris issus de la roue 2 par les contrefiches (deux des trois contrefiches sont visibles, la troisième est clairement apparente sur la photographie 22). Photographie BEA prise sur un Concorde d'Air France à Roissy le 8/12/2000.

Compte tenu du débit estimé de la fuite, un jet de kérosène liquide conséquent s'échappe de la perforation du réservoir 5, localisée 25 cm en amont du puits de train (photographie 25). Ce jet interagit violemment avec un écoulement d'air transversal de 100 m/s, dû à la vitesse de l'avion. Dans ces conditions, le jet liquide est pulvérisé en fines gouttelettes à sa périphérie tandis que des grosses gouttes, voire des paquets de combustible liquide s'échappent de sa partie aval, comme schématisé sur la figure 26. Il est donc probable que du kérosène liquide pénétre, entrainé par l'écoulement, dans le puits de train mais plutôt sous forme de gros paquets que de fines gouttelettes. Dans ces conditions, l'inflammation d'un tel milieu parait difficile, voire impossible.

B.3 Conclusions

L'allumage par étincelle d'origine électrique d'un mélange kérosène liquide / air n'est possible que dans des conditions trés particulières[18] : pulvérisation suffisamment fine du kérosène, proportions quasiment stœchiométriques des réactifs, faibles vitesses et faible niveau de turbulence de l'écoulement, énergie suffisante de l'étincelle dont la forme doit être adéquate,... Compte tenu des conditions observées dans l'accident de Gonesse, il est très peu probable que toutes ces conditions aient pu être réunies, même si, en toute rigueur, cette hypothèse ne puisse être complétement exclue. En outre, rien ne prouve la rupture d'un cable électrique suite à une projection de débris. Enfin, ce scénario ne correspond pas aux témoignages très précis recueillis sur l'initiation de la flamme lors de l'accident (voir annexe F).

[18] L'inflammation du kérosène est d'ailleurs réputé difficile : il est possible d'éteindre une allumette ou une cigarette dans un bac contenant du kérosène. Expérience à ne pas tenter avec l'essence ! Par ailleurs, un collègue chercheur au CNRS nous a appris que pour allumer des feux de nappes de kérosène (études de sécurité incendie), les difficultés d'inflammation l'obligent à recourir à des dispositifs pyrotechniques.

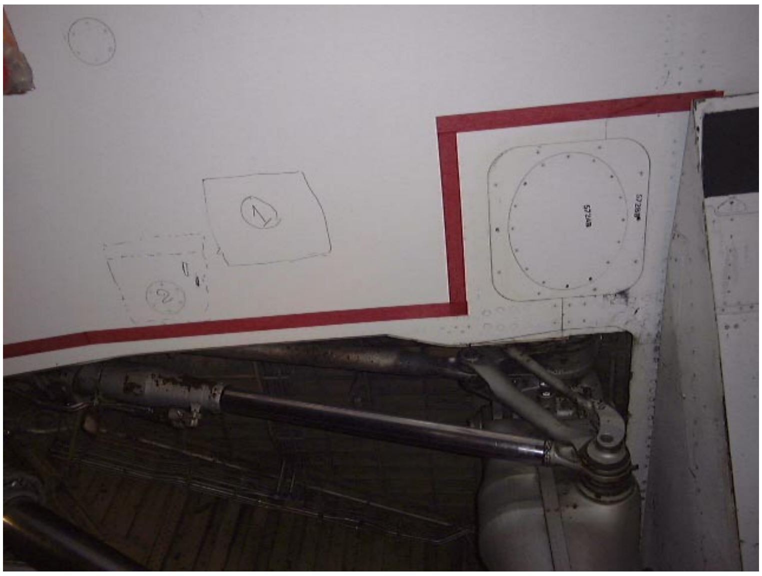


Figure 25: Photographie du puits du train principal gauche d'un Concorde. L'avant de l'appareil se trouve vers le haut de l'image. Le cadre indiqué (1) correspond à la fuite de kérosène du réservoir 5. Photographie BEA prise sur un Concorde d'Air France à Roissy le 8/12/2000.

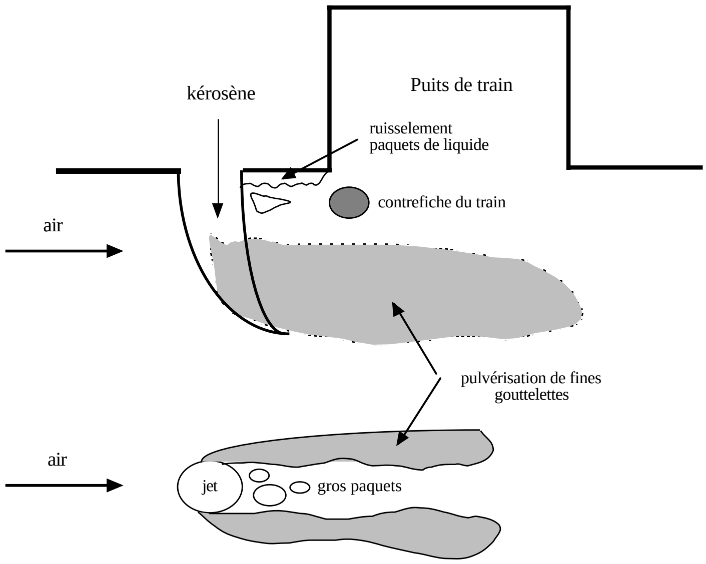


Figure 26: Schématisation de la fuite de jet liquide. En haut : vue latérale, en bas : vue de dessus. Compte tenu des conditions, le jet est pulvérisé en fines gouttelettes à sa périphérie et à son extrémité, tandis que des gros paquets de liquide se détachent en aval et son probablement entrainés dans le puits de train.

C Expérience dite de la "flamme-pilote" (ONERA)

Cette expérience conduite à l'ONERA (Office National d'Etudes et de Recherches Aérospatiales) par Pierre Moreau (Moreau 1981) a été conçue pour étudier une flamme turbulente prémélangée. La configuration retenue est schématisée sur la figure 27. Un jet turbulent prémélangé méthane/air (vitesse d'injection 55 m/s) est enflammé par un jet de gaz brûlés chauds (température 2000 K, vitesse 110 m/s) issus d'une première combustion. Le jet de gaz chauds fournit l'énergie qui permet la stabilisation de la flamme, d'où l'appellation de "flamme-pilote".[19]

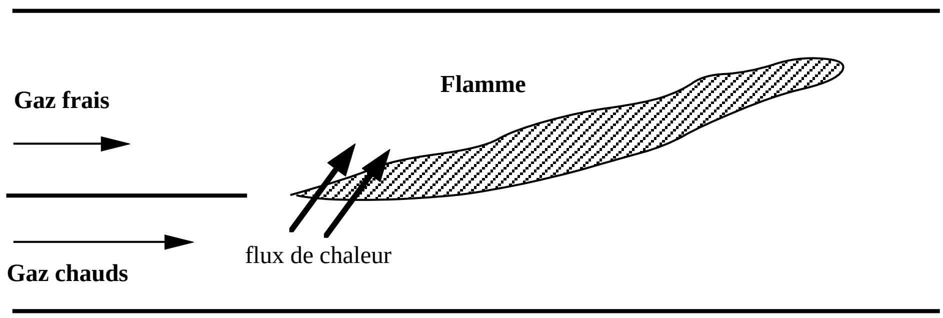


Figure 27: Expérience de P. Moreau (ONERA). Une flamme turbulente prémélangée méthane/air est stabilisée par un jet de gaz brûlés issus d'une première combustion. La chambre de combustion a une section carrée 100×100 mm^2 (section d'entrée des gaz frais : 80×100 mm^2 ; des gaz brûlés : 19×100 mm^2. Les vitesses des écoulements sont élevées : 55 m/s pour les gaz frais prémélangés, 110 m/s pour le jet de gaz brûlés qui joue le rôle d'une flamme-pilote en fournissant l'énergie nécessaire à l'inflammation du mélange méthane/air (Moreau 1981).

Il faut noter que dans cette configuration, les vitesses des écoulements, respectivement 55 et 110 m/s, sont trop importantes pour qu'une flamme prémélangée turbulente puissent les soutenir (la vitesse de flamme turbulente, dans ces conditions, est de l'ordre de 10 m/s). Les gaz frais sont ici chauffés par les flux thermiques apportés par les gaz brûlés permettant l'inflammation des réactifs et la stabilisation de la flamme.

[19]Les flammes-pilote sont souvent utilisées pour stabiliser des flammes turbulentes non-prémélangées, notamment dans les fours industriels : des petites flammes prémélangées, situées à la base de la flamme principale garantissent un accrochage stable de la flamme (Poinsot and Veynante 2001).

D Couches limites - sillages

D.1 Généralités sur les couches limites

Les couches limites sont des zones où un écoulement, parallèle à une paroi, est perturbé par la présence de cette paroi (Fig. 28). Ces couches limites, situation générique de l'interaction écoulement / paroi, ont fait l'objet de nombreuses études, résumées, par exemple dans l'ouvrage de Schlichting (1987).

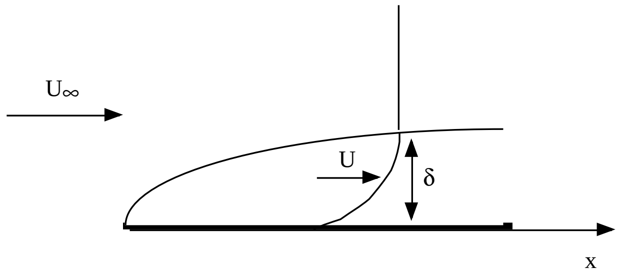


Figure 28: Schématisation d'une couche limite. L'écoulement de vitesse U_∞ est perturbé par la présence d'une paroi parallèle à celui-ci. L'épaisseur de la couche perturbée est δ.

Cette pertubation se traduit déjà par une réduction de la vitesse moyenne de l'écoulement au voisinage de la paroi où, par frottement, cette vitesse est nulle. Avec les notations de la figure 28, Schlichting (1987) donne pour l'épaisseur δ et le profil de vitesse U dans la couche limite les valeurs suivantes :

$$\delta(x) = 0.37x\left(\frac{U_\infty x}{\nu}\right)^{-1/5} \tag{15}$$

$$U(x,y) = U_\infty\left(\frac{y}{\delta(x)}\right)^{1/7} \tag{16}$$

où ν est la viscosité de l'air ($\nu \approx 2.10^{-5}\, m^2/s$) et U_∞ la vitesse amont de l'écoulement. L'origine de la coordonnée x est au bord d'attaque de la paroi tandis que y mesure la distance perpendiculairement à celle-ci.

Dans le cas du Concorde, la vitesse U_∞ correspond à la vitesse de l'avion, soit $U_\infty \approx 100\, m/s$. A une distance $x_1 = 10\, m$, ordre de grandeur de la distance du bord d'attaque au bord de fuite de l'aile au niveau de la nacelle des moteurs, $\delta(x_1) \approx 0.11\, m$, ce qui n'est pas négligeable. Par contre, la vitesse moyenne $U(x_1, y_1) = 10\, m/s$, ordre de grandeur de la vitesse de flamme maximale, est atteinte à la distance $y_1 \approx 1.1\, 10^{-8}\, m/s$ de la paroi, ce qui est infime et semble exclure la possibilité d'une remontée de la flamme le long de la couche limite. Il ne faut toutefois pas perdre de vue que la formule (16) suppose une plaque plane lisse. Il est, en effet, connu que toute rugosité de la paroi ou la présence d'un obstacle favorisera considérablement le développement de la couche limite et l'apparition de zones à faibles vitesses. Ainsi, le kérosène liquide ruisselant le long de l'aile et de la nacelle favorisera le développement de la couche limite (§ D.4.1).

En pratique, une couche limite est le siège de phénomènes fortement instationnaires et l'information sur la vitesse moyenne (Eq. 16) n'est pas suffisante. De larges structures cohérentes sont clairement apparentes, comme le montre les photographies 29 et 30. Ces structures s'étendent à travers toute la couche limite comme schématisé sur la figure 31 ("hairpin eddies" ou tourbillons en épingle à cheveux). Elles sont aussi pour effet d'entrainer du fluide externe au voisinage de la paroi. L'extension à travers toute l'épaisseur de la couche limite de ces structures est confirmée par les signaux de vitesse mesurés simultanément pour une même abscisse à différentes distances de la paroi (Fig. 32).

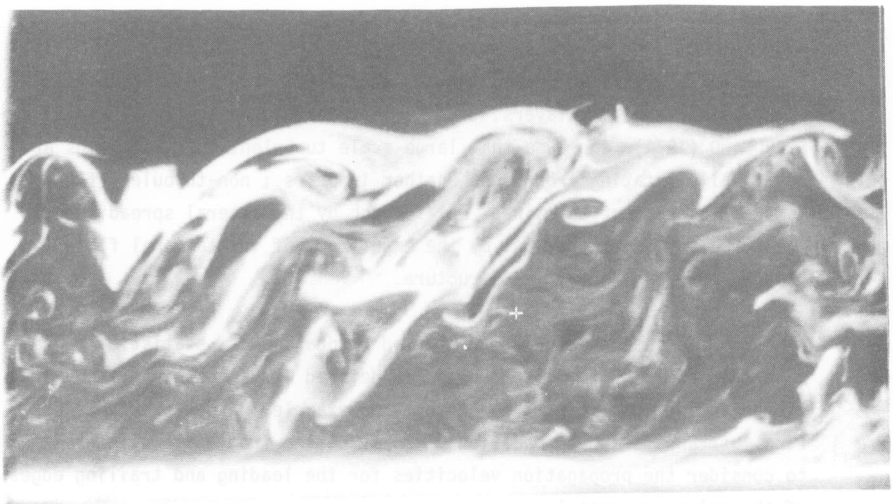


Figure 29: Visualisation d'une couche limite turbulente ensemencée par de la fumée ($U_\infty = 2.5\, m/s$, $x = 3.5\, m$). L'entrainement de fluide externe à l'intérieur de la couche limite est clairement apparent. Travaux de Wallace, Schon, Ladhari et Morel (Ecole Centrale de Lyon), cités par Comte-Bellot and Morel (1983).

Figure 30: Visualisation d'une couche limite turbulente ensemencée par de la fumée. De larges structures cohérentes sont apparentes sur toute l'épaisseur de la couche limite (Falco 1977).

Malgré ce que pourrait laisser croire l'expression (16), une couche limite n'est pas non plus homogène dans la troisième direction, parallèle à la paroi mais perpendiculaire à la direction de l'écoulement. Des mesures soignées montrent l'existence de structures tourbillonnaires ayant le même axe que l'écoulement et séparées par des zones de vitesses lentes, comme le schématise la figure 33. Ces zones sont nettement apparentes sur les mesures de vitesses effectuées dans un plan parallèle à la paroi (Fig. 34). De temps à autres, ces structures sont balayées puis se reconstituent ("bursting phenomenon"). Elles n'en constituent pas moins des régions favorables à la remontée d'une flamme.

Si la connaissance des caractéristiques moyennes, profil de vitesse moyenne (Eq. 16) ou épaisseur

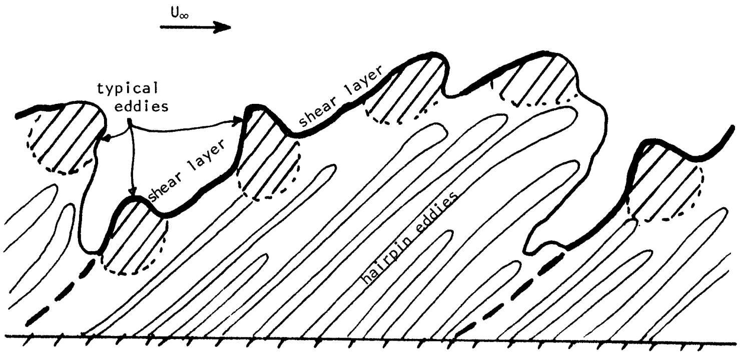


Figure 31: Schématisation des structures tourbillonnaires observées dans une couche limite (Blackwelder 1983c).

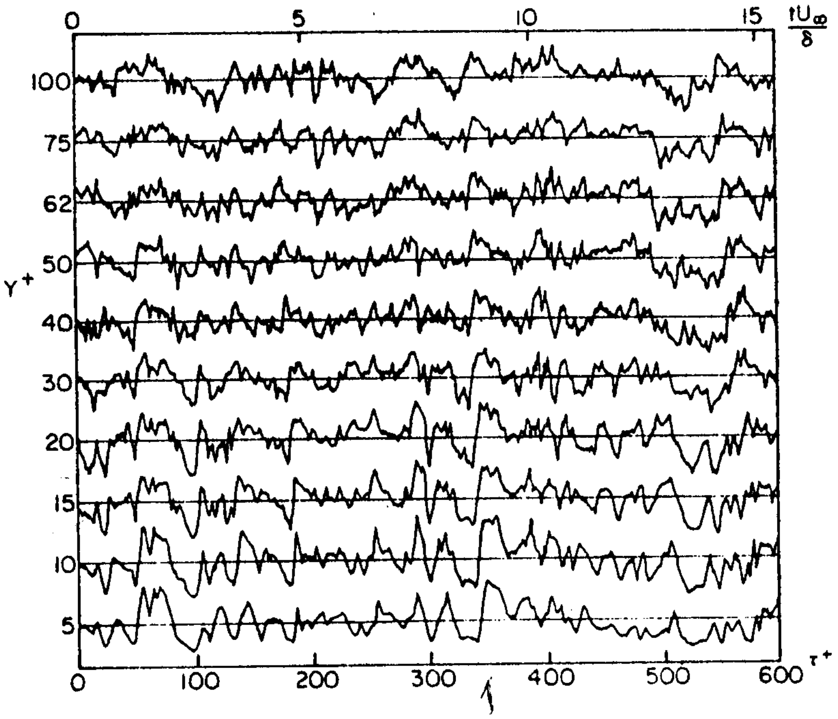


Figure 32: Evolutions temporelles simultanées de la vitesse transversale dans une couche limite à différentes distances de la paroi. La corrélation de ces signaux montre l'extension verticales des structures tourbillonnaires. Une grande structure, affectant toute l'épaisseur de la couche limite est nettement visible pour $\tau^+ \approx 350$. (Blackwelder 1983b).

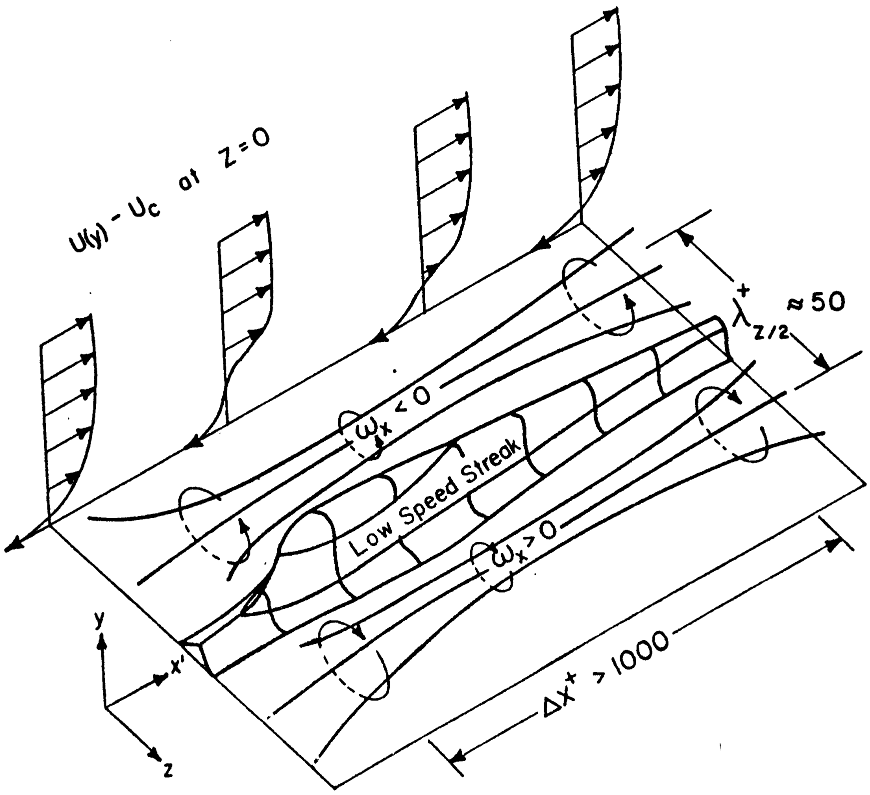


Figure 33: Schématisation des structures tourbillonnaires tri-dimensionnelles observées dans une couche limite. Ces structures sont séparées par des zones à faibles vitesses (Blackwelder 1983a).

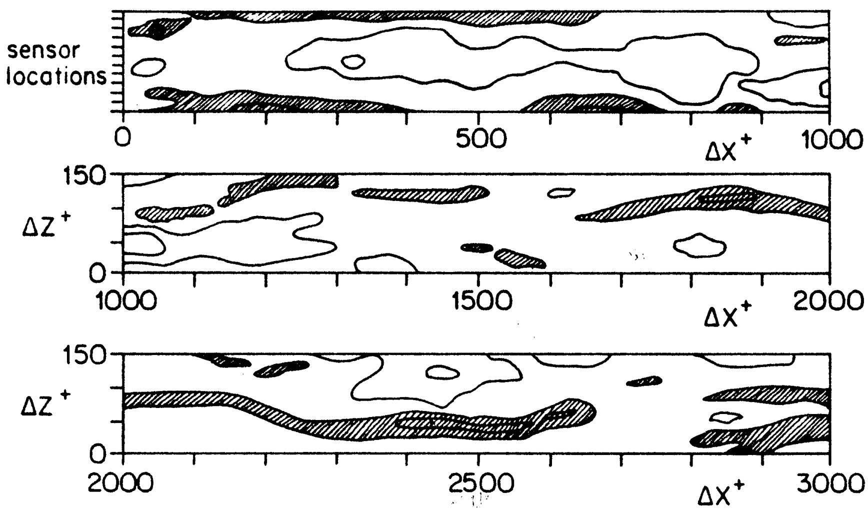


Figure 34: Mesures de vitesses axiales (direction de l'écoulement) dans un plan parallèle au voisinage d'une paroi. Les régions hachurées correspondent à des zones de failbles vitesses, c'est à dire sensiblement inférieures à la vitesse moyenne locale (Blackwelder 1983a).

(Eq. 15), d'une couche limite suffit pour de nombreuses applications, elle ne permet pas de décrire la structure fine de l'écoulement. Les écoulements turbulents sont le siège de phénomènes d'intermittence, alternance au cours du temps de poches de fluides de caractéristiques différentes. Il faut alors être très prudent avec l'interprétation des grandeurs moyennes. Ainsi, une vitesse moyenne de 90 m/s ne signifie pas forcément que la vitesse instantanée de l'écoulement oscille autour de 90 m/s. Elle peut très bien correspondre à l'alternance de poches de fluide de vitesse 100 m/s pendant 90 % du temps et de vitesse 5 m/s (passage d'une grande structure tourbillonnaire) pendant 10 % du temps correspondant à un niveau de fluctuations moyennes faible. La remontée d'une flamme le long de l'aile ou du carénage des moteurs du Concorde sera pourtant possible dès que la vitesse locale de l'écoulement est suffisamment faible, même pendant un temps très court, sans oublier que la présence de la flamme perturbera sensiblement l'écoulement afin de favoriser sa propagation (Annexe D.4).

D.2 Généralités sur les sillages

Un obstacle placé dans un écoulement induit le développement d'un sillage en son aval (Fig. 35), c'est à dire une zone où l'écoulement est plus ou moins fortement perturbé par la présence de l'obstacle. Cette perturbation se traduit tout d'abord par un déficit de vitesse moyenne : l'écoulement est fortement ralenti (la vitesse est quasiment nulle juste derrière l'obstacle avant de reprendre progressivement sa valeur initiale). Schlichting (1987) a aussi proposé des corrélation pour le défaut de vitesse maximal $u_d = U_\infty - U_{min}$ dans le sillage d'un obstacle cylindrique de diamètre d et pour la demi-largeur du sillage b :

$$\frac{u_d}{U_\infty} \approx \sqrt{\frac{C_D d}{\beta x}} \tag{17}$$

$$b \approx \sqrt{\beta C_D d x} \tag{18}$$

avec $C_D \approx 1$ et $\beta \approx 0.18$.

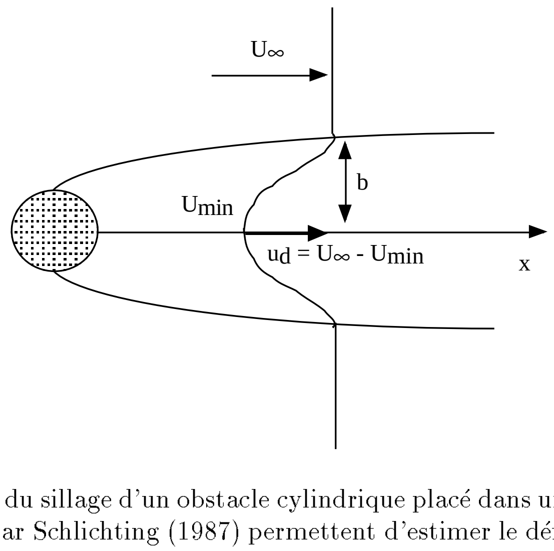


Figure 35: Schématisation du sillage d'un obstacle cylindrique placé dans un écoulement libre à vitesse U_∞. Les corrélations proposées par Schlichting (1987) permettent d'estimer le déficit de vitesse $u_d = U_\infty - U_{min}$, où U_{min} est la vitesse minimale atteinte dans le sillage, et sa demie épaisseur b en fonction de la distance x en aval de l'obstacle.

Dans le cas du Concorde, pour un fût de train d'atterrissage de $d = 0.5\,m$ de diamètre, placé dans un écoulement libre à $U_\infty = 100\,m/s$, vitesse de décollage de l'avion, la vitesse minimale ne vaut que $U_{min} = 1\,m/s$ ($u_d = 99\,m/s$) à $x \approx 2.8\,m$ en aval du train (largeur du sillage : $2b \approx 1.0\,m$). La vitesse minimale $U_{min} = 10\,m/s$ ($u_d = 90\,m/s$) n'est atteinte qu'à environ $x = 3.4\,m$ en aval du train. Le sillage atteint à cet endroit une épaisseur de $2b \approx 1.1\,m$. Dix mètres en aval de l'obstacle, la vitesse minimale moyenne vaut environ $48\,m/s$ pour un sillage d'environ $1.9\,m$ de large.

Comme pour les couches limites, les profils de vitesse moyenne sont suffisants pour un certain nombre d'application, notamment évaluer la trainée de l'obstacle. En revanche, ils ne permettent pas non plus de caractériser la structure de l'écoulement qui présente un détachement de structures tourbillonnaires, connu, au moins pour les relativement faibles vitesses, sous le nom d'allées de Von-Karman et schématisé sur la figure 36.

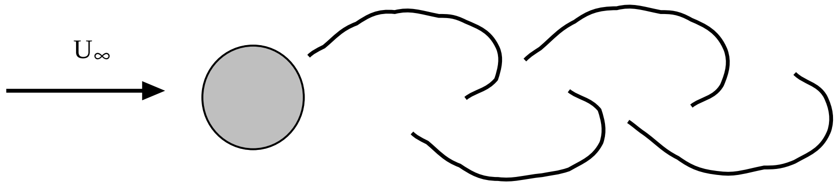


Figure 36: Schématisation du détachement tourbillonnaire appellé “allées de Von-Karman”, observé dans le sillage d'un obstacle cylindrique placé dans un écoulement libre à vitesse U_∞.

Là encore, les phénomènes d'intermittence ne sont pas négligeables (passage, en alternance, en un point donné de l'écoulement libre non pertubée et de structures tourbillonnaires à vitesse plus faible) et n'affectent pas forcément les profils de vitesse moyenne de manière très importante. Les structures tourbillonnaires peuvent subsister assez loin en aval de l'obstacle. Ainsi, il nous a été signalé que les structures dues au train avant du Concorde affectent légérement le fonctionnement du moteur 4 de l'avion au moment de la rotation.[20]

D.3 Concorde : une géométrie complexe

Lors des paragraphes précédents, la pertubation d'un écoulement par des obstacles n'a été envisagée que pour des cas simples et académiques, couches limites et sillage. La géométrie réelle du Concorde est beaucoup plus complexe comme l'attestent les photographies 22 et 37 à 40. En phase de roulage de l'avion, l'écoulement en aval du train d'atterrissage du Concorde est certainement beaucoup plus perturbé que ne le laissent supposer les expressions (15), (16), (17) et (18).

En effet, le train principal de l'avion ne se réduit pas à un simple cylindre : présence de deux contrefiches obliques (photographies 37 et 38), voisinage de l'aile, du puits de logement du train et surtout du carénage du réacteur. Le développement de couches limites importantes et d'un sillage très marqué est favorisé par tous ces élements.[21] Le train est quasiment tangent à la nacelle moteurs : le sillage du train interagit donc directement avec les couches limites à la fois sous l'aile et le long de la nacelle. La trappe du puits de train est en contact avec la jambe de train et touche pratiquement la nacelle au niveau de l'entrée d'air. Aile et nacelle forment un “coin” favorable au

[20] La situation des moteurs 1 et 4 est symétrique mais tous les moteurs tournent dans le même sens (la symétrie complète du système supposerait que les moteurs 1 et 4 ont des sens de rotation opposés). Le moteur 1 n'est, en pratique, pas affecté par le détachement tourbillonnaire dû au train avant de l'avion.

[21] Remarquons qu'en assimilant le train et ses contrefiches à un “obstacle équivalent” cylindrique de $d = 1\,m$ de diamètre conduit à des vitesses moyennes minimales de 1 et 10 m/s à des distances respectives de 5.7 m et 6.8 m en aval de l'obstacle. A 10 m en aval de ce dernier, la vitesse moyenne minimale est d'environ 25 m/s.

Figure 37: Photographie du train principal gauche d'un Concorde de l'avant vers l'arrière de l'appareil. Photographie BEA prise sur un Concorde d'Air France à Roissy le 8/12/2000.

développement de zones à faibles vitesses (photographies 39 et 40), surtout que ce coin n'est pas constitué de deux plans perpendiculaires : l'aile présente un renflement, séparé de la nacelle par un retrait, schématisés sur la figure 41 où l'écoulement ne peut prendre des vitesses élevées.

D.4 Perturbations de l'écoulement lors de l'accident de Gonesse

Jusqu'à présent n'a été envisagé que le cas d'écoulements d'air au voisinage d'une plaque plane (Annexe D.1), dans le sillage d'un obstacle cylindrique (Annexe D.2). L'extrapolation à la géométrie complexe du Concorde est plus délicate mais laisse supposer la présence sous l'aile, en phase de roulage, de couches limites et de sillage fortement perturbés susceptibles de favoriser la remontée d'une flamme (Annexe D.3). Il ne faut pas oublier de prendre en compte deux phénomènes supplémentaires, spécifiques à l'accident de Gonesse et eux aussi favorisant la remontée éventuelle d'une flamme : les perturbations de l'écoulement par le kérosène liquide et par la flamme elle-même.

Figure 38: Photographie du train principal gauche d'un Concorde de l'arrière vers l'avant de l'appareil. Photographie BEA prise sur un Concorde d'Air France à Roissy le 8/12/2000.

Figure 39: Photographie du raccord entre la nacelle moteurs gauche et l'aile d'un Concorde, vu vers l'avant de l'appareil. Photographie BEA prise sur un Concorde d'Air France à Roissy le 8/12/2000.

Figure 40: Photographie de détail du raccord entre la nacelle moteurs gauche et l'aile d'un Concorde, vu vers l'arrière de l'appareil. La partie sombre au centre de l'image et au raccord de l'aile correspond à la prise d'air du climatiseur. Photographie BEA prise sur un Concorde d'Air France à Roissy le 8/12/2000.

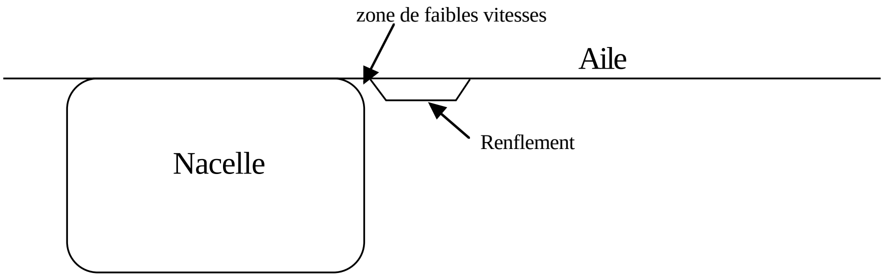


Figure 41: Schématisation du raccordement aile / nacelle moteurs d'un Concorde. Au voisinage de ce raccordement, un léger retrait peut induire le développement d'une zone à faibles vitesses favorable à la remontée d'une flamme.

D.4.1 Perturbation de l'écoulement par le kérosène liquide

L'une des caractéristiques de l'accident du 25 juillet 2000 est le fort débit de la fuite de kérosène : de 50 à 100 kg/s selon nos estimations, valeurs compatibles avec les mesures ultérieures de EADS (de 50 à 180 kg/s). La vitesse à laquelle s'échappe le liquide est de l'ordre de 1 m/s pour un trou du réservoir de 0.3×0.3 m^2 (voir § 2). Ce débit est de l'ordre de 10 à 30 fois le débit nominal d'un moteur Olympus à pleine puissance.

Dans ces conditions, il est évident qu'un film de kérosène s'est développé et a ruisselé le long de l'aile et de la nacelle moteurs coté intérieur.[22] Un tel film est susceptible de perturber fortement le développement de la couche limite dont la croissance sera plus importante que ne le laissent croire les expressions du paragraphe D.1. Il favorise aussi la remontée éventuelle d'une flamme car il constitue une zone combustible à faible vitesse.

[22]La fuite de kérosène était telle qu'une nappe liquide a même été retrouvée sur les dalles 163, 164 et 165, soit sur une surface d'environ 15 m $\times$ 10 m.

D.4.2 Perturbation de l'écoulement par la flamme

La flamme elle-même peut perturber l'écoulement en amont en induisant une déflection des lignes de courant par les effets d'expansion thermique. Cette situation est connue pour les flammes triples (Fig. 42 ; Phillips 1965; Kioni et al. 1998). Elle est observée pour les flammes de diffusion où combustible et oxydant sont injectés séparement dans la zone de réaction, lorsque la flamme est légérement détachée de l'injecteur. Ces flammes triples doivent leur nom à la présence de trois zones de réaction distinctes : la flamme de diffusion proprement dite qui se développe en aval du brûleur et deux ailes correspondants à des flammes prémélangées (combustible et oxydant sont partiellement mélangés) respectivement riche (combustible en excès) et pauvre (combustible en défaut).

Dans cette situation, l'expansion thermique due à la combustion provoque une déviation des lignes de courant en amont de la flamme (la flamme perturbe l'écoulement qui vient à sa rencontre). La flamme est capable de s'opposer à des vitesses d'écoulements sensiblement supérieures à la vitesse d'une flamme plane, comme le montre la figure 43.

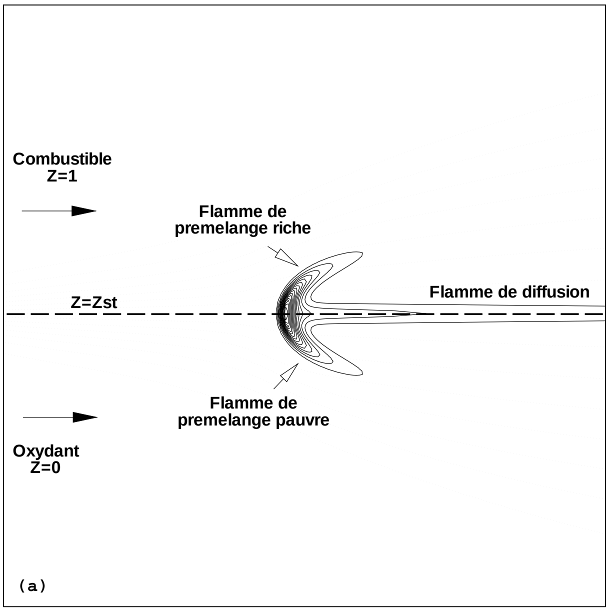


Figure 42: Flamme triple stabilisée dans un écoulement de combustible et d'oxydant introduits séparément dans la zone de réaction. Le dégagement de chaleur de la flamme induit une expansion thermique de l'écoulement qui modifie la structure de celui-ci devant la flamme. Les lignes de courant (pointillés) sont alors déviées et la flamme peut se propager à une vitesse supérieure à celle attendue sans tenir compte de la déviation de l'écoulement (Ruetsch et al. 1995).

Ce type de phénomène a clairement pu se produire sous l'aile du Concorde : la flamme allumée par les gaz chauds issus du moteur et stabilisée sur la sortie des réacteurs (voir Annexe F) a certainement induit une déviation suffisante de l'écoulement et de ses lignes de courant pour générer au niveau de la paroi de la nacelle moteurs une zone de vitesse suffisamment lente pour favoriser la remontée d'une flamme, comme illustré sur la figure 44.

Ce type de remontée de flamme a déjà été observé au laboratoire E.M2.C. dans le cas d'un obstacle au voisinage d'une paroi (Fig. 45). Il a même conduit à un résultat a priori surprenant : dans cette situation, la flamme peut même venir s'accrocher en amont de l'obstacle ! En fait, en raison de la forme anguleuse de l'obstacle, le décollement de l'écoulement est tel que la flamme arrive à remonter suffisamment pour s'accrocher dans la zone de recirculation en amont de celui-ci.

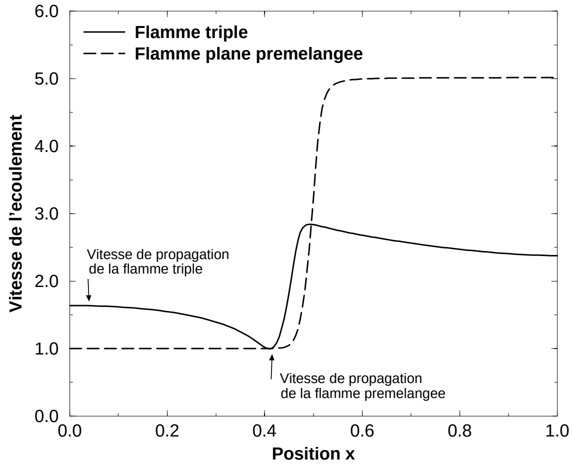


Figure 43: Profils de vitesse sur l'axe d'une flamme triple (ligne $z = z_{st}$ de la figure 42) et d'une flamme prémélangée laminaire stœchiométrique de référence (vitesse maximale atteinte par une flamme laminaire plane). L'expansion thermique au sein de la flamme prémélangée plane se traduit par une accélération après la position $x = 0.5$. La vitesse locale maximale de la flamme triple, stabilisée aux environs de $x = 0.4$, correspond exactement à celle de la flamme prémélangée mais, en raison de la déviation de l'écoulement induite par la flamme, celle-ci est capable de supporter des vitesses d'écoulements supérieures (ici environ 60 % plus élevées, comme l'indique la courbe de la flamme triple pour $x = 0$). Extrait de Ruetsch et al. (1995).

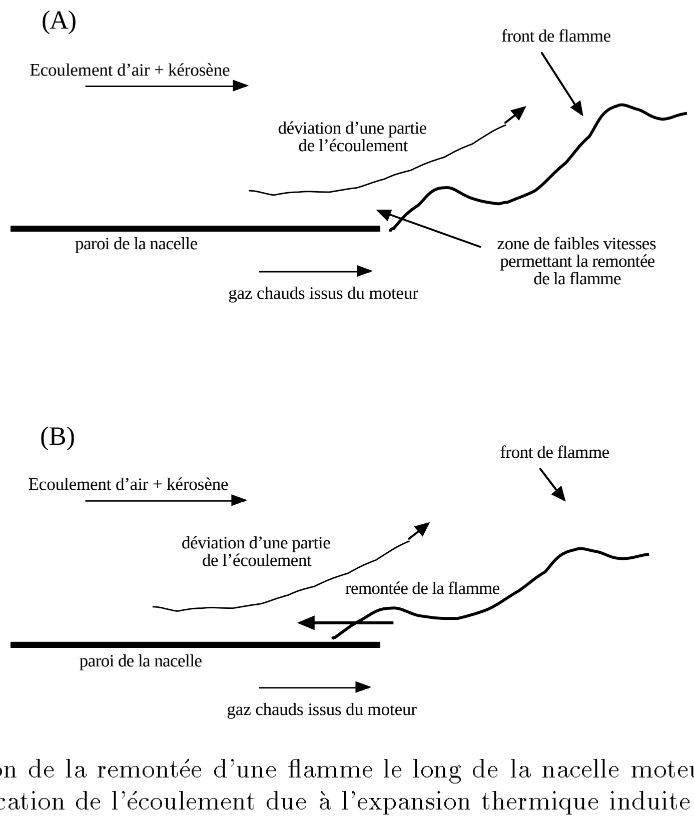


Figure 44: Schématisation de la remontée d'une flamme le long de la nacelle moteurs. Cette remontée est favorisée par la modification de l'écoulement due à l'expansion thermique induite par la flamme. (A) flamme accrochée au niveau de la sortie du réacteur ; (B) remontée de la flamme.

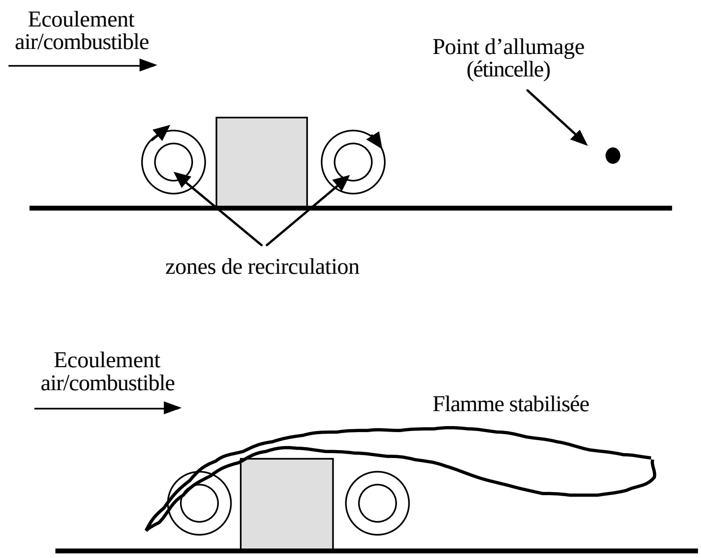


Figure 45: Schématisation de la remontée d'une flamme le long de couches limites pour s'accrocher en amont de l'obstacle. Résultats expérimentaux observés au laboratoire E.M2.C. En haut, situation au moment de l'allumage par étincelle ; En bas, flamme stabilisée en amont de l'obstacle.

E Propagation d'une flamme dans un milieu partiellement prémélangé turbulent

Les mécanismes de propagation des flammes dans un milieu où combustible et oxydant ne sont pas parfaitement mélangés, donc dans un milieu présentant des fluctuations de richesse, ne sont pas encore bien connus et parfois sujets à de nombreuses controverses.[23] Néanmoins, divers résultats expérimentaux récents permettent de mettre en évidence quelques points aujourd'hui acquis et qui ne doivent pas être oubliés lors de l'examen de l'accident de Gonesse.

L'un des ces points concerne l'ordre de grandeur des vitesses : *la simple comparaison entre la vitesse de propagation d'un front de flamme turbulent et la vitesse moyenne de l'écoulement n'est pas un critère suffisant pour déterminer les possibilités de propagation à contre courant d'une zone de combustion* car cette propagation est controlée par les vitesses locales instantanées de l'écoulement. On trouve par exemple dans la littérature des flammes de méthanol, combustible liquide, stabilisées dans un écoulement d'air dont la vitesse varie entre 40 et 150 m/s (Stepowski, Cessou, and Goix 1994; Cessou and Stepowski 1996). Une telle expérience est schématisée sur la figure 46. Elle confirme qu'il est donc possible d'observer la propagation de flammes dans un environnement où la vitesse moyenne de l'air est supérieure à celle du Concorde au décollage...

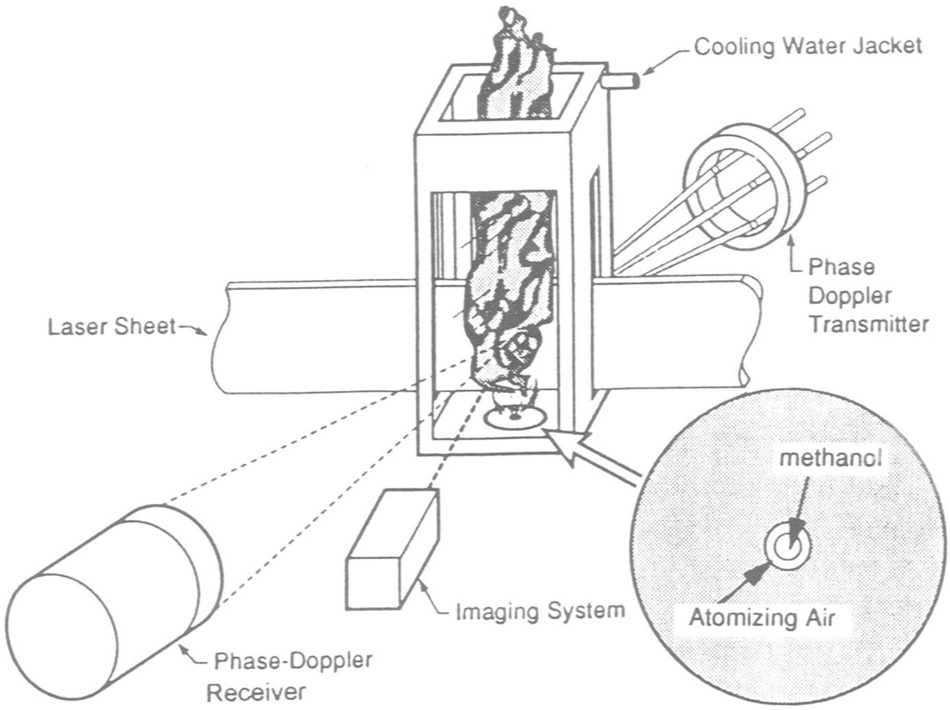
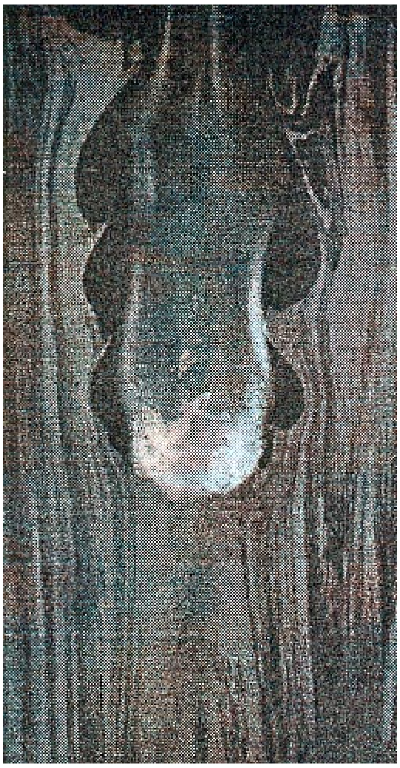


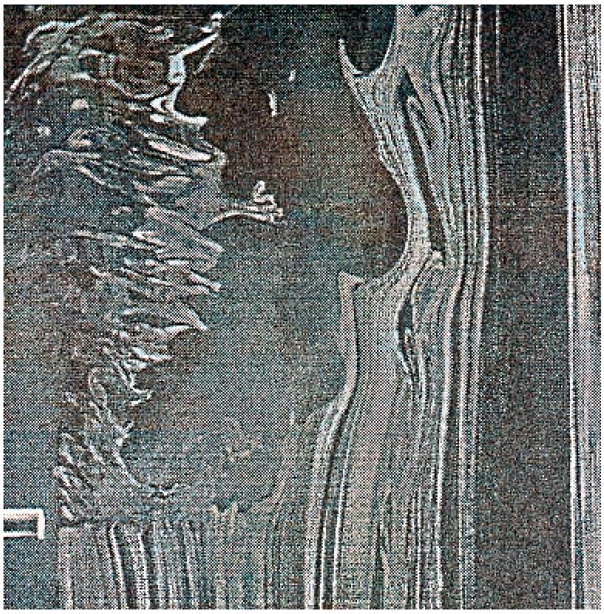
Figure 46: Configuration de la flamme turbulente étudiée par Stepowski et al. (1994). Le méthanol liquide, injecté à des vitesses de 0.5 à 1 m/s, est pulvérisé par un jet d'air à grande vitesse (40 à 150 m/s). Malgré ces conditions a priori défavorables, une flamme stabilisée est observée.

Ces possibilités de propagation d'une zone de réaction dans un écoulement dont la vitesse moyenne est largement supérieure à la vitesse d'une déflagration ont été récemment étudiées

[23]Dans certaines situations, la vitesse de propagation d'une flamme peut même être plus élevée dans un brouillard de gouttes de combustible liquide que dans le mélange parfait air/combustible gazeux correspondant (Ballal and Lefebvre 1980). L'ordre de grandeur n'est toutefois pas considérablement modifié.



(a)



(b)

Figure 47: Propagation de flammes dans des écoulements turbulents partiellement prémélangés. (a) Injection de combustible dans le sens de l'écoulement. (b) Injection dans la direction transverse de l'écoulement. Expérience réalisée par l'équipe de G. Mungal à Stanford.

expérimentalement. Si S_L est la vitesse de propagation d'un front de flamme dans un écoulement laminaire, il a été montré que pour des flammes-jets de méthane dans l'air (Fig. 47), la vitesse moyenne de l'écoulement dans la région où la flamme se stabilise pouvait atteindre des niveaux de l'ordre de $13\, S_L$, avec des vitesses maximales de l'ordre de $40\, S_L$, ce qui est bien supérieur aux vitesses de propagation d'une flamme turbulente, typiquement de l'ordre de $1.5\, S_l$ à $25\, S_L$ (Muñiz and Mungal 1997; Schefer and Goix 1998).

Ces résultats confirment que la vitesse moyenne de l'écoulement n'est pas à elle seule une quantité représentative pour étudier les problèmes de propagation. En fait, la flamme ne voit jamais la vitesse moyenne qui est une grandeur intégrée dans le temps. S'il existe localement, ne serait ce qu'un court instant, des zones où les conditions de mélange et de vitesse sont optimales, la flamme va se propager vers ces zones. De proche en proche, l'extrémité de la flamme recherche ainsi continuellement dans l'écoulement les zones où la vitesse est faible, au maximum de l'ordre de $2.5 S_l$ (Fig. 48). Cette valeur $2.5 S_l$ est la vitesse de propagation d'une flamme triple (voir annexe D.4.2), qui est le problème modèle simplifié utilisé pour analyser les flammes partiellement prémélangées (Ghosal and Vervisch 2000), tout comme la flamme plane est utilisée pour les milieux où le mélange est homogène.

Des études ont aussi montrés que la présence de structures tourbillonnaires, se développant par exemple dans une couche limite ou dans le sillage d'un obstacle (Annexe D), aide considérablement à la propagation de ce type de flammes (Favier and Vervisch 1998; Veynante et al. 1994), essentiellement pour des raisons liées à la topologie des fronts partiellement prémélangées. Un front partiellement prémélangé stabilisé dans un écoulement se déplacera, localement, vers l'amont par

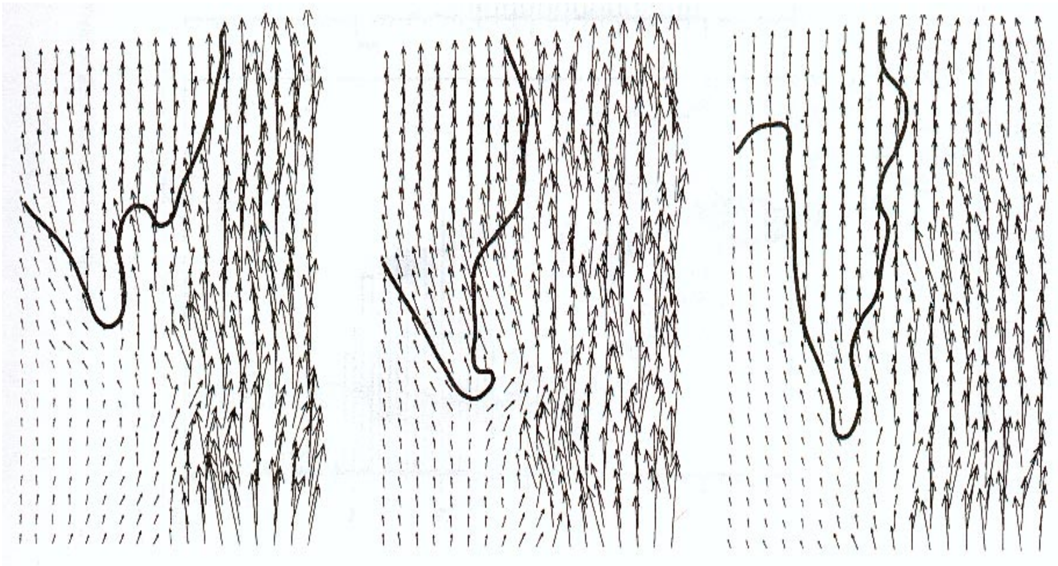


Figure 48: Champ de vitesse et position de la base de flamme lors de la propagation d'un front partiellement prémélangé, la flamme se propage dans les zones de l'écoulement à faible vitesse (Muñiz and Mungal 1997).

aspiration s'il rencontre des structures tourbillonnaires convectées par l'écoulement vers l'aval.

Lors de l'accident, l'air et le kérosène liquide s'échappant du réservoir se mélangent sous l'aile de l'avion. La turbulence fortement instationnaire dans les couches limites et le sillage du train génèrent alors des conditions idéales pour la propagation d'une flamme. La zone de réaction remonte l'écoulement de pas à pas en modifiant localement les conditions aérodynamiques (ce mécanisme est illustré à l'annexe D.4.2), tout en cherchant les points où à la fois les conditions de mélange et de vitesse sont optimales. Il est important de noter qu'il n'est pas nécessaire d'avoir une ligne de courant à la vitesse moyenne $2.5S_L$ pour assurer la propagation de la flamme. En fait, la ligne de courant moyenne où l'on observe cette vitesse est beaucoup trop proche de la paroi pour permettre la propagation d'une flamme. En revanche, pour assurer une propagation efficace vers l'amont, il suffit d'observer, localement le long des couches limites, des structures tourbillonnaires balayées par l'écoulement et en perpétuelle reconstruction, ceci de manière très intermittente. Entre, ou au coeur, de chaque structure cohérente se trouvent des zones où la vitesse est localement faible. Le chemin parcouru par la flamme pour remonter depuis le voisinage des parois des paupières jusqu'au train d'atterrissage a donc certainement été extrêmement tortueux, suivant de proche en proche les zones locales de faibles vitesses.

F Témoignages

F.1 Introduction

Nous avons eu l'opportunité de rencontrer trois témoins privilégiés de l'accident du Concorde F-BTSC. Ces témoins sont trois pompiers qui étaient en service au poste SSIS-2 qui surveille le doublet sud de l'aéroport de Roissy. Ce poste, où nous avons eu l'occasion de nous rendre, se situe au niveau de la bretelle S5 et offre une vision parfaitement dégagée sur la piste 26R distante d'environ 300 m (voir Fig. 49). Les témoignages de ces trois pompiers nous paraissent particulièrement importants pour deux raisons principales :

- De part leur position, ils ont vu de près l'inflammation de l'avion quasiment au moment où il passait par leur travers (ils le voient légérement par l'arrière du travers, comme le montre la figure 50). La quasi totalité des autres témoins a vu l'avion après la rotation et souvent dans l'axe de sa trajectoire. En outre, bien qu'au premier étage du poste SSIS-2, ils sont situés à une hauteur moindre que les quelques témoins, essentiellement des pilotes, se trouvant dans les avions environnants, ce qui leur donne une meilleure vision de ce qu'il se passe sous le Concorde.
- Leur profession leur donne une énorme expérience du feu. Leurs témoignages sur l'initiation et le développement de l'incendie sont extrêment précis et fiables.

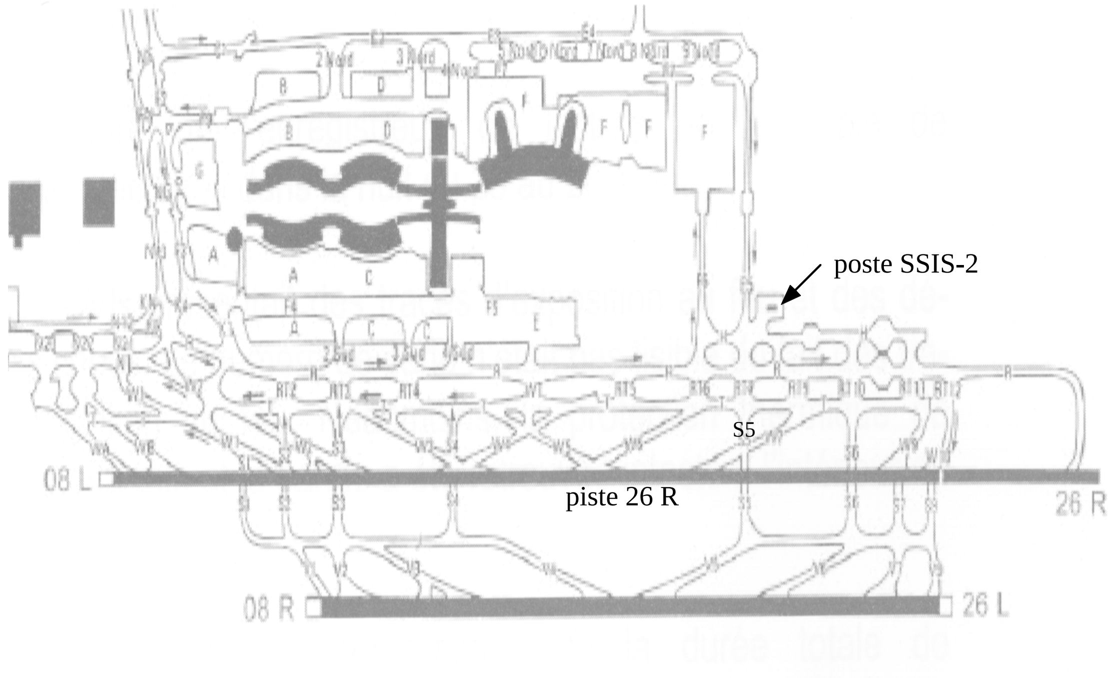


Figure 49: Localisation du poste de pompiers SSIS-2 de l'aéroport Charles de Gaulle.

Ces trois pompiers ont été interrogés par le BEA au début de l'enquète. La transcription de leur témoigagnes très précis a attiré notre attention. Nous les avons donc rencontrés, séparément (l'un d'eux a d'ailleurs pris sa retraite depuis l'accident), pour leur faire préciser, si possible, certains points sur l'initiation de l'incendie. Il faut noter que leurs témoignages n'ont jamais varié et se

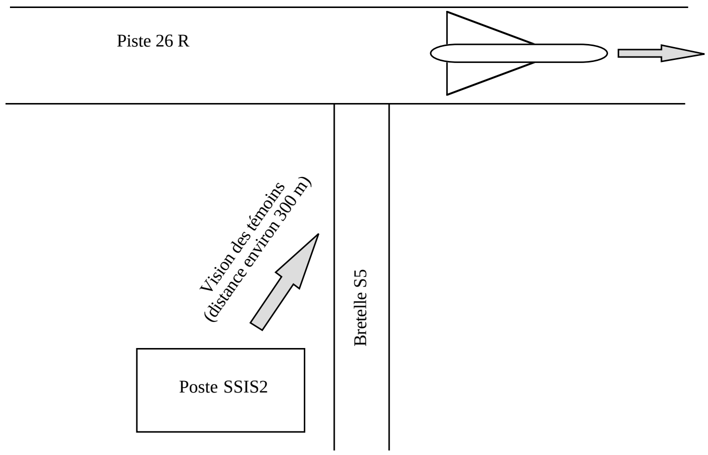


Figure 50: Position relative des témoins (poste SSIS-2) et du Concorde au moment de l'inflammation de l'avion.

complètent utilement. Les quelques différences s'expliquent par leur localisation dans la pièce où ils se trouvaient au moment de l'accident.

Enfin, à titre personnel, nous voudrions souligner le comportement extrêmement professionnel et la rapidité d'intervention de ces pompiers au cours de l'accident. Leurs témoignages ne portent que sur la phase initiale de l'incendie car ils ont aussitôt gagné leurs véhicules d'intervention, alors que l'alarme n'avait pas encore retenti. Ils ont alors perdu l'avion de vue, pour le revoir après la rotation depuis la voiture de pompiers roulant sur la piste ! Avant de continuer immédiatement vers la patte d'oie de Gonesse...

F.2 Localisation des témoins

Les trois pompiers, que nous numéroterons de 1 à 3 pour préserver leur anonymat, se trouvaient dans une salle située au premier étage du poste SSIS-2. Cette salle donne une vue directe sur la piste 26 R, distante d'environ 300 m par l'intermédiaire de trois fenêtres. Comme le montre la localisation relatives des témoins dans la pièce (Fig. 51) et des fenêtres, le premier pompier a plutôt vu le démarrage de l'avion et le début de l'accident, jusqu'à la phase initiale de l'incendie et le troisième l'initiation et le développement de l'incendie. Le témoignage du second pompier confirme et complète la fin du témoignage du premier et le témoignage du troisième.

F.3 Témoignages

Les témoignages présentés ici correspondent à une transcription brute des propos des pompiers et de leurs réponses à nos questions, sans commentaires. L'analyse de ces témoignagnes sera effectuée plus loin (§ F.4).

F.3.1 Pompier No 1

Le premier pompier, de part sa position, a surtout une vision du début de la piste 26 R. Il décrit tout d'abord une fumée noire partant du train principal gauche, accompagnée d'une forte odeur "comme lorsqu'un pneu éclate sur un camion". Cette fumée se déclenche au niveau de la bretelle S6. Il voit ensuite une flamme "comme un petit chalumeau" accrochée au niveau des tuyères

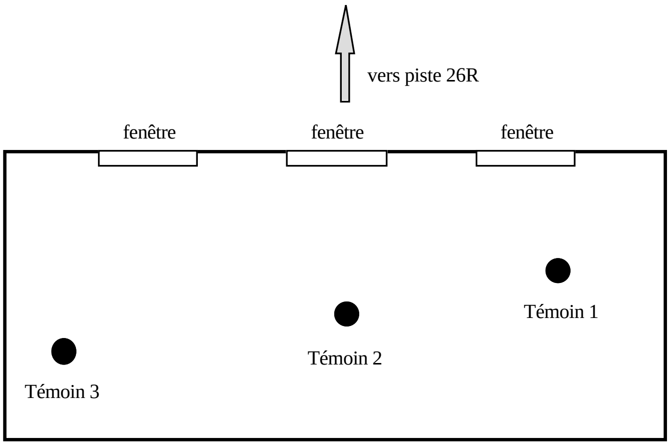


Figure 51: Position approximatives des témoins dans la pièce du poste SSIS-2.

des moteurs gauches. Cette flamme est très différente, en particulier par sa couleur rouge/jaune-orangée, de la flamme issue en fonctionnement normal de la post-combustion (quasi invisible de jour). Le dessin effectué par le témoin est schématiquement reproduit sur la figure 52.

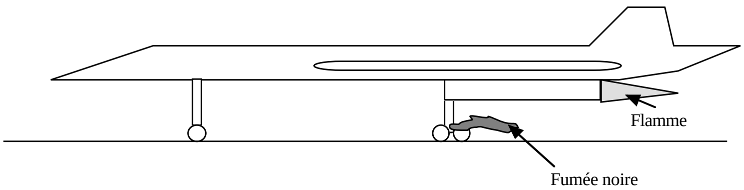


Figure 52: Reproduction schématique du dessin effectué par le premier pompier à l'appui de son témoignage.[24]

Ce pompier n'a pas vu le développement ultérieur de la flamme, probablement hors de son champ de vision, d'autant qu'il est immédiatement parti avec ses collègues pour intervenir.

F.3.2 Pompier No 2

Le second témoin mentionne également une fumée noire opaque au niveau des roues du train principal, au moment où l'avion est au travers de la bretelle S5.[25] Cette fumée est plus noire qu'un panache et aucune flamme n'est visible.[26] La flamme, assez jaune, n'est apparue qu'ensuite vers le milieu de la nacelle, sous celle-ci, et à la forme d'un petit chalumeau (Fig. 53). Cette flamme est déjà assez longue et dépasse nettement le bord de fuite de l'aile et le dard de la post-combustion.

[24]Le pompier voit, bien évidemment, le côté droit de l'avion qui se déplace pour lui de la gauche vers la droite. Néanmoins, les dessins qui illustrent les témoignages ont été effectués sur un plan 3 vues du Concorde fourni par le BEA. La vue de côté de ce plan représente le coté gauche de l'appareil et nous avons préfré conserver cette vision par fidélité aux témoignages, d'autant que l'accident concerne ce côté de l'avion.

[25]De part sa localisation dans le poste de secours, ce témoin n'a pas de vision sur le début de la piste.

[26]Il faut signaler que ce témoin situe tous les évenements, fumée issue des roues et initiation de la combustion, du coté droit de l'avion. Ce n'est qu'après, pense t-il, que la flamme s'est développée vers le coté gauche de l'avion. Cette perception est probablement due au fait que, de part sa position, il a vu ces évenements pratiquement par le travers de l'avion.

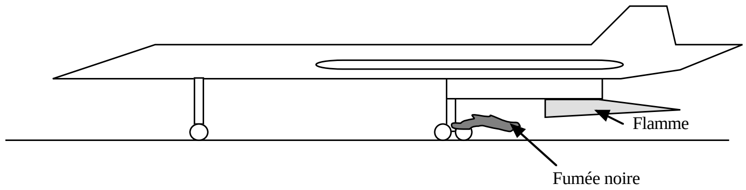


Figure 53: Reproduction schématique du dessin effectué par le second pompier à l'appui de son témoignage.[24]

La flamme s'est ensuite développée très rapidement (moins de une seconde) en prenant une couleur plus rouge/orangée. Cette transition très rapide est similaire au phénomène que les pompiers nomment "backdraft", c'est à dire un retour de flamme violent sur un appel d'air. Cette extension semble correspondre à une remontée de la flamme vers une fuite de combustible. Cette flamme généralisée sous l'aile et autour de la nacelle est longue (de 30 à 40 mètres) et est entrainée vers l'arrière de l'avion par la vitesse et le souffle du réacteur.

Ce pompier, partant en intervention, a ensuite perdu l'avion de vue. Ce n'est qu'ultérieurement, après le décollage, qu'il l'a revu depuis le camion de pompiers roulant sur la piste (vue de l'arrière de l'appareil qui est fortement cabré à ce moment là). Le témoin est formel : il n'y avait pas de flammes sur l'extrados de l'aile.

F.3.3 Pompier No 3

Le troisième témoin, situé à l'extrémité est de la pièce (à gauche sur la figure 50), n'avait pas de visibilité vers le début de la piste et n'a donc pas vu la fumée partant du train d'atterrissage. En revanche, il a parfaitement vu l'initiation de la flamme, qu'il situe aux environs de la bretelle S5. Comme le second pompier, il décrit un développement en deux étapes :

- Une première flamme jaune clair/orangée, accrochée derrière le réacteur. Cette flamme est similaire à celle issue de la post-combustion en fonctionnement normal mais n'a pas la même couleur (la flamme de post-combustion est bleue et peu visible de jour) et est beaucoup plus longue (10 à 15 m de long). Elle fait un bruit de chalumeau au moment de l'allumage, derrière la post-combustion, et ne semble pas provenir du réacteur.

- La flamme devient ensuite complétement différente. Elle est beaucoup plus rouge et plus riche. Son extension devient considérable. Elle se développe alors que l'avion a déjà levé le train avant.

La transition de la première vers la seconde flamme est illustrée sur la figure 54. Au cours de cette transition, le témoin décrit la flamme comme aspirée vers l'avant de l'avion, sous l'aile.

F.3.4 Témoin supplémentaire

Un quatrième témoignage, que nous n'avons pas recueilli personnellement, mérite également d'être mentionné. Ce témoin est un commandant de bord aux commandes d'un appareil qui se trouvait en E5 (c'est à dire aux environs du poste de secours SSIS-2) en attente de décollage. Il est, à notre connaissance, le seul témoin outre les trois pompiers à avoir vu l'avion par le travers au moment de son inflammation. Un extrait du témoignage transcrit par le BEA est présenté ici :

"Le point d'inflammation se situe à plus ou moins 100 m du niveau de la bretelle W7. La flamme s'est allumée un peu comme la flamme d'un briquet qui est réglé sur un débit trop fort.

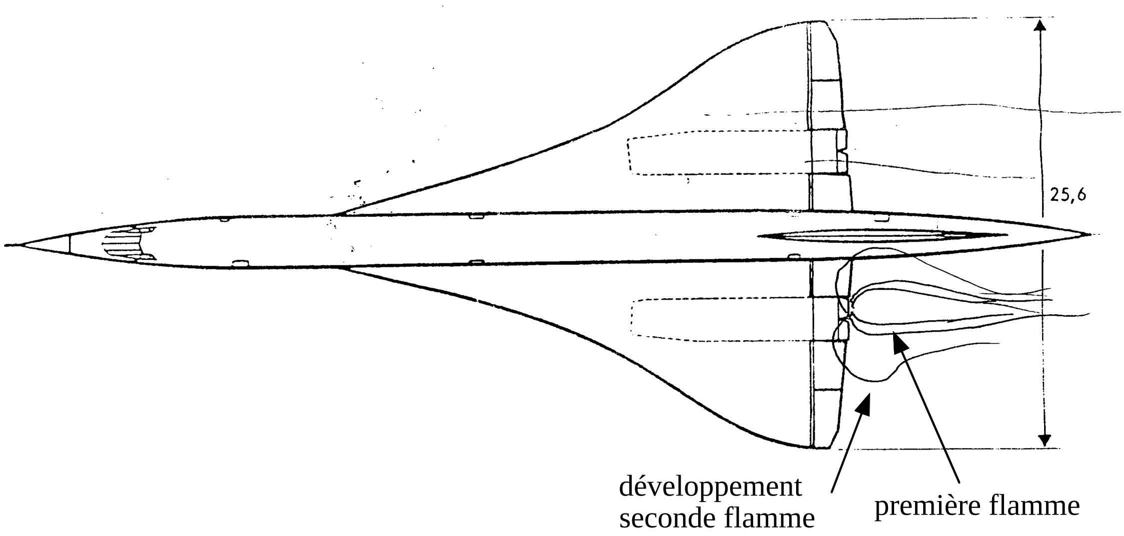


Figure 54: Dessin effectué par le troisième pompier à l'appui de son témoignage. Une flamme initiale est accrochée à la sortie du réacteur puis se développe comme si elle était aspirée vers l'avant de l'avion.

L'embrasement est instantané, passant de rien à une flamme qui garde ses dimensions. Cette flamme est suivie d'une épaisse fumée noire. Je ne distingue pas la flamme PC. La nacelle des moteurs sous l'aile gauche est entourée d'une flamme orangée à travers laquelle on distingue deux tuyères noires."

F.4 Analyses - conclusions

Ces quatre témoignages sont précis, précieux et se confirment mutuellement. Parmi les points importants :

- Trois des quatre témoins (pompiers 2 et 3, commandant de bord[27]) décrivent une inflammation en deux temps de l'avion : une première flamme type chalumeau puis une extension très importante de la combustion. Le dernier témoin, de part sa position dans la pièce, n'a vu que la phase initiale.

- Deux témoins, les premier et second pompiers, précisent que la flamme initiale était accrochée au voisinage de la tuyère des moteurs gauche. Cette précision n'est pas contredite par le commandant de bord (nous ne l'avons pas interrogé et il n'a donc pu nous préciser ce point). Seul le second pompier parle d'une première flamme accrochée au milieu de la nacelle. Si ce témoignage pourrait laisser supposer une inflammation au niveau des trappes de ventilation des moteurs (voir § 4), il est plus probable que le témoin a vu la flamme au moment où elle commencait à prendre de l'extension.

- Les témoignages s'accordent nettement sur la couleur de la flamme, plutôt claire initialement (jaune-orangée) puis plus foncée (rouge) ensuite. La flamme initiale, bien qu'accrochée à la

[27]La transcription du témoignage du commandant de bord rapporte un "embrasement instantané". Néanmoins, ce témoignage semble décrire une inflammation en deux étapes : allumage comme un briquet, puis expansion, même si ces deux étapes sont quasiment simultanées pour le témoin. Il ne faut pas oublier que son témoignage a été recueilli au début de l'enquète, probablement sans attacher trop d'importance à cet enchainement, et qu'il n'a pas été réinterrogé depuis pour préciser ce point.

sortie des réacteurs, est très différente du dard de la post-combustion en fonctionnement normal (flamme bleue, quasiment invisible de jour).

- L'enchainement des événements est un point important. Au dire de ces témoins, ils semblent se produire plus tôt que ne le laisse supposer la localisation des débris retrouvés sur la piste. En effet, les deux premiers pompiers situent l'apparition de la fumée sur les roues du train d'atterrissage aux environs de la bretelle S6. Les second et troisième pompiers situent le début de l'inflammation peu après la bretelle S5, ce que ne contredit pas le témoignage du commandant de bord ("plus ou moins 100 m du niveau de la bretelle W7"). Au vu de la disposition des locaux du poste SSIS-2 et de la position des pompiers dans la pièce, il parait douteux qu'ils aient pu se tromper sur les localisations annoncées. L'embrasement général pourrait être plus tardif (le train avant est déjà levé pour le troisième pompier).

Au vu de ces témoignagnes, il semble évident que le kérosène s'est enflammé au contact des gaz chauds issus des moteurs. Une inflammation par étincelle au niveau du puits de train ou derrière la jambe de train se serait traduite par une flamme stabilisée soit dans le puits de train, soit dans le sillage de la jambe de train et/ou des contrefiches. **Aucun témoin ne mentionne une telle situation et tous au contraire sont formels sur la localisation à l'arrière des réacteurs de la flamme initiale**. Seul le témoignage du second pompier pourrait accréditer l'idée d'une remontée de la flamme par le flux d'air secondaire entre moteurs et nacelle ou une inflammation par pompage moteur. Il est néanmoins le seul à décrire la flamme initiale comme accrochée à la moitié de la nacelle (Fig. 53) et l'a probablement vu alors qu'elle commencait à remonter.

Le témoignage du troisième pompier confirme notre analyse d'une remontée de flamme par les couches limites et le sillage du train. Il décrit, et dessine (Fig. 54), très précisément une flamme accrochée à l'arrière des réacteurs qui est "comme aspirée vers l'avant de l'avion" avant l'embrasement général.

La localisation et la chronologie des événements méritent probablement une analyse complémentaire. Pour les pompiers, les roues fumaient déjà depuis S6 et l'inflammation se produit aux environs de S5, c'est à dire bien avant l'endroit où ont été retrouvés la lamelle métallique, la plaque du réservoir et où apparaissent les traces de suies. Il est probable que la flamme initiale, d'extension limitée, n'a pas laissé de traces de suies sur la piste. Les traces de suies, à partir de la dalle 168) pourraient commencer au moment de l'expansion de la flamme.

G L'accident de Washington (14 juin 1979)

Le 14 juin 1979, le dégonflement puis le déchapage du pneu No 6 entraine l'éclatement du pneu No 5 puis la destruction de la roue sur le Concorde F-BVFC au décollage à l'aéroport de Washington-Dulles. Les réservoirs 2, 5 et 6 ont alors été perforés par des morceaux de jantes. L'analyse de cet accident est intéressante à plusieurs titres :

- Il s'agit à la fois du premier et du plus important accident (avant celui de Gonesse) ayant entrainé des perforations des réservoirs sur un Concorde.
- L'appareil a volé 24 mn avant de revenir se poser sur l'aéroport. Au cours de ce vol, plusieurs photographies ont été prises et montrent nettement le jet de kérosène pulvérisé par l'écoulement autour de l'avion.
- Le débit de la fuite est connu relativement précisément. L'ensemble des perforations a provoqué des fuites d'environ 7.5 tonnes de carburant. Le débit moyen est donc d'environ 5 kg/s.
- Cet accident a donné lieu à une étude approfondie, notamment sur les risques d'incendie (note 408.251/79, dont quelques extraits sont cités dans ce rapport) et à quatre consignes de navigabilité (CN).

Trois photographies prises lors du vol de Washington sont présentées aux figures 55 et 56. Le brouillard de kérosène, généré par l'interaction du combustible s'échappant de la fuite et de l'écoulement d'air sous l'aile de l'avion, est clairement apparent. Ce type de milieu est favorable au développement d'une combustion pourvu que les proportions de combustible et d'air soient dans les limites d'inflammabilité (voir annexe A). Il faut noter que le débit de la fuite est ici environ 10 à 20 fois plus faible que lors de l'accident de Gonesse (voir section 2).

Une petite flamme semble néanmoins apparente à la sortie du moteur 2 (moteur interieur gauche) sur la photographie 56. Les couleurs et contrastes de cette photographie ont été modifiés pour la rendre plus apparente (Fig. 57). Cette petite flamme pourrait n'être qu'un reflet sur le brouillard de kérosène mais cette explication nous parait peu vraisemblable : d'une part, elle semble également apparente, bien que beaucoup moins nettement, sur la photographie prise au moment du décollage (Fig. 55, haut), sa localisation ne semble pas correspondre à l'endroit où le brouillard de kérosène est le plus dense (et là où le reflet devrait être maximum, surtout vu l'orientation du soleil qui vient de la droite de l'appareil). Enfin, cette flamme est mentionnée par le contrôle aérien, ainsi qu'en témoigne un extrait du rapport BEA relatif à l'accident :

"La levée des roues s'effectue avec une vitesse d'environ 220 noeuds. Les paramètres des quatre moteurs indiquent à l'équipage qu'ils fonctionnent normalement. Le contrôle annonce une avarie de pneus et une flamme derrière les moteurs gauches."

Comme discuté au paragraphe 2.4, l'existence d'une telle flamme peut s'expliquer aisément. En effet, la fuite de combustible engendre un apport de kérosène aux gaz chauds issus des moteurs. Les conditions de température et la géométrie de l'ensemble moteurs-nacelle sont telles que ce kérosène peut brûler au voisinage des moteurs. En revanche, un calcul d'ordre de grandeur montre facilement que la quantité de kérosène n'est pas suffisante (richesse $\Phi \approx 0.1$) pour permettre à une flamme de se développer à l'extérieur de la nacelle, que ce soit vers l'aval ou vers l'amont.

DECOLLAGE
(19.31 TU)

PASSAGE A LA TOUR
(19.37 TU)

Figure 55: Photographies prise au cours du vol du Concorde F-BVSC après l'accident survenu au décollage de l'aéroport de Washington-Dulles le 14 juin 1979.

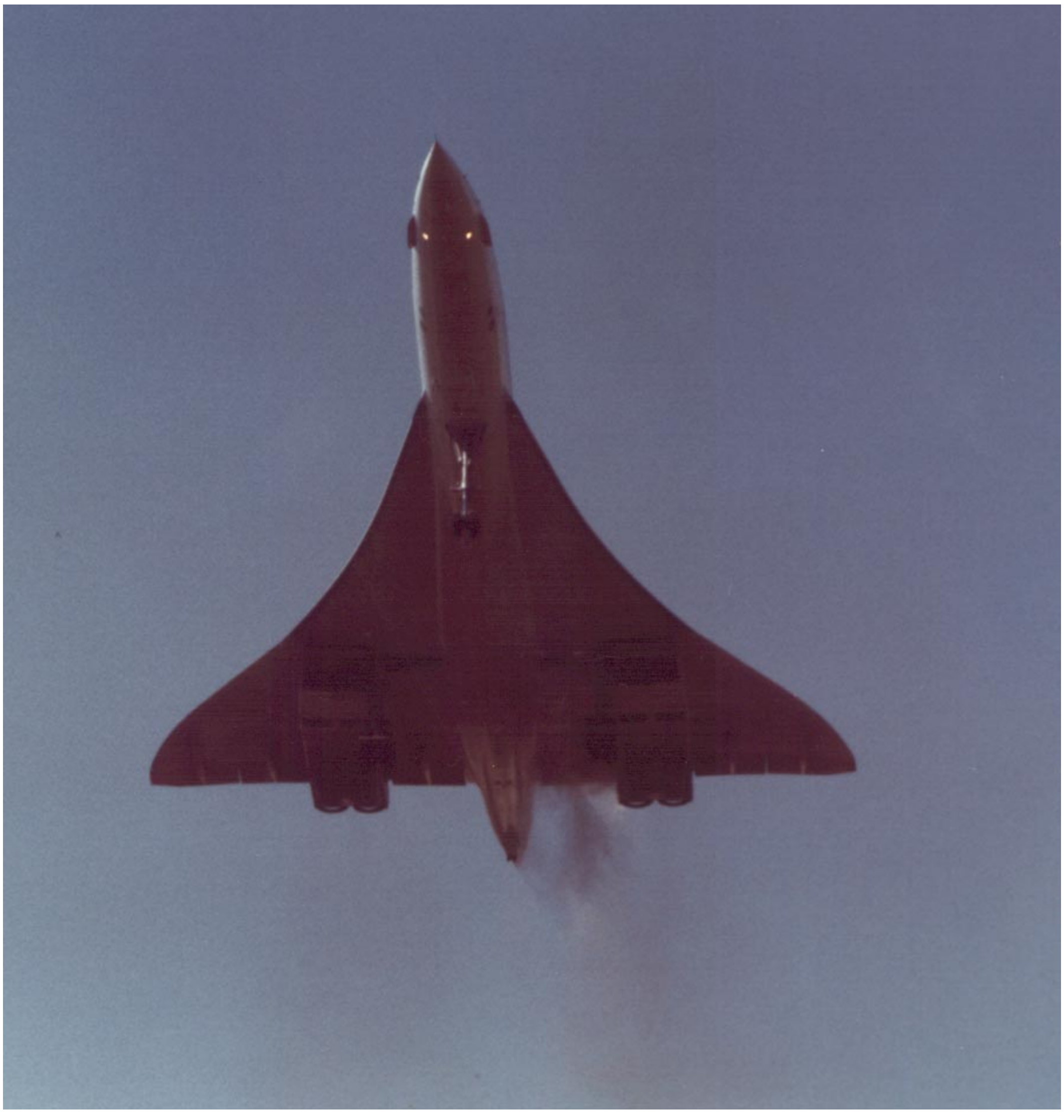


Figure 56: Photographie prise au cours du vol du Concorde F-BVSC après l'accident survenu au décollage de l'aéroport de Washington-Dulles le 14 juin 1979.

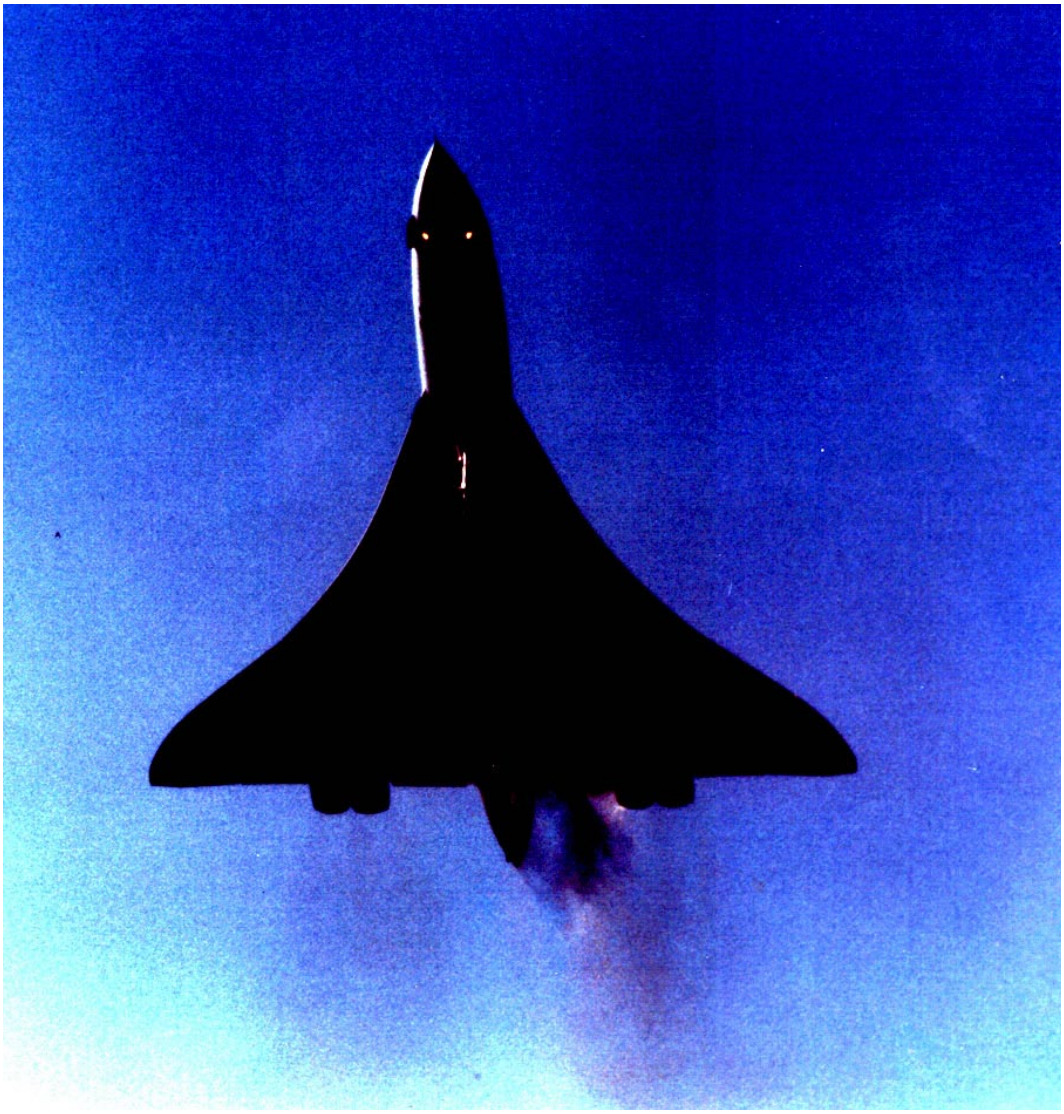


Figure 57: Modification des couleurs et contrastes de la photographie 56. Une petite flamme semble accrochée à la sortie du moteur 2 (moteur intérieur gauche, à droite sur la photographie).

H Exemples d'inflammation de kérosène par un moteur

Deux exemples d'inflammation de fuite de kérosène par les parties chaudes d'un moteur et/ou les gaz chauds issus de celui-ci nous ont été rapportés et sont brièvement présentés ici. Ces exemples ne sont pas complétement similaires à l'accident du Concorde à Gonesse mais illustrent clairement le rôle que peut jouer le moteur dans l'inflammation d'une fuite de kérosène.

H.1 Inflammation d'une fuite de carburant sur un Fouga-Magister

Un accident survenu à un Fouga-magister au début des années 1980 nous a été rapporté par un enquèteur du BEA qui en a été témoin. L'orifice de remplissage de carburant, situé sur le dessus de l'avion, derrière le cockpit, avait été mal refermé après le plein de l'appareil. En vol, le carburant s'échappant par l'orifice s'est enflammé sur les parties chaudes des réacteurs le long de la cellule de l'avion (voir figure 58). Si le pilote a pu de justesse revenir à bon port, l'arrière de l'appareil a été détruit par l'incendie.

Signalons qu'un temps minimum doit d'ailleurs être respecté sur cet avion avant de refaire le plein après l'atterrissage afin de permettre le refroidissement des parties chaudes du moteur et éviter l'inflammation du kérosène qui pourrait ruisseler.

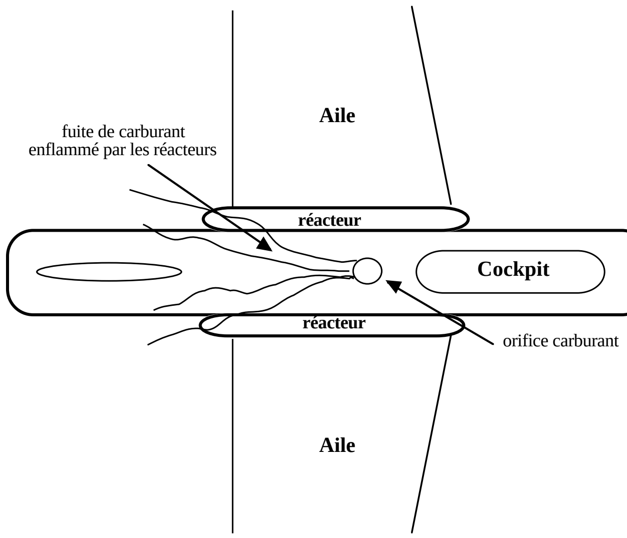


Figure 58: Schématisation de l'accident survenu à un Fouga-Magister, vu de dessus. Le carburant s'échappant par l'orifice mal refermé du réservoir s'est enflammé au contact des parties chaudes du moteur.

H.2 Une figure de voltige : "zippo trick"

Il existe une figure, pratiquée en voltige aérienne, qui consiste à larguer en vol du carburant puis à l'enflammer en allumant la post-combustion des réacteurs. Illustrée sur la photographie 59, cette manoeuvre aurait été utilisée pour symboliser le départ de la flamme olympique lors de la cérémonie de clôture des jeux olympiques de Sydney (2000). Elle aurait aussi été utilisée par le passé lors de combats aériens pour leurrer des missiles à tête chercheuse thermique. Signalons qu'elle a été explicitement mentionnée par un des témoins de l'accident du Concorde à l'appui de son témoignage (témoin N^o 10 bis).

Figure 59: Photographie illustrant une figure de voltige aérienne connue sous le nom de “zippo trick”. Du carburant largué par l’avion est ensuite enflammé par la post-combustion du moteur. Photographie extraite de la revue allemande “Flug Revue”, numéro d’Avril 2001.

Dans cette situation et à la différence de l’accident de Gonesse, la flamme est détachée de l’avion et ne remonte heureusement pas vers celui-ci. Cette différence s’explique par plusieurs raisons :

- Le largage du carburant est apparemment fait très en arrière de l’avion, au voisinage du bord de fuite.
- Les débits de combustible sont très inférieurs à la fuite de kérosène lors de l’accident du Concorde.
- La flamme est allumée derrière l’avion et non au niveau de l’arrière corps du moteur à l’intérieur de la nacelle.
- L’avion est en configuration de vol, train d’atterrissage rentré. Les perturbations aérodynamiques sont moindres qu’au décollage sans oublier la géométrie très particulière du Concorde, et ne permettent pas la remontée de la flamme.

Malgré toutes ces différences, en défaveur du Concorde lors de l’accident de Gonesse, cette figure de voltige montre la possibilité d’enflammer du kérosène par les gaz chauds issus d’un moteur équipé d’une post-combustion.

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RAPPORT TECHNIQUE D'INGENIERIE SYSTEMES

PRODUIT: **Avion Concorde**

SUJET/TITRE: **Tunnel d'Essais Incendie II – Rapport relatif aux essais d'incendie avec écoulement de carburant à partir du point B (Point de Gonesse)**

RESUME:

Le présent document décrit les résultats provisoires des essais d'incendie réalisés dans le Tunnel d'essais incendie II à BAE Systems Warton et concernant le point B d'écoulement carburant (point de fuite carburant de Gonesse) dans le cas d'activation indépendante de chacune des sources d'inflammation utilisées sur le banc de test.

Trois essais d'incendie ont été effectués en utilisant le brûleur de tuyère comme source d'inflammation. Dans chaque cas, l'inflammation s'est produite au niveau du brûleur dans un délai de 0,5 secondes après écoulement du carburant et la combustion s'est poursuivie au-delà du tunnel jusqu'à ce que le flux de carburant provenant de l'intérieur du tunnel ait diminué (13 à 24 secondes). L'incendie ne s'est pas propagé vers l'avant, à l'intérieur du tunnel.

Un essai d'incendie a été effectué en utilisant le brûleur d'entrée auxiliaire comme source d'inflammation. L'inflammation s'est produite 0,24 secondes après la libération du carburant et s'est propagée immédiatement dans le puits du train d'atterrissage. La combustion a été soutenue pendant environ quatre secondes.

Deux essais d'incendie ont été effectués en utilisant, comme source d'allumage, l'inflammation par étincelle à l'intérieur du puits du train d'atterrissage. Dans chaque cas l'inflammation s'est produite dans le puits du train d'atterrissage dans un délai de 0,4 seconde après la libération du carburant et s'est poursuivie pendant environ 8 secondes.

TABLE DES MATIERES

1. Introduction

Le présent document décrit les résultats provisoires des essais incendie réalisés dans le tunnel II de BAE Systems Warton qui concernent le point B d'écoulement de carburant (point de fuite carburant de Gonesse) dans le cas d'activation indépendante de chacune des sources d'inflammation utilisées sur le banc de test.

L'objectif de cette série d'essais est de participer à la compréhension du mécanisme d'inflammation et de propagation du feu lors de l'accident de Gonesse en simulant la fuite de carburant appropriée en présence de fortes sources d'inflammation soupçonnées d'être à l'origine de l'incendie lors de l'accident du Concorde d'Air France à Gonesse. Le tunnel d'essais incendie a été conçu pour simuler les caractéristiques critiques de l'avion Concorde dans la zone de la voilure gauche, des surfaces internes de la nacelle moteur, y compris celle du train d'atterrissage, se référer à la spécification Tunnel d'Incendie II F01/JRB/TT/jk/2979(b) Edition 2.

2. Configuration du Tunnel (Voir Figure 1)

2.1. Emplacement du Point B d'Écoulement de Carburant

L'emplacement approximatif du point B d'écoulement du carburant par rapport à chaque implantation des sources d'inflammation est le suivant :

(i) 45,5 cm à l'avant du bord avant du puits de train d'atterrissage (inflammation par étincelle).
(ii) 3,42 m à l'avant du brûleur auxiliaire.
(iii) 11,96 m à l'avant de l'ensemble brûleur de tuyère.

2.2. Mécanisme d'Écoulement de Carburant

Le mécanisme d'écoulement de carburant au point B a été conçu pour simuler la défaillance du panneau de revêtement sous la voilure qui est intervenue à la suite de la destruction du pneu à Gonesse. Ceci est représenté par une trappe amovible de 30cm x 30cm, maintenue fermée par un axe de cisaillement situé à la partie inférieure d'un réservoir cylindrique contenant 150 litres de carburant. Une bouteille d'azote sous pression de 0,5 litre est reliée au côté du réservoir, séparée par un disque fusible. Avant la libération du carburant la pression de l'azote dans la bouteille est amenée à une valeur inférieure d'environ 10PSI à celle nécessaire pour rompre le disque fusible. L'ouverture de la trappe est obtenue par une augmentation rapide de la pression de l'azote, ce qui entraîne la rupture du disque fusible. Ceci provoque une impulsion due à la pression à l'intérieur de la chambre carburant qui entraîne la rupture de l'axe de cisaillement, ouvre la trappe et libère un jet de carburant vers la paroi latérale d'admission simulée.

2.3. Sources d'Inflammation

2.3.1. Brûleur de tuyère

La tuyère moteur est représentée par quatre brûleurs d'huile internes montés dans un logement construit à cet effet, situé à l'arrière du tunnel.

2.3.2. Flamme de Surpression d'Entrée Auxiliaire

La production d'une flamme due à la surpression moteur à cet emplacement est représentée par un seul brûleur d'huile interne, équipé d'un capot permettant son fonctionnement continu pendant la durée de l'essai.

2.3.3. Inflammation par étincelle électrique

L'inflammation par étincelle électrique à l'intérieur du puits du train d'atterrissage est représentée par six dispositifs électriques de production d'étincelles. Chacun a une capacité de 12 joules, et une dissipation de 3 joules au niveau de l'électrode. Le déclenchement de chaque dispositif a été activé de façon aléatoire. Les dispositifs ont été désactivés immédiatement après l'inflammation à l'intérieur du puits du train d'atterrissage.

2.4. Systèmes de Surveillance

Le tunnel d'incendie est équipé de onze thermocouples et de trois prises de pression statique permettant de surveiller la température interne et les pressions pendant chaque essai, de plus il comprend sept caméras vidéos permettant de visualiser les parois via des témoins vitrés.

2.5. Fonctionnement du Tunnel

Avant chaque essai d'incendie, le réservoir carburant est rempli, le système de libération de carburant amorcé et la source d'inflammation choisie est activée pendant quelques secondes. Au début d'un essai, un compte à rebours de quatre minutes est utilisé au cours duquel les vérifications finales sur tous les systèmes opérationnels et de surveillance sont effectuées et la source d'inflammation est activée. A la fin du compte à rebours, l'air du tunnel est libéré suivi environ 2 secondes plus tard par la libération du carburant. L'air du tunnel est libéré à une vitesse de 85 mètres par seconde. Il est coupé après 30 secondes de fonctionnement.

3. Résultats des Essais d'Incendie

Un résumé des résultats d'essais suivants est illustré sur la Figure 2.

3.1. Position du Brûleur de Tuyère

Trois essais d'incendie ont été effectués en utilisant le brûleur de tuyère comme source d'inflammation. Dans chaque cas, l'inflammation s'est produite au niveau du brûleur dans un délai de 0,5 secondes après libération du carburant et la combustion s'est poursuivie au-delà du tunnel jusqu'à ce que l'écoulement de carburant provenant du tunnel ait diminué (13 à 24 secondes). Le feu ne s'est pas propagé vers l'avant, à l'intérieur du tunnel.

3.2. Position du Brûleur d'Entrée Auxiliaire

Un essai d'incendie a été effectué en utilisant le brûleur d'entrée auxiliaire comme source d'inflammation. L'inflammation s'est produite 0,24 secondes après la libération du carburant et s'est immédiatement propagée dans le puits du train d'atterrissage. La combustion a été soutenue pendant environ quatre secondes.

3.3. Position de l'Etincelle dans le Puits du Train d'Atterrissage

Deux essais d'incendie ont été effectués en utilisant comme source d'inflammation le procédé d'inflammation par étincelle à l'intérieur du puits de train d'atterrissage. Dans chaque cas l'inflammation s'est produite dans le puits du train d'atterrissage dans un délai de 0,4 secondes après libération du carburant et la combustion s'est poursuivie pendant environ 8 secondes.

4. Conclusions

Les essais objets du présent rapport ont indiqué la nature éventuelle de l'incendie dans la zone de l'avion représentée par le Tunnel d'Incendie II, dans le cas d'une importante fuite de carburant à l'avant du puits du train d'atterrissage lorsqu'il est soumis aux sources d'inflammation qui ont été décrites.

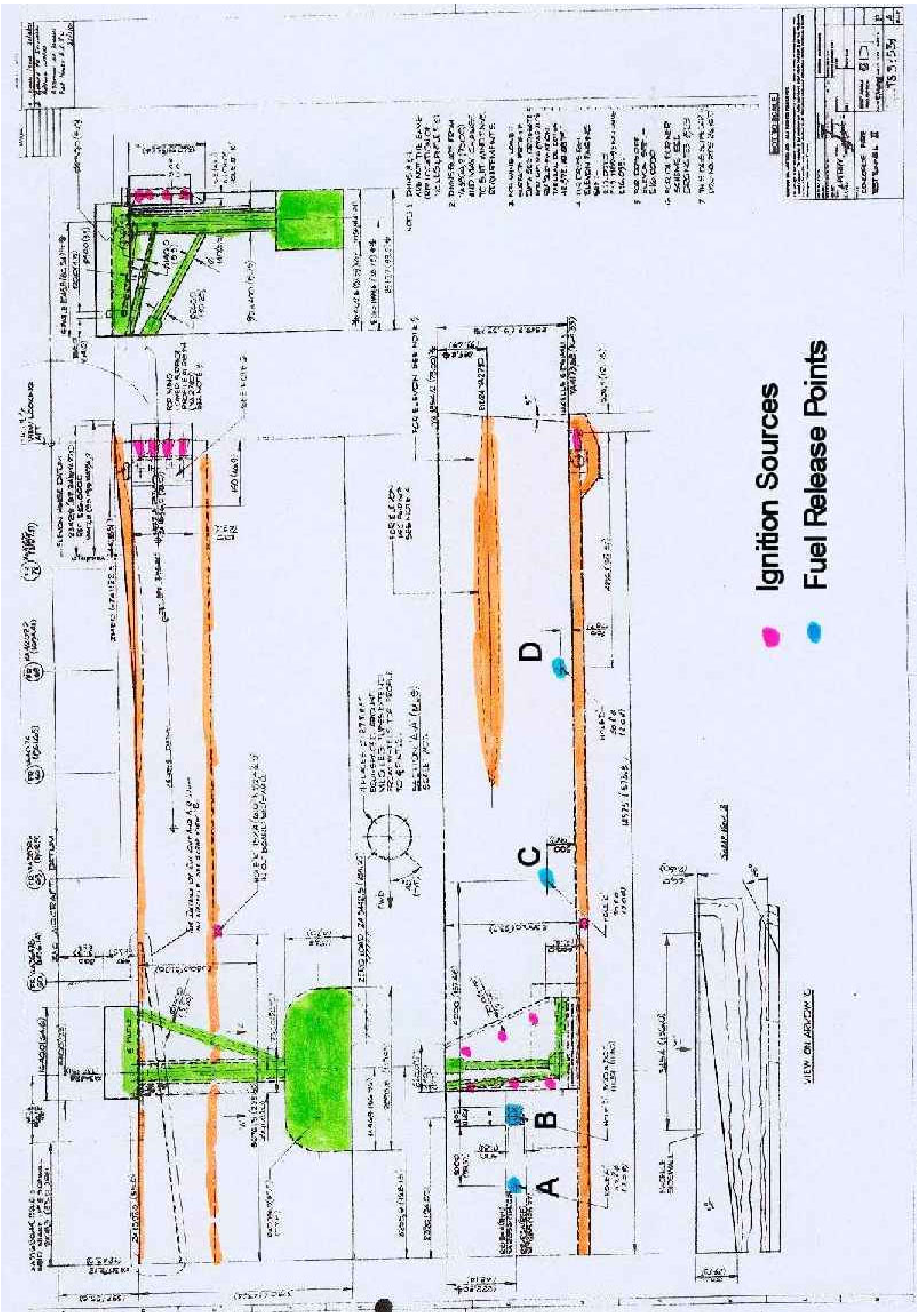


Figure 1

TUNNEL D'INCENDIE 2 POUR CONCORDE

RESULTATS D'ESSAIS PRELIMINAIRES AU 22/06/2001

POINT D'ECOULEMENT B

HSWT ESSAI No.	VOL. APPROX De CARB.(L)	DEBIT NOM. (L/s)	LIEU D'INFLAMMATION	SOURCE	DELAI D'INFLAMMATION I (SEC)	COMBUSTION SOUTENUE	COMMENTAIRES
###	150	60	TUYÈRE	4 x BRULEURS	0.36	OUI	COMBUSTION A LA SORTIE DU TUNNEL PENDANT 24,0 S.
							PAS DE PROPAGATION VERS L'AVANT.
###	150	60	TUYÈRE	4 x BRULEURS	0.52	OUI	COMBUSTION A LA SORTIE DU TUNNEL PENDANT 13,2 S.
							PAS DE PROPAGATION VERS L'AVANT.
###	150	60	TUYÈRE	4 x BRULEURS	0.48	OUI	COMBUSTION A LA SORTIE DU TUNNEL PENDANT 13,6 S.
							PAS DE PROPAGATION VERS L'AVANT.
###	150	60	ENTREE AUX.	1 x BRULEUR	0.24	OUI	COMBUSION RAPIDE A PROXIMITE DU BRULEUR.
							PROPAGATION VERS L'AVANT DANS LE PUITS DE TRAIN D'ATTERRISSAGE.
###	150	60	PUITS T/A	>ETINCELLE<	0.36	OUI	COMBUSTION DANS LE PUITS DE TRAIN D'ATTERRISSAGE PENDANT ENVIRON 8,3 S.
###	150	60	PUITS T/A	>ETINCELLE<	0.32	OUI	COMBUSTION DANS LE PUITS DE TRAIN D'ATTERRISSAGE PENDANT ENVIRON 5,6 S.

N.B. LES SOURCES D'INFLAMMATION SIGNALEES PAR > < ONT ETE DESACTIVEES LORS DE L'INFLAMMATION DU CARBURANT.

Figure 2

CONCORDE: DESTRUCTION DU PANNEAU INTRADOS

Analyse du scénario de rupture en mode 2

Dans l'explication de l'accident de Gonesse, le mode de rupture du panneau d'intrados retrouvé sur la piste est un élément important. Ce document résume l'analyse, qui en a été faite par EADS sur la base des éléments fournis par les enquêteurs, des analyses théoriques et des essais réalisés depuis.

Sans être en mesure de proposer une explication certaine, nous privilégions l'hypothèse dite de la rupture en mode 2, c'est-à-dire l'enchaînement des événements suivants:

- Roulage sur une pièce métallique
- Eclatement d'un pneu
- Impact de(s) morceau(x) de pneu
- Déformation de l'intrados dans une zone ayant été détruite par la suite
- Mouvement interne de carburant dans le réservoir n°5
- Rupture par expulsion du panneau retrouvé sur la piste.

Ce scénario semble parfaitement plausible, et reste, pour EADS, le plus probable sur la base des informations disponibles. A ce titre, il doit servir de référence dans le choix des actions à entreprendre pour la remise en service des avions.

J. GROUAS

CONCORDE: DESTRUCTION DU PANNEAU INTRADOS

Analyse du scénario de rupture en mode 2 suite à un impact de débris de pneu

1 - Faits et hypothèses préliminaires

Les faits pouvant concerner la tenue de la structure de l'intrados de voilure peuvent se résumer ainsi:

1.1 Destruction du pneu

Des enquêtes et examens effectués à la suite de l'accident, il ressort les éléments suivants:

- Une lamelle métallique, élément de capot d'inverseur, a été perdue par un DC10 décollant quelques minutes avant Concorde.
- Le pneu n°2 a éclaté en roulant sur la lamelle métallique en donnant des débris de grande taille. Des essais de roulage de pneus similaire sur une lame métallique ont confirmé ce point avec des débris de pneu pouvant atteindre 7et 11kg.
- Après l'accident il a été retrouvé des débris, dont les deux principaux pèsent 4.45 kg et 2.6 kg. Ces derniers ont été trouvés proches l'un de l'autre sur la piste.

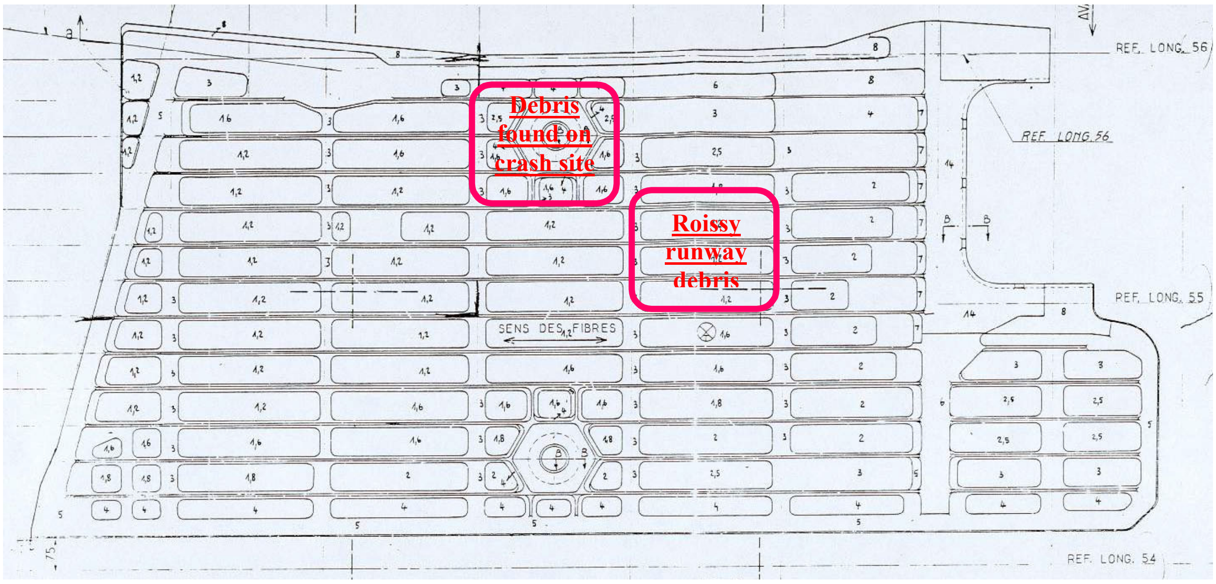
1.2 Rupture de l'intrados

Pour l'instant, sur la base des résultats d'analyses du CEAT et des informations qui ont pu lui être transmises auparavant, EADS a retenu les éléments suivants:

- Un morceau d'intrados du réservoir 5 de dimension 300x300 mm environ a été retrouvé sur la piste (scellé n° 7). Aucune trace d'impact n'est visible, mais la pièce est déformée vers l'extérieur comme si elle avait été soumise à une pression interne au réservoir
- Un autre morceau d'intrados du réservoir 5 a été retrouvé sur le lieu du crash final de l'avion avec une perforation de 30x5mm environ (scellé n° 1). Le reste de la structure avoisinante a été totalement détruit et il n'a pu être fait aucune constatation sur un impact éventuel de morceau de pneumatique sur l'intrados.

1.3 - Examen de la pièce (scellé n° 7)

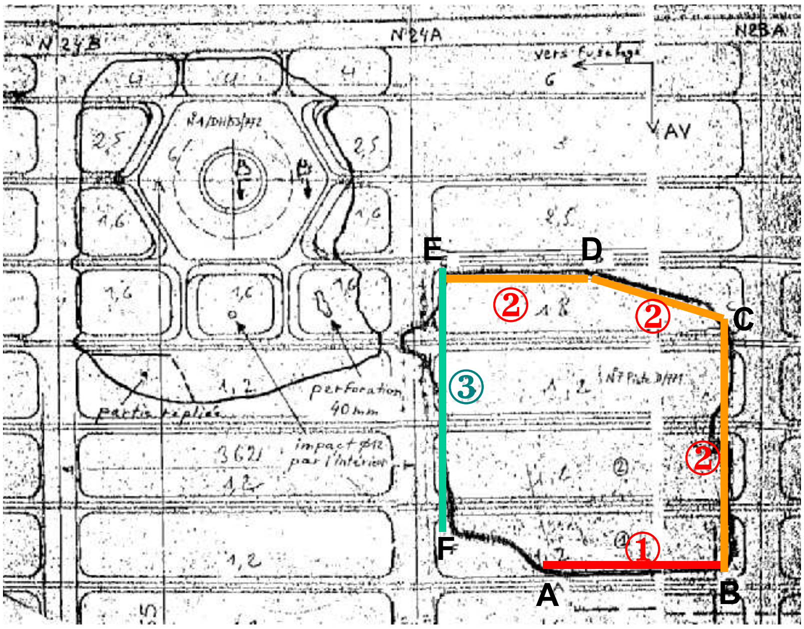
La pièce retrouvée sur la piste correspond à un morceau d'intrados côté gauche situé entre les nervures 23A et 24A et les longerons 55 et 56 (figure ci-dessous)



Des informations données sur l'examen de cette pièce, nous avons retenu les éléments suivants:

- La pièce présente une déformation générale indiquant un effort de l'intérieur vers l'extérieur.
- La déformation extérieure correspond à des rayons de courbure allant de 400 à 1300 mm perpendiculairement aux raidisseurs, alors qu'il n'y a pas de courbure apparente parallèlement à ces raidisseurs
- En dehors d'un des bords faisant apparaître un choc, qui a été identifié comme une conséquence de la chute sur la piste, il n'a pas été identifié d'autre trace d'impact sur cette pièce.
- Le faciès de rupture des panneaux sur tout le pourtour de cette pièce a été identifié de la manière suivante:
  - L'ensemble des ruptures sont d'origine statique.
  - La rupture aurait pu commencer sur la partie BC de la figure ci-dessous selon des interprétations des experts du CEAT et du CEPR. La propagation se serait faite depuis B vers C, D puis E
  - Le long de BC les sommets de raidisseurs sont déformés en compression.
  - Une rupture en mode charnière vers l'extérieur suivant EF, le point F étant certainement le dernier point à tenir.

  NB: Les experts de EADS émettent l'hypothèse d'une rupture à partir du segment AB, les écaillages de peinture sur les zones BC, CD et DE, significatives d'une propagation, n'apparaissant pas sur ce segment.



1- Initiation de la rupture AB (congé de raccordement) ou BC

2- Propagation BC puis CD et DE

3- Charnière en flexion EF

1.4 - Fuites de carburants

Dans son rapport sur l'analyse de la combustion le CNRS confirme un niveau de fuite de l'ordre de 50 à 100 l/s en s'appuyant sur l'examen de la combustion et sur les quantités de carburant. Ceci est tout à fait cohérent avec les évaluations des débits libérés par un trou de 300*300 mm telles qu'elles ont pu être faites par EADS

On peut donc estimer que la rupture correspondant au morceau d'intrados trouvé sur la piste est la rupture principale à considérer dans la chaîne des événements qui ont conduit à l'accident. On concentrera donc la suite de l'analyse sur cette rupture.

1.5 - Hypothèse préliminaire

Au vu de ces premières constatations, un scénario préliminaire de destruction de ce panneau a pu être établi (cf.: Rapport d'Etape du BEA du 15-12-00)

- Un morceau de pneu a percuté l'intrados dans une zone proche de celle de la pièce identifiée. Le choc a généré une déformation significative de ce panneau, vers l'intérieur sous l'impact, et vers l'extérieur autour de l'impact par continuité de la structure.
- Cette déformation a entraîné un déplacement du carburant dans le réservoir
- Et ce déplacement d'un fluide incompressible par un effet de convection dans le réservoir est venu amplifier la déformation vers l'extérieur du panneau trouvé sur la piste.
- L'affaiblissement des raidisseurs pourrait dans ces conditions être la conséquence de l'impact initial. Le type de dommage constaté dépend de la

position exacte de cet impact, de l'attitude du projectile au moment de cet impact et de son énergie.

1.6 - Chronologie des événements

La succession des événements telle qu'elle apparaît dans cette hypothèse est par ailleurs cohérente avec la reconstitution chronologique de l'accident réalisée par le BEA.

1.7 - Validations nécessaires

- Néanmoins ce scénario doit bien sûr être validé par des analyses et des essais appropriés. L'objectif est à la fois d'en étayer le principe et de quantifier les phénomènes pour mettre en relation les dégâts constatés et les valeurs des paramètres d'entrée.
- Dans un deuxième temps, il faut confronter les valeurs trouvées sur ces paramètres d'entrée avec les conditions de l'accident pour établir la vraisemblance du scénario de l'accident.

2 - <u>Moyens de validation des phénomènes</u>

En dehors des constats de l'accident lui-même, où les informations disponibles sont trop partielles pour suffire à étayer le scénario, il a été procédé à de nombreux travaux théoriques et expérimentaux:

2.1 - Modèles de calculs et logiciels RADIOSS:

Les études théoriques ont été menées sur la base de modélisations de l'ensemble structure et carburant du réservoir 5 utilisant le logiciel RADIOSS. Ce logiciel, disponible chez EADS, est reconnu comme étant un outil représentatif de l'état de l'art pour traiter à la fois les phénomènes de dynamique rapide (inférieur à 10^{-4}s) et les couplages fluide/structure. La méthodologie et l'ensemble des travaux exposés par la suite ont été avalisés par l'ONERA, nommé expert par le BEA.

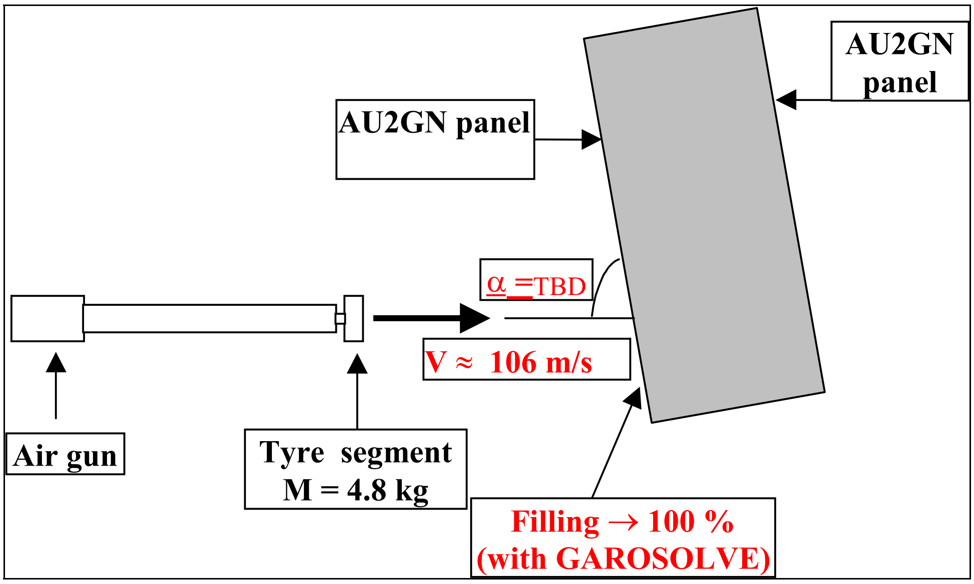
Ces modélisations ont porté sur le réservoir n°5 réel de Concorde et sur des caissons d'études qui ont été définis et fabriqués pour réaliser les essais de validation. L'ensemble des rapports sur les études théoriques est répertorié dans l'annexe 1.

2.2 - Caissons d'essais:

- Pour identifier le phénomène, EADS a réalisé des essais sur des caissons d'essais représentatifs de réservoirs, sur lesquels ont été tirés des morceaux de pneumatique à grande vitesse, dans les installations du CEAT dites du "Tir au Canon".

- Principe des essais

Les installations du CEAT permettaient la réalisation d'essais suivant le principe décrit ci-dessous.



Les limitations majeures étaient les suivantes:

- Energie maximale de projection correspondant au couple (4.8kg - 106 m/s)
- Tir horizontal
- Attitude du projectile imposée
- Taille du caisson limitée
- Nombre de tirs et de caissons limités

Il était bien sûr impossible de représenter sur ces essais tous les scénarios possibles de l'accident, et il a été choisi de réaliser des essais génériques, avec le souci d'y représenter les facteurs influents principaux. Il était donc tout à fait improbable de retrouver les conséquences semblables à celle de l'accident, mais seulement d'y trouver des indices permettant d'étayer un scénario de rupture.

- Définition des éprouvettes (annexe 2):
  L'identification des paramètres influents s'est faite de manière progressive, au fur et à mesure des essais et analyses théoriques. La définition des caissons d'essais a donc évolué de la plus simple vers la plus complexe:
  - Caisson parallélépipédique avec panneaux raidis au standard de l'avion mais avec des épaisseurs de fond de maille constantes
  - Caisson parallélépipédique avec des fonds de mailles localement renforcés
  - Caissons avec des panneaux réels, prélevés sur un avion arrêté de vol

- Mesures
  Tous ces caissons étaient équipés de mesures de déformation sur les fonds de mailles et les raidisseurs, et de pression dans le liquide, dans la

zone de l'impact et dans les zones voisines. Des mesures de déformées résiduelles ont été faites après essais et des caméras rapides ont permis de visualiser l'impact pendant le tir.

- Les conditions d'essais ont été choisies pour recaler les modèles théoriques avec un objectif d'optimiser les conditions pour obtenir des résultats quantifiables. Les valeurs des paramètres d'essais choisies ne préjugeaient en aucun cas de ce qui avait pu se passer au cours de l'accident.

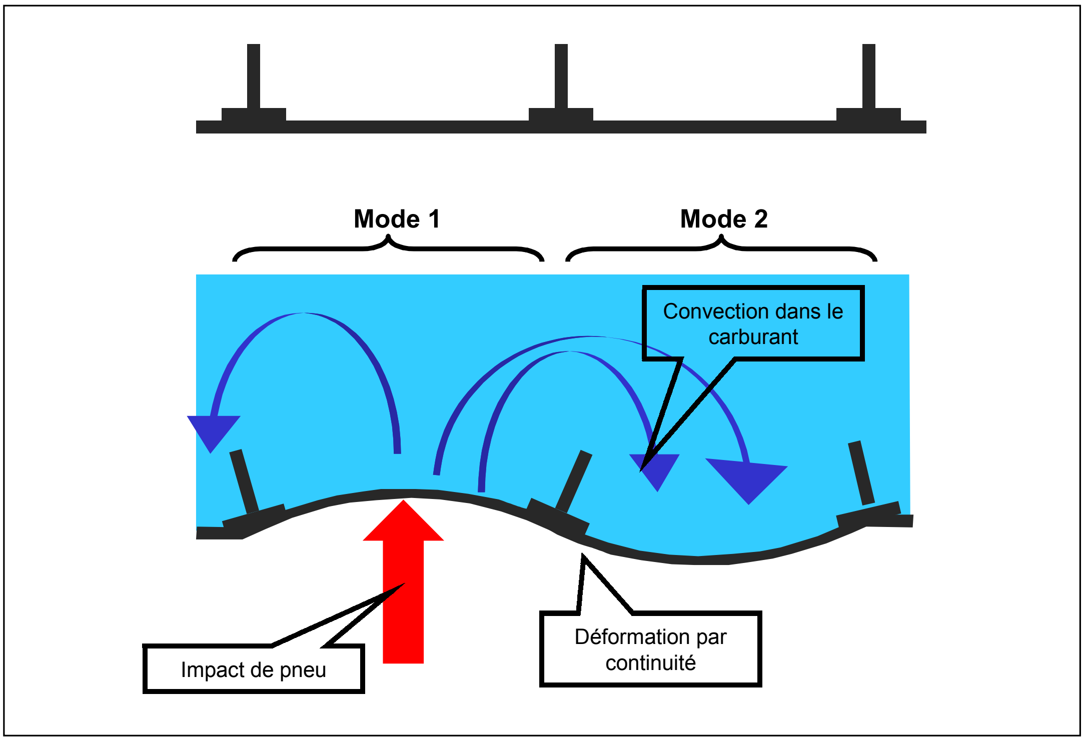
- Programmes et rapports d'essais
  L'ensemble des programmes et rapports d'essais est répertorié dans l'annexe 2.

2.3 - Eprouvettes partielles

Des essais sur petites éprouvettes ont aussi été réalisés pour caractériser les matériaux et les modèles locaux de rupture dans les conditions aussi proches que possible des conditions des tirs au CEAT et de celles, que l'on a pu estimer être celles de l'accident:
Ces essais d'éprouvettes ont eu lieu dans les laboratoires d'EADS à Toulouse et au CCR à Suresnes, et également au "Sowerby Research Center" de BAE SYSTEMS en fonction des capacités de ces laboratoires à réaliser des essais particuliers.
Le détail de ces essais sera développé dans la suite du document.

3 - Effet d'un impact sur un caisson de voilure avec carburant

3.1 - Mode 1 et Mode 2



- Sur un panneau auto-raidi, sans carburant, le choc d'un morceau de pneu entraîne
  - dans la zone du choc, une déformation dans le sens du choc
  - dans les zones voisines, une déformation dans le sens opposé par effet de continuité structurale.

- A cet impact primaire, s'ajoute un effet secondaire dû au fluide, qui est déplacé et tend à repousser la structure par un processus de convection, d'abord dans les zones les plus proches. Ces zones proches peuvent être les mailles voisines sur l'intrados ou les parois verticales, en fonction de la géométrie locale et de la position de l'impact. Sur les mailles voisines, cet effet vient s'ajouter à l'effet primaire précédemment décrit.

- Dans la pratique, il est impossible de séparer ces deux effets, en revanche, il est utile de distinguer les deux zones avec des sens de sollicitation en sens opposé:
  - Le principe de déformation sur la zone d'impact et dans le sens de l'impact sera appelé Mode 1.
  - Le principe de déformation en sens inverse, correspondant à une expulsion vers l'extérieur, sera appelé Mode 2.

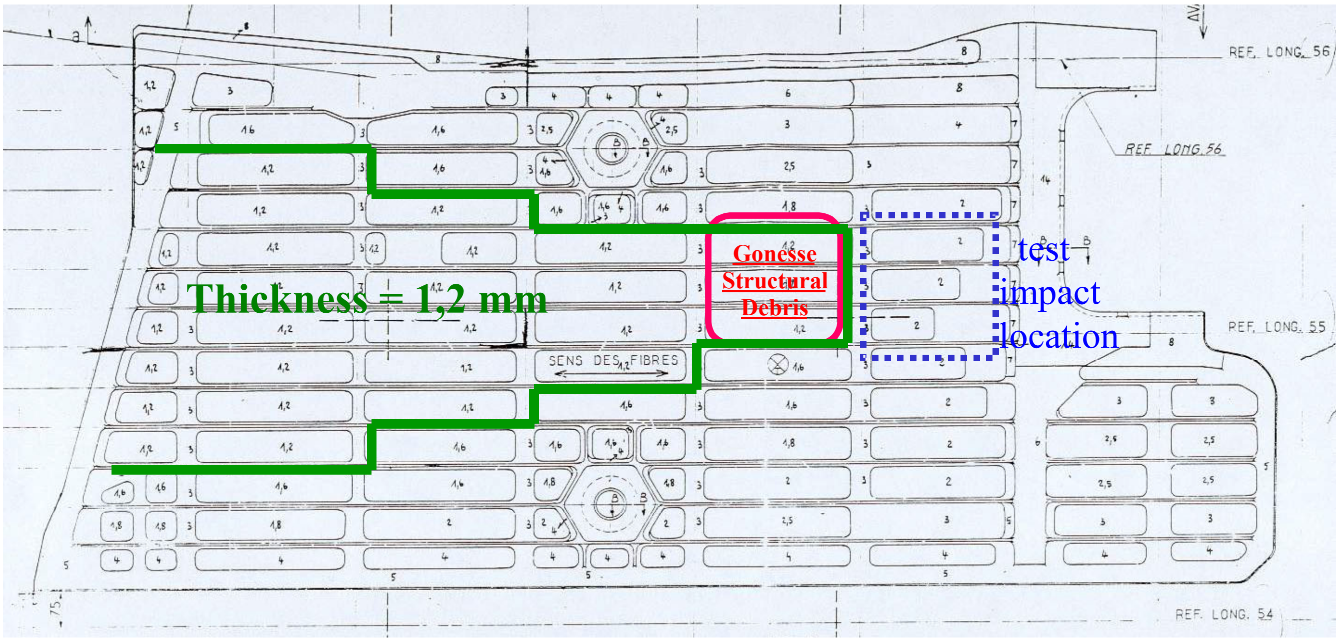
Remarque: L'existence des modes 1 et 2 est une caractéristique du type de sollicitation de la structure, indépendamment de son intensité, c'est-à-dire qu'il ne préjuge pas de l'éventualité d'une rupture. L'événement de l'accident correspond à un Mode 2, qui est allé jusqu'à rupture.

3.2 - Résultats des analyses théoriques:

Les études théoriques amènent au processus suivant:

- Le panneau se déforme sous le choc vers l'intérieur du réservoir
- Une onde de pression sphérique se propage dans le carburant à la vitesse du son, c'est-à-dire 1260 m/s environ, avec des valeurs de pression de l'ordre de 200 bars au départ, elles n'atteignent plus que 10 bars environ lorsqu'elles arrivent dans la zone où le mode 2 est attendu.
- Une convection du carburant qui se déplace à une vitesse beaucoup plus faible, soit une valeur maximale proche de la vitesse du projectile au moment et à l'endroit de l'impact (80 m/s) et s'en allant décroissant pour atteindre des vitesses réduites de moitié sur le panneau voisin
- Ce panneau se déforme vers l'extérieur sous l'action de la convection du fluide entre 3 et 6 ms après le choc, soit entre 2 et 5 ms après le passage de l'onde de pression.
- L'ensemble des études sur des panneaux de géométrie différente fait apparaître une influence très importante de la cartographie des épaisseurs et des rigidités. Pour atteindre la rupture:
  - La zone "mode 2" doit être une zone d'épaisseur faible (1.2 mm de fond de maille sur l'avion).
  - Elle doit être entourée d'une zone sensiblement plus rigide, pour supporter le choc primaire et pour limiter les possibilités de déformation à l'extérieur de la zone "mode 2".
  - La convection du fluide doit être en partie canalisée vers une direction privilégiée, par exemple, grâce à une paroi latérale.

La planche ci-dessous montre sur ce point la géométrie de la zone sur avion:

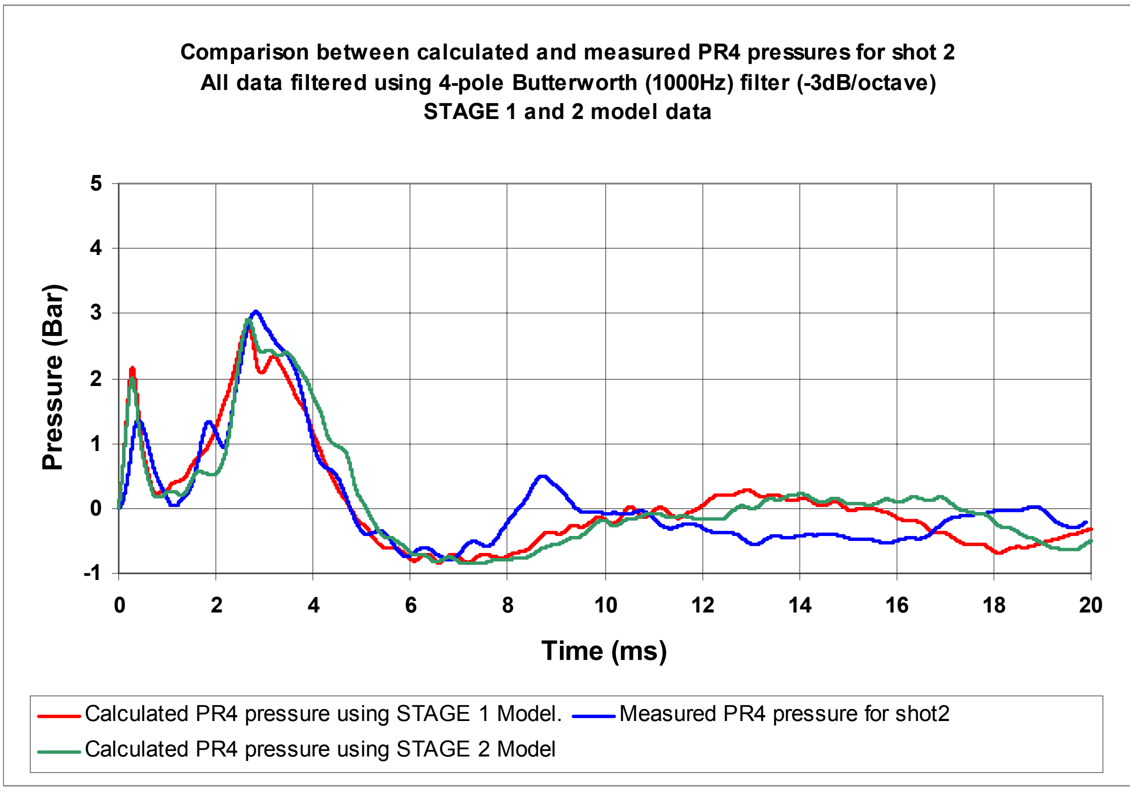


3.3 - Les expérimentations sur caissons

Les essais sur caissons confirment globalement le principe mis en évidence par les études théoriques. Une comparaison détaillée des essais et calculs fait l'objet des rapports cités dans l'annexe 2.

Le bilan de ces essais peut se résumer de la façon suivante:

- Des déplacements significatifs en mode 2 ont été observés sur tous les essais, quelles que soient la géométrie et l'énergie des projectiles.
- La séquence des phénomènes et l'évolution dans le temps des paramètres mesurés sont en accord avec le calcul.
- On retrouve l'indépendance apparente entre l'onde de pression et les contraintes. Les contraintes sont plutôt liées au déplacement d'ensemble du liquide.
- Les valeurs des paramètres mesurés sont en bon accord avec les calculs. Les courbes et le tableau synthétique suivant le confirment.


Comparison between calculated and measured PR4 pressures for shot 2
All data filtered using 4-pole Butterworth (1000Hz) filter (-3dB/octave)
STAGE 1 and 2 model data
Pressure (Bar)
5
4
3
2
1
0
-1
0
2
4
6
8
10
12
14
16
18
20
Time (ms)
Calculated PR4 pressure using STAGE 1 Model.
Measured PR4 pressure for shot2
Calculated PR4 pressure using STAGE 2 Model

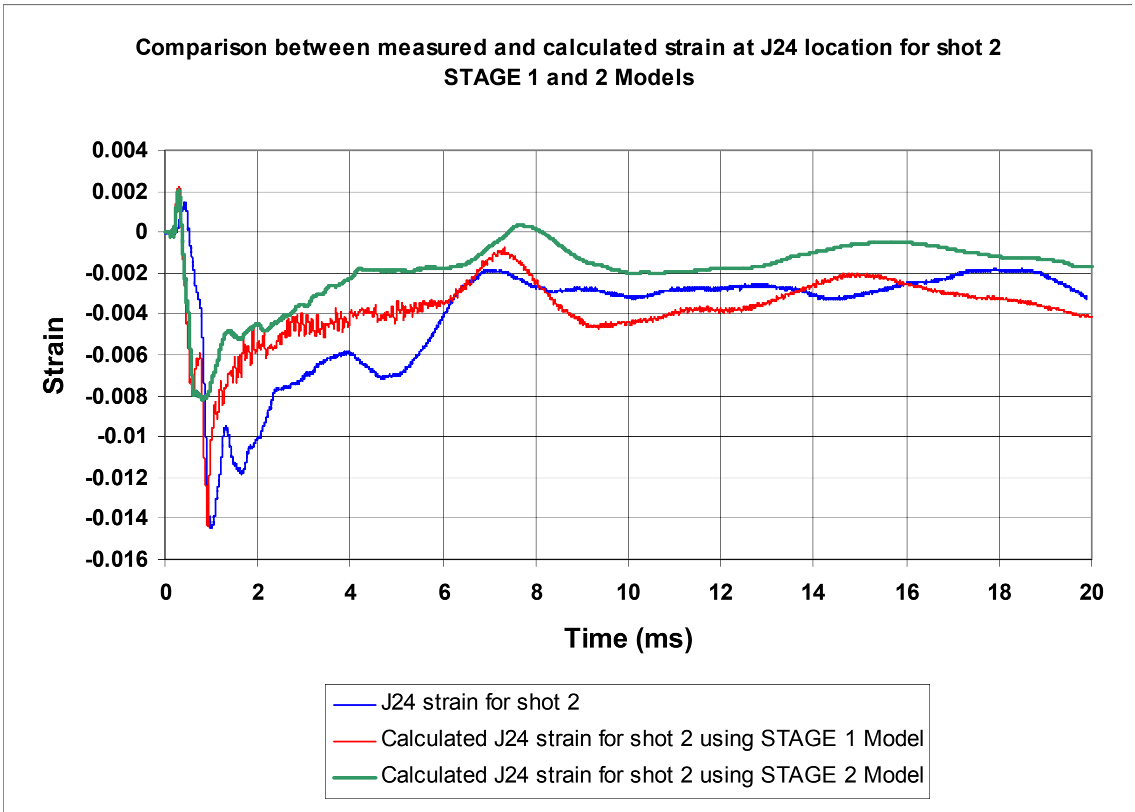

Comparison between measured and calculated strain at J24 location for shot 2
STAGE 1 and 2 Models
Strain
0.004
0.002
0
-0.002
-0.004
-0.006
-0.008
-0.01
-0.012
-0.014
-0.016
0
2
4
6
8
10
12
14
16
18
20
Time (ms)
J24 strain for shot 2
Calculated J24 strain for shot 2 using STAGE 1 Model
Calculated J24 strain for shot 2 using STAGE 2 Model

Tableau de synthèse des valeurs de calcul et d'essai obtenu lors du tir n°5

	TEST	SIMULATION
Maximum pressure (under impact)	203 bars	280 bars
Maximum pressure (away from impact, in expected mode 2 area)	10 bars	14 bars
Maximum skin strain (gauges under impact)	5,5 %	3,7 %
Maximum stiffener strain (gauges under impact)	4,3 %	3,8 %
Maximum skin strain (gauges away from impact)	0,7 %	0,6 %
Maximum stiffener strain (gauges away from impact)	0,7 %	0,7 %

Mais aucune rupture n'a pu être mise en évidence lors de ces essais.

3.4 - Les désaccords entre les essais et les études théoriques

Au vu de ces résultats, on peut affirmer que le principe du Mode 2 est bien validé et que le calcul et les essais sont en bon accord à la fois sur les phénomènes et les niveaux atteints sur les grandeurs mesurées.

L'écart se situe essentiellement sur la capacité à prédire la rupture. C'est donc le phénomène très local du mode de rupture qu'il a fallu revoir.

4 - Le mode de rupture

4.1 - Rupture en mode 2

Les modèles de rupture dépendent du type de sollicitation appliqué. On s'intéressera donc essentiellement à celui du mode 2, reconnu comme l'élément majeur de l'accident.
Cette modélisation se fait en deux étapes:
- identifier les zones fragiles sur la structure
- modéliser dans le détail ces zones avec le support d'essais sur petites éprouvettes pour en ajuster les paramètres.

4.2 - Identification des zones fragiles

Selon les informations en notre possession et au stade actuel des expertises faites sur la pièce, la rupture se serait initiée et propagée le long des congés au pied de la nervure 23A et des raidisseurs. L'ensemble des calculs avant rupture montre que ces zones correspondent à des niveaux de contraintes maximales.

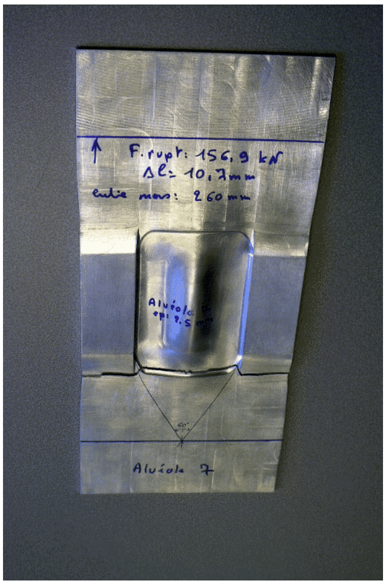
4.3 - Modélisation détaillée de la rupture

4.3.1 - Le principe

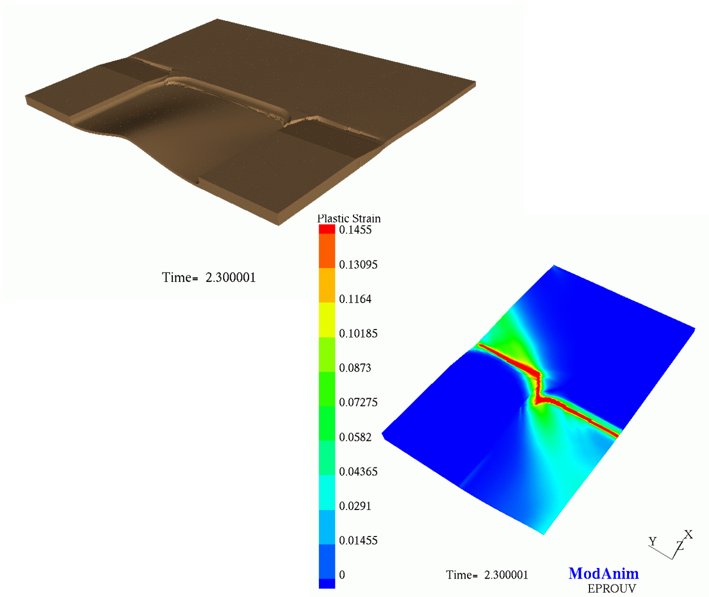
- Les modèles théoriques utilisés pour représenter les phénomènes étant à la limite des moyens de calculs accessibles aujourd'hui, les congés situés au pied des raidisseurs de panneaux n'ont pas été représentés géométriquement dans les modèles d'impact. Il a fallu modéliser le phénomène de rupture dans les congés par une approche en deux temps.

- D'abord, on a effectué une première modélisation volumique fine de la zone de congé de façon à connaître le comportement à rupture de cette zone. Cette modélisation a été confirmée par essais à rupture sur des éprouvettes spécialement définies. A titre d'illustration, on présente ci-après une de ces éprouvettes après rupture ainsi qu'une vue analogue du modèle ayant subi le même chargement.

- Ensuite, on a ajusté sur ce calcul très fin mais local, un modèle d'éléments de structure de taille susceptible d'être intégré dans une structure avion, mais ayant un comportement globalement équivalent.



Eprouvette d'essai après rupture



Modélisation rupture
et visualisation déformations plastiques

4.3.2 - Les résultats des essais

Les essais sur éprouvettes ont permis de confirmer que la zone fragile sous sollicitation en traction se trouvait bien dans le congé.

Le modèle de l'éprouvette représente bien l'essai, et pouvait servir de référence pour ajuster les modèles de rupture sur les caissons et l'avion, en fournissant une courbe effort/allongement particulière pour les éléments de cette zone.

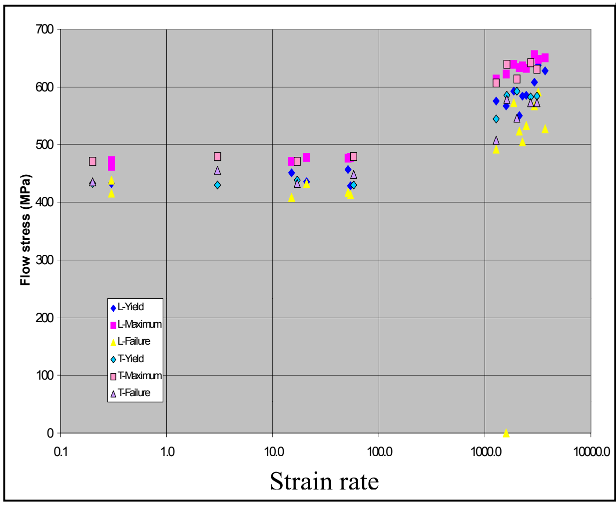
4.4 - Le comportement du matériau sous sollicitation très rapide.

L'essai précédant n'a pu être fait qu'à des vitesses de chargement de l'éprouvette relativement faibles pour des raisons de mise en œuvre.

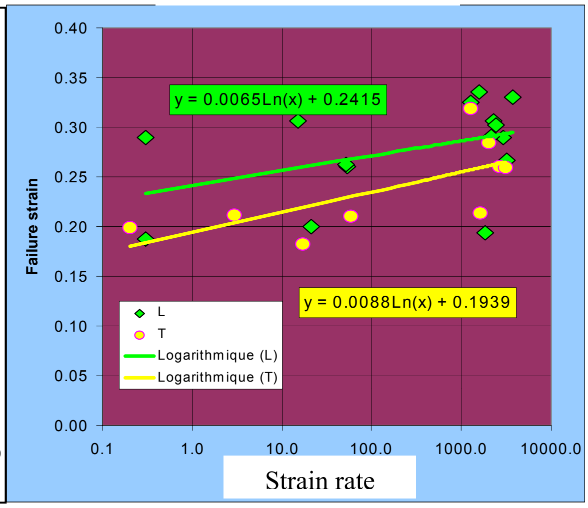
Lors de l'accident, et au vu des résultats théoriques et expérimentaux précédemment évoqués, les vitesses d'allongement sont de l'ordre de 1000 s^{-1} à 10000 s^{-1}, (c'est-à-dire qu'une longueur initiale de référence double respectivement en un millième et un dix-millième de seconde). Des essais ont été menés sur le matériau du Concorde (AU2GN) au laboratoire de BAE SYSTEMS (Sowerby Research Center), spécialement équipé pour ce type d'essais.

Les résultats présentés sur les diagrammes suivants montrent une augmentation importante des contraintes et allongement à rupture avec la vitesse de sollicitation.

FAILURE STRESS



FAILURE STRAIN



4.5 - Conditions de rupture

De ces analyses, il en ressort que dans les conditions d'impact supposées, la structure est capable d'absorber localement et avant rupture une énergie sensiblement plus grande en dynamique qu'en quasi-statique. Compte tenu de la dispersion des résultats obtenus avec des conditions initiales répétitives, le coefficient "d'amplification dynamique" sur l'énergie à rupture au cours des tirs sur caissons ou au cours de l'accident peut se situer entre 1.5 et 2.5 avec une valeur moyenne autour de 2.

Dans ces conditions, au cours de l'essai n°5 sur un panneau réel avion, l'énergie locale de déformation dans les congés peut être estimée à 65% de l'énergie de rupture. Ceci apparaît cohérent avec les mesures et déformations résiduelles trouvées.

Pour obtenir effectivement une rupture dans ce type d'essai, il faudrait donc:

- augmenter d'autant l'énergie globale des projectiles à même géométrie,
- mieux focaliser l'énergie localement par des conditions d'impact particulières,
- avoir fragilisé la structure par un endommagement préalable.

Remarque: En l'absence d'aucun moyen pour le vérifier, on prend l'hypothèse que les résultats liés aux particularités du dessin exprimés § 4.3 et à la vitesse de sollicitation du § 4.4 peuvent se superposer.

5 - Le cas de l'accident

Ayant bien identifié et vérifié le principe de la sollicitation en mode 2 de la pièce retrouvée sur la piste, et évalué des conditions d'énergie susceptibles d'amener le mode 2 jusqu'à la rupture, il convient de revenir au contexte de l'accident pour tenter de dégager des combinaisons d'événements possibles.

Si on revient aux conditions de rupture possible évoquées dans le paragraphe 4.5, la rupture peut s'expliquer dans le cas de l'accident par une combinaison d'événements suivants:

- augmenter l'énergie globale par une augmentation de masse et/ou de vitesse du débris ou en considérant un cas de débris multiples
- mieux focaliser l'énergie dans les congés. Ceci peut être obtenu par des conditions d'impact différentes en position, attitude et peut-être vitesse de rotation du ou des débris. Le mouvement du carburant et son interaction avec les accidents locaux de géométrie est susceptible aussi d'agir sur ce point.
- Avoir fragilisé la structure au préalable, ceci pouvant être la conséquence d'un endommagement en mode 1.

Tous ces points sont revus en détail ci-dessous.

5.1 - le débris de pneu

5.1.1 - masse du/des morceaux de pneu

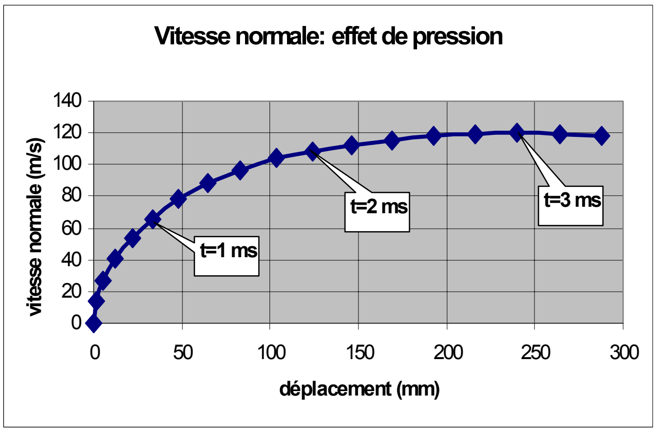
Les seuls morceaux de pneus identifiés sont ceux qui ont été trouvés sur la piste, dont les deux plus gros font respectivement 4.4kg et 2.6kg. Un impact d'un morceau plus gros reste possible, en supposant qu'il aurait pu être détruit par la suite.

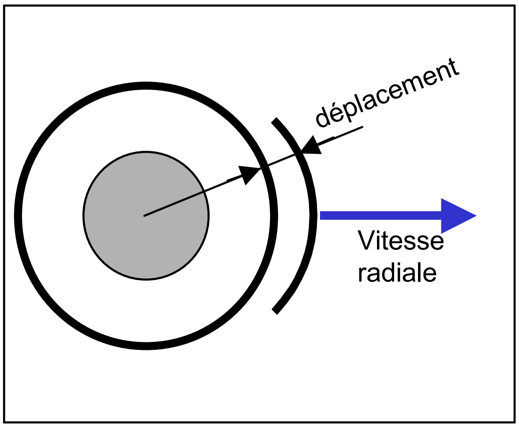
5.1.2 - vitesse du morceau à l'impact

La vitesse d'impact est la résultante de:

- la vitesse tangentielle de la roue, liée à la vitesse de l'avion (87m/s) et corrigée de l'écrasement du pneu au sol qui diminue le rayon de roulement de la roue de 12% environ. La vitesse tangentielle est donc 97m/s.

- la vitesse normale, due à l'explosion du pneu et qui dépend largement de la manière dont s'est propagée la rupture du pneu, suivant que le morceau se détache normalement à la surface sous l'effet de la pression, ou qu'il se déchire en s'ouvrant suivant une trajectoire divergente.
  Une étude a été menée dans le cas d'une expulsion sous le seul effet de la pression interne qui donne une évolution de la vitesse radiale suivant le schéma ci-dessous:





En dépit du caractère un peu théorique de ce calcul, on constate qu'une vitesse normale de l'ordre de 100 m/s peut être atteinte très rapidement.

La combinaison de ces deux vitesses donnerait une vitesse totale de 140 m/s, donc une énergie environ deux fois supérieure à celle disponible lors des essais.

5.1.3 <u>- La position de l'impact et son attitude:</u>

Le positionnement de l'impact du pneu sur la structure peut être un paramètre significatif sur le résultat. Toutes les études faites ont été menées aussi bien par analyse que par essais en centrant l'impact du pneu au milieu entre les deux nervures concernées. Un impact plus près d'une nervure pourrait occasionner une détérioration locale en mode 1 qui viendrait fragiliser la structure plus susceptible de se rompre en mode 2 par la suite.
L'attitude du morceau de pneu au moment de l'impact a aussi son importance. Si tous les calculs et essais ont été faits avec un impact à plat, il faut admettre que des attitudes et des positions d'impact différentes, pourraient aussi avoir des conséquences plus importantes. Une mise en rotation du projectile doit aussi modifier le résultat.

5.2 - le carburant dans le réservoir

La question du niveau de remplissage nécessaire dans les essais, a fait l'objet d'études particulières. L'enjeu était de rester représentatif de l'accident compte tenu des différences de taille de l'éprouvette d'essais et de sa position: le morceau de pneu est tiré horizontalement sur un caisson, mis en position quasi verticale, au lieu d'une position horizontale sur avion.

- Remplissage du réservoir 5 et l'effet d'accélération
  Au moment de l'impact du pneu sur le panneau du réservoir n°5, celui-ci devait être à 98% de sa capacité maximale. L'accélération longitudinale de l'avion étant de 0.28 g, la verticale apparente était inclinée de 15°, ce qui fait que la bulle en phase gazeuse se trouvait concentrée à l'avant du réservoir, et très éloignée de la zone d'impact.

- Les analyses effectuées sur le réservoir réel, avec des pleins de 98% et de 100%, ont montré que la surface libre était trop loin de l'impact pour influencer le phénomène du mode 2.

- Les mêmes comparaisons sur l'éprouvette d'essais ont montré un effet important parce que la surface libre se trouvait, dans les conditions de l'essai, trop près de la zone d'impact et qu'elle perturbait le mouvement de convection recherché. Les analyses ont démontré que le plein complet était la configuration représentative.

- En revanche, la forme exacte des parois du réservoir et les équipements internes n'ont pas pu être représentés complètement.

5.3 - Le niveau de contrainte du panneau avant l'impact

- L'état de chargement du panneau d'intrados de voilure pendant la phase de décollage a été évoqué comme un facteur d'amplification possible des conséquences de l'impact

- Pendant les phases au sol, ce panneau est en compression principalement sous l'effet du poids de la voilure pleine de carburant, auquel viennent s'ajouter les contraintes de roulage dues aux irrégularités de la piste. Ces contraintes de compression sont inférieures à 35 MPA dans les nervures et à 11 MPA dans les fonds de maille (cisaillement).
- Ces contraintes sont beaucoup trop faibles pour interférer de façon mesurable sur le phénomène de rupture de l'accident.

5.4 - Fragilisation initiale à l'impact

- Toutes les études effectuées par analyses et dans les conditions choisies pour les essais ont recherché des preuves de comportement en mode 2 sur des structures qui ont toujours bien résisté à l'impact primaire en mode 1.
- Les déformations en compression constatées sur les sommets de raidisseur de la pièce pourrait laisser supposer que cela n'a pas forcément été le cas lors de l'accident.
- Pour revenir à la question de la position de l'impact et aux caractéristiques du projectile mentionné dans le paragraphe 5.1.3 ci-dessus, on peut admettre

que des conditions particulières de l'impact proche de la nervure 23A auraient pu initier une destruction locale entraînant une fragilisation de la structure, dont les traces de flambage des raidisseurs sur la pièce retrouvée feraient partie.

5.5 - des débris multiples

- Les études menées ont toujours considéré l'impact d'un seul morceau de pneu sur l'intrados et l'éventualité de plusieurs morceaux atteignant la structure en même temps dans des zones proches mérite d'être considérée.

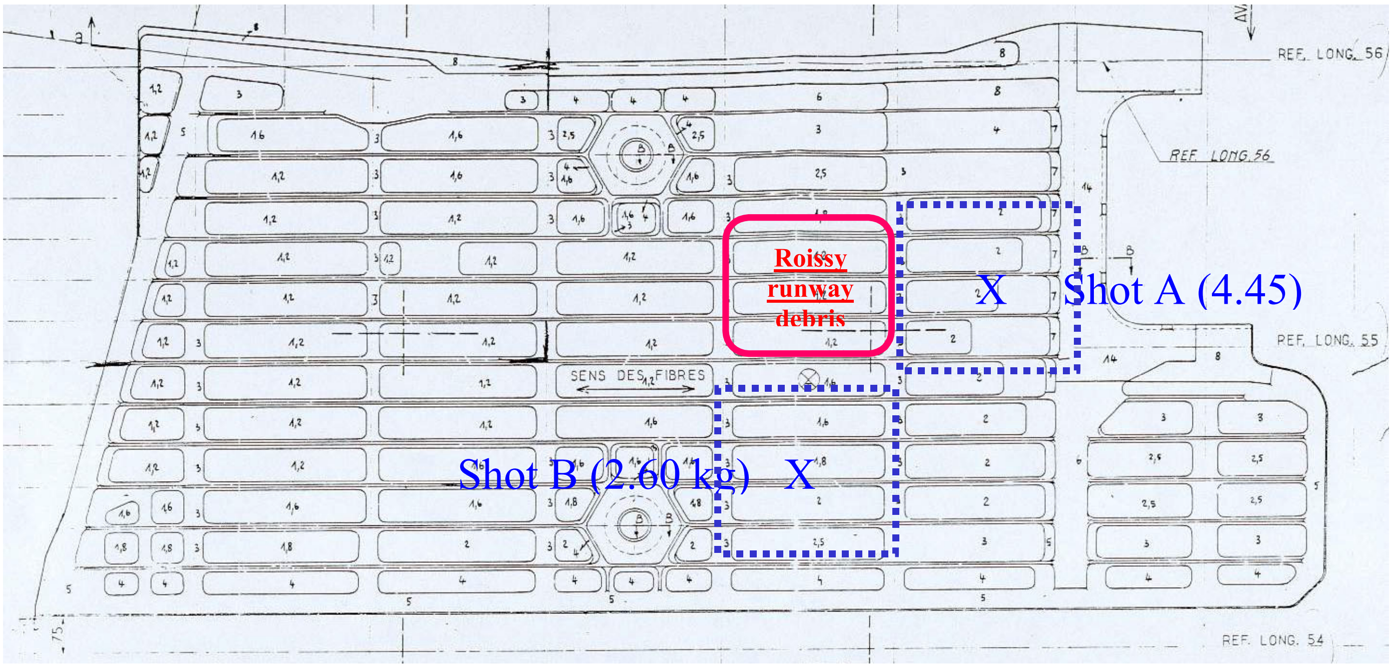
- Les deux principaux morceaux de pneu trouvés sur la piste ont les particularités suivantes:
  - Ils s'emboîtent parfaitement, et sont donc limitrophes sur le pneu,
  - Ils ont été retrouvés près l'un de l'autre

  On peut donc estimer qu'ils ont subi les mêmes événements et qu'ils ont eu des trajectoires semblables.

- L'hypothèse de deux impacts est assez cohérente avec les deux hypothèses d'initiation de la rupture évoquées § 1.3:
  - Une initiation de la rupture le long du segment AB sur le schéma de la page 2, correspondant à un des chocs (shot B sur le schéma ci-dessous)
  - Un déformation des raidisseurs selon le segment BC correspondant à l'autre choc (shot A)

- Une étude a été menée dans ce sens en supposant un premier impact au point A avec le morceau de 4.45 kg suivi d'un deuxième au point B avec le morceau de 2.6kg très légèrement décalé dans le temps (2 ms)

  On y voit clairement que les effets peuvent se superposer suivant une loi qui dépendra de la séquence et de l'emplacement des impacts.



	1 débris 4.45 kg	1 débris 2.6 kg	2 débris 4.45 + 2.6 kg
Déformation maximale en Mode 2	10 mm	5 mm	12 mm
Coefficient d'allongement en Mode 2	100 %	39 %	117 %

- Les effets des deux impacts se combinent suivant une loi difficile à appréhender, fonction de la position des impacts, de leurs attitudes et de leur chronologie.

Conclusions

- Les pièces retrouvées après l'accident sont très partielles, et aucune trace d'impact de pneu n'a pu être mise en évidence. Dans ces conditions, il n'est pas possible de décrire et de prouver de manière absolue un scénario de destruction de la structure.
- Cependant le scénario d'une rupture par la succession d'un choc primaire mode1, de mouvement de carburant dans le réservoir aboutissant à une rupture en mode 2 dans une zone moins résistante est vraisemblable.
- De très nombreuses études théoriques et essais sur caissons et éprouvettes ont été développés sur des sujets particulièrement inédits et faisant appel à des techniques à la limite de l'état de l'art, ce qui s'est traduit par une progression pas toujours régulière des travaux.
- Ils valident cependant bien la physique générale du phénomène, et tendent à montrer qu'il a fallu focaliser un niveau important d'énergie dans la zone de rupture.
- Cette focalisation d'énergie dépend des conditions de l'impact, sur lesquelles on ne peut faire que des hypothèses. Les axes à privilégier semblent être les suivants:
  - Une vitesse plus importante du morceau de pneu.
  - L'attitude du projectile et la position de l'impact qui peut se révéler localement plus endommageant.
  - Une fragilisation de la zone suite à l'impact primaire, facilitant par la suite une destruction en mode 2
  - Plusieurs impacts quasi simultanés apportant plus d'énergie dans le système.

  Une combinaison plausible de ces quatre axes est de nature à expliquer une rupture selon le scénario du mode 2 lors de l'accident.

ANNEXE 1: Etudes théoriques

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P. GADET
EADS Airbus
Technical note 581.0179/2001
June 2001

Tyre impact on aircraft panel - test program
P. GADET
Test program 577.0030/2001,
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Partie 1 : première campagne d'essais
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CEAT
S00/6508000 P1
Mars 2001

Etude du comportement dynamique de réservoir
Partie 3 : Deuxième campagne d'essais d'impact de pneumatique (NZG)
J.P. BOSCH
CEAT
S00/6508000 P3
Mars 2001

Etude du comportement dynamique de réservoir
Partie 4 : Impact sur panneau avion
J.P. BOSCH
CEAT
S00/6508000 P4
Juillet 2001

TABLE DES MATIERES

INTRODUCTION

Des éléments de l'enquête [1] concernant l'accident du Concorde survenu en Juillet 2000 mentionnent qu'un morceau de panneau de voilure intrados de 1.2 mm d'épaisseur (sous l'aile) a été retrouvé sur la piste, arraché de l'intérieur vers l'extérieur, mais sans présenter aucun signe de perforation. Cet élément ne présente pas de trace d'incendie, ce qui laisse supposer que son arrachement précéda le démarrage du feu. L'arrachement de cet élément de dimension importante ayant probablement été à l'origine de la fuite importante de carburant, cause de la catastrophe, la question se pose naturellement de savoir comment cet événement a pu se produire.

Plus récemment, et sur les lieux du crash cette fois, a été retrouvé un autre morceau d'un panneau de voilure intrados perforé, dont la position est justement périphérique du panneau arraché, et d'épaisseur 1.6 mm. Il semblerait bien que la perforation (40 mm x 20 mm, bords aigus, tranchés, et une lèvre recourbée à 45° vers l'intérieur) provienne de l'impact d'un projectile. L'analyse semble établir que ce n'est pas lors du crash, mais bien au décollage, que la perforation eût lieu. Il semble raisonnable de penser alors que, lors de l'éclatement du pneu, des éclats de natures diverses aient pu être projetés et aient percé le réservoir (d'autres incidents de ce type ont déjà été relevés au cours de l'exploitation de l'appareil) [2].

Or, la perforation d'un réservoir entièrement empli de carburant (au décollage, ce qui est un paramètre aggravant), par un projectile suffisamment rapide, peut générer ce que l'on appelle un coup de bélier hydrodynamique dans un réservoir. Le mécanisme du coup de bélier hydrodynamique est simple : un projectile, précipité dans un fluide, est brutalement ralenti (son ralentissement est fonction de son coefficient de traînée et donc de sa géométrie). Lors de ce ralentissement, l'énergie cinétique du projectile est transférée au fluide et une cavité d'un certain volume se crée autour de l'objet (le fluide est propulsé à la vitesse du projectile). En cas de confinement (pas d'espace libre dans le réservoir), le fluide étant incompressible, un chargement mécanique « proportionnel » au volume de cette cavité est donc transmis à la structure. La sévérité du coup de bélier peut donc être reliée au volume de la cavité, lui-même dépendant de mécanismes plus complexes : une onde de compression (1) se réfléchit en onde de traction si elle rencontre une surface libre, (2) se réfléchit en onde de compression si elle rencontre une surface rigide. Une onde de compression et une onde de traction se soustraient, deux ondes de compression s'ajoutent. Un jeu complexe d'ondes concurrentes incidentes et réfléchies se met donc en place, qui vont déterminer le volume de la cavité (la surface de la cavité constitue elle-même une surface libre), et donc le chargement mécanique. Lorsque la cavité finit par s'écrouler, un choc en retour peut également être généré.

De tels coups de bélier peuvent provoquer des dégâts particulièrement importants voire catastrophiques à l'intrados comme à l'extrados des caissons réservoirs (phénomène bien connu pour les avions militaires subissant des tirs). On constate souvent dans ces cas une pétalisation du panneau métallique autour du point d'impact intrados ou d'un point d'amorçage extrados (perforation de rivet, etc).

Dans les circonstances actuelles, aucun scénario ne peut être écarté a priori. Une explication possible étant que l'arrachement du panneau réservoir ait eu pour origine un tel coup de bélier hydrodynamique, l'ONERA a proposé d'étudier la pertinence de ce scénario. Cette pertinence peut être remise en question par le fait que, pour initier un tel phénomène, le projectile doive non seulement posséder une énergie initiale suffisante pour perforer la paroi de la voilure, mais surtout une énergie résiduelle après perforation suffisante pour générer le coup de bélier en question. C'est la raison pour laquelle ce type de phénomène est généralement observé pour de très grandes énergies (ce qui pour les petits projectiles signifient une très grande vitesse d'impact, de l'ordre de 1000 m/s pour 0.05 kg, ce qui donne des énergies voisines de 25 kJ). Lors de l'éclatement du pneu, les estimations ne laissent pas présager de risques d'éjectats à des vitesses supérieures à 120 m/s. Pour atteindre les énergies mentionnées précédemment, il faudrait donc un projectile de densité particulièrement importante, dont on ignorerait totalement l'origine.

D'un autre coté, la structure n'est pas rivetée mais usinée dans la masse, ce qui limite a priori le nombre des amorces de déchirure traditionnellement possible (à partir des perforations dues à la mise en place des rivets, par exemple). Il faut néanmoins considérer cette « absence » de points d'amorçage dans tous les scénarii, et en tirer la conclusion que les seules concentrations de contraintes locales liées à la présence des différences d'épaisseur, des nervures et des lisserons, auraient suffi à déclencher une rupture instable dans le matériau. En effet, le choix de l'AU2GN pour le Concorde fut principalement dicté par les caractéristiques intéressantes de cette nuance d'aluminium vis-à-vis du problème de fluage à chaud (on craignait que le supersonique ne s'échauffe en vol, ce qui a posteriori ne s'est pas avéré être le cas), et pas outre mesure vis-à-vis de sa résistance à la fatigue. Or il semblerait que ce matériau s'avérait particulièrement sensible à l'effet d'entaille (en terme de rupture). D'un autre côté, la perforation pourrait tenir lieu d'amorce potentielle, mais les investigations démontrent que, même si les phénomènes de ruine se sont développés dans des zones voisines, l'arrachement n'est pas parti de la perforation.

A la différence des investigations menées dans le cadre de l'enquête judiciaire, ou des travaux menés par EADS pour la re-certification de l'appareil, l'objectif des travaux présentés vise à la compréhension des phénomènes qui ont été à l'origine de l'accident et plus particulièrement de l'arrachement du panneau retrouvé sur la piste. L'ONERA ayant développé une méthode d'analyse numérique du phénomène du coup de bélier hydrodynamique dans les réservoirs, il a été proposé au BEA d'appliquer cette méthode pour tenter de valider ou d'infirmer ce scénario.

Plus précisément, si coup de bélier il y eût, l'ONERA propose de focaliser son analyse sur le fait que l'arrachement ne soit pas parti de la zone d'amorçage que constituait la perforation (perforation et fragment arraché ne sont distants que de quelques centimètres). Le scénario de coup de bélier pourrait en effet être infirmé si les simulations E.F. confortent l'hypothèse que l'arrachement aurait du préférentiellement démarrer de cette perforation (pétalisation autour de la perforation). Pour démontrer cela, il n'est pas forcément nécessaire de modéliser l'ensemble du caisson réservoir. Dans cette optique, des maillages fins et réguliers peuvent être utilisés, ce qui améliore le niveau de confiance attribué aux calculs. Le cas le plus critique est traité, dans lequel le fluide est totalement confiné.

Les caractéristiques en termes de trajectoire, de vitesse et de densité du projectile sont les suivantes : trajectoire à 45° par rapport à la surface au point d'impact, et dirigée vers le point de démarrage supposé de l'arrachement (cf rapport d'enquête), vitesse initiale de 120 m/s. La géométrie et le matériau du projectile sont inconnus. Il est admis que la géométrie ne joue qu'indirectement sur la sévérité du coup de bélier. Par contre, l'énergie initiale importe, puisqu'elle va s'opposer au ralentissement (traînée du projectile) et va permettre de prolonger la course et augmenter le volume de la cavité autour du projectile. L'évolution du coefficient de traînée sera du type de celle d'un barreau cylindrique de quelques 50 mm de long pour 10 mm de diamètre, doté d'un angle d'inclinaison initial dans le fluide de 30° par rapport à la paroi impactée, et se retournant violemment dès les premiers instants de la traversée. Il a en effet été constaté que ce type de configuration pouvait générer un coup de bélier hydrodynamique en paroi avant de structures métalliques [2], et l'ONERA dispose des éléments nécessaires à une telle modélisation.

L'ONERA ne modélisera pas le processus de perforation de la paroi intrados, qui sera supposée n'avoir consommé qu'une faible partie de l'énergie initiale du projectile. La simulation démarre donc juste après que le projectile ait pénétré le fluide.

1. PRESENTATION DE LA METHODE DE RESOLUTION

1.1. Simulation numérique par éléments finis

La méthode de résolution repose sur l'utilisation d'un code de calcul explicite par éléments finis (RADIOSS en l'occurrence). Ce type de code éléments finis, généralement appelé code « Crash » car particulièrement adapté à la résolution des problèmes à « petites déformations » et grands déplacements, repose sur la résolution des équations de propagation des ondes mécaniques dans les milieux continus. Le schéma d'intégration explicite permet de résoudre des problèmes présentant des nombres particulièrement importants de degrés de liberté.

Avant que de décrire plus précisément la méthodologie, quelques rappels généraux concernant les différents méthodes numériques existant doivent être faits : bien que les ondes mécaniques se propagent tout autant dans les fluides que dans les solides, une autre théorie est généralement utilisée pour traiter la première catégorie de milieu, et repose sur la résolution des équations de la mécanique des fluides. En fait, historiquement, pour chacun des problèmes fluides et structures, des techniques différentes de discrétisation de l'espace et du temps et de modélisation ont été développées. Pour les solides, on évoquera la méthode Lagrangienne (le maillage est déformable et suit exactement les déformations de la matière) et les lois de comportement. Pour les fluides, on évoquera la méthode eulérienne (le maillage de l'espace est fixe, et on étudie les équations de conservation des flux de matière au travers de la grille spatiale) et les équations d'état. Il existe une méthode plus générale, dénommée ALE pour « Arbitrary Lagrange Euler » ou « Approximated Lagrange Euler » selon les sources, qui a été développée, en théorie, spécialement pour traiter des problèmes couplés fluide/structures. La partie structure est traitée en Lagrangien, et la partie fluide est partiellement traitée en Lagrangien (pour suivre les déformées des milieux solides aux frontières du milieu fluide, et partiellement en eulérien (pour éviter d'avoir de trop grandes déformations du maillage, ce qui nuirait à la validité et à la stabilité du calcul). Pour fonctionner correctement, il est absolument nécessaire que les déformées de la grille ALE restent faibles, sous peine de voir apparaître des instabilités numériques mettant terme au calcul. L'inconvénient de cette méthode ALE, qui permet, toujours en théorie, d'appréhender le comportement de milieux fluides biphasiques et le couplage avec les structures, est d'être beaucoup plus coûteuse en terme de temps de calcul que la méthode Lagrangienne (à déformation égale du maillage).

L'objectif de notre modélisation consiste à représenter l'intrusion dans le fluide d'un corps solide, dont le coefficient de traînée évolue au cours du temps (en générant un jeu d'ondes de compression se propageant dans le fluide et chargeant la structure jusqu'à la ruine). La méthode proposée et développée par l'ONERA repose sur le constat que la seule méthode permettant de traiter « rapidement » et en 3D le problème du coup de bélier dans une structure réelle est la méthode Lagrangienne, pour peu que l'on parvienne à contrôler la déformation du maillage. Pour cela, il est décidé d'utiliser un projectile de forme conique : son double avantage est d'avoir une trajectoire stable, d'une part, et de permettre un écoulement faiblement déformé du fluide à sa frontière, d'autre part. Les dimensions et l'angle d'ouverture du cône déterminent complètement son coefficient de traînée hydrodynamique. En faisant varier continuement ces grandeurs au cours du calcul, il est donc possible de piloter un projectile de coefficient de traînée variable. Cette méthode a été développée et validée en 2D dans un premier temps [3], avant que d'être transposée en 3D.

1.2. Application de la méthode numérique à l'analyse de l'accident du Concorde

En résumant, un domaine borné de fluide est maillé autour du projectile conique. La finesse adaptée du maillage dans cette zone permet de gérer correctement les contacts et les déformations. Des interfaces virtuelles permettent d'imposer et de préserver un écoulement radial du fluide autour du projectile. Cette partie du modèle contient 57232 éléments finis de volume pour le fluide, et 48 éléments de coques pour le projectile (cf figure 1).

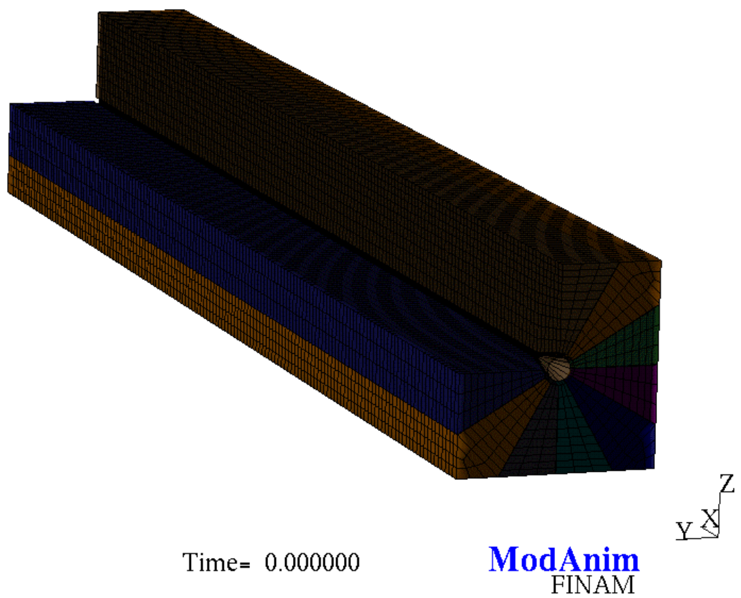

Figure n°1 – Ecorché du maillage du projectile et du fluide environnant -

Par ailleurs, un modèle éléments finis de 4 tronçons du réservoir et du reste du fluide est développé par blocs de façon la plus régulière possible. Les différents blocs sont associés au travers d'interfaces liants, permettant de joindre cinématiquement des maillages disjoints.

Les nervures, enveloppes et lisses extrados sont fusionnés avec le fluide (donc la finesse de maillage est la même pour ces différents éléments). Pour cette partie du modèle, la finesse de maillage est assez grossière, mais régulière. Elle contient néanmoins près de 71000 éléments de volume pour le fluide et non loin de 80000 éléments de coques pour la structure.

La peau et les lisses intrados sont maillés beaucoup plus finement pour traiter le problème de la rupture. Cette seule partie du modèle contient 20500 éléments de coques, à trois points d'intégration dans l'épaisseur (cf figure 2). A la différence du reste de la structure, ils sont dissociés du fluide, un interface de contact étant introduit pour gérer l'interaction fluide/structure. Le recours à ces interfaces de contact permet de gérer l'écoulement du fluide le long de la peau intrados, et de modifier la finesse de maillage sans avoir à redévelopper le reste du modèle. De tels interfaces de contacts auraient pu être généralisés, mais ils auraient fortement pénalisé les temps de calcul, ce pourquoi la fusion des maillages a été utilisée dans les zones éloignées de la zone de rupture.

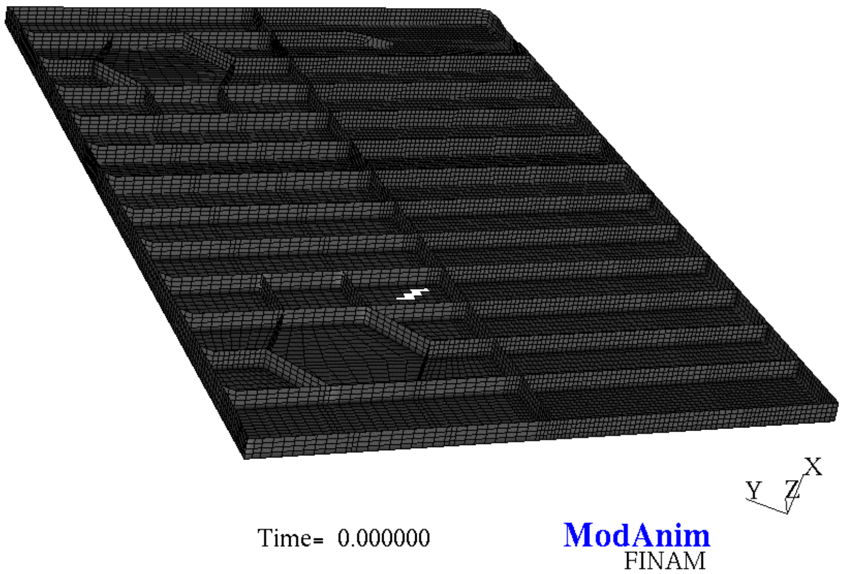

Figure n° 2 – Maillage de la peau et des lisses intrados, avec perforation initiale

Le « cartouche » contenant le projectile est ensuite assemblé dans le modèle de réservoir, les frontières des deux sous-domaines étant jointes au travers d'un interface liant. Au total, le modèle contient 200000 nœuds, 130000 éléments de volume et 102000 de coques (cf figures 3 et 4). Nous dénommerons « Tronçon 2 », le quart du modèle dans lequel la perforation est située. Nous dénommerons « Tronçon 3 » le quart du modèle dans lequel le panneau arraché se situe. La trajectoire du projectile est orientée à 45°, du Tronçon 2 vers le Tronçon 3.

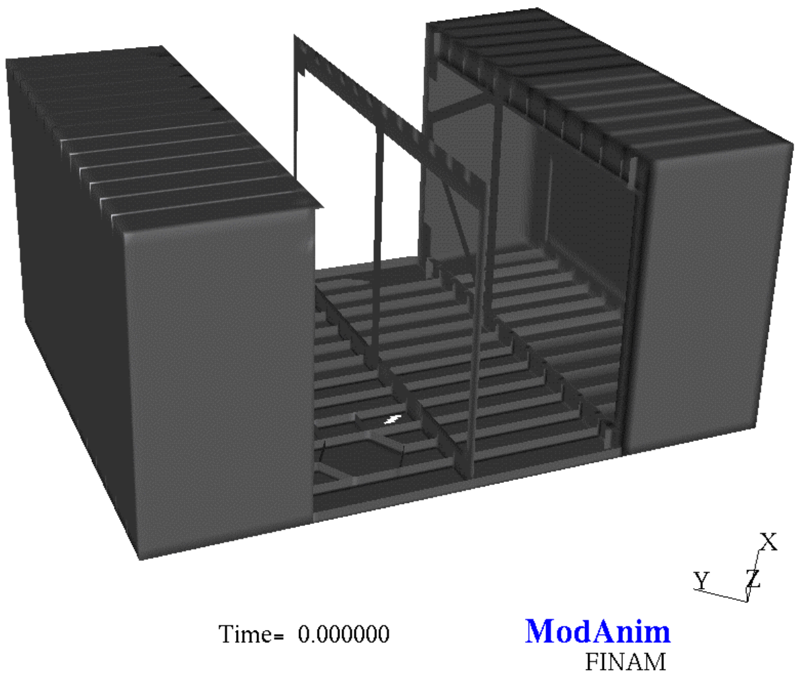

Figure n°3 – Maillage des 4 tronçons environnant la zone du panneau arraché (de 1 à 4 de gauche à droite)

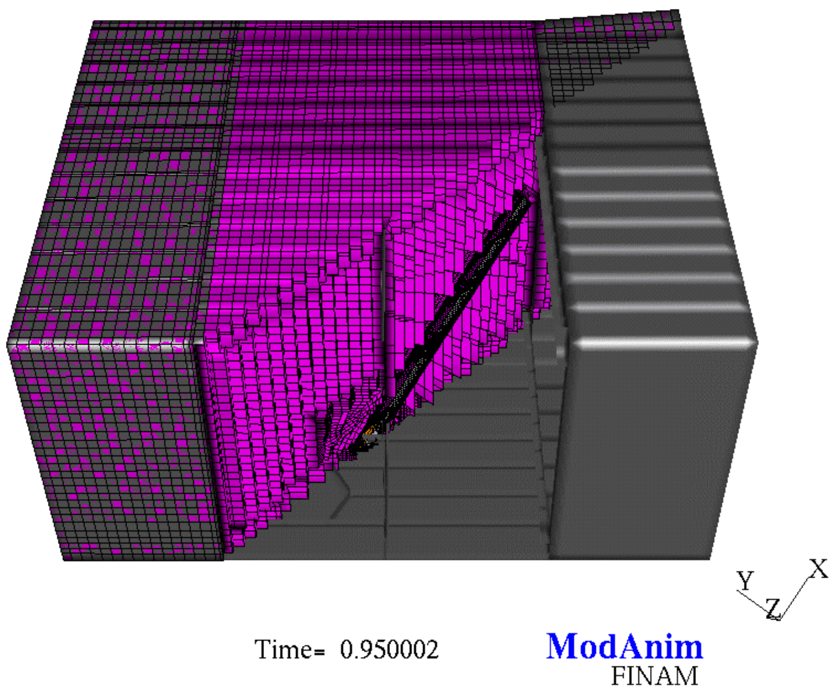

Figure n°4 – Ecorché du maillage de la structure et du fluide

Le fluide est modélisé par une loi de comportement de type hydrodynamique visqueux :

$$S_{ij} = 2\rho\nu\dot{e}_{ij}$$
$$P = C_0 + C_1\mu + C_2\mu^2 + C_3\mu^3 + (C_4 + C_5\mu)E$$
$$P \geq p_{\min}$$

où ν est la viscosité cinématique, ρ la densité, et P la pression. Les valeurs des paramètres de la loi de comportement et de l'équation d'état étant prises égales à :

$$\rho = 1.e-3$$
$$\nu = 1.e-6$$
$$C_0 = 0.$$
$$C_1 = 2723.$$
$$C_2 = 7727.$$
$$C_3 = 14660.$$
$$C_4 = C_5 = 0.$$
$$p_{\min} = -0.1$$

La pression est exprimée en Mpa, le temps en ms, la masse en g et la distance en mm.

La loi de comportement de l'aluminium est prise élastique pour l'ensemble des parties de la structure exceptées la peau et les lisses extrados. Ses caractéristiques élémentaires sont :

$$\rho = 2{,}8.10^{-3}\, g/mm^3$$
$$E = 74000.MPa$$
$$\nu = 0.3$$

La loi d'ouverture du cône au cours du temps est imposée. Elle décrit l'évolution du coefficient de traînée d'un projectile connu (barreau cylindrique de 10 mm de diamètre et 50 mm de longueur) et correspond à son retournement de 0° à 90°, en 0.4 ms. Entre 0 et 0.3 ms, l'ouverture du projectile est modérée, puis elle se précipite en 0.1 ms. A 0.4 ms, le coefficient de traînée est maximum. A ce moment, la vitesse d'ouverture du projectile s'annule puis devient négative : le coefficient de traînée diminue de nouveau progressivement (études empiriques américaines).

La masse du projectile est de 45 grammes.

L'évolution au cours du temps du diamètre du projectile et de son angle d'ouverture sont présentés sur les figures 5 et 6. Son diamètre maximal atteint 15 mm, et son angle d'ouverture maximal 30°.

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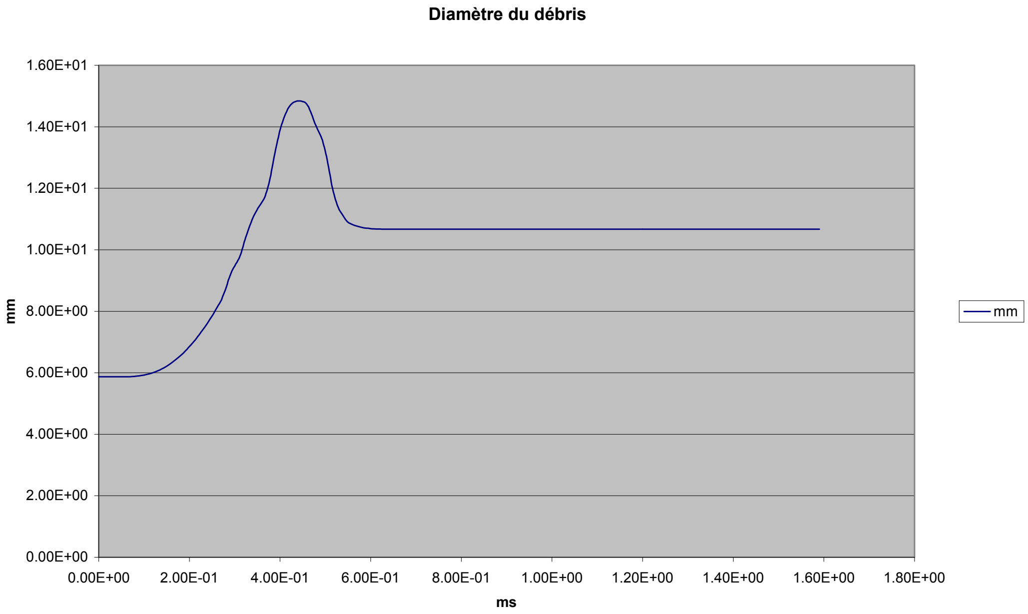

Figure n°5 – Evolution du diamètre du projectile conique en fonction du temps

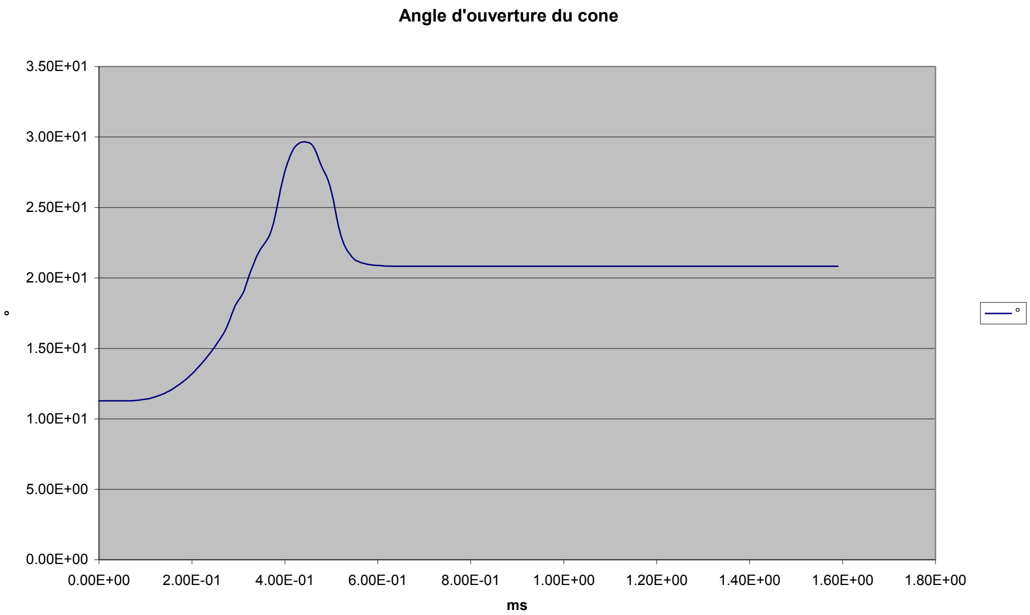

Figure n°6 – Angle d'ouverture du projectile au cours du temps

1.3. Calculs paramétriques

Les paramètres du modèles concernent la loi de vitesse du projectile, et la loi de comportement de l'aluminium, pour la description du comportement de la peau et des lisses intrados.

Une première loi de comportement élasto-plastique endommageable (loi 27) est tirée du modèle Airbus France :

$$\rho = 2{,}8.10^{-3}$$
$$E = 74000.MPa$$
$$\nu = 0{,}3$$
$$\sigma_y = 296MPa$$
$$B = 350.MPa$$
$$n = 0.2$$
$$\sigma_{\max} = 430.$$
$$\varepsilon_{t1} = \varepsilon_{t2} = 0{,}05$$
$$\varepsilon_{m1} = \varepsilon_{m2} = 0{,}055$$
$$d_{\max 1} = d_{\max 2} = 0{,}95$$
$$\varepsilon_{f1} = 0.06$$
$$\varepsilon_{f2} = 0.065$$

Dans le dernier calcul, de nouvelles valeurs, communiquées par Airbus France sont prises : σ_y=397 Mpa ; B =460. ; n=0.45.

Cette loi a l'avantage de proposer un critère de rupture en déformation maximale en traction. Cette caractéristique permet, lors du déroulement du calcul, de détecter automatiquement le développement de la rupture, et de la visualiser.

La loi de comportement tabulée (loi 36), également tirée du modèle Airbus France, permet de décrire le comportement non linéaire du matériau selon une courbe décrite préalablement. Une déformation maximale en traction définit le seuil de rupture à partir desquels la contrainte est progressivement ramenée à zéro. A partir de la version 4 du logiciel, les éléments sont détruits une fois la contrainte ramenée à zéro, ce qui permet donc de détecter automatiquement la rupture et de la visualiser. Les paramètres de cette loi sont pris égaux à :

$$\rho = 2{,}8.10^{-3}$$
$$E = 74000.MPa$$
$$\nu = 0{,}3$$
$$\varepsilon_{p\max} = 0{,}015$$
$$\varepsilon_{f1} = 0.016$$
$$\varepsilon_{f2} = 0.02$$

La courbe de comportement non linéaire est donnée en annexe.

La principale remarque concerne les paramètres à rupture des deux lois 27 et 36 données par Airbus France, pour lesquels la valeur à rupture passe de 0.06 à 0.016. Cette modification provient d'une calibration : pour les modèles E.F., les critères en question ne sont pas intrinsèques, la rupture numérique étant un mécanisme dépendant de la finesse du maillage. Il est donc incontournable de devoir « calibrer » ce paramètre. La procédure habituelle, connaissant la finesse de maillage du modèle cible, consiste à calibrer les paramètres de la loi matériau à partir des résultats d'un modèle de référence beaucoup plus fin. L'ONERA ne peut, dans le cadre de cette étude, se prononcer quant à l'exactitude de la valeur de ce paramètre. Airbus France a confirmé que les valeurs à rupture prise pour la loi 36 correspondait à une telle calibration, dans les zones de congés de raccordement. La finesse de maillage des modèles ONERA et Airbus France étant similaire, les valeurs des paramètres du modèle Airbus sont donc repris par l'ONERA.

Autre paramètre, une vitesse initiale est impulsée au projectile, qui est dans ce cas ralenti le long de sa course. Il est également possible d'imposer que cette vitesse reste constante. Dans les deux cas, l'énergie du calcul n'est jamais constante (apport continu d'énergie dans le modèle pour ouvrir le projectile).

Les valeurs de vitesse retenues sont de 120 m/s et de 360 m/s.

2. RESULTATS

2.1. Projectile de vitesse initiale 120 m/s – Loi 36

Pour une vitesse initiale de 120 m/s, les niveaux de pression maximum observés lors du calcul sont de 7,89 Mpa dans le fluide (cf figure n°7). Le projectile franchit en une milliseconde une distance de 110 mm et atteint une vitesse résiduelle de 100 m/s. Le retournement du projectile est complètement effectué, alors qu'il est encore loin de la zone arrachée (au moins 150 mm, cf figure n°8).

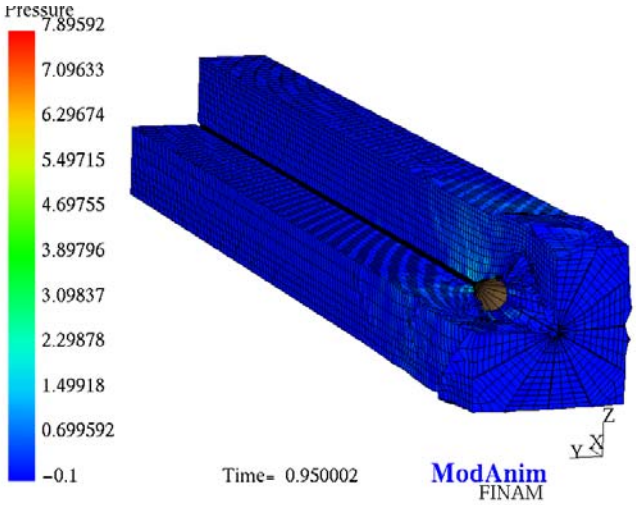

Figure n°7 – Visualisation des niveau de pression et de la progression du projectile (1 ms)

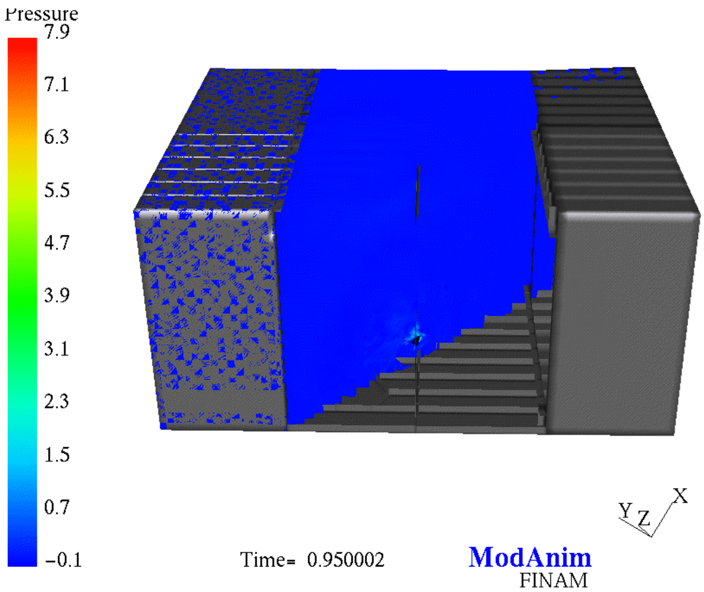

Figure n°8 – position du projectile après 1 ms (zone de pression maximale)

Les niveaux de pression maximales dans le fluide à proximité de la peau intrados, au terme du calcul, s'élèvent à 0.4 Mpa, soit 4 bars (cf figure n°9).

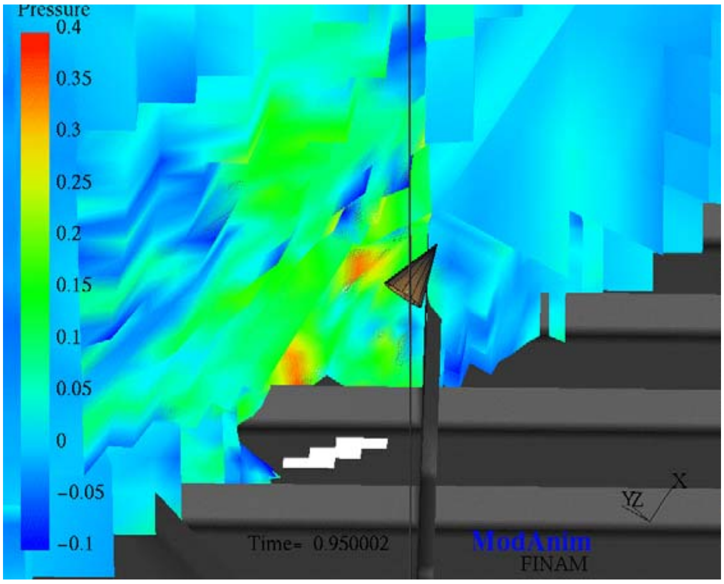

Figure n°9 – Visualisation des niveaux de pression dans le fluide, à proximité de la peau intrados

Les niveaux de contrainte et de déformations maximales dans la zone du panneau arraché sont situés comme indiqué sur la figure n°10 (éléments en blanc). Ils se situent dans des zones d'épaisseur 1.2 mm.

Le calcul est mené sur une durée d'une milliseconde. Il prend 11 heures de temps CPU sur SGI Octane R12000.

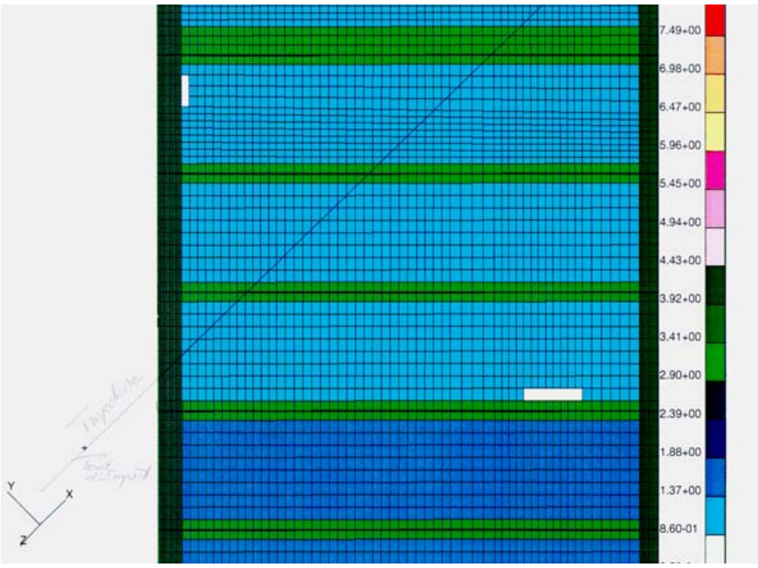

Figure n°10 – localisation des contraintes maximales dans la zone du panneau arraché

Les niveaux de contrainte et de déformation maximale pour ce calcul sont présentés sur les figures 11 à 14. Des maxima de 100 Mpa et de 1.25 E-03 def sont relevés dans la zone qui fut sujette à l'arrachement, ce qui est largement inférieur aux niveaux requis pour initier la rupture. La force de pression sur la peau intrados est relevée et présentée sur la figure n°15. Son maximum atteint 6000 N à l'instant du retournement du projectile, ce qui est somme toute une valeur raisonnable.

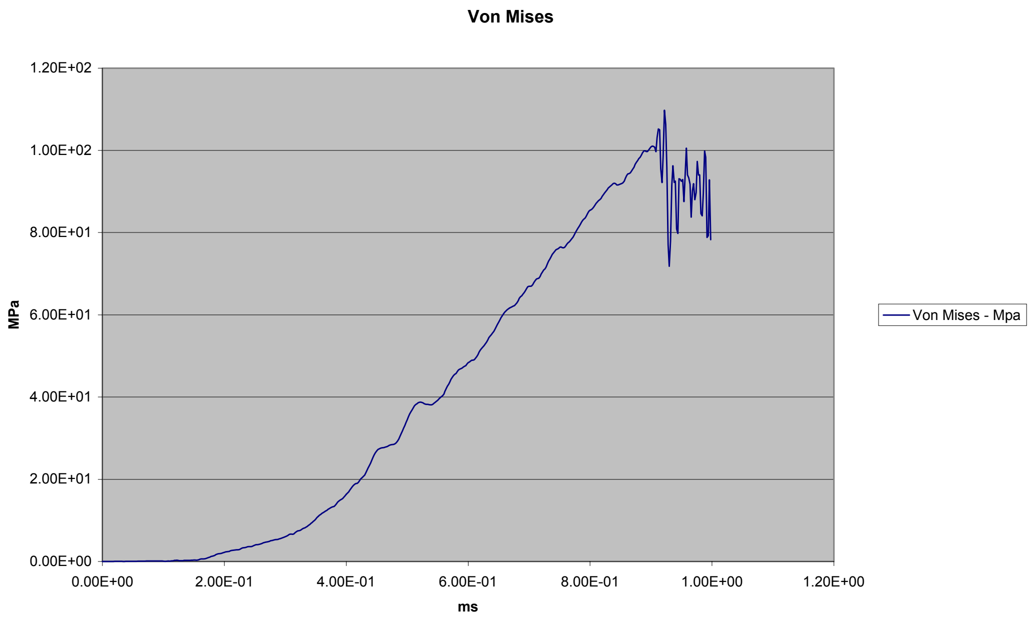

Figure n°11 – Niveau de contraintes de Von Mises maximales, dans la zone du panneau étudié

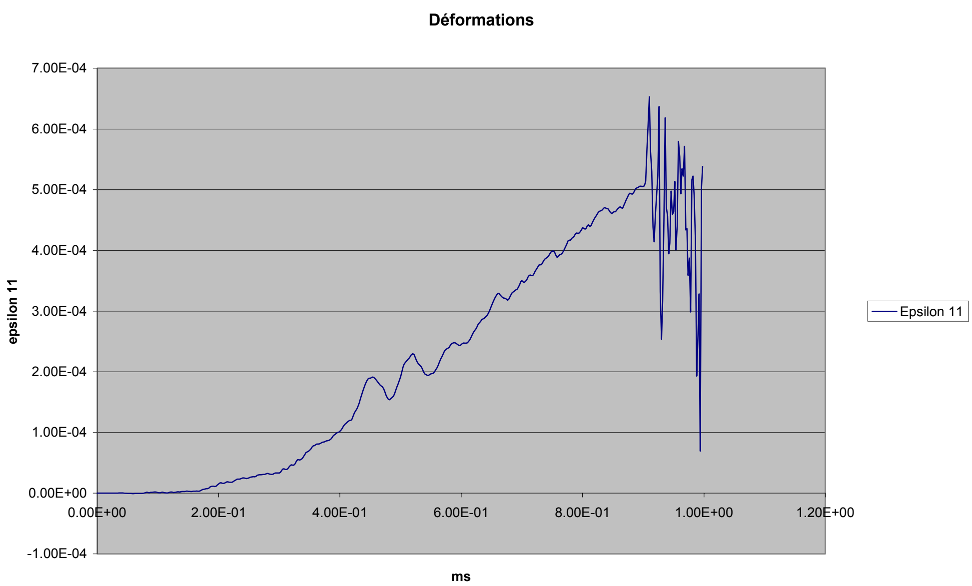

Figure n°12 – Niveau des déformations principales maximales epsilon 11, dans la zone du panneau étudié.

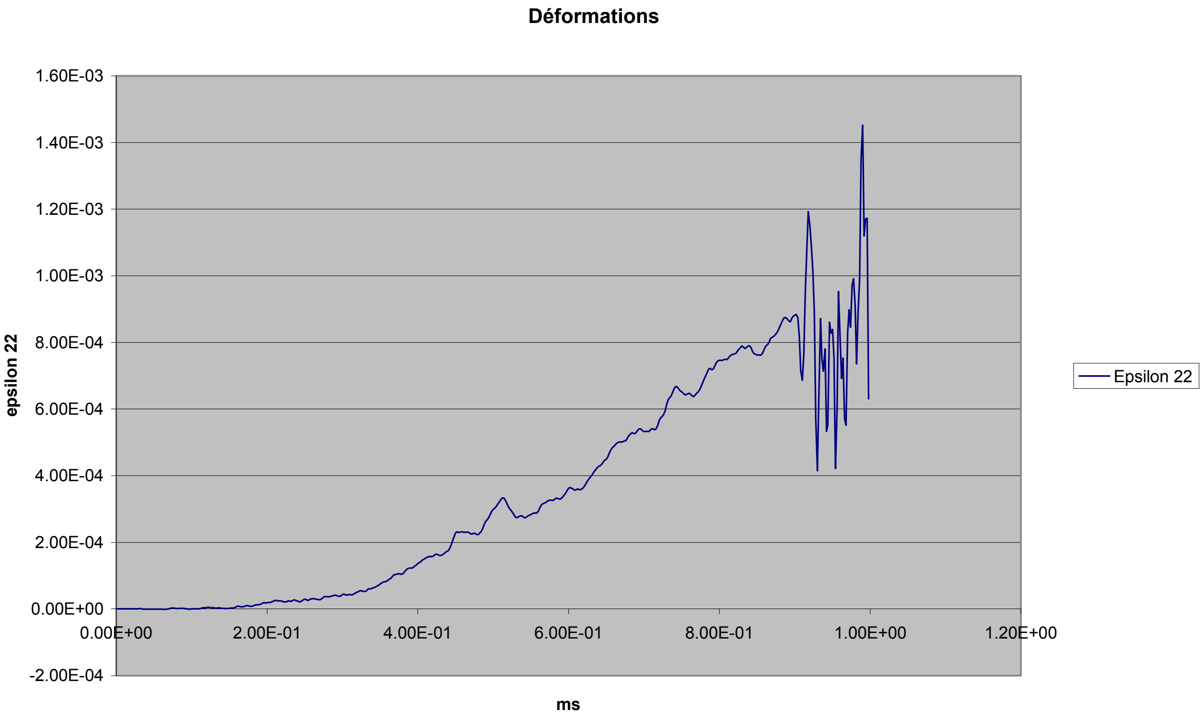

Figure n°13 – Niveau des déformations principales maximales epsilon 22, dans la zone du panneau étudié.

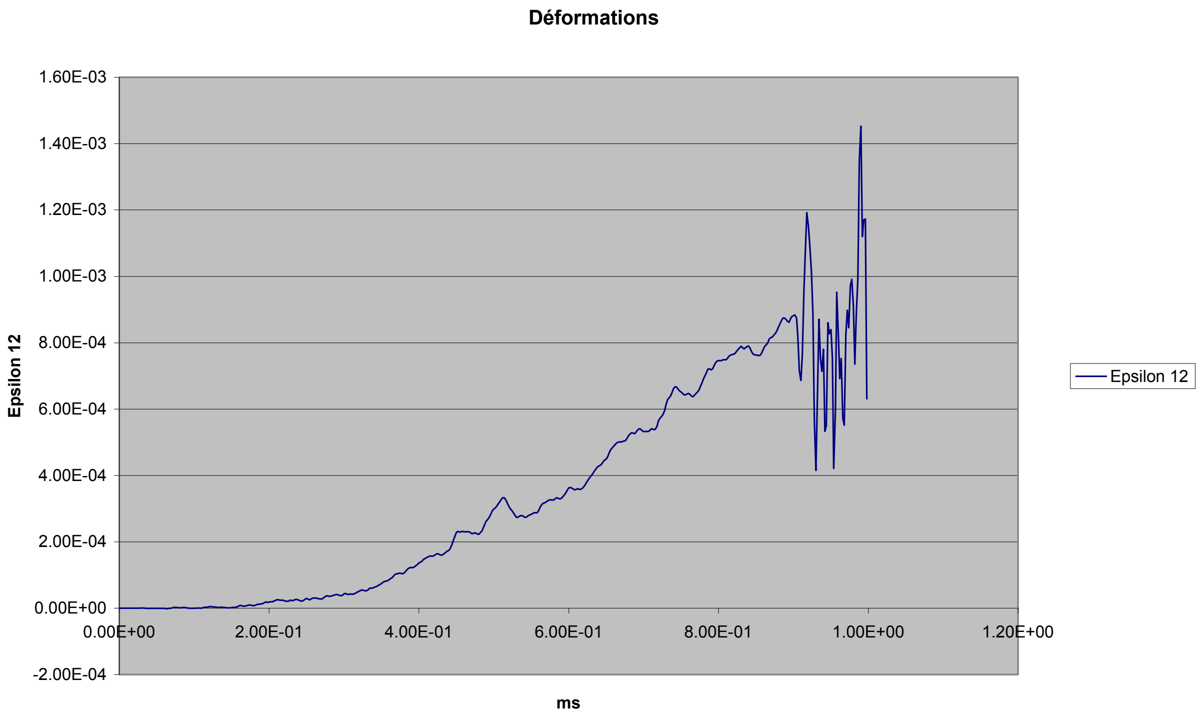

Figure n°14 – Niveau des déformations principales maximales epsilon 12, dans la zone du panneau étudié.

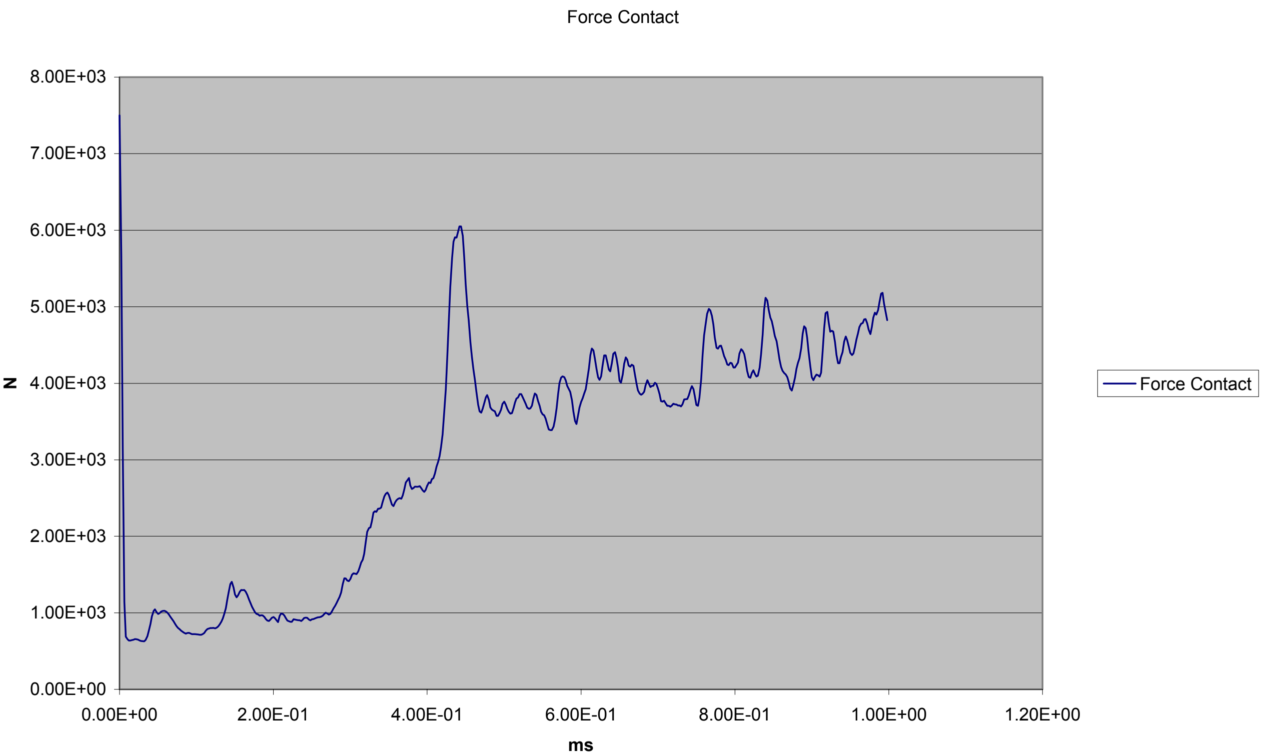

Figure n°15 – Niveau des forces de pression cumulées sur la peau intrados, dans la zone du panneau étudié.

Sur la figure n°16, on voit que la zone de contrainte maximale, pour ce cas de trajectoire, se situe plutôt à proximité du point d'impact, dans le tronçon n°2 et non le tronçon n°3.

Qualitativement, la simulation révèle bien l'apparition d'un coup de bélier (uniquement visible en simulation dynamique). Il est localisé au niveau du tronçon n°2. Les accélérations brutes, mesurées sur la peau intrados, font état de niveaux dépassant les 10 000 G (cf figure n°17). La flèche maximale dans cette zone, durant les premières millisecondes du calcul, atteint 1.5 mm (cf figure n°18). Une rupture se produit dans cette zone après 0.90 ms, au pied de la nervure séparant les tronçons 2 et 3 (cf figure n°19).

La rupture n'est pas localisée immédiatement dans la zone du coup de bélier. En fait l'onde de choc crée une surpression importante qui charge latéralement la nervure. La flexion obtenue mène à l'initiation d'une rupture en pied de nervure. La rupture s'initie des deux côtés de la nervure (un élément en flexion « positive » et son miroir en flexion « négative). Du point de vue de la rupture, c'est l'élément 5500229 qui rompt en premier (côté tronçon 3), avant l'élément 5600440 (côté tronçon 2). L'ordre de rupture est 5500229, 5600440, 5500200 et 5500233. Ce qui signifie que la rupture se propage du côté du tronçon trois.

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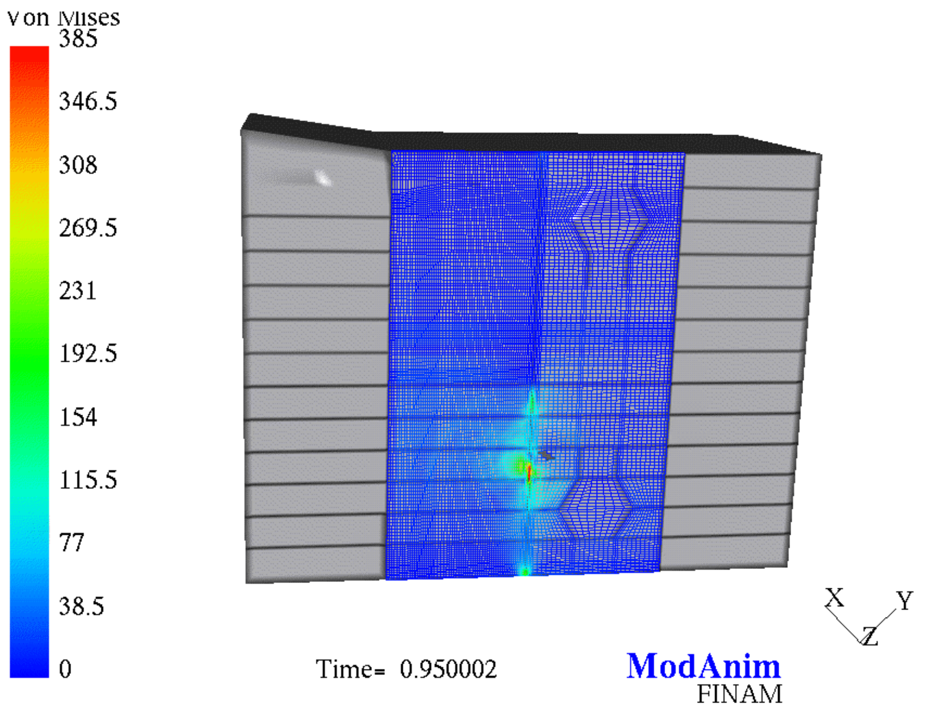

Figure n°16 – Localisation des zones de contraintes maximales sur la peau intrados

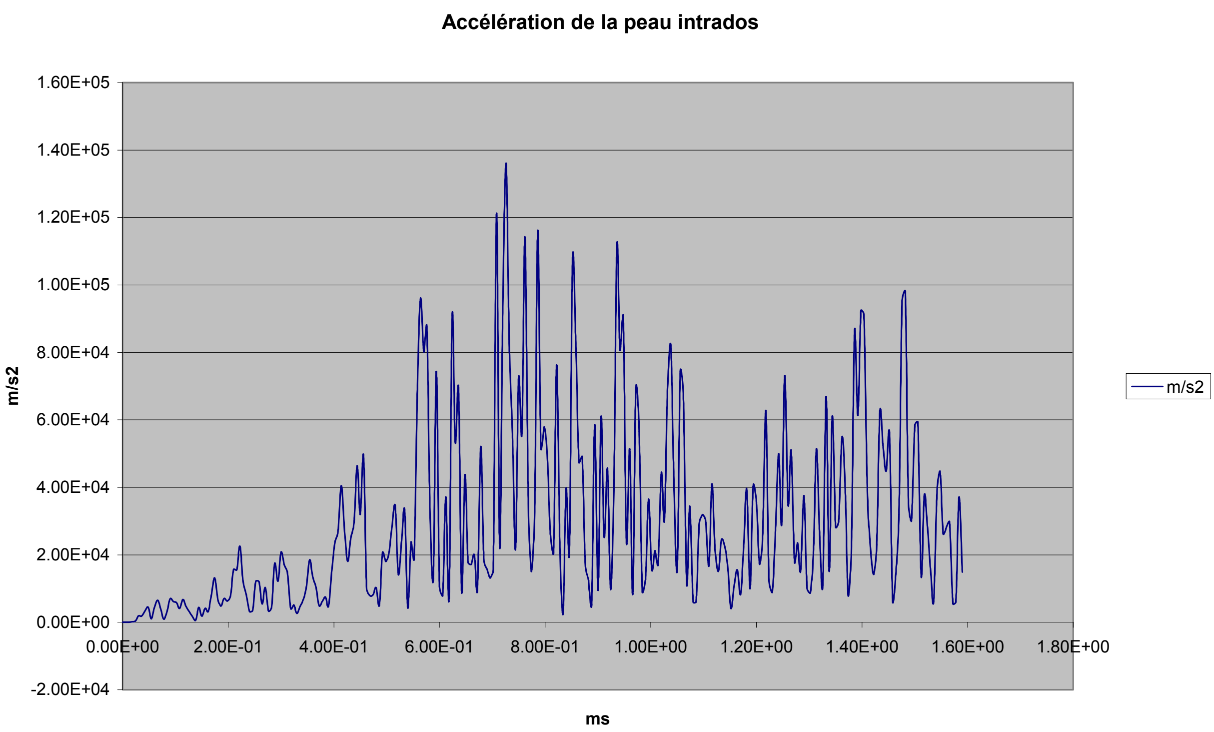

Figure n°17 – Accélérations mesurées sur la peau intrados, au lieu du coup de bélier

Figure n°18 – Déplacements mesurés sur la peau intrados, au lieu du coup de bélier

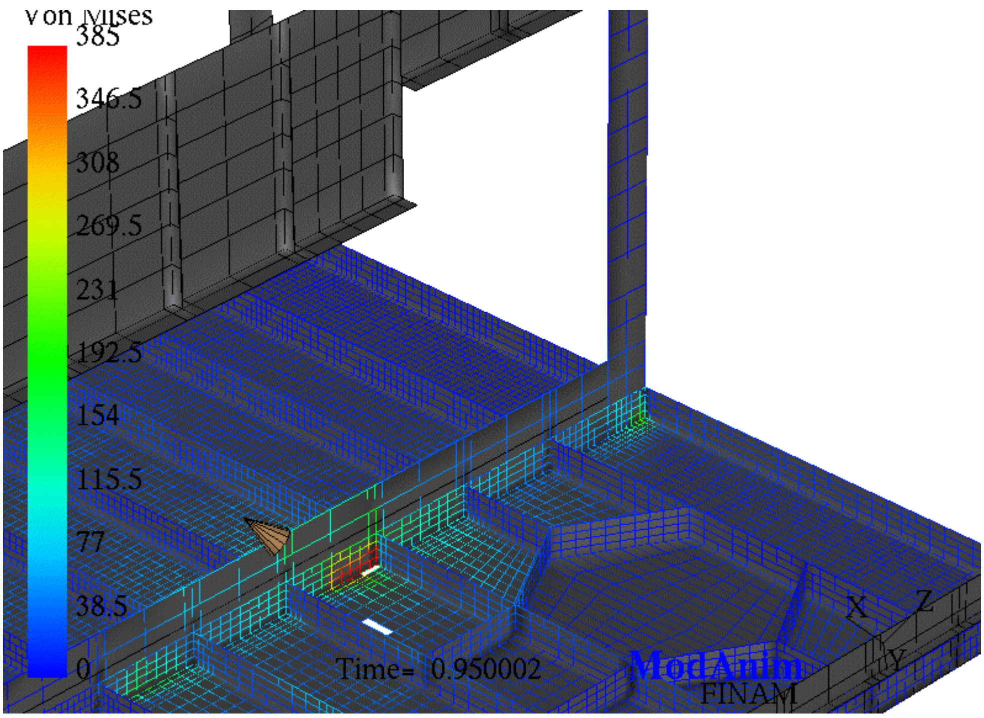

Figure n°19 – Localisation des zones de rupture sur la peau intrados

Les énergies d'hourglass et de contacts restent quasiment nulles lors du calcul, ce qui démontre que celui-ci se déroule normalement.

En conclusion, la simulation ne confirme pas l'hypothèse que la déchirure, en cas de coup de bélier hydrodynamique, aurait du partir de la perforation. Contre toute attente néanmoins, une déchirure s'initie le long de la nervure séparant les tronçons 2 et 3. Ce résultat révèle donc la possibilité (et une sévérité inattendue), à 120 m/s, d'obtenir un coup de bélier consécutif à la pénétration d'un projectile dans le réservoir. Rappelons que les hypothèses qui ont été prises correspondent à celles d'un confinement maximal du fluide dans le réservoir (pas d'air), ce qui constitue la configuration la plus critique vis-à-vis du coup de bélier hydrodynamique.

Dans un cas comme celui-ci, il est généralement admis qu'il faille procéder à une étude paramétrique poussée, afin d'évaluer la sensibilité du résultat aux différents paramètres du modèle (finesse de maillage, critère de rupture, etc).

En ce qui nous concerne, la première question qui se pose est de savoir si le projectile utilisé et sa cinématique peuvent être supposés suffisamment représentatifs. A titre d'exemple, imaginons que sa cinématique soit différente, et que le « coup de bélier » se produise plus tardivement alors que le projectile se trouve dans la partie que nous dénommons « tronçon 3 ». Le mode de chargement et donc de rupture pourraient alors être différents.

Pour lever ce doute, deux solutions peuvent être envisagées: la première consiste à prolonger la durée du calcul, en retardant le retournement du projectile ; la seconde consiste à augmenter la vitesse initiale. De cette façon, il sera peut-être possible de provoquer le coup de bélier lorsque la position du projectile est dans le tronçon 3.

2.2. Projectile de vitesse initiale 360 m/s – Loi 27

Pour des raisons de rapidité d'obtention des résultats, c'est la seconde solution qui est préférée dans un premier temps. Elle a également l'avantage d'évaluer les conséquences d'un choc a priori plus violent.

Le calcul est mené sur une durée d'une milliseconde. Il prend 11 heures de temps CPU sur SGI Octane R12000. La loi matériau utilisée est cette fois la loi 27 (avec un critère à rupture valant 0.06 et non plus 0.016).

Pour une vitesse initiale de 360 m/s, les niveaux de pression maximum observés lors du calcul sont de 30,8 Mpa dans le fluide.

Le projectile franchit en une milliseconde une distance de 300 mm et atteint une vitesse résiduelle de 260 m/s. Le retournement du projectile est complètement effectué à l'aplomb de la zone arrachée.

La répartition des contraintes maximales est présentée sur la figure n°20. Il est important de constater que la contrainte maximale de 430 Mpa est atteinte dans une région importante, et en particulier également dans la zone d'arrachement.

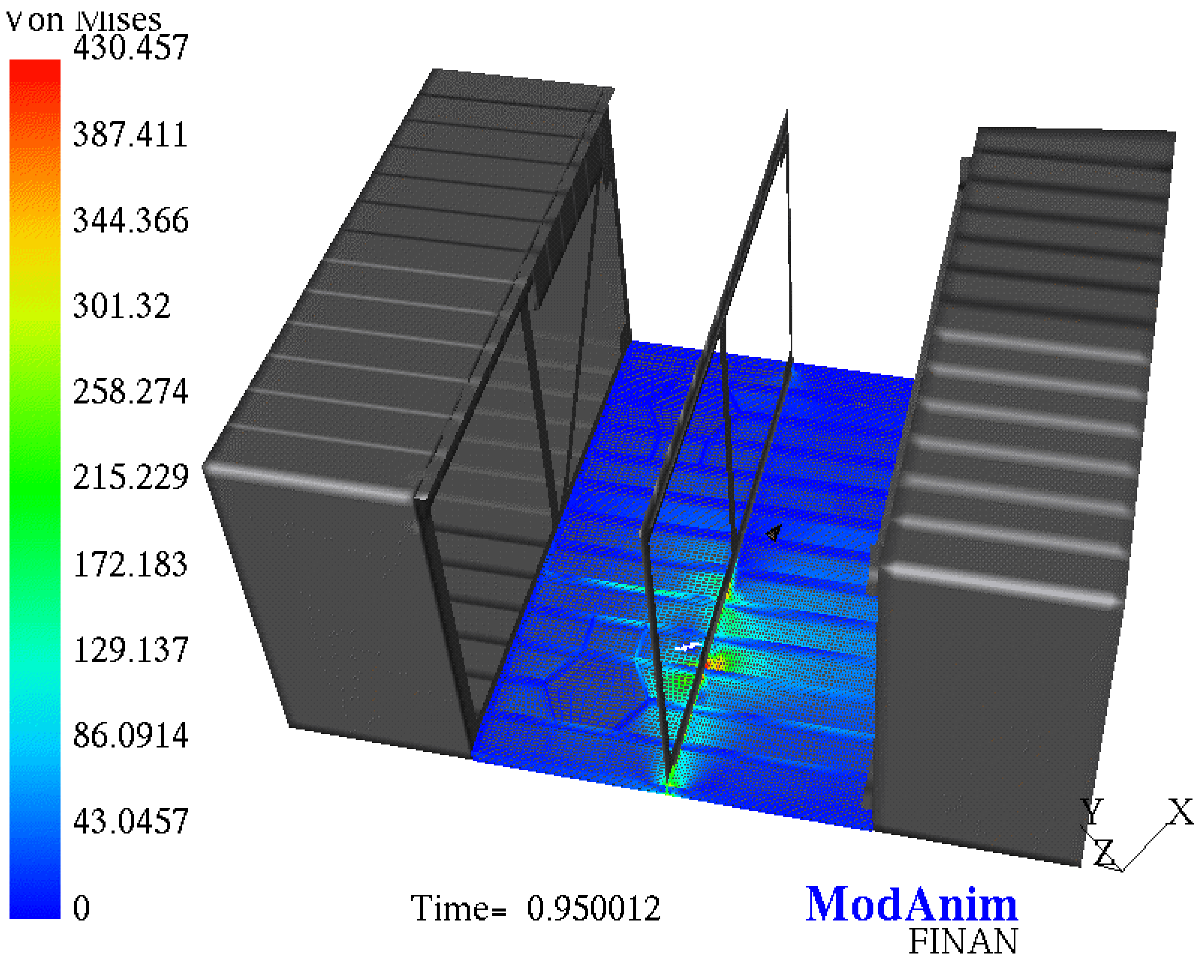

Figure n°20 – répartition des contraintes maximales pour l'impact à 360 m/s

Par contre aucun élément n'est rompu, la limite maximale en déformation dans cette zone n'étant pas atteinte (il serait sans doute plus pertinent de prendre pour critère de rupture la même valeur que pour la loi 36). La force de pression maximale exercée sur la peau intrados atteint cette fois un maximum de 12000 N, soit un équivalent de 1,2 T.

Dans la zone arrachée, et dans les éléments périphériques, la contrainte maximale de Von Mises est cette fois de 200 Mpa, ce qui est important. La déformation maximale est de 2.3 E-03, ou encore de 0,23 %.

Les énergies d'hourglass et de contacts restent quasiment nulles lors du calcul, ce qui démontre que celui-ci se déroule normalement.

En conclusion, cette simulation démontre bien que, même si les contraintes maximales restent localisées dans la même zone que précédemment, la zone du panneau arrachée commence à faire l'objet d'un chargement important. La cinématique du projectile s'avère bien être un paramètre influant.

2.3. Projectile de vitesse initiale 120 m/s – cinématique modifiée – Loi 36

Cette simulation a été effectuée en prolongeant le calcul à 120 m/s sur 3 millisecondes, et en retardant l'ouverture du projectile (ouverture qui s'étend de 0 à 1.2 ms au lieu de 0 à 0.4 ms, avec une précipitation de cette ouverture à partir de 0.9 ms). L'objectif est dans ce cas de chercher à provoquer le coup de bélier plus tardivement que dans le premier cas, et d'étudier si l'on délocalise le mécanisme de rupture.

A 0.9 ms, le projectile n'a pas encore franchit les 100 mm, et le « coup de bélier » se produit au passage de la nervure séparant les tronçons 2 et 3. La vitesse du projectile ne vaut plus que 60 m/s à 1.25 ms, puis elle décroît plus lentement.

Du point de vue de la rupture, c'est l'élément 5600440 qui rompt cette fois en premier, avant l'élément 5500229. La rupture se propage toutefois toujours dans les éléments 5500200 et 5500233.

L'énergie cinétique initiale du projectile est de 360 J.

Après l'ouverture du projectile, l'énergie totale est de 1750 J, ce qui signifie que 1390 J ont été injectés dans le modèle pour procéder à l'ouverture ***et de la fermeture*** du projectile (cette énergie, q correspondrait à celle du même projectile, propulsé à 265 m/s, ou celle d'un projectile de 250 g). Le critère important concernant l'énergie est la part transférée à la structure, via le fluide.

Après 1. ms, seuls 100 J ont été communiqués au fluide. A 1.5 ms, 120 J ont été transmis, et la croissance est linéaire.

Après s'être déformé de 0.1 10-3 m (2%) à une contrainte de 455. 10+6 Pa, l'élément fini 5500229 de 5 mm x 1.5 mm de section (soit 7.5 10-6 m^2), a absorbé moins de 0.5 J par déformation plastique. A 6 % de déformation, seuls 1,5 J auront été absorbés par cet élément. Pour absorber 150 J (énergie transmise au fluide après 2 ms), il faudra donc plastifier à 6% non loin de 100 éléments du même type, soit une zone équivalente à 10 éléments de côté, ou encore une zone de 5 cm x 5 cm. Pour absorber plastiquement les 360 J d'énergie cinétique initiale du projectile, il faudrait approximativement plastifier à 10% une zone de 7.5 cm x 7.5 cm.

Ce simple calcul montre que l'énergie transmise au fluide est suffisante pour provoquer la plastification locale bien au delà des 1.6 % du critère de rupture adopté par Airbus France comme valeur dans les congés de raccordement).

2.4. Projectile de vitesse initiale 120 m/s – Loi 27 sans critère de rupture

Dans le dernier calcul, de nouvelles valeurs, communiquées par Airbus France sont prises pour la loi 27 : σy=397 Mpa ; B =460. ; n=0.45 ; σ^{max} = 455 MPa. Aucun critère a rupture n'est imposé, et la durée du calcul est prolongée afin d'évaluer jusqu'à quelle valeur la déformation plastique se développe. Ce calcul est un calcul de vérification de l'hypothèse précédente, la cinématique du projectile étant la cinématique initiale.

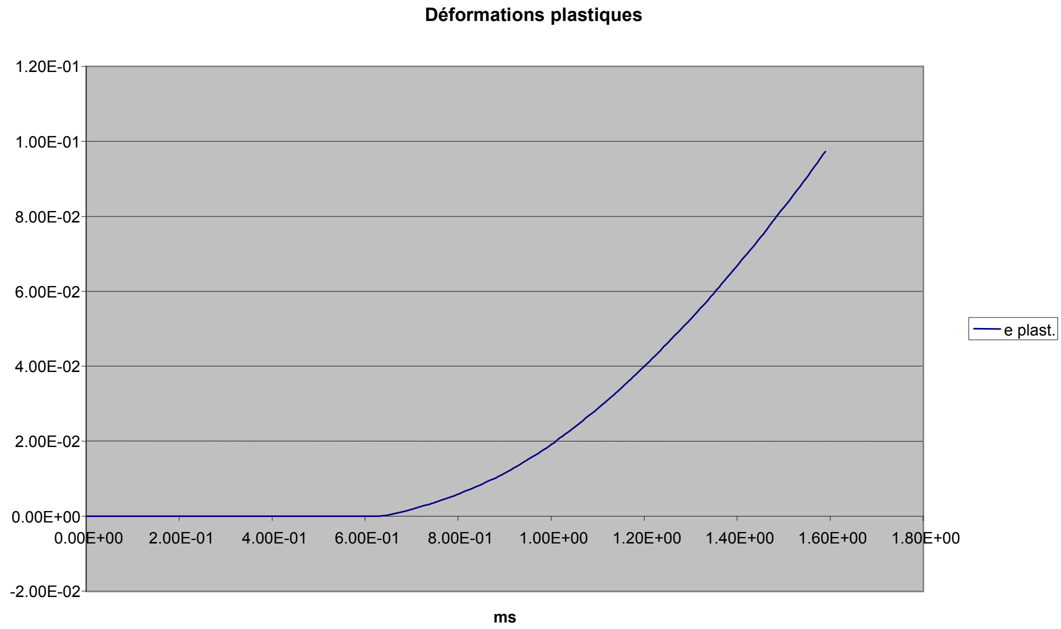

Figure n°21 – Déformations plastiques – Loi 27 sans critère à rupture

Les résultats présentés sur la figure 21 montrent que les déformations plastiques atteintes après 1.5 ms atteignent les 10 % dans l'élément 5600440. Nul doute que cette déformation continuera encore à augmenter si l'on prolonge le calcul.

3. CONCLUSIONS

Le nombre d'inconnues du problème traité rend difficile d'affirmer sans retenue si le coup de bélier hydrodynamique est le scénario réel ou non. Néanmoins, les résultats sur lesquels reposent les conclusions proviennent de calculs se déroulant proprement, sans accumulation d'erreur énergétique ni instabilités numériques, et les ordres de grandeurs obtenues sont clairement acceptables. La méthode utilisée constitue donc un outil d'analyse jugé fiable, la validité des hypothèses de base (description, unicité du projectile, positions des points d'impacts, énergie, etc) étant la principale source d'indécision face aux résultats obtenus. Par exemple, en l'absence de données expérimentales ou théoriques permettant de le quantifier, il est possible de supposer que la dynamique de retournement du projectile peut différer selon la vitesse initiale du projectile. Les valeurs du coefficient de traînée ne dépendent pas de cette vitesse en théorie, puisqu'ils ne dépendent que de la géométrie du projectile. Par contre, les valeurs utilisées ont été établies dans de l'eau, alors que le carburant réel est probablement plus visqueux. Le retournement étant un mécanisme instable, il n'est pas acquis, bien au contraire, que celui-ci prenne dix fois plus de temps pour se produire pour une vitesse d'impact dix fois moins importante. Un ralentissement d'un facteur de trois de cette dynamique de retournement a néanmoins permis de démontrer que les conséquences du coup de bélier, bien que légèrement différentes, restaient également sévères.

La méthode utilisée permet de résoudre le problème de façon directe, avec des temps de calcul acceptables permettant de mener une étude paramétrique (possibilité de mener un calcul et son exploitation par jour). Pour cela, les finesses de maillage (en particulier du fluide) autour du projectile et dans les caissons sont nettement différentes (pour réduire le temps de développement du modèle et le nombre d'éléments). Cette différence de maillage ne peut être à l'origine de distorsions importantes, le modèle étant développé pour permettre à une onde radiale de se propager proprement de la zone maillée finement vers la zone maillée plus grossièrement. Les équations d'état des deux domaines étant identiques, le seul risque est d'avoir une rupture d'impédance « géométrique », qui confinerait les pressions autour du projectile. Le calcul est donc a priori conservatif.

La simulation de l'impact à 120 m/s ne confirme pas l'hypothèse que la rupture, en cas de coup de bélier, aurait du partir de la perforation. Néanmoins, une déchirure s'initie le long de la nervure séparant les tronçons 2 et 3. Ce résultat révèle donc la possibilité, à 120 m/s, suite à l'apparition d'un coup de bélier consécutif à la pénétration d'un projectile dans le réservoir, d'amorcer une rupture le long des zones renforcées de la structure. Par ailleurs, une autre simulation, pour laquelle la cinématique est fortement modifiée afin d'initier le choc lorsque le projectile s'est déplacé plus avant dans le tronçon sujet à rupture, démontre bien que la zone de chargement maximal de la peau intrados peut être déplacée du tronçon 2 au tronçon 3 en jouant sur cette inconnue du problème.

Les nombreux calculs paramétriques, menés pour des lois de comportement différentes, mettent en évidence que – même si la valeur du critère à rupture à une forte influence sur l'initiation de la rupture – l'énergie mise en jeu dans ce scénario est suffisante pour mener à des déformations plastiques locales dépassant les 10% dans les zones « de rupture ».

S'il fallait donner une conclusion simple et directe à cette étude, c'est donc que le scénario du coup de bélier hydrodynamique ne peut pas être écarté, d'autant que rien ne prouve que d'autres perforations n'aient pu avoir lieu à proximité immédiate, et dans le tronçon n°3 cette fois, du panneau arraché. A moins que des travaux supplémentaires ne viennent remettre en question et modifier de façon conséquente certaines hypothèses de base, les simulations semblent bien démontrer, contre toute attente, qu'un coup de bélier hydrodynamique puisse produire à des vitesses aussi basses un chargement suffisant et être à l'origine de l'initiation de ruptures dans les zones de renforcement (congés, etc) de la peau intrados.

Pour conforter cette conclusion, la première des choses à faire consisterait à approfondir les caractéristiques du projectile équivalent qui, dans le contexte de l'étude, reste l'inconnue principale. Une étude paramétrique de l'influence des caractéristiques de ce projectile sur le niveau de sévérité du chargement semble être incontournable.

Une autre question que lève l'étude concerne la valeur du critère de rupture en déformation. Une investigation plus poussée sur l'AU2GN et les caractéristiques à utiliser serait donc une autre des actions à entreprendre, ne serait-ce que pour confirmer la remarque précédente.

La dernière des priorités serait de reprendre la modélisation en évitant certains des problèmes rencontrés. Il est en effet possible d'améliorer encore la cohérence et donc la confiance dans les résultats de calcul. Certaines simplifications géométriques (et certains choix de raffinement de maillage) ont été faites, par exemple, dont il serait intéressant de vérifier la faible influence.

REMERCIEMENTS

La méthode de modélisation E.F. utilisée pour cette étude a été développée sur contrat du SPAé/ST/STA, dans le cadre d'une étude pluri-annuelle menée en collaboration avec Airbus France et la DCE/CEG.

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Rapport préliminaire f-sc000725p – BEA – Août 2000

[2] « Accident survenu le 25 juillet 2000 au lieu-dit de la Patte d'Oie de Gonesse (95) au Concorde immatriculé F-BTSC exploité par Air France »
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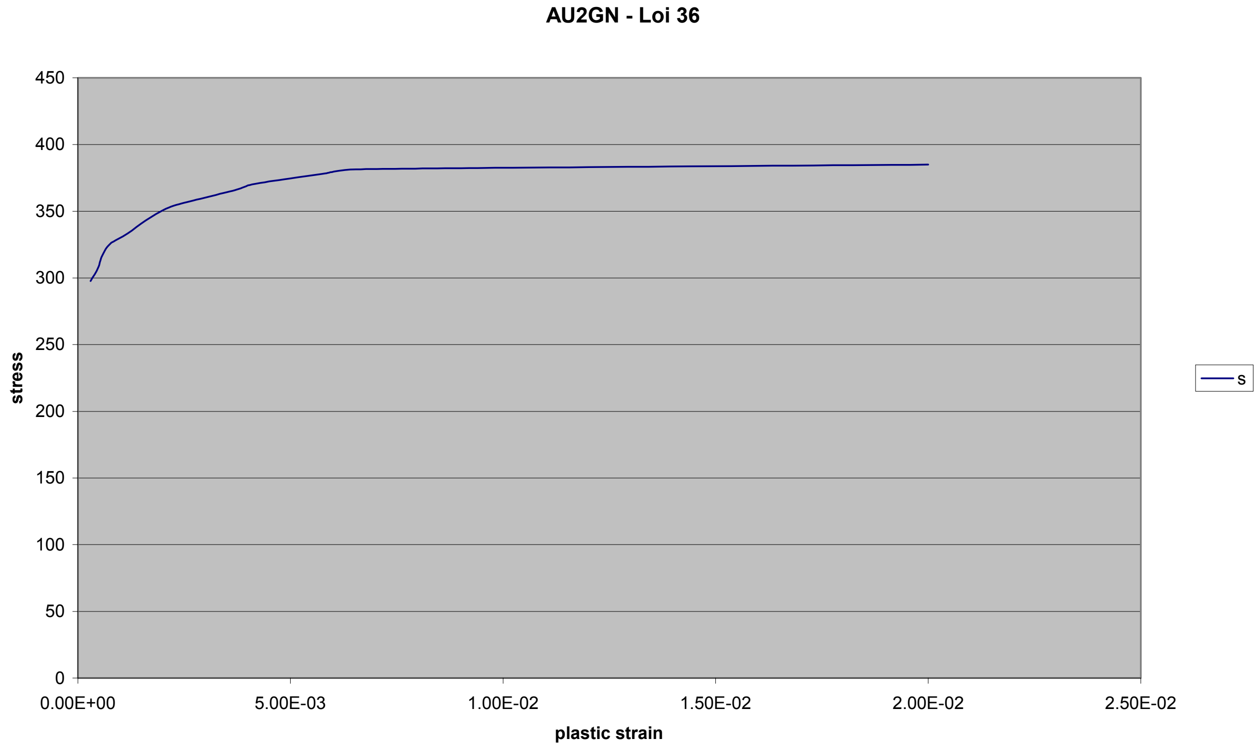
ANNEXE


AU2GN - Loi 36
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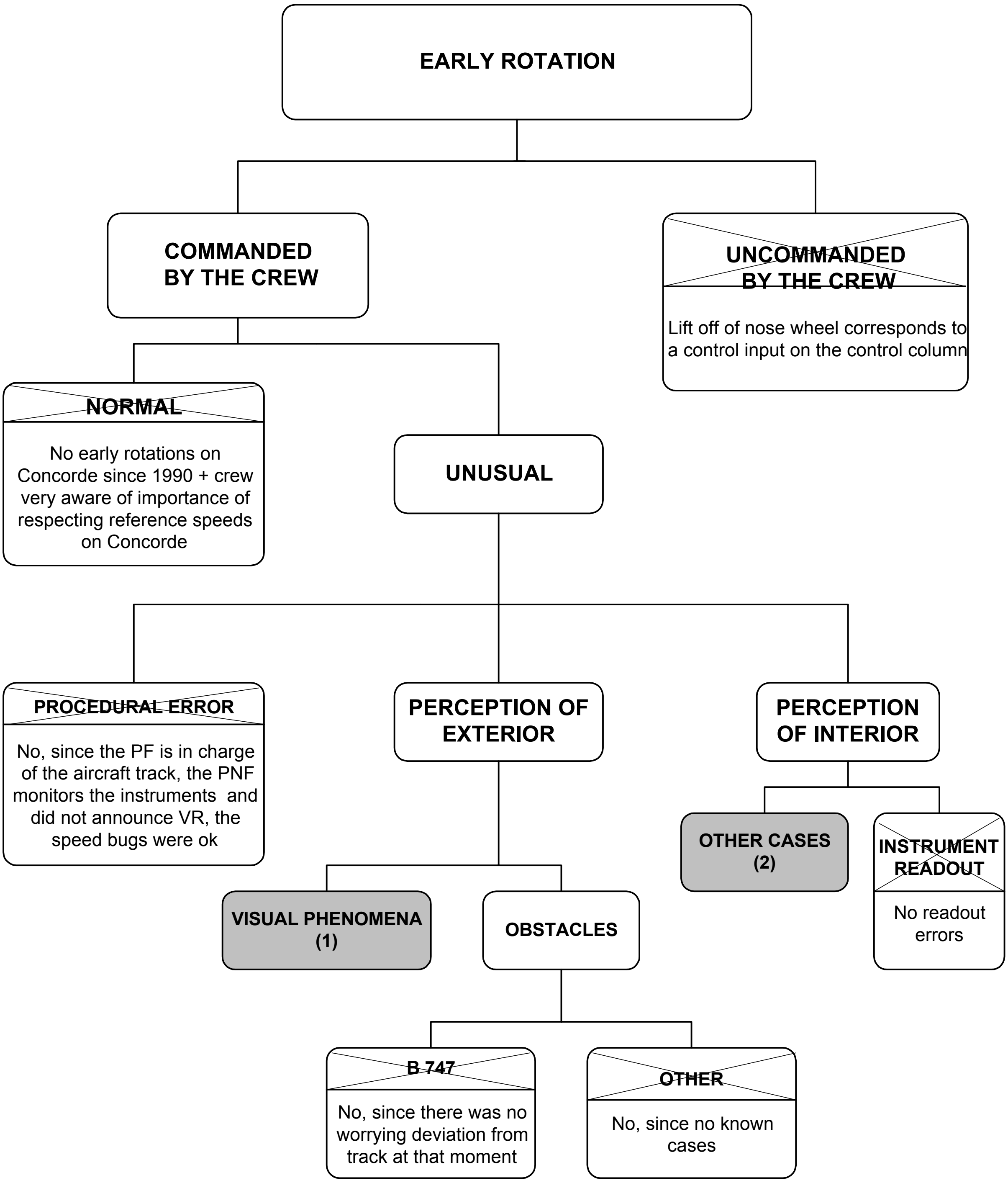
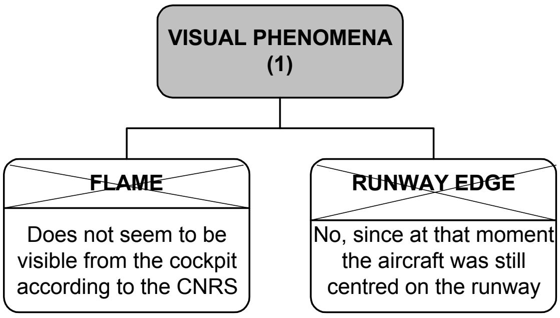
FLOW CHART ON CAUSES OF INITIATION OF EARLY ROTATION



(1)



(2) OTHER CASES

➥ MOVEMENT OF CAPTAIN'S SEAT

There's no noise thereof on the CVR and examination showed that the seat had stayed in the forward position, almost at maximum forward (in addition, the FO's seat was in maximum rear position and the FE's seat in forward position)

➥ FALL IN ENGINE READINGS

No, since rotation was before the surge recorded on the CVR

➥ SMELL

Possible but not recorded

➥ SOUND

Possible since highly unusual background noise recorded

➥ VIBRATIONS

Possible since slight variation in vertical acceleration

➥ LATERAL ACCELERATION EXPERIENCED IN THE COCKPIT

The simulations show that 2 or 3 tenths of a second before variations in lateral acceleration (ny) at the centre of gravity are recorded, lateral acceleration in the cockpit varies following a sharp rise (much more than that of lateral acceleration as recorded at the centre of gravity). This variation in the cockpit occurs almost simultaneously with the immediate loss of thrust, that's to say around cycle 602.7

Prevention of Debris-related Risks on the Movement Area

Situation Abroad

1 - Canada

1.1 History

In 1974, the Canadian civil aviation authorities, in co-operation with the national airlines, formed a “national committee on prevention of debris-related risks”. This committee was wound up in 1985.

Management of the main Canadian aerodromes is currently franchised to non-government bodies. The operators of these aerodromes must possess an aerodrome certificate issued by Transport Canada and are subject to the regulations in CAR Part III, Aerodromes and Airports.

1.2 Regulations

The regulations concerning prevention of debris-related risks are included in CAR 302 “Airports”.

Paragraph 302.07, on the operator’s obligations, specifies that the latter must comply with the published norms and recommendations. The latter require a daily infrastructure inspection. Paragraph 302.07 imposes an additional runway inspection in certain cases (accident or incident, works or potentially dangerous conditions).

Paragraph 302.08 states that the operator must publish an operations manual approved by Transport Canada. This manual must describe safety measures, amongst other things. Although the regulations do not specifically require a programme for prevention of debris-related risks, approval of the operations manual implies the description of such a programme in practice.

1.3 Technical documentation

In 1976, a “Manual for Prevention of Foreign Object Damage” was published by the authorities, which at that time managed the aerodromes. This manual, revised in 1983, contains technical instructions for the prevention of debris-related risks. Although it does not have the power of law, this manual is still the reference document for aerodrome operators.

1.4 Oversight

In the context of oversight of aerodrome certification, Transport Canada conducts an annual inspection of aerodromes in the course of which an inspection of the movement area is carried out.

1.5 Training

Since the privatisation of the aerodromes, Transport Canada no longer takes care of training related to airports.

1.6 Example: Vancouver International Airport

Vancouver International Airport has three runways and 370,000 movements per year. There are three infrastructure inspections per day.

The airport is an active participant in the NAFPI (USA). It has an active programme for prevention of debris-related risks based on:

- the active participation of all of the participants working on the airport's movement area,
- the co-ordination of actions on the prevention of debris-related risks by an airport Safety representative,
- training for those who work on the movement area,
- information campaigns (posters, thematic presentations, good conduct prize).

A commission on debris-related risks meets once a quarter. Originally it met once a month, which proved demotivating for the participants. This commission is presided over by a safety representative and groups together the companies working on the movement area. Participation is voluntary.

A symposium was organised in 1996 with the participation of several Canadian airports and industry representatives.

2 - United States

2.1 Background

All aerodromes where aircraft with more than thirty seats are operated must hold an operations certificate issued by the FAA under chapter 14 of the CFR, Part 139. To obtain this the operator must publish an aerodrome certification manual containing procedures and plans in accordance with Part 139. The FAA Airport Certification and Safety Inspectors (ACSI's) carry out annual inspections and oversight inspections of certified aerodromes.

2.2 Regulations

Control of debris on aerodromes is covered by sub-section D Operations, of Part 139.

Paragraphs 139.305 and 139.307 specify that debris of all kinds must be removed immediately from paved and unpaved areas of aerodromes.

Paragraph 139.327 (Self-inspection program) requires that the aerodrome manual describe when and how runway inspections are to be conducted, including extra or special inspections (following an accident or incident, in case of works or specific meteorological conditions).

Inspection reports must be archived for at least six months.

2.3 Advisory Circular

To assist the airport authorities to comply with the regulatory requirements, the FAA published Advisory Circular No. 150/5380-5B *"debris-related risks".*

This circular recommends the establishment of a programme for the prevention of debris-related risks. This puts the accent on the need for co-operation between all of the partners at the airport and on the importance of training and the involvement of all those working on the platform. It recommends a review of the causes and factors contributing to the presence of debris before the development of the programme for prevention of debris-related risks.

The circular also recommends the setting up of a committee for prevention of debris-related risks, grouping together the representatives of all of the organisations working on the movement area.

It suggests several solutions (areas dedicated to collected debris, equipment for cleaning the movement area) and refers to documents and reports by Aerospace FOD Prevention Inc. (NAFPI, non-profit-making association of professionals).

2.4 Training

The FAA, in co-operation with the American Association of Airport Executives (AAAE), has set up three or four day training programmes called *airport operation and safety schools*. Debris-related risks are presented by different participants in the field of aviation such as pilots, aircraft manufacturers and airport operators.

2.5 Example of Atlanta Hartsfield International Airport

Atlanta Hartsfield International Airport has four runways and a million aircraft movements a year. There is one infrastructure inspection per day.

The airport has an active programme for prevention of debris-related risks based on:

- the active participation of all of the participants working on the airport's movement area,
- the co-ordination of actions on the prevention of debris-related risks by an airport "Operations" agent,
- training for those who work on the movement area,
- information campaigns for personnel (posters, participation in infrastructure inspections).

A safety commission meets once a month. Questions on debris-related risks are systematically included on the agenda.

A specific commission on debris-related risks met in April 2001 in order to take action in advance of risks related to the work on the aerodrome extension.

2.6 Example of Washington National Airport

Washington National international airport has three runways. There is one infrastructure inspection per day.

The airport has an active programme for prevention of debris-related risks based on:

- the active co-operation of all of the participants working on the airport's movement area,
- surveillance by the aerodrome maintenance and operations personnel and by the various participants at the airport,

- the co-ordination of actions on the prevention of debris-related risks by an airport "Operations" agent,
- training for those who work on the movement area.

There is no specialised commission. There used to be one but the limited number of events and the experience acquired did not justify its continuation. It will be re-established if the circumstances warrant it.

Note: various items of equipment and materials (sweepers, receptacles for debris, magnetic bars) are used in the context of prevention of debris-related risks.

3 - Holland

The Dutch civil aviation authorities apply ICAO Annexe 14. There are no specific national regulations relating to the inspection of the movement areas nor, more generally, on the prevention of debris-related risks.

- Example of Amsterdam Schiphol Airport:

In 1995, a pilot safety group was set up at Schiphol and an airport safety management system (ASMS) was created. The Dutch civil aviation authorities approved this system in 1998. The existence of such a system is not yet a requirement.

In 1997, the integrated safety management system (ISMS) was set up. The ISMS brings together the airport authority, the air traffic control authority, and various airlines and companies working at the aerodrome. Co-operation between all those working on the movement area is ensured through participation in working groups.

- The safety rules are defined in the airport manual (Airside Regulation and Rules) and airport officers are responsible for ensuring their application.
- A runway inspection is performed three times a day. Additional inspections are carried out if the runway remains inactive for more than twenty minutes.
- The whole movement area is swept regularly and receptacles for debris are placed at different places on the apron.
- Discoveries of debris are recorded in the database on incidents and accidents on the movement area. The type of debris, the time and place of discovery are noted.
- An information campaign aimed at prevention of debris-related risks is conducted each year. Rewards are given to companies and persons who contribute to prevention.
- The level of awareness of persons working on the movement area is measured via questionnaires and their training includes a section on debris-related risks.

4 - United Kingdom

- National context

The FAA requires that aerodromes, through the certification process, supply details on their inspection policies for movement areas, including on additional inspections following any incident which might lead to the presence of debris in a critical area. The CAA does not define the frequency of inspections nor their objective.

The CAA encourages aerodromes to adopt a policy and safety management system, although this is not a regulatory requirement. The Civil Aviation Publication 642 of March 1995 offers guidance on the setting up of a system of safety management.

The safety management systems developed up to now include all aspects of airport operations, including prevention of debris-related risks. Those responsible for the aerodrome define the policy and procedures that must be applied by persons working on the movement area. This results in training programmes, information programmes, safety committees and certain sanctions.

All of the large aerodromes have a programme for permanent sweeping and publish their policy on prevention of debris-related risks in their aerodrome manual and/or in instructions. Most of the aerodromes supply a brochure entitled the “Apron Safety Code”.

- Other regulations and publications

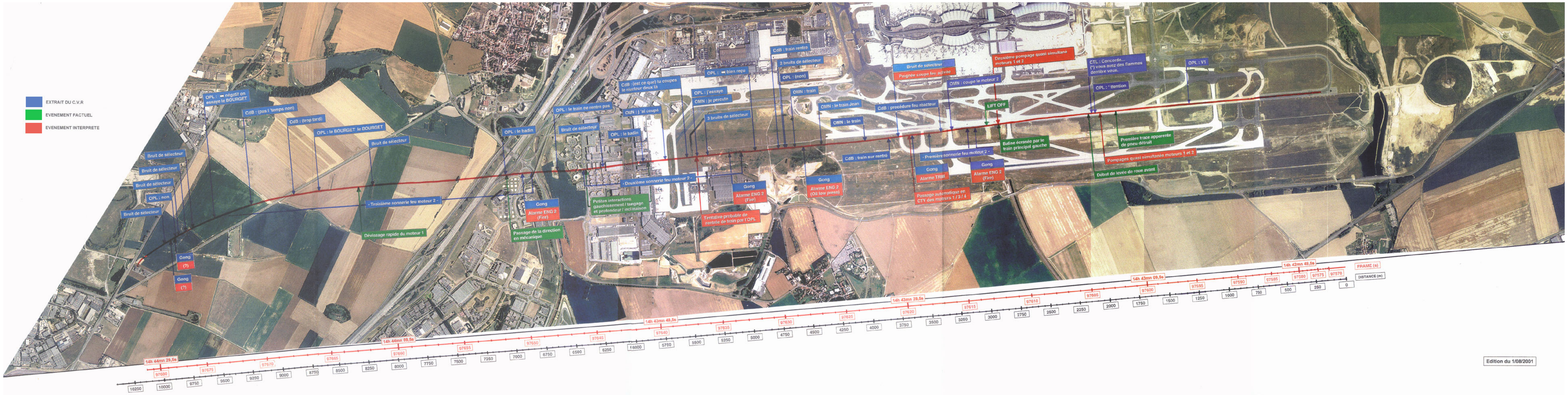
The United Kingdom has set up a system of mandatory notification for events and any damage caused to an aircraft by debris is usually reported through this system. Aerodromes must supply their comments on events that concern them and specify what steps have been taken to avoid any future repetition.

In December 2000, the CAA sent a note to aerodromes to stress the dangers of damage caused to tyres by debris. This note reiterates the requirements in terms of inspections and invites aerodromes to verify their procedures in this area.

The CAA also publishes a guide on works on aerodromes, which sets out steps to eliminate debris or to prevent it from reaching the movement area.

ANNEXE 12

Trajectoire de l'avion et répartition des éléments retrouvés sur la piste



Edition du 1/08/2001