Aircraft Break-Up

Inverted Contact of Forward Fuselage

Start of Ground Fire

Continuing break-up of outboard part of Left Wing – Fuel Tank rupture

Empennage Detachment

During inverted
Ground Slide

Ground Fire


Fire Control Officer watched takeoff.
Immediately activated Crash Alarm.
Fire Service in attendance in ~1 min
15
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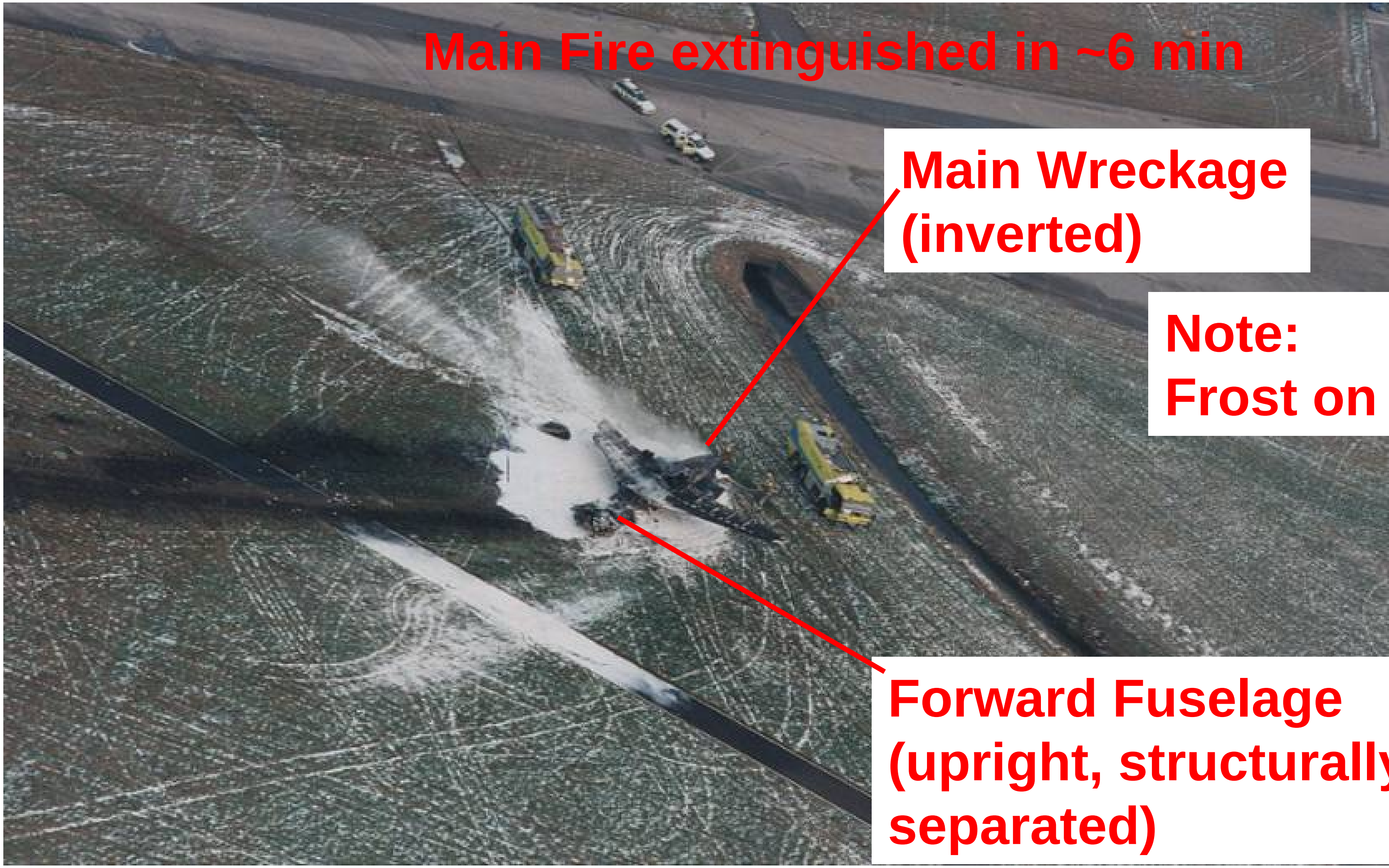
Main Wreckage



Wreckage Trail

Ground Fire Damage

Appreciable fire damage to Forward Fuselage

Forward Fuselage

Flight Deck

Main Wreckage

Possible Causes of Left Roll

- A substantial number of possibilities:
  - Engine thrust asymmetry.
  - Fuel lateral imbalance.
  - System malfunction:
    - Primary Flight Controls.
    - Secondary Flight Controls.
    - Pitch Trim.
  - Air data malfunction - incorrect speeds.
  - Excessive takeoff rotation rate – longitudinal CG (fuel shift ?).
  - Structural failure.
  - Door opening.
  - Pilot incapacitation.
  - Wake turbulence.
  - Jet efflux.
  - Airframe icing.

CG – Centre of Gravity

Icing

- Lots of circumstantial evidence pointing at icing, but:
  - No direct wreckage evidence of airframe ice at takeoff.
- Reported wing frost seen could have been affected by:
  - Solar radiation.
  - Fuel in wing tanks (melting or re-freezing).
  - Engine exhaust gas flows.
  - APU exhaust gas flow.
  - Crash effects:
    - Shock loading.
    - Ground fire.
    - Fire extinguishing.

APU Effects

- With the aircraft parked in a tail wind:
  - The APU exhaust gas would drift forwards over the right wing.
  - Aircraft ground testing showed, after 1 hour APU running:

Wing Station	Mean Temperature Increase - ºC	
	Left Wing	Right Wing
Root	1	2
1/3 Semi-Span	1	3
2/3 Semi-Span	1	5
Tip	3	8

  - *ie* minor effect on left wing, major effect on right wing.

Investigation

- Lengthy investigation, with evidence from:
  - Site
  - Wreckage
  - Witness accounts
  - FDR & CVR data
  - RT & Radar recordings
  - Autopsy & toxicology
  - Refuelling facility
  - Design information
  - Flight test data
  - Aircraft ground tests
  - Computer models

FDR - Flight Data Recorder
CVR - Cockpit Voice Recorder
RT - Radio Telephony

Investigation Findings

- No signs of aircraft structure or system malfunction.
- Aircraft loading was not grossly out of limits
- No possibility of wake turbulence effects.
- Traces of a drug (diphenhydramine) in both pilots.

Diphenhydramine

- Diphenhydramine:
  - A sedating anti-histamine compound used in cold, allergy and sleep-aid medications.
  - A constituent of ‘Exedrin PM – asprin free’, found in the crew baggage – sold non-prescription & non-pharmacy in USA.
  - Some evidence that it impairs short-term memory and attention, significant for divided-attention tasks.
  - Testing of driving simulator performance suggested greater impairment than blood alcohol at 100 mg/ml.

Aviation & Over-The-Counter Drugs

- In the USA between 1994 - 1998:

	Number	Percentage
Pilots killed in flying accidents	1,683	
Those with over-the-counter drug traces	303	18

  - 54 of the cases with drug traces involved diphenhydramine.

Diphenhydramine Medication Warnings

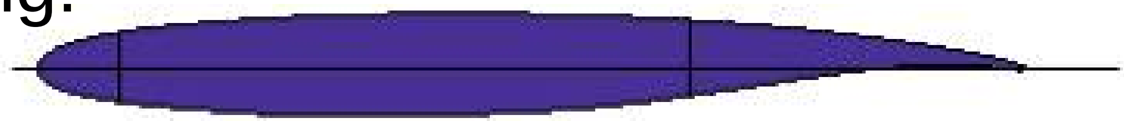
- Packaging of relevant over-the counter medications found in the USA tends to:
  - Warn of the need to avoid alcohol (potentiates the effects).
  - Not refer to driving or operating machinery (unlike UK).

Investigation Conclusions

- All possible causes of the uncontrollable left roll were eliminated, except for:
  - Stall of the left wing at an abnormally low AoA due to frost contamination.
- Wing contamination:
  - May have been asymmetric, due to APU exhaust gas.
  - Asymmetry not necessary for the wing drop to occur.

Wing Stall Characteristics

- Supercritical aerofoil wing:



  - Widely used.
  - At high AoA has a particularly high suction peak, just behind the leading edge, creating a separation bubble.
  - The suction peak is:
    - Higher and steeper as leading edge curvature becomes tighter.
    - Increased by trailing edge flap deployment.
    - Reduced by drooped leading edge – inefficient at cruise.
    - Reduced by leading edge slats or flaps – not fitted.
  - At the stall, compared to lower-speed aerofoils:
    - Flow separation nearer the leading edge – more abrupt loss of lift.

AoA – Angle of Attack

Spanwise Stall Characteristics

- Traditional design is for wing root to stall first.
- With appreciable wing sweep:
  - Root-first stall is impractical.
  - Stall may start at mid-span or even tip.
  - Data suggested stall likely to result in departure, irrespective of pilot action, maybe of up to:
    - Roll Rate - 70º/sec
    - Bank Angle - 85º
  - <u>Intended that the SPS would prevent the aircraft from reaching a wing stall condition</u>.

SPS – Stall Protection System

Effect of Roughness on the Wing

- Surface roughness – published information suggested:
  - BL can be prone to separation at a lower AoA, if roughness elements have:
    - A sufficient density (number of elements per area), and
    - A height that is substantial compared to the BL thickness.
  - For wings with a relatively low t/c & relatively high leading edge curvature:
    - The separation bubble tends to burst (*ie* wing stalls) at an AoA appreciably below the normal stall AoA.

BL - Boundary Layer
t/c - Thickness/Chord Ratio
AoA - Angle of Attack

Effects of Contamination

- Roughness – *eg* Frost:
  - Roughness approximately equivalent to <u>medium-fine</u> emery paper can typically cause <u>large effects</u> on stall behaviour, *ie* reductions in the order of:
    - C_{Lmax} - 30%
    - Stall AoA - 5º
  - Contamination thickness not very relevant – effects are dominated by roughness.
  - For the Challenger type wing, <u>leading edge</u> roughness appears to be more important than upper surface roughness.

CL_{max} - Maximum Lift Coefficient

Data Analysis

- Data from FDR & Computer Modelling indicated that:
  - Normal load factor for the aircraft at rotation was deficient, *ie*:
    - Lift was less than it should have been for the recorded AoA.
    - *ie* there was abnormal airflow over at least part of the wing.
    - Fuselage AoA for uncontaminated stall - 13.1°
    - Fuselage AoA at start of left roll - 7.8°
    - *ie*, stall occurred early by - 5.3°
  - Wing stalled before the AoA reached the SPS trip points.
  - Consistent with moderate roughness on the leading edge – in the range of the JAA/FAA definition of '*a small amount of ice*'.

FAA - Federal Aviation Administration
JAA - Joint Airworthiness Authorities

Knowledge of the Effects of Roughness

- Roughness effects well known to aerodynamicists.
- Many <u>pilots</u> probably unaware that, on some wings, relatively mild leading edge roughness:
  - Has such major aerodynamic effects.
  - Can render the SPS ineffective.

Failure to De-Ice

- P1, at least, detected that there was wing frost (commented to P2).
- Why was the aircraft not de-iced ?:
  - No direct evidence.
  - Human factors, thus necessarily speculative, but relevant.

P1 – Commander
P2 – Co-Pilot

Crew Experience

- Crew inexperience led to failure to de-ice ?
  - P1 was Director of Flight Operations for the operator.
  - Both pilots were highly experienced:
  - Flight Time:
    - Total - 10,000 – 20,000 hr
    - On Type - ~800 hr (over ~3 yr period)

Failure to De-Ice

- Possible reasons:
  - Either or both Pilots:
    - Believed the frost would not have a significant effect.
    - Believed the frost would melt before takeoff.
    - Observed the right wing clear & assumed that both were clear.
    - Believed the ice detection system would warn of contamination.
    - Forgot, after pre-flight preparations, that frost was present.
    - Intended to use wing anti-ice system before takeoff, but forgot.
    - Intended to rotate at higher speed than scheduled, but forgot.

Aircraft Manuals

- Flight Manual & Operating Manual:
  - Warnings along the lines of:
    - *'Takeoff must not be attempted if snow, ice or frost are present in any amount on the wings and tail surfaces of the airplane*.'
- Thus, clear warnings available, but:
  - No prohibition of ice at takeoff in Limitations Sections.

‘*Polished Frost*’

- FAR Part 91.527:

  “No pilot may takeoff an airplane that has:

  (2) Snow or ice adhering to the wings or stabilizing or control surfaces; or

  (3) Any frost adhering to the wings or stabilizing or control surfaces, unless that frost has been polished to make it smooth.”

- Similar statements on ‘*Polished Frost* ’ in:
  - FAR Parts 125 & 135.
  - Operator’s Flight Operations Manual.

‘*Polished Frost*’

- ‘Polished Frost’ concept:
  - Unable to establish its origins.
  - Not recognised in Canada or UK.
  - Could have undermined the Flight Operations Manual warnings.

Crew Condition during Flight Preparations

- Evidence of crew condition:
  - Some possible indicators that both pilots' judgement and concentration may have been deficient:
    - Trouble inputting FMS data.
    - Surprisingly high level of ATC readback errors.
    - Failure to follow through P1's queries on wing frost.
    - Failure to check anti-icing system.

FMS – Flight Management System
ATC – Air Traffic Control

Crew Condition Factors

- Possible factors causing decreased judgement and concentration:
  - Circadian dysrhythmia (jet-lag) – eastward time zone shift.
  - Tiredness – probably inadequate sleep on preceding two nights.
  - Effects of diphenhydramine.
- Unrealistic to assume that all pilots will always be at peak performance.

Recommendations

- It was recommended for:

1. NAAs to delete references to polished frost.
2. Contamination warnings to be included in Limitations.
3. FAA review guidance to crew on non-prescription medications.
4. FAA encourage warnings on over-the-counter medications.
5. Manufacturer reassess fault tolerance & integrity of SPS.
6. FAA & JAA consider airframe ice warning system.

FAA - Federal Airworthiness Administration
NAA - National Airworthiness Authority
JAA - Joint Airworthiness Authorities

Takeoff Ice Prevention

- The measures intended to eliminate pre-takeoff ice contamination are <u>procedural</u>, and thus:
  - Liable to human error:
    - Rely on quality of crew inspection, judgement, memory.
    - Access difficulties could deter proper inspection (tailplane ?).
    - Partial de-icing caused by uneven heating could mislead.
    - Could be unsuspected contamination after inspection.
  - Appears <u>unlikely to be a highly reliable system</u>.

Procedural Prevention of Takeoff Ice

- Long established system - generally effective, but:
  - Substantial number of accidents over the years.
  - Accidents continue – believe subsequently to have been two or three other accidents with this wing type (many in service).

Icing Accident Prevention

- Attributing the accidents to '*crew error* ' is likely to do little to prevent recurrence – errors happen.
- Suggests objective indication to the crew is necessary:
  - Small surface ice detectors have been available for some time:
    - Flush mounting (conformal, flat or curved).
    - Detection threshold – tenths of a millimetre of ice.
    - Differentiate between ice and fluid deposits.

Airframe Ice Detection System Advantages

- Detection System:
  - Would give warning of pre-takeoff contamination:
    - Possibly integrated with Takeoff Configuration Warning.
  - Would also provide direct monitoring and warning of:
    - In-flight icing of aerodynamic surfaces.
    - Performance of anti-icing & de-icing systems.

Airframe Ice Detection System

- Modern aircraft systems:
  - Monitor large numbers of aircraft parameters.
  - Alert the crew to anomalies in many areas.
  - It seems anomalous that they do not monitor arguably the most essential parameter for an aeroplane:
    - The aerodynamics – will they work today ?