AIRCRAFT ACCIDENT REPORT 5/2004

Air Accidents Investigation Branch

Department for Transport

Report on the accident to Bombardier CL600-2B16 Series 604, N90AG at Birmingham International Airport 4 January 2002

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Department for Transport
Air Accidents Investigation Branch
Berkshire Copse Road
Aldershot
Hampshire GU11 2HH

July 2004

The Right Honourable Alistair Darling
Secretary of State for Transport

Dear Secretary of State

I have the honour to submit the report by Mr P D Gilmartin and Mr C G Pollard, an Inspector of Air Accidents, on the circumstances of the accident to Bombardier CL600-2B16 Series 604, N90AG, which occurred at Birmingham International Airport on 4 January 2002.

Yours sincerely

Ken Smart
Chief Inspector of Air Accidents

Contents

FIGURES

APPENDICES

GLOSSARY OF ABBREVIATIONS USED IN THIS REPORT

AAIB	Air Accidents Investigation Branch
ac	Alternating current
AD	Airworthiness Directive
AFCS	Automatic Flight Control System
AFM	Airplane Flight Manual
AFS	Airport Fire Service
agl	above ground level
AIC	Aeronautical Information Circular
amsl	above mean sea level
AOA	angle of attack
APU	Auxiliary Power Unit
ATC	Air Traffic Control
ATIS	Automatic Terminal Information Service
BL	boundary layer
BUTE	Bent-Up Trailing Edge
°C	Degrees Celsius
CAA	Civil Aviation Authority
CAP	Civil Aviation Publication
CAS	Corrected Airspeed
CFD	Computational Fluid Dynamics
CFR	Code of Federal Regulations
CG	Centre of gravity
C_L	lift coefficient
C_{Lmax}	maximum lift coefficient
CVR	Cockpit Voice Recorder
dc	Direct current
EICAS	Engine Indicating and Crew Alerting System
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulations
FCC	Flight Control Computer
FCO	Fire Control officer
FDR	Flight Data Recorder
FMS	Flight Management System
FMY	Fort Myers Airport
FOM	Flight Operations Manual
hrs	hours
ICAO	International Civil Aviation Organisation
ISA	International Standard Atmosphere
ITT	Inter Turbine Temperature
JAR	Joint Airworthiness Requirement
kg	Kilogram(s)
kt	knot(s)
lb	pound(s)
ltr	Litre
°M	Degrees Magnetic
M	Mach number
MAC	Mean Aerodynamic Chord
mb	Millibar
METAR	Meteorological Aerodrome Report
mg	milligramme
MHz	Megahertz (frequency)
mm	millimetres
MTOW	Maximum Takeoff Weight
MZFW	Maximum Zero Fuel Weight
N_1	Low Pressure RPMs
N_2	High Pressure RPMs
NASA	National Aeronautics and Space Administration
nm	Nautical mile(s)
NTSB	National Transportation Safety Board
OAT	outside air temperature
PBI	West Palm Beach Airport
PCU	(hydraulic) power control unit
PDK	Dekalb Peachtree Airport
PF	Pilot Flying
PIC	Pilot in command
PNF	Pilot Not Flying
QNH	Corrected mean sea level pressure
Rp	Roughness parameter
RPM	Revolutions per minute
SIC	Second in command
SN	Serial number
SPS	Stall Protection System
t/c	Thickness/chord ratio
TCCA	Transport Canada Civil Aviation
UK	United Kingdom
US(A)	United States (of America)
USG	US gallons
UTC	Universal Time Co-ordinated
V_1	Decision Speed
V_2	Take-off safety speed
V_R	Rotation speed
V_{fto}	final take-off speed
V_{MCG}	Minimum control speed on the ground
WMFS	West Midlands Fire Service

Air Accidents Investigation Branch

Aircraft Accident Report No: 5/2004 (EW/C2002/1/2)

Registered Owner and Operator	Owned by Fleet National Bank, leased to AGCO Corporation and operated by Epps Air Service Inc
Aircraft Type	Bombardier CL600-2B16 Series 604 Commonly known as Challenger 604
Nationality	United States of America
Registration	N90AG
Place of Accident	Birmingham International Airport Latitude: 52° 27’ N Longitude: 001° 44’ W
Date and Time	4 January 2002 at 1207 hrs

Dates and times in this report are UTC unless otherwise stated

Synopsis

The accident was notified to the Air Accidents Investigation Branch (AAIB) by Birmingham Air Traffic Control (ATC) at 1220 hrs on 4 January 2002. The following inspectors participated in the investigation:

Mr P D Gilmartin	Investigator in Charge
Mr C G Pollard	Investigator in Charge (from May 2003)
Mr A N Cable	Engineering
Mr R W Shimmons	Operations
Mr P N Giles	Operations
Mr N Dann	Operations
Mr A Foot	Flight Recorders

Immediately after takeoff from Runway 15 at Birmingham International Airport the aircraft began a rapid left roll, which continued despite the prompt application of full opposite aileron and rudder. The left winglet contacted the runway shoulder, the outboard part of the left wing detached and the aircraft struck the ground inverted, structurally separating the forward fuselage. Fuel released from ruptured tanks ignited and the wreckage slid to a halt on fire; the Airport Fire Service was in attendance less than 1 minute later. The accident was not survivable.

Numerous possible causes for the uncontrolled roll were identified but all except one were eliminated. It was concluded that the roll had resulted from the left wing stalling at an abnormally low angle of attack due to flow disturbance resulting from frost contamination of the wing. A relatively small degree of wing surface roughness had a major adverse effect on the wing stall characteristics and the stall protection system was ineffective in this situation. Possible asymmetric de-icing by the Auxiliary Power Unit (APU) exhaust gas during pre-flight preparations may have worsened the wing-drop tendency.

N90AG's pilots should have been aware of wing frost during pre-flight preparations but the aircraft was not de-iced and the ice detector system would not have alerted them. It was considered that the judgement and concentration of both pilots may have been impaired by the combined effects of a non-prescription drug, jet-lag and fatigue.

Possible contributory factors were; the inadequate warnings on the drug packaging, Federal Aviation Administration (FAA) guidance material suggesting that polished wing frost was acceptable and melting of the frost on the right wing by the APU exhaust gas.

The investigation identified the following causal factors:

1. The crew did not ensure that N90AG's wings were clear of frost prior to takeoff.

2. Reduction of the wing stall angle of attack, due to the surface roughness associated with frost contamination, to below that at which the stall protection system was effective.

3. Possible impairment of crew performance by the combined effects of a non-prescription drug, jet-lag and fatigue.

Seven safety recommendations have been made.

1. Factual information

1.1 History of the Flight

This is based on eyewitness accounts, flight recorder and other information.

1.1.1 Flight Background

N90AG (Figure 1) was based at Dekalb Peachtree Airport (PDK), Atlanta, Georgia, USA. On 3 January 2002, the crew came on duty at 0900 hrs (0400 hrs local time in Atlanta) at PDK in preparation for a planned flight to the UK. An additional company pilot, not qualified on the Challenger 604 and not forming part of the flight crew, was on board as an observer for transatlantic experience. He is referred to as the 'observer' throughout this report.

The aircraft and crew departed PDK at 1015 hrs for a flight to Fort Myers Airport (FMY) in Florida to pick up a passenger. After landing at FMY at 1135 hrs, N90AG departed at 1200 hrs for a flight to West Palm Beach Airport (PBI) to pick up a second passenger. The aircraft landed at PBI at 1230 hrs and departed at 1259 hrs.

After an uneventful flight, N90AG arrived at Birmingham Airport at 2039 hrs. The Meteorological Aerodrome Report (METAR) for 2050 hrs was as follows: Surface wind 120°/6 kt; visibility 8 km; cloud scattered; temperature minus 1°C, dew point minus 2°C; QNH 1026 mb. On arrival, the commander had stated that the refuelling could be done the following morning in time for the planned 1200 hrs departure to Bangor Airport, USA.

The aircraft was parked on the Western Apron while at Birmingham. There was no precipitation while the aircraft was on the ground at Birmingham. Over the night of 3/4 January 2002 the air temperature remained below zero, with a minimum temperature of minus 9°C at 0550 hrs. Initially the sky was clear, with increasing, but variable cloud cover after midnight. The surface wind overnight was south-easterly at about 3 knots.

The two pilots and the observer spent the night in a local hotel. Records indicated that they checked in at approximately 2115 hrs and had a meal and some alcohol between 2144 hrs and 2315 hrs, before retiring to bed. The handling pilot for the return to the USA made a phone call home at 0200 hrs.

1.1.2 Pre-Flight Preparation

The next morning, the handling pilot and the observer arrived at the aircraft together at approximately 1040 hrs. Evidence from the dispatchers indicated that the APU was started at about 1050 hrs (see 1.18.1.1a). The commander arrived at approximately 1100 hrs. At different times, each of the two crew members was seen to carry out an independent external inspection of the aircraft. Aircraft refuelling commenced at about 1105 hrs and the aircraft fuel tanks were reported full at about 1140 hrs. Then, following the arrival of the two passengers, the aircraft doors were closed. The occupants were the same as on the arrival flight. During the morning, various witnesses had seen frost/ice on the wing surfaces of N90AG (see 1.18.1.1).

Other aircraft had been de-iced during the morning, with associated reports of severe to moderate ice accumulation. Evidence from the Cockpit Voice Recorder (CVR) indicated that the operating pilots discussed the presence of frost on the leading edge prior to engine start. However, neither requested de-icing and N90AG was not de-iced. The Birmingham METAR at 1150 hrs was as follows: surface wind 150°/6 kt; visibility 8,000 metres; cloud scattered at 700 feet agl and broken at 800 feet agl; temperature minus 2°C with dew point minus 3°C; QNH 1027 mb.

1.1.3 Accident Flight

Following ATC clearance, engine start was at 1156 hrs and N90AG was cleared to taxi at 1201 hrs. All radio calls during the accident flight were made by the commander, seated in the right cockpit seat. During taxi, the crew completed their normal Before Takeoff Checks; these included confirmation that the control checks had been completed and that anti-ice might be required immediately after takeoff. Flap 20 had been selected for takeoff and the following speeds had been calculated and briefed by the pilots: V_1 137 kt; V_R 140 kt; V_2 147 kt. By 1206 hrs, the aircraft was cleared to line up on Runway 15. At 1207 hrs, N90AG was cleared for takeoff with a surface wind of 140°/8 kt. The pilot in the left seat was handling the controls.

Takeoff appeared normal up to lift-off. Rotation was started at about 146 kt with the elevator position being increased to 8°, in the aircraft nose up sense, resulting in an initial pitch rate of around 4°/second. Lift-off occurred 2 seconds later, at about 153 kt and with a pitch attitude of about 8° nose-up. Once airborne, the elevator position was reduced to 3° aircraft nose-up whilst the pitch rate increased to about 5°/second.

Immediately after lift-off, the aircraft started to bank to the left. The rate of bank increased rapidly and 2 seconds after lift-off the bank angle had reached 50°. At that point, the aircraft heading had diverged about 10° to the left. Opposite aileron, followed closely by right rudder, was applied as the aircraft started banking; full right aileron and full right rudder had been applied within 1 second and were maintained until the end of the recording. As the bank angle continued to increase, progressively more aircraft nose-up elevator was applied. Stick-shaker operation initiated 3.5 seconds after lift-off and the recorders ceased 2 seconds later. The aircraft struck the ground, inverted, adjacent to the runway. The last recorded aircraft attitude was approximately 111° left bank and 13° nose-down pitch; the final recorded heading was about 114°(M).

1.2 Injuries to Persons

Injuries	Crew	Passengers	Others
Fatal	2	2	1 (Observer)
Serious	-	-	-
Minor/none	-	-	-

1.3 Damage to Aircraft

The aircraft was largely destroyed by impact and fire damage (Figure 2).

1.4 Other Damage

Other damage consisted of minor scraping of the runway shoulder and disruption of the surrounding ground.

1.5 Personnel Information

1.5.1	Commander	Male, aged 51 years	
	Location:	Right cockpit seat, non-handling pilot	
	Licence:	US Airline Transport Pilot’s Certificate	
	Medical certificate:	Class 2, valid to 28 February 2002	
		Limitations: Wear lenses for near vision	
	Flying experience:	Total all types:	Approximately 10,000 hours
		Total on type:	800 hours
		Total last 28 days:	53 hours
		Total last 24 hours:	9.5 hours
	Previous rest period:	Off duty:	2109 hrs on 3 January 2002
		On duty:	1100 hrs on 4 January 2002

The commander had worked for Epps Air Service Inc since 1968 and was the current Director of Operations. He had completed his aircraft rating on the Challenger 604 series aircraft on 4 April 1999 at the Bombardier Aerospace Training Centre and was one of four company pilots to fly N90AG.

Designated the Pilot In Command (PIC) by the company for this flight, he would normally have occupied the left cockpit seat. The company Flight Operations Manual, however, permitted a qualified Second in Command (SIC) to occupy this seat at the Commander's discretion. As PIC he was responsible for clearly defining the handling pilot at any given time during a flight.

1.5.2	Handling pilot	Male, aged 58 years	
	Location:	Left cockpit seat	
	Licence:	US Airline Transport Pilot's Certificate	
	Medical certificate:	Class 1, valid to 31 January 2002	
		Limitations: Possess glasses for near vision	
	Flying experience:	Total all types:	Approximately 20,000 hours
		Total on type:	Approximately 800 hours
		Total last 28 days:	26 hours
		Total last 24 hours:	9.5 hours
	Previous rest period:	Off duty:	2109 hrs on 3 January 2002
		On duty:	1030 hrs on 4 January 2002

The handling pilot was one of the four company captains qualified on the Challenger 604 and had completed his aircraft rating on the Challenger 604 series aircraft on 9 April 1999 at the Bombardier Aerospace Training Centre. He had worked for Epps Air Service Inc since 1968.

1.6 Aircraft Information

1.6.1 General information

Manufacturer:	Bombardier Aerospace
Type:	Bombardier CL600-2B16 Series 604 Commonly known as Challenger 604
Aircraft Serial No (SN):	5414
Year of manufacture:	1999
Certificate of Registration:	Valid
Certificate of Airworthiness:	Issued 14 September 1999, valid
Engines:	2 General Electric CF34-3B turbofan engines
Total airframe hours:	1,594 hours, 797 flight cycles

1.6.2 Aircraft weight and centre of gravity

1.6.2.1 Aircraft weight and centre of gravity calculation

The aircraft was weighed at the Bombardier Completion Centre, Tucson, Arizona on 10 September 1999. N90AG was fitted in the ten passenger configuration, for which the aircraft's basic operating weight was 27,200 lb and the longitudinal Centre of Gravity (CG) was at 32.5 % Mean Aerodynamic Chord (MAC). This basic operating weight included 2 pilots, each weighing 170 lb, and an allowance for crew baggage and aircraft supplies.

The aircraft type was subject to Airworthiness Directives (ADs) which limited the aft CG at high all-up weights and the associated limitations were as follows (see 1.6.2.2):

Maximum Take-Off Weight (MTOW)	-	48,200 lb with an aft CG limit of 34.5% MAC.
Maximum Zero Fuel Weight (MZFW)	-	32,000 lb with an aft CG limit of 35% MAC.

Records from the refuelling vehicle indicate that the aircraft was refuelled with 10,110 litres of Jet A1 kerosene with a specific gravity of 0.8, equating to 17,834 lb. This would indicate that the aircraft fuel tanks were full, as the total capacity is just under 20,000 lb.

The actual seating of the passengers and the positioning of the baggage could not be determined precisely. It was probable that the observer, weighing 205 lb, was seated on the jump-seat. The two passengers each weighed 190 lb and there was 150 lb of luggage in the baggage bay. This would result in an estimated zero fuel weight of 27,936 lb. With a full fuel load, less 100 lb taxi fuel, the estimated take-off weight would have been 47,836 lb; this was within MTOW limits.

If both passengers had been seated in the rearmost cabin seats, the resultant CG would have been 36% MAC, with an associated trim setting of -3.8° (negative trim corresponds to horizontal stabiliser nose down). With both passengers in the forward seats, the scheduled trim setting for the resultant CG of 34.5% MAC would have been -4.1°.

The evidence from the wreckage examination (see 1.12.2.3) indicated that the passengers were not in the rear seats, but with any seating combination the aircraft would have been within the originally certificated normal weight and CG limits for takeoff (see 1.6.2.2). As a result of the restrictions imposed by the Airworthiness Directives, however, if the passengers and observer had not been seated in the most forward seats available to them, the aircraft would probably have been marginally outside the revised permissible aft CG limit.

Based on the calculated weight of 47,836 lb, the take-off speeds would be as follows:

V_{MCG}	111 kt
V_1	137 kt
V_R	141 kt
V_2	147 kt

1.6.2.2 Airworthiness Directives

Up to February 2001, the certificated MTOW of N90AG was 48,200 lb with an aft CG limit of 38% MAC. However, following an accident to a Challenger 604 aircraft on 10 October 2000, Airworthiness Directives were issued by the US Federal Aviation Administration (FAA) and Transport Canada Civil Aviation (TCCA). These resulted from preliminary investigation findings which had highlighted the possibility that fuel migration, under conditions of acceleration and/or climb, could result in the aft CG limit being exceeded. The ADs required the Airplane Flight Manuals (AFM) to be amended to reflect an aft CG limit of 34.5% MAC for weights above the minimum landing weight of 38,000 lb.

1.6.3 Aircraft Description

1.6.3.1 General

The Challenger is a swept wing aircraft with a T tail and conventional tricycle landing gear, powered by two turbofan engines mounted one either side on the rear fuselage (Figure 3). It is constructed chiefly of aluminium alloy. Fuel is carried in wing and fuselage tanks. The flight deck has two pilot’s seats and a jump-seat. A baggage bay is located at the aft end of the cabin and the rear fuselage behind the cabin forms an aft equipment bay. N90AG’s cabin was fitted with corporate seating for 10 passengers.

1.6.3.2 Background

The Challenger 604 was designed and constructed by Bombardier Aerospace, a Canadian company that acquired Canadair in 1986. It is a member of a family of aircraft, all known as Challengers, which share a common wing design and are covered by a single Type Approval certificate.

The original design was the Canadair Model CL600 (Canadian Type Approval in 1980), from which was developed the Model CL601 (Type Approval in 1983). The Model CRJ, a regional jet transport, and the Challenger 604 were developed from the CL601. The Challenger 604, which is generally similar to the Challenger 601 but with considerably increased basic and maximum operating weights, received Type Approval from TCCA in 1995.

At the time of this accident there were approximately 538 Challengers of all variants in service world-wide, of which approximately 203 were Challenger 604s, which were generally in use as corporate transports.

1.6.3.3 Wing

The aircraft has a swept, tapered wing of aluminium alloy construction (Figure 3). Each wing has a conventional torque box as its main structural element, integral with a wing centre-section torque box contained within the fuselage profile. The leading edge of each wing is formed by three polished aluminium alloy D-section elements attached with flush fasteners to the flanges of the torque box forward spar. The design provides an approximately 1 to 2 inch gap between the spar and the aft, vertical shroud member of the D-section elements. A winglet is attached to each wingtip, 4.2 feet high and angled upwards and outwards at 75° to the horizontal. The winglets have aluminium alloy spars and aluminium and composite skin panels.

The wing has an overall span of 64.3 feet, a quarter chord sweep angle of 25° and an incidence washout of 4° between the root and tip. It has a single crank in the wing leading and trailing edges 8.4 feet outboard of the wing root. Wing chord and maximum thickness are respectively 13.1 feet and 1.8 feet at the wing root and 4.2 feet and 0.4 feet at the tip. The aerodynamic characteristics of the wing are described in Section 1.18.4.

Dual navigation lights and a white strobe anti-collision light are fitted at each wingtip and, on N90AG, each winglet carried a white rear navigation light. A power supply unit for the strobe light is located within the wingtip on each side. Electrical power cables for these components are routed along the wing torque box front spar. The power supply voltages and circuit breaker ratings are 115v ac/2 amp for each of the navigation lights and 28v dc/5 amp for the strobe power supply unit.

1.6.3.4 Primary Flight Controls

The flight deck is fitted with dual controls operating conventional elevator, aileron and rudder control surfaces (Figure 3). Left and right aileron and elevator controls can be split but are normally connected together. Pilot control inputs are transmitted by mechanical systems to hydraulically powered control units (PCUs) operating the surfaces. Each elevator and aileron is operated by dual PCUs and the rudder by triple PCUs. The systems include mechanisms for providing artificial feel in all three channels.

The position of each of the five primary control surfaces is monitored by a rotary synchro transducer, which is mechanically driven by surface movement via a short rod and bellcrank linkage. In each case the synchro output is converted to a digital signal which is passed to the Engine Indicating and Crew Alerting System (EICAS) displays and to the Flight Data Recorder (FDR). No filtering is performed on the signal between the transducer and the FDR.

1.6.3.5 Secondary Flight Controls

a. Trim

For aircraft pitch trim the horizontal stabiliser incidence relative to the aircraft can be adjusted by a motor control unit. This is a screwjack actuator driven by twin electric motors, operated by flight deck switches. The normal range for take-off pitch trim is between -3° to -8°; outside this range, the configuration warning activates on thrust lever advance for takeoff. The aircraft manufacturer considered that there would be no difficulty achieving the target pitch angle on takeoff with the trim set anywhere within the normal range.

For roll trim, an electric screwjack actuator provides inputs to the aileron PCU control circuit; the maximum authority is limited by mechanical constraints to ±7.5° aileron angle, with a tolerance of ±0.5° (full aileron travel is 19.3° up to 19.8° down). A similar system provides the rudder trim capability, with a maximum authority mechanically limited to 8.3° left to 8.8° right, with a tolerance of ±0.5° (full rudder travel is ±25° with a tolerance of ±0.5°). Position sensor(s) incorporated in each actuator provide signals for flight deck indication and for the FDR.

b. Auto Flight

An Automatic Flight Control System (AFCS) integrates autopilot, flight director and yaw damper functions. In autopilot operation, servo motors signalled by Flight Control Computers (FCCs) feed inputs into the elevator and aileron PCU control runs. The AFCS authority in roll is designed to be limited to 4°/second roll rate and 27° roll angle. Aircraft turn co-ordination and yaw/roll stabilisation is provided by dual yaw dampers, each comprising an electric screwjack actuator; outputs are additive. The actuators are controlled by the aircraft's Inertial Reference Units via the FCCs and provide inputs to the rudder PCU control circuit, independently from the autopilot system. Combined yaw damper authority is mechanically limited to ±5° up to 265 kt CAS (rudder nominal full travel ±25°).

c. Wing Flaps

Each wing is fitted with two hinged trailing edge flaps, normally set at 20° for takeoff. No leading edge devices are fitted.

The flaps are operated by ball screwjack actuators driven via flexible driveshafts from an electric Power Drive Unit located in the main landing gear bay. The flaps are held at the selected setting by two disc brakes, one at either outboard end of the drive system.

The flap assemblies have a leading edge vane attached to each main flap panel to provide a double-slot configuration when flaps are in the extended position. The inboard flap vanes are sprung-loaded to allow them to retract towards the main flap panel during the latter stages of flap stowage; the outboard flap vanes are rigidly mounted. The vanes extend past the trailing edge structure into the airflow when flap angle is beyond approximately 20°.

The wing undersurface over the span of each outboard flap is fitted with a hinged Bent-Up Trailing Edge (BUTE) door. This is spring-loaded to hinge upwards when the flaps extend. When the flaps are in the landing position, the door directs the airflow over the leading edge vane. With flaps in the take-off position, the door is in contact with the lower surface of the leading edge vane.

d. Flight Spoilers

A flight spoiler panel hinged at its forward edge to the upper surface of each wing can be deployed into the airflow to provide lift reduction. Each flight spoiler panel is operated by dual hydraulic PCUs controlled via a mechanical signalling system by a lever in the flight deck centre console. Monitoring of the position of each flight spoiler panel for the EICAS displays and for the FDR is as for the primary flight control surfaces.

e. Ground Spoilers

A ground spoiler panel is located inboard of the flight spoiler panel on each wing. Each panel is operated by a hydraulic actuator to either a fully retracted or fully deployed position. They are designed to deploy automatically, when armed, to provide lift dump on landing or for rejected takeoff. Position indication sensing for each panel is provided by a proximity sensor, located adjacent to the panel’s central hinge; position signals are passed to the EICAS displays and to the FDR.

1.6.3.6 Fuel

Individual integral fuel tanks are formed by the wing centre-section torque box and by the torque box of each wing between the root rib and a closure rib approximately three feet from the wing tip. There are two double-walled tanks located underfloor in the fuselage, one forward of the wing centre-section and one beneath the baggage bay. There are also two saddle tanks in the aft equipment bay and a further tank in the tailcone. The wing tanks are referred to as the 'main tanks'. The centre-section tank and the two underfloor tanks are interconnected and treated as a single 'auxiliary tank'. Similarly, the saddle and tailcone tanks are interconnected and treated as a single 'tail tank'.

Each engine is supplied from a collector tank, each of which is normally fed from its respective main tank. The APU is supplied from the right main tank. Fuel transfer between main, auxiliary and tail tanks is controlled by a fuel system computer. When the aircraft is on the ground and the main tanks contents reduce to 93% of capacity, they are automatically replenished from the auxiliary tank. In flight, fuel is pumped from the tail tank to the auxiliary tank, via a transfer shut-off valve; this automatic transfer is inhibited until weight off both main landing gear wheels is sensed. Check valves prevent rearward transfer of fuel from the auxiliary tank to the tail tank. The pipes connecting the individual elements of both the auxiliary and tail tanks are not provided with shut-off or check valves and thus fuel transfers freely between the elements of each tank group under gravity or acceleration forces.

A capacitance fuel contents system provides signals for flight deck fuel quantity indication and for refuel and fuel transfer systems. Fuel quantity indications are presented on the EICAS, including individual indications for each wing tank. A sensor in the left wing tank provides indication on the EICAS of bulk fuel temperature; this parameter is not recorded on the FDR. The maximum content of each tank on refuelling is nominally 98% of the tank capacity, with 2% of the volume remaining as vent space. This is determined by automatic operation of the high level cut-off system. Fuel tank maximum contents are:

Tank	**Maximum Contents**		
	US Gallons	**lb**	**ltr**
Left Wing Main	720	4,860	2,733
Right Wing Main	720	4,860	2,733
Forward Auxiliary	217	1,465	822
Centre-Section Auxiliary	750	5,063	2,839
Aft Auxiliary	95	641	360
Left Saddle	132	894	501
Right Saddle	132	894	501
Tailcone	197	1,330	745
TOTAL	**2,967**	**20,007**	**11,234**

The main vent for each wing tank consists of an open duct passing from the outboard end of the tank to an inverted U duct located in the fuselage sidewall and then to an overboard port on the trailing edge of the wing between the inboard and outboard flaps. Each of the other tank elements is provided with a high-level vent.

1.6.3.7 Ice Protection

a. Ice Detectors

Two independent airframe ice detectors are installed, mounted one either side of the forward fuselage. Each detector has a vibrating cylindrical probe extending into the airflow, a microprocessor and a probe heater. It is powered from the Essential AC busbar. Ice collecting on a probe causes its vibration frequency to change and the system is designed to activate an ice signal within one second of detecting, on either probe, a frequency change equivalent to an ice thickness of approximately 0.020 inches.

When an ice signal is triggered, it is latched on for 60 seconds and the heater switches on for five seconds to de-ice the probe. The signal provides a flight deck master caution light, an EICAS amber 'ICE' message and an aural chime warning. Manual selection of wing and engine cowl anti-ice causes the EICAS message to change to green. The warnings are inhibited during takeoff when airspeed is above 80 kt, until a radio altimeter height of 400 feet is reached.

b. Airframe Anti-Icing System

The wing leading edges can be thermally anti-iced using engine bleed air from the compressor 14th Stage. The hot air is ducted through valves to the inboard end of a titanium piccolo tube running spanwise inside the D-section leading edge of each wing. It is distributed within the leading edge by the piccolo tube and exhausted via louvres in the bottom of the leading edge D-section. No other flight surfaces have anti-icing provision.

Subsequent to N90AG's accident, cases were reported where sections of the piccolo tubes had inadvertently been installed in the wrong wing. This would result in incorrect configuration of the piccolo tube outlet holes and could degrade the effectiveness of the system.

Relevant flight deck indications of the status of the wing anti-ice system are as follows:

'L/R WING A/ICE' caution message -	Low air pressure, insufficient heat. Message inhibited when thrust reverser selected.
'WING A/ICE OK' advisory message-	Successful test of wing anti-ice system.
'WING A/ICE ON' advisory message-	Sufficient heat available for anti-ice system.

c. Air Sensor Anti-Icing System

The air data sensors described in 1.6.3.8 each has a built-in electrical heater element(s) for anti-icing, controlled by two Air Data Sensor Heater Controllers.

1.6.3.8 Air Data Sensors

Air data for aircraft systems is sensed by pitot probes, static ports and angle of attack (AOA) sensors. Each main AOA sensor, one mounted either side of the forward fuselage, consists of a pivoted trailing vane connected to a rotary potentiometer that provides an electrical signal proportional to the airflow direction relative to the wing. Sensor AOA, which is related to fuselage AOA by a formula, is used throughout the report except at 1.18.4.4 where fuselage AOA has been used.

The aircraft manufacturer has reported that wear between the wiper and the coil of the wire-wound potentiometer of the main AOA sensors has been identified as a problem. This can short out individual turns of the coil and thereby cause a 'flat spot', ie a band where a change in AOA results in no change in output voltage. The flat spot has typically first appeared in the 1-2° region and grown asymmetrically about this value. A Bombardier Advisory Wire (No 600T-2182, Revision 3) addressing the problem was issued in December 2001 (see 1.6.4) and an Airworthiness Directive (CF-2002-05), requiring a check of the AOA transducer every 300 flight hours, was issued by Transport Canada on 18 January 2002.

There is a standby pitot-static probe mounted on the left side of the forward fuselage and an auxiliary AOA sensor on the right. Signals from the auxiliary AOA sensor provide a low speed awareness indication on the primary flight display airspeed scale.

1.6.3.9 Stall Protection

A Stall Protection System (SPS) provides flight deck warning of an approach to a wing stall condition and automatic prevention of aircraft entry to an AOA regime where wing stall can occur, with possible severe wing-drop or deep stall entry as a result. The system is automatically inhibited when the aircraft is on the ground, ie until weight off either main landing gear is sensed.

The system is controlled by a dual-channel SPS computer, with the channels operating most system functions independently of each other. Each channel receives signals from its respective main AOA sensor and applies filtering to avoid nuisance activation of the system due to turbulence. The filtered signals are output to the FDR and to sideslip compensators in the computer which adjust them for aircraft turn, slip or skid effects in response to lateral accelerometer signals. The filtered and sideslip-compensated signals are then compared with three computed trip point values.

On reaching the 1st trip point, engine auto-ignition is activated. At the 2nd trip point, each SPS channel independently activates a stick-shaker motor on the respective flight deck control column to provide tactile and aural warning. If either channel detects that the 3rd trip point has been reached, flight deck warnings are activated, consisting of two red flashing ‘STALL’ lights on the glareshield and, after a one second delay, a horn sound. In the event that both SPS channels compute that the 3rd trip point has been reached, a stick-pusher motor connected to the right elevator control run is activated to provide an aircraft nose-down control input. The stick-pusher discontinues operation if either SPS channel senses an AOA reduction of at least 5° from the trip value, or a reduction in aircraft vertical acceleration below 0.5g, or if the autopilot/stick-pusher disconnect button on either control column is operated.

The trip point angles are decreased as flap deployment angle increases and reduced as pressure altitude increases between 2,000-15,000 feet. In order to provide early warning and protection during high entry rate approaches to the stall, a phase advance function is used to reduce the trip point angles for stick-shaker and stick-pusher operation. The computed phase advance term is applied to the trip point angles if the rate of increase of AOA exceeds 1.0 ±0.2°/s, after a two second delay from weight off either main landing gear being sensed. The nominal (non-adjusted) AOA sensor angle in the take-off configuration below 2,000 feet altitude is 19.2° for stick-shaker initiation and 23.1° for stick-pusher initiation.

The output from the auxiliary AOA sensor is used to provide an indication on the primary flight displays of the nominal stick-shaker speed. Display of the indication commences three seconds after weight off either main landing gear is sensed.

1.6.3.10 Auxiliary Power Unit - APU

The aircraft is fitted with an APU, a small gas turbine powerplant installed in the rear equipment bay capable of supplying aircraft electrical and air conditioning systems when main engines are not operating. It can also be used to generate hydraulic power by means of electrically powered hydraulic pumps. The exhaust gas from the APU is ducted to an overboard port on the right side of the rear fuselage beneath the engine pylon (Figure 3). The port is 10 inches in diameter and fitted with vanes to direct the exhaust gas away from the engine nacelle and the fuselage.

1.6.4 Aircraft History

Since its delivery from new until the accident, N90AG had been operated by the same company. During this period, the aircraft's line maintenance had been carried out by the operator and heavy maintenance had been contracted to a service centre operated by the aircraft manufacturer. By the time of the accident N90AG had undergone three major inspections. The maintenance records over several months prior to the accident indicated that the level of reported defects had been generally low. There had been few flight control system or other possibly relevant discrepancies, all of which had been cleared at the time N90AG departed Atlanta, Georgia, for its flight via Florida to Birmingham. This was an estimated 9.7 operating hours and 3 flight cycles prior to the departure on the accident flight. The Aircraft Maintenance Log subsequent to departure from Atlanta would normally have been carried on the aircraft and was not recovered. Any maintenance action considered necessary in this period away from base would normally have been co-ordinated with the maintenance organisation and no evidence was found to suggest that any problems had arisen.

The Bombardier Advisory Wire concerning the AOA sensor problem (see 1.6.3.8), received by the maintenance organisation on 21 December 2001, announced that Service Bulletin 604-27-011, introducing an AOA vane inspection, would be released in January 2002. Compliance for N90AG was scheduled during a 1,600 hour Check that was programmed for 10 January 2002.

1.7 Meteorological Information

1.7.1 General

The synoptic situation at 1200 hrs on 4 January 2002 showed a high pressure system centred over eastern Germany feeding a light southerly flow over central and southern England.

The wind at the time of the accident was as follows:

Surface	140°/6 kt
1,000 ft	150°/15 kt
2,000 ft	160°/20 kt

1.7.2 Meteorological Aerodrome Reports

METARs showed that at 1150 hrs on 4 January, the surface wind was 150° at 6 kt. The visibility was 8 km. The cloud was scattered at 700 feet and broken at 800 feet. The air temperature was -2°C and the dew point -3°C and the QNH was 1027 mb.

By 1220 hrs the visibility had reduced to 7 km and there was no longer any scattered cloud and the QNH had fallen to 1026 mb.

The Automatic Terminal Information Service (ATIS) was broadcasting the following message on frequency 126.275 MHz:

> ‘BIRMINGHAM INFORMATION SIERRA; TIME ONE ONE FIVE ZERO. RUNWAY IN USE ONE FIVE. SURFACE WIND ONE FOUR ZERO FIVE KNOTS. VISIBILITY EIGHT KILOMETRES; SCATTERED SEVEN HUNDRED FEET; BROKEN EIGHT HUNDRED FEET; TEMPERATURE MINUS TWO; DEW POINT MINUS THREE; QNH ONE ZERO TWO SEVEN; RUNWAY DAMP, DAMP, DAMP. ACKNOWLEDGE RECEIPT OF INFORMATION SIERRA AND ADVISE AIRCRAFT TYPE ON FIRST CONTACT.’

The aircraft had been parked overnight on a heading of 319°M, from about 2050 hrs on 3 January, when the surface wind was 120°/6 kt and the temperature/dew points were -1°C/-2°C. By 0550 hrs on 4 January, the surface wind was calm and the temperature/dew points had reached minimum values of -9°C/-9°C. The surface wind remained light from the south east, and the temperature/dew points had slowly increased to -2°C/-3°C at the time of the accident. There had been no precipitation overnight. The main cloud base was broken to overcast and lowered from 1,200 feet to 800 feet as the morning progressed.

Overnight, Birmingham Airport was under the influence of a severe frost, which had improved to moderate by the time of the accident.

1.7.3 Aircraft icing

As detailed in CAA Civil Aviation Publication (CAP) 512: *"any deposits of ice, snow or frost on the external surfaces of an aircraft may drastically affect its performance. This can be due to reduced aerodynamic lift and increased aerodynamic drag resulting from the disturbed airflow over the aerofoil surfaces, or due to the weight of the deposit over the whole aircraft. The operation of an aircraft may also be seriously affected by the freezing of moisture in controls, hinges and micro-switches, or by the ingestion of ice into* the *engine. Furthermore, since the in-flight de-icing system may not become effective until the aircraft is established in the climbout, the measures taken to remove frozen deposits on the ground must also be such as to provide adequate protection during the initial stages of flight.*"

General and type specific regulations regarding protection from contamination are contained within national regulations, aircraft flight manuals and company operations manuals; relevant extracts from these publications are included in Section 1.18.5.

1.7.4 Icing conditions at Birmingham

The effect of the environmental conditions at Birmingham Airport on the formation of frost/ice on the surfaces of a parked aircraft, during 3/4 January 2002, was considered by specialists from The Meteorological Office at Bracknell. Their estimate was that, with the aircraft parked exposed to a minimum temperature/dewpoint of -9°C/-9°C, at dawn, there would have been a deposit of frost on the upper surfaces of wings and horizontal stabiliser.

This was confirmed by witness reports of frost on N90AG and other aircraft. One of these was a Canadair CRJ, which had been positioned, on the evening of 3 January 2002, close to where N90AG was parked later that evening. The CRJ was towed from that location the next morning at about 1030 hrs and was then found by the captain on his pre-flight inspection to require de-icing; he considered that the frost was some 1 to 2 mm thick over the aircraft surfaces.

The following sources of heat could have affected the amount of frost/ice remaining on N90AG's surfaces at the time of the accident:

1. Engine and/or APU Exhaust - The APU was started at approximately 1050 hrs. This aspect is considered in Section 1.16.4.

2. Fuel - The aircraft was refuelled at 1105 hrs. This aspect is considered in Section 1.18.2.2.

3. Solar Radiation - No direct measurement of the ground level solar radiation at Birmingham Airport for the morning of the accident was available. Evidence from nearby observations indicated that the sunlight would probably have been diffused through a localised layer of thin cloud, rather than direct.

Information from the handling agent determined the position on the Western Apron in which N90AG had been parked overnight prior to the accident flight. Post accident observation of this area showed that the aircraft would not have been either partially or wholly in shadow from any ground object on the morning of the accident between shortly after sunrise until the time that it departed for takeoff. During this period the sun would have been generally behind and moving to the left of the aircraft as the sun's elevation increased and it appeared that no significant shading of the left wing by the fuselage or empennage would have occurred.

1.8 Aids to navigation

Not applicable.

1.9 Communications

At the time of the accident the aircraft was in contact with the Birmingham Tower controller on frequency 118.3 MHz. The communications on this frequency were recorded on the CVR and the relevant aspects are included in Section 1.11.2.

1.10 Aerodrome information

A map of Birmingham Airport is included as Appendix 1. The physical characteristics of Runway 15 were:

Magnetic Heading	146°
Dimensions	2,605 x 46 metres
Surface	Asphalt
TORA/ASDA	2,575 metres

Threshold Elevation	303 feet amsl, with a slight upslope to the end of the runway at 325 feet amsl

Runway 06/24 intercepts Runway 15 at a distance of 1,590 metres from the threshold of Runway 15.

1.11 Flight Recorders

1.11.1 General

The aircraft was fitted with an L3 Solid State Digital Flight Data Recorder (FDR), Part Number S800-2000-00, SN 02578. The FDR was capable of recording a range of analogue, digital and discrete flight parameters on a continuous 25 hour loop. The FDR was activated at first engine start by an engine oil pressure switch. The aircraft was also fitted with an A100S Solid State Cockpit Voice Recorder (CVR), Part Number 5100-0030-61, SN 02446, which recorded crew speech and area microphone inputs on a continuous 30 minute loop when electrical power was applied to the aircraft. Both the FDR and CVR data were recovered successfully.

1.11.2 Cockpit Voice Recorder

The CVR started at about 1137 hrs. The crew speech and radiotelephony was mainly clear and free from distortion, as was the area microphone. In the following narrative, quotations from the recording are in *ITALIC CAPITAL LETTERS* and any words which it has not been possible to discern with reasonable certainty are denoted by *(????)*.

The handling pilot, seated in the left cockpit seat, started to programme the Flight Management System (FMS), supervised by the commander, at 1139 hrs. He had some difficulties which resulted in the process being re-started at about 1141 hrs and it was finally completed by 1146 hrs. Prompted by the commander, the handling pilot then went on to determine the take-off speeds and engine settings, which he completed at 1149 hrs: he quoted an aircraft weight of *"FORTY EIGHT THOUSAND"*, a power setting of *"EIGHTY-NINE POINT FOUR"* and speeds of *"ONE THIRTY-SEVEN, ONE FORTY, ONE FORTY-SEVEN, ONE SEVENTY-SEVEN"*(V_{fto}).

At about 1150 hrs there were sounds and voices external to the cockpit, which were probably related to baggage and the passengers arriving at the aircraft. At 1153 hrs the following conversation took place between the commander and the handling pilot:

Commander: *“GOT A (????) FROST ON THE LEADING EDGE, ON THERE, DID YOU-ALL LOOK AT IT?”*

Handling pilot: *“HUH?”*

Commander: *“D’YOU (????) THAT FROST ON THE LEADING EDGE – WINGS?”*

Handling pilot: *“ DID I FEEL ‘EM?”*

Commander: *“YEAH, DID YOU-ALL CHECK THAT OUT?”*

Handling pilot: *“YUH”*

At 1154 hrs the crew tuned in to the ATIS frequency and the information (see 1.7.2) was recorded on the CVR. At 1155 hrs the commander requested clearance to start engines; this was granted by Birmingham Ground Operations and the commander was told that the Outside Air Temperature was minus two degrees Celsius. The transponder code to be used once airborne (zero three seven two) was passed to the aircraft but was incorrectly read back by the commander twice before the correct code was repeated.

At 1157 hrs the aircrew carried out the Pre-Start-up Checklist. The fuel state was quoted by the handling pilot as *“TWENTY THOUSAND”*. The right engine was started at 1158 hrs, and the left one at 1159 hrs. The After Start Checklist was carried out, and clearance to taxi was obtained at 1201 hrs.

During the taxi to Runway 15, the crew carried out the Pre-Take-off Checklist, briefed the takeoff and safety speeds and briefed the airfield departure procedure. When the anti-ice checklist item was reached the handling pilot stated that *“WE MAY NEED IT RIGHT AFTER TAKEOFF”*.

Clearance to line up and wait was granted at about 1206 hrs, and the aircraft was cleared for takeoff at 1207 hrs. During the take-off roll, the sound of the nosewheel rolling over the runway centreline could be heard, which prompted the commander to tell the handling pilot to *“GET OFF THAT CENTRELINE*”. The aircrew cross-checked their airspeed indications when the instruments started to register, and at 100 knots, the take-off speeds (V_1, V_R, V_2) were called. The speeds called out on the CVR correlated closely with the FDR recorded airspeed values. There were no audio warnings activated until shortly after takeoff when the automatic voice “Bank Angle” sounded; this occurred within two seconds of the end of the recording. The sound of a stick-shaker was just audible during the last crew speech, also within two seconds of the end of the recording.

1.11.3 Flight Data Recorder

Time histories of relevant flight parameters during the accident are shown in Appendix 2. Prior to the left roll shortly after takeoff, there was no recording of any warning of aircraft systems malfunction.

Appendix 2a shows engine parameters related to aircraft attitude and heading. The left and right engine Inter Turbine Temperatures (ITT), Low Pressure RPMs (N_1) and High Pressure RPMs (N_2) were normal from engine start to the end of the recording, with no indication of engine failure or anomaly. For the take-off roll, the FDR showed that the engines were set to about 88.4% N_1 on the left engine, and 88.5% N_1 on the right.

The data showed that engine start, and taxi towards the nominated runway, were uneventful. The anti-ice system remained 'OFF' during the accident flight; it had not been used during the preceding flight from West Palm Beach to Birmingham.

Appendix 2b shows the elevator, rudder and aileron positions, together with pitch, heading, roll, AOA and airspeed; Appendix 2c, shows the same parameters for the final 8 seconds of the record on an expanded time scale. The takeoff appeared normal up to the time of lift-off. Comparison of the recorded airspeed with the integrated longitudinal acceleration recorded during the take-off ground roll indicated that N90AG's rotation speed had been close to the correct value. Rotation was initiated at about 146 kt with the elevator position being increased to 8°, in the aircraft nose up sense, resulting in an initial pitch rate of around 4°/second. Lift-off occurred 2 seconds later (1207:54 hrs), at about 153 kt and with a pitch attitude of about 8° nose-up. Once airborne, the elevator position was reduced to 3° (aircraft nose-up) whilst the pitch rate increased to about 5°/second. A comparison with the previous takeoff by N90AG at West Palm Beach on 3 January 2002, under similar weight and CG positions, showed similar figures. The aircraft pitch trim setting was -4.9° for the takeoff from Birmingham and -5.0° for the takeoff from West Palm Beach.

Immediately after lift-off the aircraft started to bank to the left. Opposite aileron, followed closely by rudder, was applied as the aircraft started to bank; full right aileron and full right rudder had been applied within 2 seconds and were maintained until the end of the recording. The rate of bank increased rapidly and 2 seconds after lift-off the aircraft had reached 50° left wing down. At that point, the aircraft heading had diverged from the runway heading by about 10° to the left. There appeared to be no reduction in roll rate in response to the application of right aileron and rudder. As the bank angle continued to increase, progressively more aircraft nose-up elevator was applied, up to a maximum of 22°. This was close to the full nose-up deflection of 23.6°. The last recorded aircraft attitude was 111° left bank and 13° nose-down pitch (relative to the horizontal), about 5.5 seconds after lift-off.

1.11.4 Summary

Timings from the CVR and FDR, in conjunction with information from Sections 1.1.2 and 1.1.3 are summarised as follows:

Time UTC - hr min:sec	**Time From Lift-off - seconds**	**Event**
1040		Handling Pilot arrival
1050 (approx)		APU start
1100		Commander arrival
1158		Initiation of first engine start
1200 (estimated)		APU shutdown
1202		Start of taxi
1207:22		Start of takeoff
1207:54	0	Lift-off
	2	Full opposite aileron and rudder applied
	2	Bank angle 50° left
	3.5	*“Bank Angle”*
	3.5	Stick-shaker sound
	5.5	End of recording

1.12 Wreckage and Accident Site Examination

1.12.1 Accident Site

On-site examination was limited in order to avoid excessive delay in reopening the airport and focused predominately on the initial parts of the wreckage trail. Co-operation with the airport authority was good and adequate information on relevant aspects of the accident site was gathered.

Initial ground contact marks attributable to N90AG’s accident were found on the tarmac-surfaced left shoulder of Runway 15, approximately 1,415 metres from the runway start and 24 metres left of its centreline (Figure 4). In the following description distances are measured from the start of the initial mark and directions are in the direction of aircraft travel.

The initial mark consisted of a light, narrow scrape tracking 10° left of the runway heading, followed after 3 metres by a second, parallel, similar mark. Geometric considerations and detailed wreckage damage evidence indicated that the markings had been made by two trailing static wick assemblies mounted on blocks protruding from the left winglet outboard surface. Calculation showed that the winglet would be horizontal over a range of aircraft attitudes, from pitch and bank angles respectively of 0°/81° to 18°/73°, neglecting any wing deflection under load.

Additional paint and aluminium scrape marks on the runway were evident after 5 metres, becoming progressively more prominent, and between 15-30 metres formed an area of heavy, wide marking. The marks could be matched with areas of heavy abrasion damage found on the outboard face of the left winglet.

At 40 metres, the scrape marks crossed the left edge of the shoulder onto the ground adjoining the runway. The terrain was flat, of medium weight soil covered with short grass and was found covered with a heavy frost on the afternoon of the accident. The contact continued, in the form of a furrow ploughed in the ground, generally smooth and becoming progressively deeper, but with areas of unevenness and with signs of increasing anti-clockwise roll. Broken parts of the outer portion of the left wing found in the area, together with damage and packed earth deposits on this portion of the wing, made it clear that the furrow had been created by the outboard part of the left wing. After a total scrape distance of 120 metres, the start of a trail of burnt and sooted vegetation was evident around the furrow. At the same point along the trail, around 7 metres left of the wing furrow, a ground crater had been formed, in which flight deck components were embedded, including structural members and a number of flight deck transparencies. It was clear that the crater had been formed by inverted ground impact of the forward fuselage. Shortly after this point the ground furrow formed by the left wing ceased.

The crater formed the start of a second furrow, which became a progressively wider and shallower trail strewn with increasing quantities of debris from the fuselage structure and internal contents. This trail generally lay within an area of burnt and sooted vegetation. The wreckage in the trail included the empennage and seven of the passenger seats. The trail of debris and burning crossed Runway 06/24 and continued across the grass to the point at which the main wreckage came to rest, 320 metres beyond the fuselage ground contact point.

1.12.2 Wreckage Examination

1.12.2.1 General

The main wreckage consisted of the centre and aft fuselage with both powerplants and the wings, with the exception of the outboard part of the left wing, attached. It was lying inverted with both main landing gear legs attached, extended and downlocked. The main wreckage had suffered widespread fire damage that was generally light, but somewhat more severe in the region of the forward part of the wing centre-section and around the left wing stub. The wreckage section comprising the remains of the forward fuselage (forward of the wing centre-section) was found in approximately its normal position relative to the main wreckage, but upright. It was structurally separated from the main wreckage but remained connected to it by cables and pipelines.

All fuel tanks were found virtually empty, with the exception of the aft fuselage underfloor tank, which retained approximately 40 USG of fuel.

No evidence of frost deposits on the aircraft was found but it was noted that at the time of the examination the wreckage had been subjected to impact, shock loading and heating associated with the accident and unavoidable disturbance associated with the fire fighting operation.

The forward fuselage section lacked structural continuity and, after initial inspection on site, was separated from the main wreckage and cut into a number of pieces for removal. The main wreckage was transported intact to an area of the airport apron, together with the wreckage from the accident trail, for further examination. When this had been carried out, both wings were cut off and all items were transported to the AAIB facility at Farnborough for relevant further examination.

1.12.2.2 Wings

The left wing was found severely damaged, with disruption extending approximately 21 feet inboard (spanwise) from the tip. The left winglet and wingtip had detached as a unit as the result of a generally chordwise fracture of the wing 1.5-2.5 feet inboard of the tip. The failure was consistent with the effects of a combination of compressive overload and clockwise rotation of the winglet relative to the wing (viewed in the direction of aircraft travel). The winglet had numerous abrasion markings on its outboard surface, particularly heavy in the region of the winglet spar where the full thickness of the aluminium skin had been removed in places.

Inboard of the tip fracture, a 10 foot section of the wing torque box had broken up and largely separated, together with the leading edge and trailing edge structure in this area and the left aileron. Further inboard from this broken up area an additional 10 foot section of the torque box was severely disrupted and distorted and heavily sooted, with overtemperature damage in places. The deformation overall was indicative of upward and rearward overload of the outer part of the wing (relative to aircraft axes), possibly combined with spanwise compressive loading. Many of the damaged parts of the outboard wing were either coated or packed with earth, in many cases with sooting over the top of the earth deposits.

The remainder of the wing remained generally intact and undamaged, with the exception of some fire damage and localised impact damage to the centre-section forward spar. This impact damage could be matched in places with parts of the detached forward fuselage structure and included extensive splits in the web of the centre-section forward spar. Local damage in the region of the wing/fuselage upper right attachment fitting had caused a small rupture of the right wing tank.

1.12.2.3 Fuselage

The forward fuselage was found with most of the above-floor structure absent. Parts of the missing structure were found in the crater and along the wreckage trail. The remaining parts of the forward fuselage had suffered moderately heavy fire damage, with some destruction of components. However, there were no signs, such as large quantities of ash or re-solidified aluminium alloy deposits, that major parts of the absent structure had been destroyed by fire.

The remainder of the fuselage, aft of approximately the middle of the wing centre-section, remained intact. Three passenger seats remained in situ at the rear of the cabin. The fuselage portion had suffered crushing of the upper parts of the cabin, structural damage at the rear, associated with detachment of the empennage and tailcone, and localised fire damage in the forward areas. The attachments of the fin to the fuselage had suffered fractures consistent with the effects of gross overload.

1.12.2.4 Flight Controls

Primary and secondary flight control systems sustained severe damage in the forward fuselage, precluding complete examination in this area. Control runs in the outboard left wing and fin root areas also suffered some damage, but no components were destroyed in these areas. The rest of the systems remained in place and with little damage. Detailed examination of the systems (generally excluding the forward fuselage) revealed no evidence of pre-accident disconnection or malfunction. In particular, all primary and secondary flight control surfaces remained attached to their hinges and all actuators and position sensors remained attached to their mountings and connected to the respective control surface, with the exception of the left aileron. In this case the rod connecting the aileron to its PCUs had fractured and the position sensor rod had detached from the transducer; detailed examination showed that both features were consistent with the effects of ground impact damage.

It was apparent that the extensions of a number of flight control system actuators, such as control surface PCUs, could readily have been changed during the accident by inertial, impact and residual system forces. The setting of other actuators, generally the screwjack type actuators that tended to be irreversible, were most unlikely to have changed after power supplies were lost. The settings found for the latter actuators were as follows, together with the corresponding system configuration as determined with the assistance of the aircraft manufacturer.

Flaps - All four trailing edge flap panels and their mounts and actuators, together with the inboard flap vanes and outboard BUTE doors, remained intact and attached and with little damage. Examination revealed no anomalies. Measured actuator extensions showed that all four flap panels were deployed at close to the 20° position. No evidence of any abnormality was found; for each of the flaps, the difference in extension of its two actuators was 0.1 inches or less. The mean actuator extensions and the corresponding flap angles determined from the aircraft manufacturer’s functional test procedure, together with the requirements for the 20° setting, were:

Flap Panel	**Actuator Mean Extension *(inches)***	**Derived Nominal Flap Angle *(degrees)***	**Required Nominal Flap Angle at 20° Setting *(degrees)***
Left Outboard	2.62	21.9	20.4
Left Inboard	4.42	19.7	19.2
Right Inboard	4.38	19.6	19.2
Right Outboard	2.52	20.9	20.4

The estimated tolerance on the derived angles above was ±1.5° and the specified tolerance on the required angles was ±1°. With allowance for these tolerance bands, the maximum possible deviation of the derived flap angles from the requirements was 2°. The maximum possible mismatch between corresponding left and right flap panels (requirement ±1°) was 4°.

Pitch Trim - The pitch trim actuator had been damaged in a manner consistent with the effects of overload when the empennage had contacted the ground. The damage prevented accurate estimation of the trim actuator setting.

Aileron Trim - The setting of the aileron trim actuator was calculated to correspond to aileron deflections of 0.6 ±1.0° in the aircraft left wing down sense, ie near the centre of the nominal available trim range of 7.5° either side of neutral.

Rudder Trim - The setting of the rudder trim actuator was calculated to correspond to a rudder position of 2.0° ±1.0° aircraft nose right from neutral, ie 11-36% of the available trim range to the right.

1.13 Medical and Pathological Information

1.13.1 General

Two pathologists, one an aviation pathology specialist, performed autopsies on the five deceased occupants of N90AG. In each case, death had resulted from multiple injuries and had been instantaneous.

In the commander, there was no evidence of any disease which may have caused or contributed to the accident. It was not possible to determine if any disease was present in the handling pilot.

1.13.2 Toxicology

Toxicological examination revealed detectable amounts of diphenhydramine in both the commander and the handling pilot. No alcohol or drugs of abuse were found in the specimens from either pilot.

1.13.3 Diphenhydramine

Diphenhydramine is a sedative anti-histamine used in a number of cold and allergy preparations on sale to the public. It is also used in a number of products used to aid sleep. Examination of the luggage removed from the wreckage site revealed a number of medications within the baggage belonging to the crew. In the handling pilot’s bag there was a quantity of ‘Excedrin PM - aspirin free’; this medication contains 500 mg of acetaminophen & 38 mg of diphenhydramine citrate per tablet.

The aviation pathologist who carried out the autopsy undertook further research to determine the possible significance of the toxicology findings concerning diphenhydramine. His report on this research is included as Appendix 3. He concluded that both pilots had disturbed and inadequate sleep for the two nights preceding the accident and that it was possible that they were suffering from circadian dysrhythmia (jet-lag). Evidence indicated that both had consumed some alcohol on the evening of 3 January and diphenhydramine was found in their tissues. The Pathologist concluded that it was possible that the tiredness, possible jet-lag and diphenhydramine had all combined to impair the ability of the pilots to deal with the situation with which they were faced.

1.13.4 Human Factors

Following the results of the toxicology tests, a Principle Psychologist was briefed on the circumstances of the accident and contracted to report on the possible human factors aspects of the accident. This included possible fatigue, drug and social factors. His report is included at Appendix 4.

In his conclusion, the Principle Psychologist stated that two errors had occurred. Firstly, the handling pilot had failed to arrive at a proper appreciation of the icing situation during his external inspection. Secondly, the discussion initiated by the commander did not adequately address the issue or arrive at a proper conclusion. The evidence for causal factors underlying these errors was slight. The available evidence suggested that both pilots were probably suffering fatigue on the morning of the accident flight and that this could have predisposed them to errors of judgement and reasoning. This factor probably contributed to the second error and may have contributed to the first.

1.13.5 Medication

Appendix 3 states that non-prescription drugs were found in 18% of the pilots killed in flying accidents in the USA between 1994 and 1998. Of these, diphenhydramine was the most common drug, being found on 54 occasions.

Following this accident, it was found that many medications containing diphenhydramine are sold over the counter in the USA, without a prescription being required. ‘Excedrin PM’ was readily available as was ‘Nytol’, another medication containing diphenhydramine and intended to aid sleep. The packaging for both medications contained warnings about the need to avoid alcohol but had no reference to driving or operating machinery.

In the UK, similar drugs were found to be more difficult to obtain and to have additional warnings on the packaging. For example, ‘Nytol’ is obtainable but only from a Pharmacy; the packaging contains the following warning: “*May* *cause drowsiness. If affected do not drive or operate machinery. Avoid alcohol drink."*

Following the medical report, a review of medical publications available for pilots in both the USA and UK was carried out. In the UK, the Civil Aviation Authority (CAA) regularly update and publish Aeronautical Information Circulars (AICs) on the subject. The most recent, at the time of this accident, was AIC 58/2000, dated 29 June, which is included as Appendix 5 and covers the subject in reasonable detail. Important elements are that the use of any medication may be potentially hazardous and that flight crew personnel should consult authorised aviation medical examiners before using any medication.

In the USA, advice on the use of non-prescription medication is given in a pamphlet entitled 'Over the Counter Medications and Flying' which is prepared and published by the FAA Civil Aeromedical Institute. This defines 'Over-the-counter medications' and emphasises that *"when you treat yourself with non-prescription medication, you become your own doctor and pharmacist. Therefore you must inform yourself of the possible adverse reactions that you might encounter."* In its 'Summary Advice', this publication draws attention to the need to "*READ and follow label directions for use*" and to the possibility that the label may warn of side effects; it also suggests consulting a physician or Aviation Medical Examiner if in doubt.

The US National Transportation Safety Board (NTSB) made a series of recommendations, on 13 January 2000, relating to the use of licit medications by persons operating passenger transport vehicles and involved in investigated accidents. The study supporting these recommendations was based on transport accident statistics which showed the significant and increasing incidence of the involvement of non-prescription (described in US literature as over-the-counter) *'medications whose effects could potentially impair the vehicle's operator'*. These recommendations were directed towards the US Department of Transportation, its modal administrations (including FAA) and to the US Food and Drug Administration (see Appendix 6).

1.14 Fire

In accordance with CAP 168 (Licensing of Aerodromes), Birmingham Airport Fire Service (AFS) was operating to Category 8 on 4 January 2002. This category covers aircraft with an overall length of less than 61 metres and with a maximum fuselage width of 7 metres.

At the time of the accident, a Fire Control officer (FCO) was manning the Operations Room. Eleven fully qualified firefighters were on duty, to man five fire vehicles. These vehicles were designated 'Fireguard', a Ford Ranger Command Vehicle, and 'Fire 3', 'Fire 4', 'Fire 5' and 'Fire 8'. Operations had been declared as 'Normal', with Runway 15 in use.

The FCO was at her normal duty position with a clear view of Runway 15. She was watching N90AG as it took-off. Shortly after the aircraft got airborne, the FCO saw the aircraft roll to the left and was aware that the aircraft was going to crash. She immediately activated the crash alarm, at 1207 hrs, and proceeded with her emergency actions.

The fire fighters reacted promptly and all fire vehicles headed for the scene of the accident. As they did so, ATC informed the Fire Officer (Incident Commander) in 'Fireguard' that there were five occupants on board the aircraft. The fire vehicles arrived at the main body of the wreckage within one minute of the crash alarm and commenced fire fighting. Within six minutes, the main fire had been extinguished. Thereafter, the fire fighters continued to extinguish the smaller fires and to look for any survivors. Two bodies were located within ten minutes of the crash alarm and a further two bodies were located within a further three minutes. The AFS continued to try and locate the fifth occupant of the aircraft while also monitoring the crash scene. After extensive efforts, including the use of a thermal imaging camera, the fifth body was located in the wreckage at 1310 hrs.

The AFS was reinforced by the West Midlands Fire Service (WMFS), which arrived at the Airport at 1219 hrs and was at the scene of the accident by 1232 hrs.

In total, the AFS used 30,000 litres of water, 1,160 litres of foam concentrate and small amounts of BCF and Dry Powder. The WMFS used 400 litres of water.

1.15 Survival Aspects

The severe damage to the flight deck and forward part of the passenger cabin indicated that the ground impact was not survivable in these areas of the aircraft. All of the occupants, except for one of the pilots, had been ejected following the inverted fuselage ground impact. The rear part of the cabin remained generally intact but it was likely that it had been exposed for a period to appreciable concentrations of toxic gases from the substantial fire that was initially centred around the wing centre-section.

1.16 Tests and Research

1.16.1 Simulation

The aircraft manufacturer used a computerised model that provided an approximate mathematical representation of the aircraft to predict the expected aircraft response to the flight control surface deflections recorded on N90AG's FDR for the conditions prevailing at the time of the accident. The conditions used for the simulation were:

Aircraft Weight - 48,000 lb
Aircraft Longitudinal CG - 34% MAC
Aircraft Lateral CG - Fuselage centreline
Flaps - 20°
Landing Gear - Down
Trim - Stabiliser -4.9°, aileron and rudder neutral
Spoilers - Retracted
Atmospheric Conditions - Sea Level, ISA
Engine Power Setting - 88.5% Fan Speed

The model's Stall Protection System was disabled to allow the model to follow the FDR recorded elevator angle; however the simulation did not accurately model the aircraft characteristics beyond the AOA for stick-pusher operation (23.1° sensor vane angle in this case).

The results showed an aircraft pitch response for the model during the initial part of the rotation that was similar to that shown by N90AG's FDR data, indicating that the longitudinal CG estimate was valid. Major differences in the response after lift-off were apparent:

1. The model showed the aircraft rolling right wing down, compared to the left wing down roll shown by the FDR.

2. The AOA increase to beyond 23° in response to increasing aircraft nose-up elevator deflection was greater for the model than for N90AG (although not accurately represented).

3. The normal load factor (vertical g) for the model increased to 1.25g after initial rotation and then increased further as increasing aircraft nose-up elevator deflection was applied. In contrast, the FDR data showed the load factor decreasing during this period.

The model was also used to study the difference in aircraft response for two different horizontal stabiliser settings. The stabiliser trim setting calculated from the aircraft checklist schedule for the longitudinal CG of 34% MAC was -4.2°, compared to the -4.9° setting (greater aircraft nose-up setting) based on FDR data. The model showed less aircraft pitch response with the -4.2° setting, with a lower peak pitch rate, peak pitch attitude, maximum AOA and rate of climb than for the -4.9° setting.

The above aspects are discussed in Section 2.4.1.

1.16.2 Angle of Attack Sensor Operation

The FDR recording showed a large and abnormal difference in the uncorrected AOA values indicated by the left and right AOA sensors. This developed between lift-off and the end of the recording, with the left sensor indicating up to 20° less than the right sensor. Correction of the data using the lateral acceleration information showed that a major part of the difference was due to sideslip. However, the analysis, in conjunction with knowledge of previous problems of this type by the aircraft manufacturer, suggested that the potentiometer associated with the left sensor had a flat spot (see 1.6.3.8) between approximately 0.5-6.5° and that this had also caused the left sensor to under-read outside of this range. Application of a formula established to allow correction of the left sensor data for AOA values above 6.5° produced close correlation between the FDR recording traces for the left and right sensors after lift-off.

1.16.3 Stall Protection System Operation

An assessment was made in conjunction with the aircraft manufacturer of the points at which the SPS functions should have activated, based on the FDR data. Correction of the recorded AOA values for lateral acceleration was made and estimates were made of the phase advance angles (see 1.6.3.9) associated with the rate of AOA increase indicated by the right AOA sensor. From these, it was estimated that the SPS functions associated with the right sensor should have initiated at approximately the following points:

Function	**Sensor AOA** ***(degrees)***	**Time After First Main Wheel Lift-off** ***(seconds)***	**Time Before End of FDR Recording** ***(seconds)***
Right stick-shaker initiation	17.9-18.5	2.7-3.9	1.6-1.8
Right stick-pusher signal initiation	20.9-21.3	3.4-4.6	0.9-1.1

Thus it was estimated that the right stick-shaker should have initiated 3.3 ±0.6 seconds after the aircraft started to lift-off and a right stick-pusher signal should have occurred approximately 0.7 seconds later and initiated the flight deck visual warnings. The warning horn initiation point would have closely coincided with the end of the FDR recording.

Parts of the left AOA sensor trace showed a similar rate of AOA increase to the right sensor, suggesting that the computed phase advance angles should have been similar for both SPS channels. With allowance for this level of phase advance and after correction for lateral acceleration, the left sensor trace did not at any point approach the shaker or pusher trip point angles. Therefore, it was predicted that neither the left stick-shaker nor the stick-pusher would have operated. After correction for the apparent flat spot on the left sensor potentiometer and for lateral acceleration, the left sensor angle closely coincided with that indicated by the right sensor (see 1.16.2). This suggested that, in the absence of the flat spot, the left stick-shaker should have initiated at around the same time as the right stick-shaker and the stick-pusher should have operated approximately one second before the end of the recording.

1.16.4 APU Exhaust Effects

During the investigation the possibility was investigated that ice contamination present on the aircraft surfaces could have been affected by the APU exhaust flow while the aircraft was parked. Observation of another Challenger 604 aircraft, in low wind conditions with the observer sensing the gas flow and temperature differences around the aircraft and observing the associated refractive visual distortion effects, showed that the mixing of the APU hot exhaust gas plume with ambient air generated an extensive region of warm gas. This extended laterally beyond the right wing tip in light wind conditions, suggesting that a tailwind could generate a flow of warm gas around much or all of the right wing while having little influence on the left wing. During the investigation, a Challenger pilot noted that he had experienced two occasions when ice and frost on the right wing had melted when the aircraft had been parked in a light tailwind with the APU running.

The effect was investigated further by ground testing, conducted under AAIB auspices at the aircraft manufacturer’s facility, in which measurement was made of the change in surface temperature of a parked Challenger 604 aircraft with the APU running. Testing to establish the effects of engine running was precluded by health and safety considerations. Conditions were chosen to be as similar as possible to those experienced by N90AG, with the test carried out in the open, at night (to eliminate solar heating effects) in conditions of no visible moisture and with the test aircraft positioned tail into a light wind. The aircraft was fuelled to close to full wing tanks and heat-soaked in the prevailing ambient conditions prior to the test.

Surface temperature measurements were made at 36 positions on the wing and horizontal stabiliser before APU start and then with the APU running and supplying various levels of aircraft services. Measurements were also made at appropriate intervals of the wing tank bulk fuel temperature, ambient temperature, wind speed and direction and APU exhaust gas temperature. Conditions varied somewhat during the test but the ambient temperature remained around 15°C and there was a tailwind of approximately 5 kt from 8° left of the aircraft's centreline for the majority of the test duration. The wing tank bulk fuel temperature was indicated as 17°C. The mean temperature of the APU exhaust gas at the exhaust port was 455°C with a low service load and 466°C when supplying the two electro-hydraulic pumps.

Appreciable variation between stations in the surface temperature measurements before APU start was found, but repeatability of the measurements at each station appeared to be good. Analysis of the results showed that APU running in the prevailing conditions had no appreciable effect on horizontal stabiliser surface temperatures. However, after 30 minutes running, while the surface temperatures on the left wing were little changed, temperatures on parts of the right wing increased appreciably, on both upper and lower surfaces, approximately as follows:

Right Wing Station	**Temperature Increase* - *(°C)***
Root	0
1/3 Semi-Span	1
2/3 Semi-Span	2
Tip	4

Following a further 30 minutes APU running, there was a generally small increase in the left wing temperatures and a substantial increase in the right wing temperatures, as follows:

Wing Station	**Temperature Increase* - *(°C)***	
	Left Wing	**Right Wing**
Root	1	2
1/3 Semi-Span	1	3
2/3 Semi-Span	1	5
Tip	3	8

* Temperature increase from the initial 'APU off' condition, averaged between leading and trailing edge stations and, for the right wing, averaged between upper and lower stations at the same spanwise position.

1.17 Organisational and Management Information

1.17.1 Federal Aviation Administration regulations

The Code of Federal Regulations (CFR) details rules adopted by the US Federal Government. The CFR divides the rules into 50 titles covering all areas subject to federal regulation. Title 14 contains rules related to aviation and space. Within Title 14, subchapter F deals with ‘Air Traffic and General Operating Rules’ and Part 91 of that subchapter covers ‘General Operating and Flight Rules’. Subchapter G deals with ‘Air Carriers and Operators for Compensation or Hire: Certification and Operations’. Part 135 of that subchapter covers ‘Operating Requirements: Commuter and On Demand operators and rules governing persons on board such aircraft’.

N90AG was owned by Fleet National Bank and leased to AGCO Corporation. In accordance with the leasing arrangement, the aircraft was required to be maintained and inspected under Title 14 CFR Part 91 of the Federal Aviation Regulations (FAR) for operations to be conducted under the lease. Additionally, the lessee was responsible for the operational control of the aircraft, unless the aircraft was subleased to an air carrier or air taxi operator certificated under Part 121 or Part 135, respectively, of the FARs. N90AG was operated and maintained by Epps Air Service Inc (Epps AS). This company was certified by the FAA to conduct operations under the provision of Title 14 CFR Part 135 and did so in accordance with their company Flight Operations Manual (FOM).

1.17.2 Accident flight

1.17.2.1 General

As the passengers were employees of the lessee, the flights on 3 and 4 January 2002 were conducted under Part 91 regulations. Nevertheless, for flights carrying employees of the lessee, the crew operated the aircraft under the authority of the FOM except that compliance with certain Part 135 regulations was not legally required. For the accident flight, the following differences, which may have been relevant, were:

Part 91 flights have no requirement for paper records of weight and CG calculation. Nevertheless, there was a requirement for a weight and CG calculation to be carried out prior to the flight. Post accident investigation confirmed that the aircraft was within weight limits and that the take-off airspeeds used by the pilots were correct. Dependent on the seating of the observer and passengers, there was a possibility that CG was aft of the revised limit.

Part 91 flights have no specific flight and duty time limits. Nevertheless, the company roster their crews to remain within reasonable limits. On 3 January the crew reported for duty at 0900 hrs (0400 hrs local time in Atlanta). Both pilots had left home approximately one hour before report time; the handling pilot had gone to bed about 0200 hrs (2100 hrs local time on 2 January) but the movements of the commander could not be determined. They then completed 12½ hours total duty time, of which 9½ hours was flight duty. This involved flights from Dekalb-Peachtree Airport to Fort Myers Airport, then to West Palm Beach Airport and finally to Birmingham International Airport. They went off duty at 2130 hrs on 3 January and were due back for duty at 1000 hrs on 4 January, a rest period of 12½ hours. These duty and rest times complied with the limitations for Part 135 operations.

1.17.2.2 Crew qualifications and responsibilities

As detailed in Section 1.5.1, the right seat pilot was designated as the commander. Federal Aviation Regulations (FAR) Title 14 CFR includes the following definitions of pilot-in-command (PIC):

> *"The person who has final authority and responsibility for the operation and safety of the flight."*
>
> *"Has been designated as pilot-in-command before or during the flight; and holds the appropriate category, class, and type rating, if appropriate, for the conduct of the flight."*

The Epps AS Flight Operations Manual details procedures for operating crews. The following instructions were relevant to the accident flight:

> *"The Operations Officer will assign or reassign a Pilot in Command and a Second in command (SIC) for each flight requiring two pilots as necessary to complete the day's itinerary."*
>
> *"The PIC will normally occupy the left seat on all flights; however, a qualified SIC may occupy the left seat at the discretion of the PIC. The PIC is responsible for clearly defining which pilot is the Pilot Flying (PF) and which is the Pilot Not Flying (PNF) at any given time during a flight."*

> *"The PIC of the aircraft is the final authority for the safe conduct of all his flights within the standards of this manual."*
>
> *"Unless otherwise briefed by the PIC, the following guidelines concerning crew duties for pre-flight and during a flight will apply: The PIC is responsible for obtaining a weather briefing, filing flight plans, placing fuel orders, and ensuring that all necessary flight equipment is aboard. The SIC is responsible for preparing the aircraft for the flight, including interior and exterior pre-flight inspection."*

The 'Trip Sheet' issued by the company to cover the flights by N90AG on 3 and 4 January 2002 detailed the PIC. Additionally, the flight plan for the flight originating at Birmingham Airport on 4 January 2002 included the same name as PIC.

1.18 Additional information

1.18.1 Operational

1.18.1.1 Witness evidence

Evidence relevant to the investigation was taken from various witnesses. Most of this is referred to elsewhere in the report but, for reference, the relevant evidence is detailed below:

a. Aircraft dispatchers

Two dispatchers were involved in the reception and dispatch of N90AG on 3 and 4 January. Both had met the commander and handling pilot on previous visits. Following the arrival of the aircraft, one of the dispatchers saw a crew member put pitot covers on and install landing gear safety pins. The two dispatchers independently saw the commander and handling pilot carry out external inspections of the aircraft on 4 January 2003. At about 0600 hrs on 4 January, a dispatcher observed frost on the aircraft; by 0900 hrs, he noticed that the frost was now soft. Sometime prior to engine start, the other dispatcher saw a layer of thin slush on the leading edge of the left wing; he moved his finger along it and it came off as he did so. He brought this fact to the attention of the observer. Neither dispatcher was asked to provide de-icing for N90AG. The handling pilot and the observer arrived at the aircraft at about 1040 hrs. The APU was started at about 1050 hrs. The commander was picked up from his hotel by one of the dispatchers and arrived at the aircraft at about 1105 hrs.

b. Aircraft refueller

The refueller arrived at N90AG at 1100 hrs. After connecting the refuelling hose to the aircraft at the right wing root, he went to the cockpit where a crew member asked him to fill the aircraft full of fuel. Subsequently, as he was refuelling, he saw that the leading edge of the right wing had a light covering of frost but the upper surface of the right wing had only moisture on it, which flowed off as he touched it. He also considered that the frost on the leading edge was melting as the refuelling continued. He did not notice any frost on the fuselage and did not look at the left side of the aircraft.

c. Commander of CRJ aircraft

The commander of a CRJ aircraft, which had been parked adjacent to N90AG overnight, commenced his pre-flight external inspection at 1125 hrs. By this time his aircraft had been moved to the Terminal side of the airfield. He noticed that there was about 1 to 2 mm (approx 0.06 inch) of hoar frost covering all the upper surfaces of the aircraft. The frost was soft as he moved his finger along areas on the wing and fuselage. He had no doubt that de-icing was required and called for this service through his company’s agents.

d. De-icing personnel

No request was made for N90AG to be de-iced. Information from the de-icing company at the airport indicated that if a request had been made at about 1030 hrs, it would have taken about 5 minutes for the de-icing rig to get to the location and a further 10 minutes to complete the de-icing of the aircraft.

1.18.1.2 Aircraft performance

The Aircraft Flight Manual was examined to determine take-off performance and scheduled speeds under the following conditions:

Aircraft weight - 48,000 lb
Flap setting - 20°
Headwind - 7 kt
Temperature - minus 2°C
QNH - 1027 mb

The Results were as follows:

V_1 - 137 kt
V_R - 141 kt
V_2 - 147 kt
N_1 - 87.4%
Net Take-off Distance - 4,780 feet

1.18.2 Aircraft Fuel

1.18.2.1 Fuel Load

The aircraft was reportedly refuelled to full tanks on the morning of the accident flight at the request of one of the pilots. Records indicated that 10,110 litres

(2,671 USG) of fuel was delivered by tanker at approximately 1115 hrs by one of the established fuel suppliers at Birmingham Airport. Two other aircraft had previously been refuelled from the same tanker during the morning. During the investigation, checks were made in conjunction with the fuel supplier to ascertain whether the actual fuel quantity loaded onto N90AG could have differed significantly from the recorded value.

The aircraft fuel supply tankers and hydrant vehicles at the airport were replenished from shared consortium storage tanks that were in turn replenished by road tanker and/or pipeline. Consortium tank contents were indicated by gauges and confirmed by a daily dip check; the quantities loaded into tankers and hydrant vehicles were indicated by static loading meters and the quantity delivered to an aircraft was indicated by a loading meter on the vehicle. The gauges and meters were calibrated every six months. Inspection indicated that it would not be possible to incorrectly configure delivery hoses and/or valves in a way that would produce false indications of the delivered quantity either by static loading meters at the bulk storage or by the tanker meter.

A daily reconciliation of the airport fuel system contents against inputs and outputs was routinely carried out, within the limits imposed by fuel volume variations caused by temperature changes. It was considered that the system would detect an incorrect loading exceeding about 200 litres. A monthly dip check of the consortium tank contents was compared to the calculated values after adjustment for temperature effects; correspondence was expected to be within 3 mm, equivalent to a 368 litres difference. No anomaly in the reconciliation results was found.

There were no signs of appreciable fluid spillage having occurred in the area where N90AG had been parked.

1.18.2.2 Fuel Temperature

Attempts were made during the investigation to estimate the temperature of the fuel in the aircraft's tanks, in relation to the possibility of ice contamination of the wings having contributed to the accident. No firm evidence was available. Some records of the temperature of fuel samples taken from the consortium tank in use on the evening prior to the accident were available. However, the samples were from the bottom of the tank and the temperature would not necessarily have coincided with the temperature of the fuel delivered to the tanker, which was taken from a floating inlet in the tank.

The tanker used to refuel N90AG had a 38,000 litre tank with internal baffles and 5 mm thick aluminium walls. It had been filled at 1845 hrs on 3 January and had then been parked outside overnight before commencing its first refuelling at 0530 hrs on the morning of the accident (4 January), following a sample check. The supplier did not record the temperature of tanker fuel samples; another fuel supplier at the airport did, but the data was not directly comparable as the tankers were of a different type and had different replenishment and delivery histories. Available temperature records were as follows:

Date	**Time**	**Consortium Tank Sample Temperature - *(°C)***	**Other Tanker Sample Temperature - *(°C)***
3-1-02	1645	1.5	
3-1-02	2030	0	
4-1-02	0700		-2
4-1-02	0949		0
4-1-02	1130		0.5

From the available evidence it appeared that the temperature of the fuel in N90AG’s wing tanks would probably have been around 0°C. Accurate prediction of the temperature would involve an appreciable number of considerations. These included convective flow and temperature stratification in the consortium tank, the tanker and the aircraft; fuel sloshing in the tanker and aircraft due to manoeuvring; and radiant and conductive heat transfer between both the tanker and the aircraft and their surroundings, both overnight and while in service during the morning. Given the number and complexity of the variables involved, neither testing nor calculation that would be sufficiently representative to provide accurate estimation of tank temperatures was considered practical.

1.18.2.3 Fuel usage before takeoff

An estimate was made of the fuel used between the time of APU start and the beginning of the take-off roll. This indicated that the APU would have consumed about 30 USG, all from the right main tank, and the main engines would have consumed approximately 15 USG from each main tank. This usage would not have reduced the fuel in the right wing to the point where the automatic fuel management system would have started to replenish the right main tank from the auxiliary group.

1.18.2.4 CG shift due to acceleration and pitch-up during takeoff

Since the most aft static CG possible was 36% MAC (see 1.6.2.1), if both passengers had been occupying the rearmost seats in the cabin, a calculation of the rearwards shift of CG resulting from fuel migration during takeoff was undertaken. Allowance was made for the fuel used by the APU before taxi and the main engine fuel usage up to the point at which the aircraft started to roll to the left after takeoff. The calculations showed that the CG would have migrated 2% aft during the take-off roll and stabilised at that position. The resulting CG at the point of lift-off would, therefore, have been at 38% MAC.

1.18.3 Possible Roll Asymmetry Anomalies

It was noted that the FDR recording indicated that the aircraft response to primary flight control inputs had been normal during all the previous recorded sectors (25 hours of data). This confirmed that all three primary flight control systems had been functioning normally, with control surfaces operating in the correct sense. This was also the case for the autopilot, the yaw dampers, the ground and flight spoilers and the flaps. Evidence from the CVR revealed that the trims had been checked during the pre-takeoff checklist.

Information on the effects of abnormal control surface deflections and other anomalies that could possibly have caused an undemanded roll was provided by the aircraft manufacturer. The effects, for the condition prevailing for N90AG's lift-off, were predicted to be as described below.

1.18.3.1 Ailerons

Information was obtained on the roll rate that would be produced by full opposite deflection of both ailerons. Data available from the flight test of another Challenger 604 aircraft at conditions that were as close as possible to those for N90AG's lift-off indicated a peak roll rate of 30-32°/second. The flight test aircraft had landing gear retracted and was operating at a lower all-up weight and a higher dynamic pressure than N90AG, suggesting that N90AG's peak roll rate due to full aileron deflection would have been somewhat lower.

There was no indication of aileron trim on the FDR recording, but aileron angles recorded were sensibly neutral throughout the taxi and takeoff, suggesting that the trim had been set close to neutral.

1.18.3.2 Rudder

Should a full rudder deflection occur in flight, the initial aircraft reaction would be a roll in the opposite direction. The initial rolling moment would be approximately 38% of that generated by the ailerons at full deflection. However, as the sideslip resulting from full rudder application built up, a rolling moment in the direction of rudder deflection would be generated. Thus a full left rudder application would initially produce a right roll that could be countered by partial aileron application but, as sideslip developed, the net rolling moment would become left wing down. Full aileron application would be insufficient to counter this beyond a sideslip angle of 15°.

The FDR data indicated that both yaw dampers were engaged. Analysis of the FDR indicated that the rudder was deflecting to oppose aircraft heading changes during ground taxiing manoeuvres prior to the final takeoff, including during the final turn on to the runway. The magnitude of the rudder deflection was, on occasion, close to the maximum yaw damper authority of 5°, indicating that both yaw dampers were operative and responding in the correct sense. There was no indication of rudder trim on the FDR recording, but the rudder angle was consistent with the aircraft motion throughout the taxi and takeoff, suggesting that the trim had been set close to neutral.

1.18.3.3 Asymmetric Elevator

The rolling moment generated by full deflection of the elevators in opposite directions would be controllable with about a third of full aileron deflection. The aircraft would not respond in pitch in such a case, as the pitching moment of the elevators would be in opposition.

Both elevator angles were recorded on the FDR and the data indicated that both elevator surfaces were moving in the correct sense at all times. The initial aircraft response in pitch during the rotation manoeuvre was consistent with that expected, and with that seen during the previous takeoff.

1.18.3.4 Autopilot

Control surface deflections due to autopilot malfunction or incorrect selection would have been apparent from the FDR recording. The data indicated that the autopilot was off throughout the takeoff.

1.18.3.5 Spoilers

The rolling moment generated by the deployment of a single spoiler panel would be controllable with about a third of full aileron control deflection in the case of a flight spoiler and one half in the case of a ground spoiler. Either event occurring on the ground during takeoff should generate a caution message on the EICAS and be recorded by the FDR. Calculation suggested that deployment of both a flight and ground spoiler panel on the same wing could be countered by almost full aileron deflection.

The FDR; the data indicated that all spoilers were in the stowed position throughout the takeoff.

1.18.3.6 Asymmetric Flap

The manufacturer's simulation data indicated that full aileron deflection would be able to control an asymmetry between left and right flaps of about 15° at N90AG's lift-off conditions.

The FDR flap angle parameter, derived from the left inboard flap, suggested that the flaps were set to the take-off position at the time of the accident. An appreciable degree of flap asymmetry would be expected to cause the aircraft to assume a wing-down attitude during a take-off ground roll, particularly as it approached lift-off speed. No such tendency was evident from the FDR data.

1.18.3.7 Flap Vane Jam

Calculations by the manufacturer indicated that, on the inboard flap, jamming of the spring-loaded vane in the closed position would have an insignificant aircraft roll effect with 20° flap selected.

1.18.3.8 BUTE Door Jam

The aircraft manufacturer reported that results of wind tunnel testing on an RJ700 aircraft showed that overall wing lift is insensitive to BUTE door position with the flaps in the 20° take-off position. The effect of positioning the door at approximately its mid position compared to its normal fully up position was found to be insignificant. The BUTE door of the Challenger 604 is similar in function and performance to that of the RJ700. It was therefore estimated that asymmetric deployment of the Challenger 604 BUTE doors would not generate a significant rolling moment.

1.18.3.9 Asymmetric Fuel Load

The aircraft manufacturer assessed that there would be sufficient aileron roll power to balance a full left wing fuel tank load with the right wing fuel tank empty. An appreciable degree of wing fuel asymmetry would be expected to cause the aircraft to assume a wing-down attitude during the take-off ground roll, particularly as it approached lift-off speed. No such tendency was evident from the FDR data. Furthermore, the aircraft tanks had been filled to capacity.

1.18.3.10 Door Opening

The possibility was considered that a rolling moment could have resulted from the aerodynamic disturbance associated with an opening of the cabin door, or other door or hatch, during the takeoff. The aircraft manufacturer's experience of previous cases indicated that such an event would not generate a substantial rolling moment.

1.18.4 Wing Aerodynamic Characteristics

1.18.4.1 General

The following information on the wing aerodynamic characteristics was obtained from published research papers, from independent specialists and from the aircraft manufacturer.

1.18.4.2 Supercritical Wing

The Challenger wing has supercritical aerofoil sections, ie sections designed to operate efficiently with substantial regions of supersonic flow while at the design cruise mach number (M). For high-speed subsonic aircraft in the transonic flight regime (M 0.7 to M 1.0) acceleration of the airflow over the wing causes the speed of the airflow over parts of the wing to exceed the speed of sound. A standing shock wave is formed towards the rear of the aerofoil where the airflow decelerates to subsonic speeds. A strong normal shock, with an associated high pressure gradient that can induce boundary layer separation (see 1.18.4.3), can result in a large increase in drag.

In comparison with previous types of aerofoil, supercritical aerofoils have a reduced camber, an increased leading edge radius, reduced curvature on the upper (suction) surface, and a concavity in the rear part of the lower (pressure) surface (Figure 5). At cruise conditions the profile maintains supersonic flow over a large part of the upper, suction surface of the aerofoil that is then decelerated towards the rear by a weak shock wave. As well as improving aerodynamic efficiency, the design allows a thicker wing section for a given aircraft critical mach number, providing for a more efficient wing structure and additional wing tank fuel capacity compared to previous types of high-speed aerofoil.

The first supercritical aerofoils were designed and analysed at the USA's National Aeronautics and Space Administration (NASA) Langley facility in the 1970s. Supercritical aerofoils have gained wide acceptance and are fitted to most modern high-speed commercial transport aircraft (eg Airbus, Boeing, Cessna Citation X, Raytheon Premier). The Challenger wing, designed by Bombardier (previously Canadair) in 1976, is believed to be the first production aircraft wing to utilise supercritical aerofoils; they are generally similar to those used on more recently designed wings. The Challenger aerofoil thickness/chord ratio (t/c) is relatively low, in common with virtually all current transonic aircraft, ranging from around 14% at the root to 10% at the tip.

1.18.4.3 Wing Stall

The airflow in proximity to the wing surface is slowed by its passage over the surface to form a boundary layer (BL), ie a layer of air, generally adjacent to the surface, within which velocities are less than the free-stream velocity. Within the BL the local stream velocity increases with distance from the surface, with the outer edge of the BL defined as the location where the local velocity reaches 99% of free-stream velocity. In order to generate wing lift efficiently, the BL must remain relatively thin and generally attached to the surface. Separation of the BL from an extensive area of the upper surface of a wing results in a stall, causing substantial lift loss and drag increase. The lift coefficient C_L, (a non-dimensionalised measure of lift) reaches a maximum (C_{Lmax}) at an AOA just below the stall angle.

Loss of energy from the BL can, if sufficient, cause flow separation. This can result from an excessive adverse pressure gradient, ie an excessive rate of increase in static pressure with distance from the point of peak suction (generally on the upper surface of the aerofoil leading edge). The BL over an aerofoil in an undisturbed airflow is initially laminar, ie streamwise flow within the BL without mixing across the BL. In practice, transition to turbulent flow (with mixing across the BL occurring) generally occurs after a short distance. Available evidence suggests that transition for the Challenger wing typically occurs at around 5% chord.

Supercritical aerofoils tend to generate a relatively flat suction profile over most of the wing upper surface at typical cruise angles of attack. At lower speeds, on both supercritical and conventional aerofoil sections with a relatively low t/c (in the order of 9-12%) the upper surface pressure profile develops an increasingly high and steep peak just behind the leading edge as the AOA increases. At high AOA the high adverse pressure gradient associated with a steep peak can cause the BL flow in the region to separate from the surface for part of its chordwise travel before transitioning to turbulent flow and reattaching to the wing upper surface, forming a laminar separation bubble.

The chordwise extent of the bubble increases with increasing AOA and the stall AOA at a particular spanwise wing station is reached when the flow does not reattach, ie the separation bubble bursts, producing a major reduction in the net suction over the upper profile of the section. Depending on the wing geometry, this change in flow pattern in one spanwise region can influence the flow at adjacent wing stations. This can cause the collapse to extend rapidly across the whole of one wing, causing a sudden major reduction in the lift and increase in the drag generated by that wing. The flow separation near the leading edge produces a more abrupt loss of lift than for the thicker aerofoil types (greater than 15% t/c) more typical of previous, lower-speed aerofoils, where the initial separation tends to occur nearer the trailing edge.

The upper surface suction peak becomes higher and steeper as the curvature of the flow around the leading edge becomes tighter. The upper surface curvature can be reduced at high AOA by use of an aerofoil with a drooped leading edge, rather than a generally symmetrical leading edge, as used on the Challenger wing. The manufacturer noted that appreciable droop would severely degrade the high speed performance of the wing and would therefore be impracticable. The suction peak is also increased by deflection of trailing edge flaps. A common means of suppressing the peak is the addition of leading edge slats or flaps, deploying in concert with trailing edge flaps.

It is traditional practice on lower performance aircraft to arrange the wing geometry such that the wing root regions stall at a lower AOA than the tip regions in order to minimise the rolling moment due to lift asymmetry between the wings at incipient stall. However, this is usually impractical for a wing with the appreciable sweep that is normally used for modern transport aircraft in order to increase the transonic cruise speed. Such designs typically aim to force the initial stall to occur near mid span. The aircraft manufacturer reported that flight testing has shown that the wing stall for the Challenger typically begins at the leading edge of the outboard section of one of the wings. The manufacturer noted that flight testing had shown that, with N90AG's take-off configuration and Mach Number, the uncontaminated Challenger wing would stall in free air (ie out of ground effect) at a sensor AOA of 25-26°, in the absence of appreciable sideslip. Ground effect would reduce the angle by an estimated 3-4° when the aircraft height above ground was 0-10 feet.

The manufacturer noted that the aircraft's response is highly dependent on pilot actions once the stall is detected and that large variations in roll rate and peak roll angle can occur. Aileron inputs would normally be ineffective in controlling the roll rate once a wing had stalled, until it was unstalled by reducing the overall AOA. Data for sample Challenger flight test stalls with flaps at 20° showed appreciable wing drops, with roll rates up to 70°/second and bank angles up to 85°. Other information indicated that a rapid wing-drop at the stall would be likely to occur in most cases, irrespective of pilot technique. It was intended that the SPS would prevent the aircraft from reaching a wing stall condition.

1.18.4.4 Effect of Roughness

The available information showed that the lift characteristics of wings at a high AOA can be appreciably changed by a relatively small level of surface roughness. The earlier transition to turbulent flow promoted by roughness could be expected to delay BL separation. However, the evidence indicated that where the individual roughness elements are of a height that is substantial compared to the thickness of the BL they can, if sufficiently dense, significantly affect the character of the BL, making it prone to earlier separation. For wings with a low t/c, this can cause the separation bubble to burst (see 1.18.4.3) at an AOA appreciably below the uncontaminated stall AOA. The effects could reportedly be related to a 'Roughness Parameter' (Rp), defined as:

$$Rp = 10A(k/c)N$$

Where:

A = Cross-sectional area of an individual roughness element (square inch)
k = Roughness element height (inch)
c = Aerofoil chord (inch)
N = Roughness distribution density (number of elements per square inch).

The Rp for a JAR and FAA definition of a 'small amount of ice' was reportedly $365\text{-}474 \times 10^{-6}$.

Published information indicated that, on low t/c aerofoils, roughness on the leading edge alone would generally have a major effect and typically cause a reduction of C_{Lmax} in the order of half that which would result from distributed roughness (ie over the whole upper surface, including the leading edge). The information suggested that a relatively small degree of roughness could typically cause reductions in the order of 30% for C_{Lmax} and 5° for stall AOA compared to an uncontaminated wing. Preliminary independent calculations based on the published information and on N90AG's FDR data were consistent with similar reductions in C_{Lmax} and stall AOA for N90AG just after lift-off.

Further estimates were made by the aircraft manufacturer. The effects of wing surface contamination on the Challenger stall could not be determined directly from flight test data or from simulation model predictions. The manufacturer used Computational Fluid Dynamics (CFD) techniques, validated by wind tunnel and flight tests, to estimate the effects. These indicated that contamination on the leading edge was particularly significant; combined contamination on the leading edge and the wing and flap upper surfaces causes only slight reductions in peak lift and stalling angle compared to contamination on the leading edge alone.

The fuselage AOA at which N90AG began to roll to the left after lift-off was estimated from the FDR data as 7.8°. This was 5.3° lower than the 13.1° fuselage AOA at which it was predicted that an uncontaminated wing would stall. The manufacturer's CFD analysis estimated that, if the wing-drop had been caused by a premature stall of the left wing due to wing leading edge and upper surface contamination, the 5.3° reduction in stall angle would have required an Rp at the critical wing station of 200-400 x 10^{-6}.

A second analysis estimated that, if contamination had caused N90AG's left wing to stall prematurely, the associated reduction in C_{LMAX} was 0.5. CFD analysis indicated that this would require an Rp of 140-450 x 10^{-6} on the wing leading edge. This was of a similar order to the above estimate based on stall angle reduction. It was noted that the analysis indicated that an overall contamination thickness of up to 0.12 inches had little effect on the lift characteristics; the effects were dominated by the roughness.

Example dimensions for sample rectangular section roughness elements that would produce the above values of Rp were:

Roughness Element			**Rp x 10^6**
Height ***(inch)***	**Width** ***(inch)***	**Number per Linear Inch** ***(/inch)***	
0.019	0.020	10	140
0.022	0.020	10	200
0.032	0.020	10	400
0.034	0.020	10	450

As a comparison, measurements suggested an estimated Rp of approximately 300 x 10^{-6} for medium-fine emery abrasive paper (P100 grade).

1.18.5 Aircraft de-icing requirements

1.18.5.1 US Federal Aviation Administration Regulations

The following US Federal Aviation Regulations (FARs) dealing with icing of aircraft on the ground were relevant:

> 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."*
>
> FAR Part 135.227: *"No pilot may takeoff an aircraft that has frost, or snow adhering to any rotor blade, propeller, windshield, wing, stabilizing or control surface, to a powerplant installation, or to an airspeed, altimeter, rate of climb, or flight attitude instrument system, unless under the following conditions: (1) Takeoffs may be made with frost adhering to the wings, or stabilizing or control surfaces, if the frost has been polished*

> *to make it smooth. (2) Takeoffs may be made with frost under the wing in the area of the fuel tanks if authorized by the Administrator."*
>
> FAR Part 135.345: *"Initial, transition, and upgrade ground training for pilots must include instruction in at least the following, as applicable to their duties:···· (6) Knowledge and procedures for ···· - (iv) Operating airplanes during ground icing conditions, (i.e., any time conditions are such that frost, ice, or snow may reasonably be expected to adhere to the airplane), if the certificate holder expects to authorize takeoffs in ground icing conditions, including: ··· (B) Airplane deicing/anti-icing procedures, including inspection and check procedures and responsibilities; ··· (D) Airplane surface contamination (i.e., adherence of frost, ice, or snow) and critical area identification, and knowledge of how contamination adversely affects airplane performance and flight characteristics; ··· (G) Techniques for recognizing contamination on the airplane."*

1.18.5.2 Challenger 604 Operating and Flight Manuals

The following information regarding aircraft ground icing was included in Bombardier Challenger 604 Operating and Flight Manuals:

> Flight Manual Limitations for operation in icing conditions on the ground: *"The engine cowl anti-ice* system *must be on when the OAT is 10°C (50°F) or below and visible moisture in any form is present (such as fog with visibility of one mile or less, rain, snow, sleet and ice crystals). The wing anti-ice system must be on for takeoff when the OAT is 5°C (41°F) or below and visible moisture in any form is present (such as fog with visibility of one mile or less, rain, snow, sleet and ice crystals. The wing anti-ice must also be on for takeoff when the OAT is 5°C (41°F) or below and the runway is contaminated with surface snow, slush or standing water."*
>
> Flight Manual, Normal Procedures, included a check *"Wing Anti-Ice/Isolation Valve - First Flight of the Day (Engines Running)."* This requires the selection of the 'Anti-Ice Wing' switch to 'NORM', which will open both wing anti-icing valves. There is also a requirement to check the 'Anti-Ice Cowl' switches before flight with the engines running.
>
> Flight Manual, Normal Procedures, included the following warning: *"Small accumulations of ice on the wing leading edge can change the stall characteristics, the stall speed and the stall margin provided by the stall protection system."*

Operating Manual Volume 1 reflected the limitations contained within the Flight Manual.

> Operating Manual Volume 1, Normal Procedures - External Safety Procedures required, for the wings and empennage: *" - Flight control area and surfaces: Clear;…..Ensure surfaces clear of dirt, sand, snow or frost."* Temporary Revision 604/5 (Jan 11/99) required that: *"During cold weather operations, the flight crew must ensure that the airplane fuselage, wings and tail surfaces are free from ice, snow or frost (Refer to Chapter 6; SUPPLEMENTARY PROCEDURES)."* These procedures were also required during the 'External Walkround'.

Operating Manual Volume 1 included the requirement to check the 'Wing' and 'Cowl' anti-ice systems after engines start.

> Operating Manual Temporary Revision 604/5 (Jan 11/99) included the following note: *"…operating on ramps or taxiways which are contaminated with surface snow, slush or standing water when the OAT is 5°C (41°F) or below, can cause the wing leading edge to become contaminated with ice. Just prior to takeoff, select the wing anti-ice system on and advance the thrust levers, as required, until the L and R WING A/ICE cautions are extinguished, to remove any leading edge ice contamination."*
>
> Operating Manual Volume 1, Supplementary Procedures, had the following information on 'Cold Weather Operations, Airframe Deicing and Anti-icing, General Precautions': *"Takeoff must not be attempted if ice or frost are present in any amount on the wings and tail surfaces of the airplane. As a consequence of this requirement, the following general precautions must be observed in cold weather operations: 1. Contrary to the misconception that only the forward section aerodynamic surfaces are critical areas, all areas of the wings and tail surfaces, and their attached control surfaces, are critical areas as regards the effect of frozen contamination. 2. It must never be assumed that an apparently dry and loose form of frozen moisture, for example, dry snow, will be removed by the slipstream during the initial takeoff roll. For example, a dry snowfall that remains free and uncompacted on the ground may melt and later refreeze to form an adhesive layer on the surfaces of an airplane just removed from the hangar."*
>
> Operating Manual Volume 1, Supplementary Procedures, allowed the mechanical removal of loose snow or ice but then required an inspection of, among other areas: *"Wings – leading edges, upper and lower surfaces."*

> Operating Manual Volume 1, Supplementary Procedures, cold weather takeoff included the following instruction: *"If wing leading edge roughness is observed or suspected in any way, DO NOT attempt to take off."*

1.18.5.3 Flight Operations Manual

The following information regarding aircraft ground icing was included in the Epps Air Service Inc Flight Operations Manual:

> Section 18, page 1 dealt with company cold weather pre-flight inspection techniques. Amongst others, it detailed the following as critical areas, which *"should be completely free of contaminants except that frost may be polished smooth"*: wing leading edges, upper surfaces, and lower surfaces; stabilizing device leading edges, upper surfaces, lower surfaces, and side panels; high lift devices such as flaps; wing lift spoilers; all control surfaces. The page concluded with the following statement: *"If under any circumstance the crew cannot ascertain that the aircraft is clean, takeoff should not be attempted. The decision to takeoff following the pre-takeoff inspection remains the responsibility of the Pilot in Command."*

> Section 18, page 5 contained the following instructions: *"The majority of deicing/anti-icing of Epps Air Service aircraft will be conducted by contractors; however, the PIC retains the responsibility for the entire de-ice/anti-ice procedure. No aircraft operated by Epps Air Service may takeoff with frost adhering to the underwing surfaces or stabilizing or control surfaces. Such frost must be removed by one of the methods mentioned above (Note: Procedures for deicing/anti-icing all company operated aircraft are detailed within the FOM). However, upperwing, control and stabilizing surface frost may be polished smooth by the pilot. If it is not polished smooth then it too must be removed by one of the methods mentioned above."*

1.18.6 Aircraft de-icing

All other aircraft which had spent the previous night parked at Birmingham Airport and were scheduled to depart during the morning were de-iced. This included a CRJ that had been parked adjacent to N90AG. Reports from the operators of the various de-icing rigs indicated that the icing was severe, covered most of the airframe and was generally up to about ½ inch deep on the wing surfaces.

Of the 14 aircraft that departed in the 1½ hour period prior to the accident, 10 had arrived after 0900 hrs that morning and the other 4 were de-iced. The departure immediately preceding the accident was an Embraer 145, which had landed at 1043 hrs and took off again at 1204 hrs. The last aircraft which had spent the night at Birmingham and departed before the accident was a Boeing 757, which was de-iced at 1015 hrs and took off at 1156 hrs.

1.18.7 Ice Detectors

Surface icing detectors of a number of different types and employing a variety of operating principles have been available commercially for many years. Modern piezo-electric type detectors are small, can differentiate between fluid and ice deposits and can be incorporated flush with either a flat or curved surface. Many of the devices are capable of detecting very small thicknesses of ice. -NASA has patented a system capable of monitoring large areas of aircraft surfaces for ice contamination.

1.18.8 Aircraft wake turbulence

Wake vortices are formed when air flows around the tip of a lift-producing wing. The air flows from the area of relatively high pressure under the wing to the area of relatively low pressure above it, producing two vortices behind the aircraft, typically separated by about three quarters of the aircraft's wingspan. Viewed from the rear, the left vortex will be clockwise and the right anti-clockwise. The vortices can persist for some time and in still air tend to drift slowly downwards. They either level off, usually not more than 1,000 feet below the flight path of the aircraft or, on approaching the ground, level off at a height roughly equal to half the aircraft's wingspan and move outwards at about 5 kt. The decay process of wake vortices is complex and is strongly influenced by atmospheric condition. In conditions of light winds, vortices may stay in the approach and touchdown areas or sink to the landing or take-off paths of succeeding aircraft.

The most common hazard associated with wake turbulence is that it induces a rolling moment in an aircraft encountering it, which may exceed the roll control available to counter it. This is particularly so if the wing span of the encountering aircraft is significantly shorter than that of the generating aircraft.

The severity of the wake turbulence is determined by the weight, wing span and speed of the aircraft. Because of this, international rules have been implemented to reduce the probability of a vortex wake encounter to an acceptably low level, and to minimise the magnitude of the upset when an encounter does occur. Aircraft are divided into weight categories and wake turbulence spacing minima are then applied between aircraft of different categories. The International Civil Aviation Organisation (ICAO) has separated aircraft into the following three weight categories: Heavy with a maximum take-off weight of 136,000 kg or more; Medium with a maximum take-off weight between 7,000 and 136,000 kg and Light with a maximum take-off weight of 7,000 kg or less. UK has introduced an additional category of Small for aircraft with a maximum take-off weight of between 17,000 and 40,000 kg; UK considers aircraft between 40,000 and 136,000 kg as Medium and those of 17,000 kg or less as Light.

For departing aircraft of the same category there are no minimum separation requirements for wake turbulence reasons. The wake turbulence separation criteria for aircraft departing from the same runway, in the same direction, is at least two minutes for other aircraft behind a Heavy aircraft; this timing also applies for Light aircraft behind a Medium aircraft.

The two departures on Runway 15 immediately prior to the accident were a Boeing 757 (ICAO and UK Medium category) at 1156 hrs and an Embraer 145 (ICAO Medium category and UK Small category) at 1204 hrs. N90AG was an ICAO Medium category and UK Small category.

The Boeing 757 (approx 110,000 kg) took off about 11 minutes before N90AG started its takeoff. Both the Embraer 145 and the Challenger are in the same weight category (UK Small), both having a maximum take-off mass of about 20,000 kg, and their wing spans are similar at 20 metres and 19.6 metres respectively. The Embraer was airborne at about 1203:30 hrs and the accident occurred shortly after the Challenger lifted-off at 1207:54 hrs, some four minutes later. The departure intervals between these aircraft were greater than the current requirements.

A National Air Traffic Services review of the records of past wake turbulence events in the UK showed that 2,542 wake vortex encounters had been recorded since 1990. Of these, 629 were outbound encounters (between 0 and 6,000 feet). No encounters were recorded where the separation had been greater than 220 seconds.

One other aircraft movement of possible significance was a BAe146, which had landed and was clear of the runway at 1206:30 hrs, 30 seconds before N90AG was cleared to take off. Examination of a video recording from a security camera in the terminal area showed that the BAe146 was on the main apron when the Challenger passed the intersection where the BAe146 had left the runway. Nevertheless, the possibility was considered as to whether the jet efflux of the BAe146 may have been a factor in the accident to N90AG. The BAe146 manufacturer provided information on the aircraft jet efflux characteristics at both idle and take-off power. The aircraft has no thrust reversers. The idle power exhaust velocity contour extends to some eight metres at 22 kt and the take-off power exhaust velocity extends to some 230 metres at 31 kt. The main apron is a distance of 370 metres laterally from Runway 33.

1.18.9 Previous Accidents and Incidents

The Transportation Safety Board of Canada provided information on previous occurrences involving accidents and incidents to Canadair CL600 series aircraft involving uncommanded roll events. This covered the period from 1 January 1992 to 22 April 2002 and numbered a total of 17 occurrences, not including the accident involving N90AG. Of these, 15 were incidents resulting in no serious damage to the aircraft. These 15 incidents included instances of asymmetric flap, spoiler and thrust reverser activation, turbulence encounters and stiffness in roll control; all were controllable by the pilot.

The two accidents were at Fredericton, New Brunswick, on 16 December 1997 to a Canadair CL600-2B19 (RJ) and at Wichita, Kansas, on 10 October 2000 to a Challenger 604.

The Fredericton accident occurred when the aircraft stalled following a go-around; no indication was found of any failure or malfunction of any aircraft component prior to or during the flight but the aircraft had flown through an area of icing prior to the final approach. The investigation determined that the go-around was attempted from a low-energy situation outside the flight boundaries certified for the published go-around procedures. It was considered that a thin layer of mixed ice with some degree of roughness had probably accumulated on the leading edge of the wings; wing anti-icing had not been selected ‘ON’.

The Wichita accident (Ref: NTSB Aircraft Accident Brief NTSB/AAB-04/01) occurred during takeoff on a scheduled test flight. Just after takeoff, the aircraft rolled to the right and contacted the runway in a 90° bank in a slightly nose low attitude. No evidence of mechanical malfunction nor airframe icing/frost was found during the investigation. The NTSB determined that:

> *“the probable cause of this accident was the pilot’s excessive takeoff rotation, during an aft centre of gravity (c.g.) takeoff, a rearward migration of fuel during acceleration and takeoff and consequent shift of the airplane’s aft c.g. to aft of the aft c.g. limit, which caused the airplane to stall at an altitude too low for recovery”.*

The maximum rate of rotation achieved during the takeoff at Wichita was established, by the NTSB, to be 9.6°/sec. Information held by the manufacturer indicated that this was very high compared with the maximum observed in normal operations, of between 3.4 and 6.1°/sec, and higher even than the 7.5°/sec maximum rate achieved during Certification performance take-off testing. The aircraft static CG had been at 37.9% MAC before the start of the take-off roll but it was calculated that fuel migration resulting from the acceleration on the runway and the high pitch-up rate had resulted in a dynamic aftwards drift of the CG to 40.5% MAC, 20 seconds after the start of roll. The data indicated that the linear acceleration on the runway was similar but the pitch rate was considerably higher than that achieved by N90AG at Birmingham.

As a result of the preliminary findings of the investigation into this accident, the United States and Canadian Authorities issued Airworthiness Directives (see 1.6.2.2).

In addition to the occurrences detailed above, other CL600 incidents were brought to the attention of the investigators during the investigation. One of these involved a takeoff following three days of heavy snow and strong wind while the aircraft was parked outside. Despite extensive aircraft clearing procedures, the pilot experienced an uncommanded roll to the right after takeoff. Conversation with the pilot revealed that the roll rate was about 5 to 6° per second and that the roll was arrested at about 30° angle of bank using full aileron and rudder; the winglet scraped the runway surface. After landing, no fault was identified with the aircraft and the commander considered that the probable cause for the uncommanded roll was an accumulation of snow within the flap system; the flaps had not been cycled during the snow clearing operation. One other incident occurred during a pre-delivery flight when the pilot reportedly experienced an uncommanded roll after takeoff on a newly painted aircraft. Discussion with the pilot revealed that this resulted in an uncommanded roll of less than 3° per second and was easily controlled with very light control forces.

2. Analysis

2.1 Introduction

The two pilots, who were both qualified and experienced on type and had flown together many times, had flown N90AG to Birmingham the day before the accident. After a rest period greater than that required by the relevant regulations, the pilots returned to duty for a planned flight back to the USA with sufficient time to complete the necessary pre-flight preparations. The available evidence indicated that the pilots were generally operating in accordance with their company procedures but that there were a number of omissions. There were no reports of aircraft unserviceability.

The recorded information and witness evidence showed that, after an apparently normal take-off run, N90AG had begun to roll to the left immediately after lift-off. The roll had continued, despite the prompt application of full corrective aileron and rudder. The left wing contacted the runway and the aircraft then crashed inverted. The investigation of the accident focused on establishing the reasons for the uncontrolled roll.

2.2 The Accident

The recorded data, in conjunction with the evidence from the site and the wreckage examination, showed that the left winglet had contacted the runway shoulder around 3.5 seconds after lift-off, with the aircraft banked around 80° left. The characteristics of the subsequent increasingly heavy scrape marks and the corresponding abrasion damage to the left winglet confirmed that the wing contact occurred while the aircraft was rolling to the left and initially descending at a comparatively low rate. After a short scrape, overload forces caused the left winglet to detach. The outboard part of the left wing contacted the ground and progressively deformed and broke-up, while the aircraft continued to roll to the left. The disruption caused massive breaches of the left wing main fuel tank and the released fuel ignited about 1.5 seconds (120 metres) after initial ground contact, possibly as the result of sparking from damaged electrical wiring associated with the wingtip and winglet lights.

The evidence showed that, almost coincident with the fuel ignition, the forward fuselage had struck the ground inverted, resulting in severe damage to its upper regions and structural severance of the fuselage at the front of the wing centre-section. It was likely that this was the point at which the recorders had ceased working, approximately 5.5 seconds after lift-off. The extent and severity of the damage suggested that the ground impact was not survivable.

Markings on the wreckage indicated that localised rupture of the right wing fuel tank and substantial ruptures of the centre-section fuel tank had resulted from the structural separation of the forward fuselage. It also appeared likely that, with the aircraft inverted, fuel would have been released from the right wing tank through the vent system. Shortly after the inverted ground contact of the fuselage, contact of the horizontal stabiliser on the ground caused detachment of the fin from the fuselage and thus separation of the whole empennage. The characteristics of the wreckage trail burn pattern indicated that, as the wreckage slid along the ground, the fuel released from the centre and right wing tanks had also been ignited. This caused the forward fuselage to be subjected to a substantial fire for a relatively short period, until it was extinguished by the AFS.

2.3 Possible Causes of Uncontrolled Roll

A number of possible reasons for an uncontrolled roll were identified, each of which was examined to evaluate the probability that it had contributed to the accident. The possible scenarios and related evidence were as follows:

2.3.1 Powerplant Malfunction

The possibility was considered that there had been a loss of thrust from the No 1 engine or a deployment of its thrust reverser. However, the FDR recording indicated that all parameters associated with the two engines remained normal and synchronised from the application of take-off power until ground impact (Appendix 2a). The power set on both engines was consistent with that ordered by the commander at the start of the take-off roll. The evidence that N90AG's ground roll distance was normal for the conditions indicated that no significant thrust anomaly had occurred during the ground roll. FDR discretes relating to thrust reverser deployment and the lack of variation in engine parameters showed that neither thrust reverser had deployed. It was therefore concluded that both powerplants had functioned normally until ground impact.

2.3.2 Fuel Imbalance

The possibility was considered that a substantial fuel imbalance between the wing tanks could have contributed to the accident. The aircraft was reportedly refuelled to full prior to engine start. It was established that it was not possible for the fuel delivery tanker to be incorrectly configured such that its load meter would give a false indication of the fuel quantity dispensed (see 1.18.2.1). Additionally, any major discrepancy between the quantity actually delivered and that recorded should have been apparent from the refuelling company's records and none was evident. The CVR showed that the crew had observed indications of a full fuel load from cockpit instrumentation.

The refuel quantity was only 304 USG less that the total capacity of the aircraft tanks. The arrival fuel quantity was unknown but it appeared unlikely to have been substantially less than this, suggesting that the refuelling must have filled, or virtually filled, all the aircraft tanks. Only a relatively small amount of the fuel would have been used by the time of the accident, some 10 minutes after engine start, and there were no reports of significant quantities of fuel release from the aircraft prior to the accident. The evidence thus strongly indicated that the fuel tanks had been close to full at the time of takeoff. In this case it would not have been possible for a fuel system malfunction or mis-selection to have caused appreciable quantities of fuel to transfer from the right wing tank to any other tank and create a left wing heavy condition.

In addition, the absence on the FDR recording of a wing-down attitude during the take-off ground roll indicated that there was not a substantial fuel asymmetry present. The evidence indicating that the maximum possible fuel load asymmetry would be controllable with aileron made N90AG's behaviour, of continuing to roll rapidly in spite of full opposing aileron and rudder inputs, inconsistent with the effects of fuel asymmetry. Thus the possibility that fuel load asymmetry had contributed to the accident was dismissed.

2.3.3 Longitudinal centre of gravity

Calculations indicated that the aircraft CG would have remained within the aft limit of 34.5% MAC if the observer and passengers had been seated in the most forward available seats. It is probable that the observer had been seated in the jump seat as he was on this flight specifically to observe the operation. Although the wreckage examination suggested that the rearmost cabin seats had been unoccupied it could not be conclusively shown that the passengers had not been seated in these seats. It was, therefore, possible that the static CG was as far aft as 36% MAC (see 1.6.2.1).

The revised aft CG limit, of 34.5% at aircraft weights above 38,000 lb, had been instituted to accommodate the potential magnitude of the effects of fuel migration during acceleration and climb, highlighted by the Wichita accident. Calculations established that the furthest aft position to which the CG could have migrated during the takeoff of N90AG at Birmingham, even assuming the passengers to have been seated in the rearmost seats, was 38% MAC (see 1.18.2.4).

The aircraft type was known to be fully controllable with a CG as far aft as the originally certificated aft limit of 38% MAC. Furthermore, simulator studies conducted by the manufacturer, FAA, NTSB and Transport Canada had indicated that the aircraft would remain controllable with the CG as far aft as 42% MAC. It was concluded, therefore, that the longitudinal CG position had not been a causal factor in this accident.

2.3.4 Rate of rotation during takeoff

The maximum pitch rate of 5°/sec, achieved by N90AG after lift off, was considerably lower than that recorded by the aircraft at Wichita and lower than 6°/sec, the maximum rate normally observed during operations. It was, therefore, concluded that the rate of rotation had not been a causal factor in this accident.

2.3.5 Pitch Trim

The simulation model information (see 1.6.1) showed greater aircraft pitch response with the -4.9° setting used than for a value of -4.2°, close to the scheduled value of -4.1°. With experience on a specific aircraft, it is not unusual for a pilot to select a trim setting not strictly in accordance with the scheduled value. It was noted that the selected setting was virtually the same as that for the previous takeoff, with similar weight and CG conditions, which was uneventful. The manufacturer confirmed that the trim setting should not have resulted in any difficulty in achieving the target pitch angle. Therefore, the pitch trim setting was not considered relevant.

2.3.6 Primary Flight Control System Malfunction

The FDR indicated that primary flight control surface deflections were as would be expected in the circumstances. However, the possibility was considered that the roll had been caused by control surface deflections, commanded or uncommanded, that had not been recorded.

It appeared unlikely that the recorded data had been false, in that the deflection of each of the five primary control surfaces was individually signalled by a transducer driven directly by the surface, rather than by some more remote, upstream part of the system. All the transducers and associated links were intact and attached, with the exception of that for the left aileron and in this case the disconnection of the operating link from the transducer was fully consistent with the effects of the ground impact damage. It was also notable that the FDR record covering N90AG’s flight to Birmingham the day before the accident indicated that there had been no anomaly between primary flight control surface deflections and the aircraft response.

It did not appear that a full aileron control input would produce a roll rate quite as high as that experienced by N90AG, according to the manufacturer's assessment, although it would have been of the same general order. For such an input to have occurred and not been recorded, it would have been necessary for both aileron surface deflections to have been indicated falsely on the FDR. The evidence also indicated that the roll rate caused by deflection of just one aileron would be substantially less than the rate achieved, even without the other aileron surface deflecting in response to crew inputs to counter the effect.

A full rudder deflection could overpower the aileron control once a substantial sideslip angle had built up. However, the FDR record showed neither the initial adverse right roll that would have been expected in the event of a left rudder deflection nor a substantial sideslip angle, until the aircraft had already reached an extreme bank angle.

The roll effect caused by opposing deflections of the two elevator surfaces was calculated by the aircraft manufacturer to be readily controllable with ailerons. Should such a malfunction have occurred, it would have been apparent on the FDR record, again unless the indications of both elevator surface deflections were false. Furthermore, the recorded aircraft pitch response would not have been achievable.

In view of this evidence, the possibility that anomalies leading to deflections of the primary flight control surfaces, which had gone unrecorded, had contributed to the accident was dismissed.

2.3.7 Secondary Flight Control System Malfunction

The FDR record did not suggest any anomaly in the secondary flight controls but again the possibility of the recorded data having been incorrect was considered.

With regard to the possibility of mis-trimming having contributed to the accident, the recorded aileron and rudder trim settings were consistent with the trim actuator extensions found and were towards the central part of the available range. The roll rate achieved could not have been produced by even a full mistrim situation, given the mechanical authority limit in both trim channels. Similar considerations of the mechanical limitation of the authority of both the aileron autopilot servo and the rudder yaw damper precluded the possibility of an AFCS malfunction having caused the uncommanded roll.

All four trailing edge flap panels and their mounts and actuators remained intact and attached and deployed close to the normal 20° take-off setting, corresponding with the FDR record. The evidence indicated that the position of the screwjack actuators could not have been changed appreciably by crash forces. While tolerances were such that the correct rigging of the panels could not be positively confirmed, the maximum possible deviation was small, particularly in relation to the manufacturer's assessment that an asymmetry of up to 15° between left and right flaps would be controllable with aileron. No evidence of anomaly with the flap vanes or BUTE doors was apparent and information indicated that anomalous positioning of either would not produce a significant rolling moment with a take-off flap setting. Thus it was clear that incorrect flap setting or flap system asymmetry had not contributed to the accident.

The FDR record indicated that all four spoiler panels had remained retracted during the takeoff. The evidence indicated that the effect of any one panel deploying would be readily controllable with aileron. In the event of both the ground and flight spoiler panels on one side deploying, almost full aileron would be required. However, such a malfunction would be apparent on the FDR record unless a false indication for both panels were given, which was considered highly unlikely.

There was thus no evidence of anomaly with any of the secondary flight controls and it was clear that none of the postulated failures would have produced the roll rate experienced by N90AG while being opposed by the recorded aileron and rudder control inputs. The possibility that secondary flight control system malfunction had contributed to the accident was therefore dismissed.

2.3.8 Air Speed Indicator Malfunction

Damage to the forward part of the aircraft precluded examination or calibration of the airspeed indicator systems. However, integration of the recorded longitudinal acceleration during the take-off ground roll and comparison with the recorded airspeed indicated that N90AG's rotation speed had been close to the correct value for the conditions. The possibility that inaccurate airspeed indications had led the crew to utilise an incorrect speed schedule during the takeoff was dismissed.

2.3.9 Structural failure

It appeared likely that the only structural failures that could result in rapid rolling of the aircraft in the circumstances of the accident would be associated with the wings. However, the evidence from the ground markings, wreckage examination and witness evidence indicated that the aircraft had been complete at initial ground impact. This evidence also showed that the damage to the left wing structure and flight controls was fully consistent with the effects of the ground contact; the right wing remained intact. The possibility that pre-impact structural failure of the aircraft had contributed to the accident was therefore dismissed.

2.3.10 Door Opening

Had an aircraft door been open during the takeoff it was likely that this would have been apparent to eyewitnesses to the accident and evident from the wreckage examination and this was not the case. Furthermore, evidence suggested that such an occurrence was unlikely to generate a substantial rolling moment (see 1.18.3.10) and the possibility that opening of an aircraft door had contributed to the accident was therefore dismissed.

2.3.11 Pilot incapacitation

The evidence was reviewed to consider whether pilot incapacitation of some sort could have been a factor in the accident either during the take-off manoeuvre.

During the ground roll on the runway, the calls from the commander, and the responses from the handling pilot, were in accordance with company procedures. The handling pilot would have been the first to have become aware of any problem with the aircraft response. As the aircraft began to bank to the left, he responded with an exclamation of surprise indicating that he was fully aware that there was a problem. Almost immediately, he applied full corrective aileron and rudder control and then maintained these inputs up to the impact; the correct application of aileron and rudder was confirmed on the FDR. The handling pilot’s response was immediate and indicated that he was trying to correct an uncommanded movement of the aircraft. It was not company policy for the commander to have his hands or feet on the respective controls. As the recorded control inputs were exactly those required to attempt to correct the uncontrolled roll, it was considered that incapacitation of either pilot during the take-off roll was not a factor in the accident.

2.3.12 Wake Turbulence

For wake turbulence to have been a factor in the accident, two components must have been involved. The vortices must have been generated and the atmospheric conditions must have been suitable for their persistence.

The decay process of wake vortices is complex and strongly influenced by atmospheric conditions. In conditions of light winds, vortices may sink to the take-off paths of succeeding aircraft. The surface wind at the time of the accident was 140°/ 8 kt. This would have tended to drift any remaining vortices from left to right, but would not have been conducive to the vortices remaining in the vicinity of the runway. However, although there have been no recorded wake turbulence events in the UK with a separation greater than 220 seconds the possibility that a wake vortex encounter had contributed to the accident was considered in detail.

The onset of the uncommanded left roll for N90AG was shortly after lift-off at 1207:54 hrs. FDR information revealed no indication of any perturbations indicative of turbulence. If wake turbulence had been a factor, the roll could only have come from the effect of wing tip vortices. The fact that the aircraft rolled to the left meant that, under the conditions which obtained at the time, only the down flow from the inboard side of a left tip vortex causing a down force on the left wing would have been significant. The activities of three aircraft were considered to evaluate the possibility of interaction with N90AG.

Prior to N90AG's takeoff, a BAe 146 landed on Runway 15 and exited the runway to the left at the intersection with Runway 06; it reported clear at 1206:30 hrs. The aircraft touched down prior to the point at which N90AG got airborne and, therefore no airborne generated wing vortices would have been present to affect N90AG. The only effect to following aircraft would have been turbulence but there was no indication of any on the FDR.

The two aircraft which departed before N90AG were a Boeing 757, some eleven minutes before N90AG, and an Embraer 145 about four minutes before N90AG. The Boeing 757 is defined as 'Medium' category by both ICAO and the UK, and UK regulations required a two minute separation for any following 'Small' category aircraft. However, there was then some seven minutes separation before the Embraer 145 took-off and there were no reports of any turbulence from the crew of that aircraft.

There was no required separation interval between N90AG and the Embraer 145 and it is highly unlikely that any vortices generated by the Embraer would have caused N90AG a significant problem. N90AG's separation from the Boeing 757 was more than five times greater than that required and three times longer than the maximum period recorded for any wake encounter in the UK.

It was, therefore concluded that wake turbulence had not been a factor in causing N90AG to roll uncontrollably to the left.

2.3.13 Airframe Icing

2.3.13.1 Evidence of Icing

Conditions at Birmingham on the night before the accident were conducive to the formation of frost on N90AG. During the morning of 4 January, all other aircraft with flights originating from Birmingham were de-iced and reports related to these aircraft, one of which had been parked adjacent to N90AG, indicated that they had accumulated an extensive covering of frost on their external surfaces. It was inevitable that N90AG had been similarly affected.

It was probable that any frost deposits present on N90AG at takeoff would have been removed by the effects of the impact, shock loading and/or heating that occurred during the accident and/or by the effects of the extinguishant used during the fire fighting operation. The lack of frost deposits on the wreckage was therefore not considered to reflect the situation during the takeoff and it was not possible from the wreckage examination to determine whether frost had been present during the takeoff.

Both of N90AG's pilots were seen to make independent external inspections of the aircraft and, from evidence on the CVR, it was clear that the commander was aware of frost on the wing leading edge. In addition, some witnesses stated that the left wing had some frost on its surface; one witness (the refueller) stated that the right wing upper surface was clear of frost and that the light frost on the right wing leading edge was melting as refuelling progressed. Thus it was evident that there was frost contamination on at least some of the wing surfaces of N90AG during the preparations for the accident flight, although there was no evidence to enable the extent of the coverage or its thickness or roughness to be quantified.

It was unknown whether the thickness and coverage of the frost had been sufficient to trigger the aircraft ice detector system. Had this been the case, a flight deck warning should have occurred when N90AG was first electrically powered up. At this time, however, a very large number of transient start-up warnings would have been triggered and an 'ICE' warning would not have stood out amongst the rest. The warning should have been latched on for 60 seconds, but by the end of this period the ice detector probe heaters should have eliminated any frost on the probes and further triggering would not have been expected. Any warning given would have occurred before the FDR started and the associated aural warning would have been over-recorded on the CVR by the time of the accident.

It was apparent that the coverage and characteristics of the reported frost on the wings could possibly have changed somewhat by the time takeoff occurred because of the effects of a number of influences acting during the pre-flight preparations. These included the effects of solar radiation, the heating or cooling effects of the fuel in the wing tanks and the heating effects of APU and engine exhaust gas flows. The mechanisms were complex and definitive data was generally lacking and so in most cases it was not possible to accurately quantify the effects. However, the available indications that the solar radiation was relatively weak and that the bulk fuel temperature was probably around 0°C suggested that these two factors probably did not have a major effect on the frost in the time between the frost reports and the takeoff. It was also noted that the available sunlight would not have had a significant asymmetric effect on frost on the wings as observations showed that N90AG would not have been partially in shadow while parked prior to the accident flight.

N90AG happened to be subjected to a slight tailwind while parked and this could have drifted a warm mixture of engine exhaust flow and ambient air forward over the airframe. However, the wind was light and any such effect would have ceased almost immediately the aircraft started taxiing, three minutes after the start of the first engine. The influence could therefore have been present for a relatively short time only and it was judged that the effect would probably not have been major.

This was not necessarily the case for the exhaust gas from the APU (see 1.16.4). It was clear from observations during the investigation that the APU exhaust gas flow could appreciably raise the ambient temperature around parts of the parked aircraft and that in a tailwind situation the predominant effect would be on the right wing. N90AG's APU was operating for a little over an hour, until shortly before the aircraft began taxiing. The testing conducted on a similar aircraft in generally similar conditions showed that in a comparable time period the mean surface temperatures on the right wing rose by around 3°C at $^{1}/_{3}$ semi-span, 5°C at $^{2}/_{3}$ semi-span and 8°C in the tip region. Over the same period there was generally a much smaller increase in surface temperature for the left wing. As the reported ambient temperature at the time N90AG was being prepared was -2°C, the test results indicated that heat from the APU exhaust gas could have reduced, eliminated or smoothed the frost on parts of the right wing, while hardly affecting that on most of the left wing. This would have been generally consistent with the evidence from the refueller. It was likely that the outboard portions of the right wing would have been particularly susceptible to any such de-icing or smoothing effect, as any fuel heat sink effect reduced with the wing taper, or was absent near the tip, and the temperature increment was higher in the outboard regions.

With regard to the other flight surfaces, no direct evidence was available as to the presence of frost, but it appeared likely that the empennage would also have been contaminated. Solar radiation would, again, probably not have had a major effect by the time of takeoff, possible heat transfer with bulk fuel was not applicable and the testing indicated the APU exhaust gas would have had little influence.

In summary, it was evident that there was frost contamination on at least some of N90AG's wing surfaces during the preparations for the accident flight. It was also probable that frost contamination was present on the empennage. If the frost were sufficient to trigger the aircraft ice detector system, an initial warning should have been given, but probably would have gone unnoticed and would not have been repeated (see 1.6.3.7). By the time of the takeoff, the frost on the empennage and the left wing had probably not altered greatly, but the frost on the right wing, particularly over the outboard regions, may have been reduced, eliminated or smoothed by heating from the APU exhaust gas. There was no evidence to enable the coverage, thickness or roughness of the frost on any parts of the airframe at the time of takeoff to be quantified.

2.3.13.2 Effects of Airframe Surface Contamination

The available evidence indicated that a relatively small degree of surface roughness could affect the airflow over a lifting surface sufficiently to result in a stall at an AOA appreciably below the stall AOA for an uncontaminated aerofoil. The effect appeared to result from boundary layer disturbance caused by sufficiently dense roughness elements that were of a height that was appreciable in relation to the thickness of the boundary layer.

The effect was predominantly related to the roughness of any surface contamination, rather than to its thickness. The evidence suggested that wing upper surface roughness with an Rp in the low part of the range associated with the JAR/FAA definition of a 'small amount of ice' would typically cause reductions in the order of 5° for wing stall angle and 30% for maximum C_L. The roughness level approximately corresponded to that of medium-fine emery paper.

While the magnitude of the effect appeared to be well known to aerodynamic specialists, this did not seem to be the general case in the aviation industry. Although the 'Clean Wing' concept is known and adopted within Public Transport operations, it was perhaps more generally appreciated that serious aerodynamic degradation could result from the thick ice deposits that could accumulate in-flight if the anti-icing system were not used.

2.3.13.3 Effects of Wing Characteristics

The aircraft manufacturer's analysis indicated that leading edge roughness, rather than roughness distributed over the whole upper surface, would be particularly detrimental to the Challenger wing, in common with other designs of high speed wing. A particular effect of wing surface roughness in the case of the low t/c aerofoils used for supercritical wings appeared to be that sufficient flow disturbance could cause collapse of the characteristic separation bubble formed at high AOA due to the high suction peak generated. The stall flow separation consequent on collapse of the bubble tended to occur near the leading edge and thereby produce a more abrupt loss of lift than for low speed aerofoil types, where the initial separation tended to occur further aft.

Leading edge droop or leading edge slats or flaps were used on some aircraft types to reduce the suction peak. Some evidence suggested that the lift loss at the stall could be particularly sudden and marked for a relatively thin aerofoil with a symmetrical leading edge and, as on the Challenger wing, no leading edge slats or flaps.

For the type of wing used on the Challenger, a stall condition in one region could extend rapidly across the wing and cause a sudden major reduction in the lift and increase in the drag generated by that wing. It also appeared that the Challenger characteristics at wing stall were influenced by the reported typical stall initiation near the tip of a wing, rather than the more conventional design arrangement of initiation further inboard. A significantly greater rolling moment due to asymmetric lift would be associated with a tip stall.

The evidence indicated that in practice the Challenger would commonly experience a rapid and severe wing-drop when taken to the stall (uncontaminated), and aileron inputs would normally be ineffective in controlling the roll rate once a wing had stalled, until it was unstalled by reducing the AOA (see 1.18.4.3). Thus, while asymmetric contamination of left and right wing surfaces could accentuate the tendency for an abrupt wing-drop at the stall, it was clear that this was not a necessary condition for this to occur.

While the Challenger stall characteristics were clearly not benign, this is understood to be not atypical for the class of aircraft with swept, high-performance wings and the design intention was that the SPS would prevent the stall from being reached. However, the SPS was unable to detect or compensate for extensive wing contamination. The system could accommodate reasonably expected levels of contamination due to bugs, localised ice accretion and de-icing fluids. However, a relatively low level of roughness associated with frost contamination could reduce the stall AOA to below those at which the stick-shaker, the stall warnings and/or the stick-pusher would activate.

2.4 Discussion

2.4.1 Loss of Control

Most of the possible reasons for the rapid uncontrollable roll that occurred on lift-off and led to the accident could be dismissed. Assessment of the FDR data (see 1.16.1) showed that, although N90AG's pitch response to the increasing aircraft nose-up elevator deflection applied after initial rotation was normal, the vertical load factor achieved was substantially below the expected value. This suggested that the horizontal stabiliser and elevators were operating normally, but that there was a substantial deficit in wing lift.

Such a situation could only have been the result of abnormal airflow over at least part of the wing and was fully consistent with the effects of surface roughness associated with frost contamination. The evidence suggested that the frost contamination was probably present on the aircraft during the takeoff. Aerodynamic studies show that a low level of roughness associated with frost could generate sufficient flow disturbance to cause an aerodynamic stall of the wing at an AOA that was substantially below the normal value. Information also suggested that a rapid roll at the stall, uncontrollable by ailerons, would be probable, irrespective of the level of spanwise asymmetry of any contamination present.

The overall evidence therefore indicated that the accident had resulted from a stall of the left wing at an abnormally low AOA, caused by the effects of frost contamination. Melting or modification of the frost on the right wing by heat from the APU exhaust gas may have caused an asymmetry, particularly involving the outboard parts of the wings, that accentuated the tendency for the left wing to stall first. However, the evidence showed that the wing-drop could also have occurred in the absence of this effect.

2.4.2 The stall protection system

The AOA at which the stall occurred was below the range over which the SPS would normally provide a warning of stall approach and automatic stall prevention. The flat spot that affected the left AOA sensor output signal prevented the left stick-shaker and the stick-pusher from operating correctly. The correct initiation of these functions, in the absence of the fault, would have been only around two seconds and one second respectively before fuselage ground impact. This was at a point where the aircraft had already stalled and reached an extreme attitude and it is most unlikely that either one would have materially affected the outcome. It was therefore concluded that the SPS fault did not contribute to the accident. However, correct operation of the SPS system in many circumstances is clearly vital.

Information on the sensor wear problem had been promulgated only a short time prior to N90AG's accident and the associated AD was issued afterwards. While it may have been difficult to achieve more rapid identification of the problem and action to rectify it, it was undeniable that the procedure intended to ensure ongoing airworthiness failed to prevent a serious deficiency in this essential system on N90AG. This suggested that additional measures were required.

> It is therefore recommended that Bombardier Aerospace reassess the fault tolerance of the stall protection system for the Challenger 604 and other aircraft models with a similar system and the measures aimed at verifying its integrity in service. (Safety Recommendation 2003-59).

2.4.3 Failure to de-ice the aircraft

The pilot in the right seat was the commander and he, therefore, had overall responsibility for the safe conduct of the flight. However, company regulations detailed certain responsibilities for the handling pilot, as SIC, and these included the exterior pre-flight inspection. Therefore, both pilots had a responsibility for ensuring that the aircraft was fit for flight.

The two pilots were seen to do independent external inspections of the aircraft and should have been aware of the frost on the surfaces of the wings. Without exact timings of when these inspections were done, it was not possible to determine if any effects of the APU exhaust would have been apparent to one or both of the pilots. Nevertheless, a witness confirmed the existence of frost on the left wing during the time of the second inspection (by the commander). Furthermore, the commander was clearly aware of the contamination as he subsequently commented on the frost to the handling pilot.

It was considered significant that this was the only aircraft which had been parked at Birmingham over the previous night which had not been de-iced before taking off that day. With de-icing available, a number of possible reasons was considered as to why the crew members did not arrange for the aircraft to be de-iced. These were that the crew member(s) may have:

1. Believed that the degree of frost contamination they observed was acceptable and would not have a significant effect on the aircraft's aerodynamic performance.

2. Believed that the prevailing atmospheric conditions would melt the frost contamination before takeoff.

3. Observed that the right wing had been cleared of frost contamination by the APU exhaust flow and believed that the frost had cleared from both wings.

4. Forgotten, after their pre-flight preparations, that frost contamination was present.

5. Intended to clear the wing leading edges of frost before takeoff by operating the anti-icing system but omitted to do so.

6. Intended to counteract the effects of frost contamination by rotating the aircraft at a higher airspeed than that scheduled but omitted to do so.

7. Been unaware of the operating rationale of the airframe ice detector system and believed that it would warn of significant frost contamination.

However, the available evidence did not allow any firm conclusions to be reached as to the likely reason(s) for the failure to de-ice.

The investigation reviewed the regulations and the manufacturer's instructions concerning aircraft operations in icing conditions (see 1.18.5). Because the crew had been trained and qualified in USA, the Federal Aviation Administration (FAA) regulations and guidance were examined, as was the relevant information within the Bombardier aircraft manuals and the company manuals. Relevant references were as follows:

a. 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."*

b. FAR Parts 125 and 135 also included similar statements allowing frost, if it had been polished smooth.

c. The Epps AS company Operations Manual also contained references to *'polished frost'* and reflected the wording of FAR 91/135.

d. None of the Bombardier manuals included references to *'polished frost'*.

e. The Bombardier Challenger 604 Flight Manual Limitations section allowed '*Flight in icing conditions*' but made no reference to takeoff. However, the following warning was highlighted in the ABNORMAL PROCEDURES (Ice and Rain Protection): "*Even small accumulations of ice on the wing leading edge can change the stall speed, stall characteristic or the warning margins provided by the stall protection system*".

f. The Bombardier Challenger 604 Operating Manual included clear statements about the need to ensure that surfaces were clear of ice, snow or frost. For example, the SUPPLEMENTARY PROCEDURES (Cold Weather Operations) included the following statement: "*Takeoff must not be attempted if snow, ice or frost are present in any amount on the wings and tail surfaces of the airplane.*"

During the investigation, attempts were made to determine the definition of 'Polished Frost' and indeed how to polish frost. Nothing was found and the conclusion was that the explanation could have been lost in aviation history. However, when considering why the crew of N90AG did not de-ice the aircraft, despite evidence that there was frost on the leading edge of the wing, the anomaly of 'Polished Frost' may be a factor. The existence of such a concept in both FAA and company documents gives an indication that some form of frost is acceptable and this may have influenced the attitude of this crew.

Enquiries were made of other national organisations to establish if the concept of 'Polished Frost' was widespread; neither UK nor Canadian Authorities recognise the concept. It is considered that the concept of 'Polished Frost' is particularly inappropriate and potentially dangerous to modern aircraft types and detracts from the importance of strictly observing the clean wing principle.

> Accordingly, it has been recommended that the US Federal Aviation Administration, and all Authorities who follow FAA practice, delete all reference to 'Polished Frost' within their regulations and ensure that the term is expunged from Operations Manuals. (Safety Recommendation 2003-54).

Additionally, in view of the susceptibility to contamination of wings with low thickness/chord ratios, it would be appropriate for Bombardier to include the requirement to ensure the wings are clear in the Limitations section of the aircraft manuals; this would also be appropriate for other aircraft types.

> It has therefore been recommended that Bombardier Aerospace include the following specific limitation within appropriate aircraft manuals: ‘Wings and tail surfaces must be completely clear of snow, ice and frost prior to takeoff’. (Safety Recommendation 2003-55).

Bombardier Aerospace has already taken action in line with this Recommendation.

In this respect, it would be appropriate for other relevant aircraft with modern supercritical wings to have a similar specific limitation within their aircraft manuals.

> Accordingly, it has been recommended that the Civil Aviation Authority require the following specific statement within the limitations section of the flight manuals of aircraft with a significant susceptibility to ice contamination: ‘Wings and tail surfaces must be completely clear of snow, ice and frost prior to takeoff’, and communicate this recommendation to other civil airworthiness authorities responsible for the primary type certification of new aircraft types. (Safety Recommendation 2003-56).

2.4.4 Ice Detection

Although N90AG had an ice detector system, its design was such that it would probably not have provided an alert to the pilots before takeoff, except possibly when they first powered-up the aircraft electrical system (see 2.3.13.1). The system was designed to warn only of in-flight ice accumulation on the airframe. The means intended to eliminate pre-takeoff contamination of aerodynamic surfaces were entirely procedural, in common with most aircraft.

These procedures naturally leave room for human factors error, relying as they do on crew inspection, judgement and memory. Inspections in some circumstances could clearly be compromised by access difficulties and/or by adverse environmental conditions; for example, adequate inspection of the Challenger tailplane would not generally be a straightforward matter. It also appeared that crew members could be misled by asymmetric de-icing caused by uneven heating effects, eg partial exposure to solar heating or warm gas efflux. Additionally, a risk could also be created on occasion by contamination following a ramp inspection, involving factors that were hard to control or quantify, such as ice accumulation during taxi and hold-over times for de-icing treatments.

While the ground procedures have been long established, are widely used, and generally effective, over the years a number of accidents have occurred which have been caused by failure, for various reasons, to adequately de-ice before takeoff. It was also the case for N90AG's accident that the procedural approach failed to prevent the attempt to takeoff with contaminated lifting surfaces.

It would therefore appear sensible to provide crews with an objective indication of ice contamination of lifting surfaces. This appeared to be a practical proposition, given the availability of small ice detectors that could be incorporated flush with either a flat or curved surface, could have a detection threshold in the order of tenths of a millimetre of ice thickness and could differentiate between fluid and ice deposits. (see 1.18.7) As well as providing a pre take-off warning, perhaps integrated with the take-off configuration warning, a system based on such sensors could also provide direct monitoring of the in-flight status of aerodynamic surfaces and the performance of anti-icing systems. As noted above, the avoidance of ice contamination appears to be particularly important for high-speed aircraft where a small amount of ice can have a large aerodynamic effect and render stall protection systems ineffective.

> It has therefore been recommended that the Federal Aviation Administration and Joint Airworthiness Authority review the current procedural approach to the pre take-off detection and elimination of airframe ice contamination and consider requiring a system that would directly monitor aircraft aerodynamic surfaces for ice contamination and warn the crew of a potentially hazardous condition. (Safety Recommendation 2003-60).

2.4.5 Crew Performance and Judgement

Evidence as to the condition of the pilots prior to the flight was reliant on witness statements and the CVR. The witnesses varied from those who had previously met at least one of the pilots and those who had never met either of them. None of the witnesses considered that there was anything unusual about the behaviour of the pilots; most commented favourably on their friendly attitude. Therefore, from witness comments, the pilots did not appear to be incapacitated in any way.

However, there were some indications that they were not being as thorough as would be expected from experienced pilots. Evidence from colleagues indicated that the commander, as the company Director of Flight Operations, was a highly conscientious and safety aware individual. The handling pilot was also highly experienced and conscientious. Nevertheless, there were certain indications from the available evidence, including the CVR, that neither pilot was performing to the optimum and this mainly concerned judgement and concentration. The following aspects were considered relevant by the investigation team as possible indicators that the judgement and concentration of both pilots may have been deficient:

a. There was frost on the aircraft wing(s) and no attempt was made by either pilot, who had each carried out an external inspection, to call for de-icing equipment. Additionally, during the pre-flight checks, the commander asked the handling pilot twice if he had seen the frost on the leading edge. The response by the handling pilot was vague, indicating that he may not have heard or understood the question. The subject was not mentioned again. It is considered highly unusual that two experienced pilots would not have discussed and agreed a position on the frost situation.

b. The handling pilot programmed the route into the FMS under the direction of the commander. The indications were that the handling pilot was having trouble inputting the information and needed to start again after making a number of errors.

c. After start, the commander contacted ATC for various clearances. During this period, he made some errors in acknowledging information. Dialects and accents can cause confusion between US and UK nationals but the number of mistakes which occurred was surprising.

d. After engines start, the checklist required the ‘WING ANTI-ICE’ to be selected to ‘NORMAL’ to open both wing anti-icing valves (see 1.18.5.2). There was no indication that this check was carried out. Completion of the check would have resulted in hot air being distributed through the leading edges of the wings and an indeterminate amount of de-icing.

e. During taxi, the crew completed the standard pre-take-off checks. At one point, this required a decision on the use of anti-ice. For a crew operating effectively, this should have reminded at least one of the pilots that frost contamination had been seen on the wings. The fact that neither pilot mentioned frost at this juncture was surprising.

In summary, whilst the handling pilot displayed a high level of motor skills during his reaction to the uncontrolled roll, both pilots showed some deficiencies in judgement and concentration in the period between arriving at the aircraft and the take-off roll.

2.4.6 Medical Aspects

The evidence showed that neither of the two crew members attempted to arrange for de-icing of the aircraft even though both were seen to do an external inspection and the commander initiated a conversation about frost on the leading edge prior to engine start. While there was some information about 'Polished Frost' within FARs and company documentation that may have influenced their awareness of the importance of a 'Clean Wing', the Aircraft Flight Manual contained numerous warnings about the effect of ice, snow or frost on the aerodynamic performance of the aircraft. Medical and Human Factor specialists agreed that both pilots exhibited symptoms of decreased concentration and judgement and were of the opinion that it was possible that these symptoms were caused by a combination of jet-lag, tiredness and the effects of diphenhydramine.

Of these three components, jet-lag and tiredness have been addressed by aviation authorities and national regulations are in place to highlight associated potential problems and to attempt to mitigate against their effects. However, the effects of using common and easily available non-prescription drugs may not have been given the same attention. Appendix 3 states that non-prescription drugs were found in 18% of the pilots killed in flying accidents in the USA between 1994 and 1998. Of these, diphenhydramine was the most common drug, being found on 54 occasions.

The medications, 'Excedrin PM' and 'Nytol', both containing diphenhydramine and intended to aid sleep, were available without prescription in the USA. The packaging for both contained warnings about the need to avoid alcohol but had no reference to driving or operating machinery. In the UK, similar drugs were also available without prescription but were more difficult to obtain and had additional warnings on the packaging relating to driving and operating machinery.

The review of published advice on medication available to pilots in both the USA and the UK showed slight differences of approach in the two countries. In the UK, the regularly updated AIC, published by the CAA, highlights the types of drug which are of particular concern and points out that the use of any medication is potentially hazardous. It specifically encourages flight crew members to consult authorised aviation medical examiners before using any medication.

The USA pamphlet, 'Over the Counter Medications and Flying' is equally discouraging about self medication and flying, and points out that pilots should inform themselves of the effects of any non-prescription medication they choose to use. The fact that two experienced and safety conscious pilots such as the crew of N90AG used medication containing diphenhydramine indicated that crews may not be sufficiently aware of the potential dangers of using non-prescription medications.

That the use of self administered non-prescription medication constitutes a serious concern for aviation safety has been reinforced by the series of Recommendations made, in January 2000, by the NTSB. These related to establishing the effects of licit drugs, requiring improved standards of labelling and regulating their use by vehicle operators. The findings of this accident investigation support those Recommendations, the intentions of which are internationally applicable. In view of this, it would be appropriate for the FAA to review the guidance given to flight crews about the dangers of using non-prescription medication. It would also be appropriate for the FAA to instigate action to ensure that non-prescription medication packaging contains appropriate warnings about possible side effects of the ingredients.

> It is, therefore, recommended that the Federal Aviation Administration act upon the National Transportation Safety Board Recommendations A-00-4, A-00-5 and A-00-6 and, in particular review the guidance given to flight crew members about the dangers of using non-prescription medication. (Safety Recommendation 2003-57).
>
> It is also recommended that the Federal Aviation Administration take measures to encourage action by the US Food and Drug Administration in line with the National Transportation Safety Board Recommendation, I-00-5, to ensure that over-the-counter medication contains appropriate warnings on any associated potential dangers in operating aircraft. (Safety Recommendation 2003-58).

3. Conclusions

(a) Findings

1. The flight crew members were properly licensed to conduct the flight.
2. The pilot in the right cockpit seat was the designated commander.
3. The pilot in the left cockpit seat was the handling pilot and SIC.
4. Frost deposits had formed on the aircraft while parked overnight in sub-zero temperatures.
5. The pilots did not request aircraft de-icing and the aircraft was not de-iced before takeoff.
6. Frost contamination of aircraft lifting surfaces was present when the aircraft took-off.
7. As the aircraft lifted off, the left wing stalled at an abnormally low angle of attack, causing the aircraft to roll rapidly to the left.
8. The roll could not be stopped despite immediate and full application of corrective aileron and rudder controls.
9. The left wing tip contacted the ground and the aircraft crashed inverted.
10. The aircraft suffered fire damage and severe structural damage.
11. The accident was not survivable.
12. The deployment of the Airport Fire Service was expeditious and effective.

13. The aircraft weight was within normal limits. The position of the longitudinal centre of gravity could not be determined accurately but did not contribute to the accident.

14. The pitch trim was not set in accordance with the schedule but this did not contribute to the accident.

15. Wake turbulence from preceding aircraft did not contribute to the accident.

16. Aircraft system malfunction or structural failure did not contribute to the accident.

17. There was a fault with the aircraft stall protection system but this did not contribute to the accident.

18. A small degree of wing surface roughness can cause a major reduction in the wing stall angle of attack.

19. Wing surface roughness associated with frost contamination caused sufficient flow disturbance to result in a wing stall at an abnormally low angle of attack. The stall protection system was ineffective in this situation.

20. The Challenger 604 aircraft typically does not stall symmetrically and any tendency to roll could be accentuated by asymmetric ice contamination.

21. APU exhaust gas flow during pre-flight preparations probably caused some asymmetry in the frost contamination.

22. Long standing FAA guidance material suggesting that polished wing frost was acceptable is inappropriate.

23. The means intended to ensure that the aircraft's aerodynamic surfaces were clear of ice contamination were procedural.

24. The airframe ice detection system fitted was not designed to provide an effective crew warning of pre-take-off frost contamination of the wings and did not do so.

25. Crew rest periods were in accordance with FAA regulations but the performance of both crew members may have been affected by jet-lag and fatigue.

26. Traces of a non-prescription drug containing diphenhydramine, typically used to aid sleep, were found in both pilots.

27. Specialist medical opinion was that it was possible that the judgement and reasoning of both crew members had been adversely affected by a combination of jet-lag, tiredness and the effects of diphenhydramine.

28. Typically there were no warnings about drowsiness or avoiding operating machinery on the packaging of sleep aid drugs sold in the USA containing diphenhydramine.

(b) Causal factors

1. The crew did not ensure that N90AG's wings were clear of frost prior to takeoff.

2. Reduction of the wing stall angle of attack, due to the surface roughness associated with frost contamination, to below that at which the stall protection system was effective.

3. Possible impairment of crew performance by the combined effects of a non-prescription drug, jet-lag and fatigue.

4. Safety Recommendations

The following safety recommendations have been made:

4.1 **Safety Recommendation 2003-54**: It is recommended that the US Federal Aviation Administration, and all Authorities who follow FAA practice, delete all reference to 'Polished Frost' within their regulations and ensure that the term is expunged from Operations Manuals.

4.2 **Safety Recommendation 2003-55**: It is recommended that Bombardier Aerospace include the following specific limitation within appropriate aircraft manuals: 'Wings and tail surfaces must be completely clear of snow, ice and frost prior to takeoff.'

4.3 **Safety Recommendation 2003-56**: It is recommended that the Civil Aviation Authority require the following specific statement within the limitations section of the flight manuals of aircraft with a significant susceptibility to ice contamination, 'Wings and tail surfaces must be completely clear of snow, ice and frost prior to takeoff', and communicate this recommendation to other civil airworthiness authorities responsible for the primary type certification of new aircraft types.

4.4 **Safety Recommendation 2003-57**: It is recommended that the Federal Aviation Administration act upon the National Transportation Safety Board Recommendations A-00-4, A-00-5 and A-00-6 and, in particular review the guidance given to flight crew about the dangers of using non-prescription medication.

4.5 **Safety Recommendation 2003-58**: It is recommended that the Federal Aviation Administration take measures to encourage action by the US Food and Drug Administration in line with the National Transportation Safety Board Recommendation, I-00-5, to ensure that over-the-counter medication contains appropriate warnings on any associated potential dangers in operating aircraft.

4.6 **Safety Recommendation 2003-59**: It is recommended that Bombardier Aerospace reassess the fault tolerance of the stall protection system for the Challenger 604 and other aircraft models with a similar system and the measures aimed at verifying its integrity in service.

4.7 **Safety Recommendation 2003-60**: It is recommended that the Federal Aviation Administration and Joint Airworthiness Authority review the current procedural approach to the pre takeoff detection and elimination of airframe ice contamination and consider requiring a system that would directly monitor aircraft aerodynamic surfaces for ice contamination and warn the crew of a potentially hazardous condition.

C G Pollard
Acting Principal Inspector of Air Accidents
Air Accident Investigation Branch
Department for Transport
July 2004

Unless otherwise indicated, recommendations in this report are addressed to the regulatory authorities of the State having responsibility for the matters with which the recommendation is concerned. It is for those authorities to decide what action is taken. In the United Kingdom the responsible authority is the Civil Aviation Authority, CAA House, 45-49 Kingsway, London WC2B 6TE or the European Aviation Safety Agency, Office G-12 02/74, Rue de Genève 12, B-1049 Brussels, Belgium.