Defence
Safety
Authority

Service Inquiry

Griffin HT Mk1
ZJ241,Snowdonia

09 August 2016

Defence Safety
Authority

Intentionally Blank

PART 1.1

Covering Note & Glossary

Intentionally Blank

PART 1.1 – COVERING NOTE

14/06/18

DG DSA

SERVICE INQUIRY INTO THE ACCIDENT INVOLVING A GRIFFIN MK1 ZJ241 AT YR ARAN, SNOWDONIA, WALES ON 9 AUG 16

1. The Service Inquiry Panel assembled at Farnborough, on the 15 Aug 16 by order of the DG DSA for the purpose of investigating the accident involving Griffin ZJ241 on 9 Aug 16 and to make recommendations in order to prevent reoccurrence. The Panel has concluded its inquiries and submits the provisional report for the Convening Authority's consideration.

2. The following inquiry papers are enclosed:

Part 1 REPORT	Part 2 RECORD OF PROCEEDINGS
Part 1.1 Covering Note and Glossary	Part 2.1 Diary of Events
Part 1.2 Convening Orders & TORs	Part 2.2 List of Witnesses
Part 1.3 Narrative of Events	Part 2.3 Witness Statements
Part 1.4 Findings	Part 2.4 List of Attendees
Part 1.5 Recommendations	Part 2.5 List of Exhibits
Part 1.6 Convening Authority Comments	Part 2.6 Exhibits
	Part 2.7 List of Annexes
	Part 2.8 Annexes
	Part 2.9 Schedule of Matters Not Germane
	Part 2.10 Master Schedule

PRESIDENT

[Signature]

[redacted]
Major
President
ZJ241 SI

MEMBERS

[Signature]

[redacted]
Lieutenant RN
Engineering Member
ZJ241 SI

[Signature]

[redacted]
Flight Lieutenant
Aircrew Member
ZJ241 SI

Intentionally Blank

GLOSSARY

Acronym/ Abbreviation	Explanation
/rev	per revolution
AAIB	Air Accident Investigation Branch
AAMC	Alternative Acceptable Means of Compliance
AD	Airworthiness Directive
ADH	Aircraft Duty Holder
ADI	Attitude and Direction Indicator
ADS	Aircraft Document Set
AFCS	Automatic Flight Control System
AFCU	Automatic Fuel Control Unit
ALARP	As Low As Reasonably Practicable
AMC	Acceptable Means of Compliance
AMP	Aircraft Maintenance Programme
AMSL	Above Mean Sea Level
AOA	Aircraft Operating Authority
AOB	Angle Of Bank
AOC	Air Officer Commanding
AOR	Area of Responsibility
AP	Aircraft Publication
APCM	Aircraft Post Crash Management
APCMIO	Aircraft Post Crash Management Incident Officer
ARB	Airworthiness Review Board
ARCC	Aeronautical Rescue Coordination Centre
ARM	Accident Route Matrix
ASB	Alert Service Bulletin
ASIMS	Air Safety Information Management System
ASM	Air Safety Manager
ASMP	Air Safety Management Plan
ASSWG	Air System Safety Working Group
ATC	Air Traffic Control
ATSB	Australian Transport Safety Bureau
ATT	Attitude Retention mode
AWC	Air Warfare Centre
BHT	Bell Helicopter Textron
C2I	Competant to Instruct
CAA	Civil Aviation Authority
CAM	Cockpit Area Microphone
CAME	Continuing Airworthiness Management Exposition
CAMO	Continuing Airworthiness Management Organisation
CAP	Civil Air Publication
CAR	Corrective Action Report
CCB	Configuration Control Board
CFI	Chief Flying Instructor
CFS(H)	Central Flying School (Helicopters)
CHF	Commando Helicopter Force
CI	Control Indicator
CivCAM	Civilian Continuing Airworthiness Manager
CofG	Centre of Gravity
CR&O	Component Repare and Overhaul
CSMIP	Crash Support & Major Incident Plan

Acronym/ Abbreviation	**Explanation**
CVR	Cockpit Voice Recorder
DA	Duty Aviator
DAEMS	Defence Aviation Error Management System
DAIB	Defence Accident Investigation Branch
DASAB	Delivery Duty Holder Air Safety Assurance Board
DASOR	Defence Air Safety Occurrence Report
DDH	Delivery Duty Holder
DE&S	Defence Equipment & Support
DFT	Director Flying Training
DHELs	Director Helicopters (Defence Equipment & Support)
DHFS	Defence Helicopter Flying School
DIO	Defence Infrastucture Organisation
DO	Design Organisation
DSTL	Defence Science & Technology Laboratory
Dtech	Director Technical MAA
DTEO	Defence Test & Evaluation Organisation (now QinetiQ)
DUS	Design Usage Spectrum
EASA	European Aviation Safety Agency
ECC	Emergency Coordination Cell
ED	Environmental Damage
EFS	Executive Flying Supervisor
ESVRE	Establish, Sustain, Validate, Recover, Exploit
ETPS	Empire Test Pilot School
FAA	Federal Aviation Authority
FAR	Federal Aviation Regulation
FBH	FB Heliservices (Now Cobham)
FDR	Flight Data Recorder
FLIR	Forward Looking Infra-red
FOB	Flying Order Book
FOR	Flight Occurrence Report
FRC	Flight Reference Cards
ft	Feet
FTS	Flying Training Squadron
G	Acceleration, 1G is 1 x the force of gravity
GOR	Ground Occurrence Report
Gp	Group
HELS OC	Helicopters Operating Centre
HF	Human Factors
HFACS	Human Factors Analysis Classification System
HUMS	Health and Usage Monitoring System
Hz	Hertz
HzR	Hazard Report
IGE	Inside Ground Effect
IMC	Instrument Meteorological Conditions
ISAA	Independent Structural Airworthiness Advisor
JARTS	Joint Aircraft Recovery and Transportation Squadron
JHC	Joint Helicopter Force
JOLIC	Joint Observer Lead In Course
Kts	Knots
LIDAR	Light Imaging Detection and Ranging

Acronym/ Abbreviation	Explanation
RAF	Royal Air Force
RAFCAM	Royal Air Force Centre of Aviation Medicine
RAFRLO	Royal Air Force Regional Liaison Officer
RFI	Request For Information
RFM	(Bell) Rotorcraft Flight Manual
RHS	Right Hand Seat
RIN	Retirement Index Number
RPM	Revolutions Per Minute
RTS	Release To Service
RTSA	Release To Service Authority
RWTES	Rotary Wing Test and Evaluation Squadron
SAR	Search and Rescue
SARTU	Search And Rescue Training Unit
SAS	Stability Augmentation System
SATCO	Senior Air Traffic Control Officer
SCT	Staff Continuation Training
SERW	Single Engine Rotary Wing
SF-01	Safety Form-01
SI	Service Inquiry
SLOps	Squadron Leader Operations
SOI	Statement of Operating Intent
SOIU	Statement of Operating Intent and Usage
SPMAP PT	Special Projects Multi-Air Platforms Project Team
SQEP	Suitably Qualified & Experienced Person
SQN	Squadron
SSI	Structurally Significant Item
SSSI	Sites of Special Scientific Interest
Stds	Standards
TAA	Type Airworthiness Authority
TAS	Traffic Advisory System
TCH	Type Certificate Holder
TO	Training Officer
Trg	Training
VAL	RAF Valley

Acronym/ Abbreviation	Explanation
Llbs	Pounds
LOAA	Letter Of Airworthiness Approval
LTC	Local Technical Committee
MAA	Military Aviation Authority
MAOT	Mobile Air Operations Team
MAR	Military Aircraft Register
MAR	Military Aircraft Release
MARC	Military Airworthiness Review Certificate
MCA	Maritime and Coastguard Agency
MDRE	Manual Data Recording Exercise
MDS	Main Drive Shaft
MDSC	Main Drive Shaft Coupling
MEMS	Maintenance Error Management System
METAR	Meteorological Aerodrome Report
MFTA	Mountain Flying Training Area
MGB	Main Gearbox
MilCAM	Military Continuing Airworthiness Manager
MM	(Bell) Maintenance Manual
MOD	Ministry of Defence
MOE	Maintenance Organisation Exposition
MOLIC	Maritime Operational Lead In Course
MOR	Mandatory Occurrence Report
MRCO	Military Registered Civilian Owned
MRP	Military Regulatory Publication
MRT	Mountain Rescue Team
N1	Engine Gas Generator Speed
N2	Free Power Turbine Speed
NAS	Naval Air Squadron
NDT	Non-Destructive Testing
Nr	Main Rotor speed
NRI	Non Routine Inspection
NTSB	National Transportation Safety Board
OC	Officer Commanding
OCU	Operational Conversion Unit
ODH	Operational Duty Holder
OEM	Original Equipment Manufacturer
OGE	Outside Ground Effect
Ops	Operations
OSN	Operations Safety Notice
P&WC	Pratt and Whitney
PAC	Power Assurance Check
PCMIO	Post Crash Management Incident Officer
PFD	Penetrant Flaw Detection
POB	Persons On Board
PSEWG	Platform Safety & Environmental Working Group
PT	Project Team
QHCI	Qualified Helicopter Crewman Instructor
QHI	Qualified Helicopter Instructor
R	Revolution
RA	Regulatory Article

~~OFFICIAL SENSITIVE~~

PART 1.2

Convening Order & TORs

Intentionally Blank

Defence Safety Authority

Service Inquiry Convening Order

16 Aug 16

SI President
SI Members

Hd Defence AIB
DSA MAA Legad

Copy to:

PS/SofS
MA/Min(AF)
PS/Min(DP)
PS/Min(DVRP)
PS/PUS
DPSO/CDS

MA/VCDS
NA/CNS
MA/CGS
PSO/CAS
MA/CDM
MA/Comd JFC

MA/Dir MAA
PSO/AOC 22 (Tng) Gp
MA/MAA D (Tech)
MA/DES Hels Dir
Dir DDC

DSA DG/SI/04/16 – CONVENING ORDER FOR THE SERVICE INQUIRY INTO THE AIRCRAFT INCIDENT INVOLVING GRIFFIN, ZJ241 ON 9 AUG 16 AT 1330L IN THE VICINITY OF YR ARAN, SNOWDONIA

1. A Service Inquiry (SI) is to be held under Section 343 of Armed Forces Act 2006 and in accordance with JSP 832 – Guide to Service Inquiries (Issue 1.0 Oct 08).

2. The purpose of this SI is to investigate the circumstances surrounding the subject aircraft incident and to make recommendations in order to prevent recurrence.

3. The SI Panel will formally convene at Ministry of Defence Main Building, Whitehall, London at 1400L on Tue 16 Aug 16.

4. The SI Panel comprises:

President: [redacted] **Major** [redacted]

Members: **Ops Member –** [redacted] **Flight Lieutenant** [redacted] **RAF**
Eng Member – [redacted] **Lieutenant** [redacted] **RN**

5. The legal advisor to the SI is **Wg Cdr** [redacted] **(DSA MAA Legad)** and technical investigation/inquiry assistance is to be provided by the Defence Accident Investigation Branch (Defence AIB).

6. The SI is to investigate and report on the facts relating to the matters specified in its Terms of Reference (TOR) and otherwise to comply with those TOR (at Annex). It is to record all evidence and express opinions as directed in the TOR.

7. Attendance at the SI by advisors/observers is limited to the following:

Head Defence AIB – Unrestricted Attendance.

Defence AIB investigators in their capacity as advisors to the SI Panel – Unrestricted Attendance[1].

Mrs [redacted], RAFCAM HF Psychologist – Unrestricted Attendance.

8. The SI Panel will work initially from RAF Valley iaw JSP832, Ch2 Annex F. Permanent working accommodation, equipment and assistance suitable for the nature and duration of the SI will be requested by the SI President in due course.

9. Reasonable costs will be borne by DG DSA under UIN D0456A.

Original Signed

R F Garwood
Air Mshl
DG DSA – Convening Authority

Annex:

A. Terms of Reference for the Service Inquiry into the Aircraft Indcident Involving Griffin ZJ241 on 9 Aug 16 at 1330L in the vicinity of Yr Aran, Snowdonia.

[1] Dep Hd, SO1 Air and investigators as authorised by Hd Defence AIB.

ANNEX A TO
Griffin ZJ241 SI Convening Order
Dated 16 Aug 16

TERMS OF REFERENCE FOR THE SERVICE INQUIRY INTO THE AIRCRAFT INCIDENT INVOLVING GRIFFIN ZJ241 ON 9 AUG 16 AT 1330L IN THE VICINITY OF YR ARAN, SNOWDONIA.

1. As the nominated Inquiry Panel for the subject SI, you are to:

a. Investigate and, if possible, determine the cause of the occurrence, together with any contributory, aggravating and other factors and observations.

b. Ascertain whether the personnel (Service and civilian) were acting in the course of their duties.

c. Examine what policies, orders and instructions were applicable and whether they were complied with.

d. Establish the level of training, relevant competencies, qualifications and currency of the individuals involved in the incident.

e. Identify if the levels of planning and preparation met the activities' objectives.

f. Review the levels of authority and supervision covering the task during which the incident occurred.

g. Investigate and comment on relevant fatigue implications of an individual's activities prior to the matter under investigation.

h. Determine the state of serviceability of relevant equipment.

i. Determine any equipment deficiencies.

j. Ascertain if aircrew escape and survival facilities and equipment assemblies were fully utilised and functioned correctly.

k. Determine whether Aircraft Post-Occurrence Management procedures were adequate and complied with.

l. Determine and comment on any broader organisational and/or resource factors.

m. Determine the level of injuries sustained.

n. Ascertain value of loss/damage to the Service.

o. Make appropriate recommendations to DG DSA.

2. During the course of your investigations, should you identify a potential conflict of interest between the Convening Authority and the Inquiry, you are to pause work and consult DG DSA. Following that advice it may be necessary to reconvene reporting directly to MOD PUS.

3. You are to ensure that any material provided to the Inquiry by any foreign state, is properly identified as such, and is marked and handled in accordance with MOD security guidance. This material continues to belong to those nations throughout the SI process. Before the SI report is released to a third party, authorization should be sought from the relevant authorities in those nations to release, whether in full or redacted form, any of their material included in the SI report, or amongst the documents supporting it. The relevant NATO European Policy (NEP) or International Policy and Plans (IPP) team should be informed early when dealing with any foreign state material.

Intentionally Blank

PART 1.3

Narrative of Events

Intentionally Blank

PART 1.3 – TABLE OF CONTENTS

Synopsis 3

Background Information 3

Pre-Flight Events 4

Sortie Events 7

Post Accident Events 11

Post Occurrence Management 12

Accident Investigation 13

Damage to the aircraft, site and civilian property 14

PART 1.3 – NARRATIVE OF EVENTS

All times local (Zulu plus 1 hour).

Synopsis

1.3.1. On Tuesday 9 August 2016 at 1334 hours (hrs), a Defence Helicopter Flying School (DHFS) Griffin HT Mk1 helicopter was involved in an accident on the peak of Yr Aran mountain in Snowdonia, North Wales. The aircraft was destroyed by fire shortly after landing on the summit.

1.3.2. The aircraft was operated by 202(R) Sqn based at RAF Valley. 202(R) Sqn is a detached unit of DHFS and delivers instruction to student pilots and crewmen in maritime and mountain flying techniques.

1.3.3. The crew were tasked to pick up a passenger from the top of Yr Aran and fly to a field landing site near Betws-y-Coed. As the aircraft touched down next to the passenger an episode of severe vibration and component failures occurred and the aircraft was shutdown. All five crew and passenger escaped without injury.

Background Information

1.3.4. **Aircraft**. The Griffin HT Mk1, tail number ZJ241 (Figure 1), was a Bell 412 EP, Military Registered Civilian Owned (MRCO) aircraft. The aircraft held a valid Military Airworthiness Review Certificate (MARC). Annex F

Figure 1 - Griffin HT1, ZJ241.

1.3.5. **202(R) Squadron**. Prior to April 2016, 202(R) Sqn had been named the Search and Rescue Training Unit (SARTU) and was responsible for delivering a basic understanding of Search and Rescue (SAR) techniques to all RAF trainee helicopter crews, as well as conducting a lead-in course for aircrew selected for full-time SAR duties. The Sqn had operated the Griffin helicopter since the formation of DHFS and from 2009 has also used AW139 helicopters for overseas student training. Prior to the disbandment of Military SAR in 2015, the training focus had widened to include Royal Navy students progressing from basic helicopter training to Operational Conversion Units (OCU). SARTU then became 202(R) Sqn, formerly one of the disbanded frontline SAR squadrons, in April

2016.

1.3.6. **RAF Valley**. RAF Valley is home to the advanced Fast Jet training programme of the RAF and RN, provided by IV(R) Squadron using Hawk aircraft. At the time of the incident major runway works were being completed which resulted in all jet flying operations being detached to RAF St Athan in South Wales.

1.3.7. **Defence Helicopter Flying School (DHFS)**. The Defence Helicopter Flying School is located at RAF Shawbury with a permanent detachment at RAF Valley. It provides basic helicopter training for pilots from the three Services as well as Foreign and Commonwealth Countries in both Griffin and Squirrel helicopters. The School was formed on 1 April 1997 and although it is a military school, the aircraft are maintained and managed by Cobham Aviation Services (formerly FBHeliservices or FBH). The Commandant of DHFS is also the Delivery Duty Holder (DDH), legally accountable for the safe operation, airworthiness and maintenance of all aircraft within DHFS, including those at RAF Valley.

1.3.8. **Cobham Helicopter Services**. Cobham are responsible for providing the aircraft, engineering, training facilities and for continuing airworthiness.[1] They maintain a first-line engineering presence at RAF Valley and first-line/depth engineering facility at RAF Shawbury. Approximately 40% of all aircrew instructors at DHFS[2] are ex-military Cobham employees.

1.3.9. **Bell Helicopter Textron**. Bell, the Design Organisation, are the manufacturer of the Bell 412 (Griffin) helicopter. They have been building helicopters in the United States since 1942 and provide aircraft for both the civilian and military sectors. The Bell 412 was first produced by Bell Helicopter in 1981 and is a derivative of the UH-1H "Huey" aircraft. Annex G

1.3.10. **Crew composition**. The crew consisted of 5 people who were all members of 202(R) Sqn: Aircraft Commander A, an experienced pilot and instructor, and the aircraft captain at the time of the accident; Aircraft Commander B, an experienced pilot but new instructor; the Crewman Instructor, a very experienced instructor; and the Student Pilot and Student Crewman who were both relatively new to flying. The Passenger was not part of the crew but was also an experienced pilot.

Pre-Flight Events

1.3.11. **Preceding month flying and maintenance**. ZJ241 had been at RAF Valley since 4 Jul 16, following a period at RAF Shawbury that involved 300-hour scheduled maintenance[3] and some fault diagnosis on the navigation system. Flight testing was carried out, including vibration analysis. Exhibit 1

1.3.12. Since delivery back to RAF Valley, ZJ241 had completed 97:40 airframe flying hours. Some minor fault rectification was carried out, including a number of different Exhibit 2

[1] Continuing airworthiness encompasses all of the processes that ensure, at any time in its operating life, the aircraft complies with the airworthiness requirements in force and is in a condition for safe operation. Source: EC1321/2014 Article 2 [EC, 2014].
[2] https://www.raf.mod.uk/rafshawbury/aboutus/dhfs.cfm.
[3] A '300-hour' check includes partial strip of the aircraft for inspections and removal of items due overhaul and life expiry.

gearbox magnetic plug chip captions[4] and a left-hand wiper motor bracket fault. A total of 5 Defence Aviation Safety Occurrence Reports (DASOR) had been raised on ZJ241 in the previous month of which there were 3 anomalous chip captions, 1 hoist range issue and a non–technical report. Exhibit 3 Exhibit 4 Exhibit 5 Exhibit 6 Exhibit 7

1.3.13. **Preceding 7 days flying and maintenance**. ZJ241 flew 16:35 hours in the week preceding the accident. Routine scheduled maintenance was conducted, which included engine compressor and compressor turbine rinses, a 25-hour check, a 7-day inspection and a 100-hour maintenance package. Exhibit 2

1.3.14. **Aim of sortie**. The aim of the flight was split into two phases that were part of the same flight but separate sorties with different operating crew. Exhibit 8

a. **DHFS-tasking sortie**. The aim of the task was to pick up the Passenger from the summit of Yr Aran and deliver to a field landing site near Betws-y-Coed, where Aircraft Commander A would also disembark. It was also to provide additional mountain flying experience for the Student Pilot and Student Crewman, in preparation for the following sortie. Exhibit 9 Exhibit 8 Witness 4

b. **Training sortie**. Following the crew change from Aircraft Commander A to Aircraft Commander B, they were to conduct a mountain training sortie for the Student Pilot and Student Crewman. Witness 8 Exhibit 8

1.3.15. **Planning**. Co-ordination of the plan was delegated to Aircraft Commander B. Sortie planning was initially conducted by Aircraft Commander B, then by the Duty Executive, who was scheduled to fly the sortie, and lastly handed to Aircraft Commander A who actually flew the sortie on the day of the accident. Exhibit 9 Witness 9 Witness 4

1.3.16. **Published weather**. The synoptic situation was a slightly unstable polar maritime air mass. The Area Forecast showed the 2000 ft temperature as 8ºC and wind 20 kts from 310º.[5] Cloud base was 1500 ft becoming 2500-3000 ft during the period. The Met Office mountain weather forecast for the wind in the Snowdon area was 17-22 kts gusting 26 kts. Exhibit 10 Exhibit 11

1.3.17. **Performance calculations**. Four out of the 5 crew independently calculated the performance figures using either the performance graphs or a computer program called Easyweigh. The calculated take-off weight was 11250 lbs. The aircraft could hover outside ground effect + 5% thrust margin at 11300 lbs, up to 4000 ft. The aircraft is considered to be 'Safe Single Engine' (SSE) if it can maintain safe flight in the event of an engine failure. The SSE figures calculated for the day were; Inside Ground Effect (IGE) at 10372 lbs, and Outside Ground Effect (OGE) at 9655 lbs at the summit of Yr Aran, which meant that the aircraft was not considered SSE.[6] Witness 2 Witness 3 Witness 4 Exhibit 12 Witness 8 Exhibit 13

---

[4] Magnetic plugs detect ferrous material in the transmission fluid as an early breakdown warning system. These had been designated as insignificant with no further rectification required.
[5] The Area Forecast is issued for a 25 km radius from RAF Valley and is valid between 0600Z and 1800Z. All heights are in feet (Above Mean Sea Level).
[6] Aircraft figures calculated for the met conditions at the top of the mountain.

1.3.18. **Briefing**. The crew conducted a "MATE brief"[7] which was split into two parts. Aircraft Commander B led the training sortie brief at 1200 hrs and Aircraft Commander A led the tasking sortie brief at 1215 hrs for an anticipated lift time of 1300 hrs.	Witness 8 Witness 4
1.3.19. The Student Pilot briefed the meteorological conditions, airspace, NOTAMs[8] and air traffic details. A technical brief[9] was completed by the Student Crewman followed by the performance figures. The crew discussed that they would not be 'Safe Single Engine' in the hover for a large part of the sortie including at the top of the mountain. The requirement for immersion suits was discussed, noting that lakes often provide the flattest area on which to land in an emergency over mountainous terrain. The Student Pilot briefed the route and Aircraft Commander B stated that this would be a 'tutorial' as it was the first time the students had been into the Mountain Flying Training Area (MFTA)[10]. An emergencies brief was carried out.[11] The emergency of the day was "Single Engine Failure". Escape routes, the need to regularly keep the crew updated, and lastly mountain flying techniques were discussed.	Witness 3 Witness 2 Witness 8 Witness 2
1.3.20. Aircraft Commander A joined the crew at the end of the instructional sortie brief to complete the tasking sortie pre-flight brief. The tasking was explained, noting that although it included flying in the mountains, it did not form any part of the student pilot's instructional mountain sortie. Nevertheless, any appropriate airmanship or experience points would be passed on. It was reiterated by Aircraft Commander A that during the task, the aircraft would not be Safe Single Engine and there would be regular updates of escape routes. A separate emergencies brief was carried out, where it was stated that for emergencies, Aircraft Commander B would sit in the 'jump seat'[12] and assist any emergency by reading the Flight Reference Card (FRC) actions. The Student Pilot's role was to assist and lookout.	Witness 2 Witness 4
1.3.21. **Authorisation**. Both sorties were self-authorised. It was standard practice to self-authorise for course syllabus sorties and Aircraft Commander A self-authorised because he believed that because it was a field landing site, that he should authorise the sortie. Consideration was given to changing the crew composition to avoid the need to self-authorise. However, Aircraft Commander A decided that, on balance, self-authorisation was preferable.	Exhibit 8 Annex A Witness 4
1.3.22. **Outbrief**. Following the authorisation, Aircraft Commander A conducted an out-brief with the 202 (R) Sqn Duty Aviator[13] using the designated format on the Operations desk.[14] The Sqn Duty Executive was also briefed on the task by Aircraft Commander A but was already familiar with the details, having originally been scheduled to fly the sortie.	Witness 4 Witness 9

---

[7] "MATE brief" is the term used for a standardised briefing format consisting of the topics: Meteorological conditions, Air Traffic, Technical details and Execution. This represents guidance provided in Regulatory Article 2305(5).

[8] NOTAM (Notice to Airmen) is a notice filed with an aviation authority to alert aircraft crews of potential hazards along a flight route or at a location that could affect the safety of the flight.

[9] The technical brief includes all aircraft technical details and any equipment faults or considerations.

[10] The MFTA delineates Snowdonia and is a method of utilising the area in an efficient and safe manner.

[11] A DHFS mnemonic WADFIR was used: Warning to the crew, Achieve safe flight, Diagnose the problem, FRC's, Intentions, Radio Call.

[12] The 'jump seat' is the seat just behind the cockpit and in between the two front seats. It has good visibility of the cockpit instruments and the actions of the crew.

[13] The Duty Aviator is given the out-brief, in accordance with 202 Sqn orders. Self-authorisation is discussed further in section 1.4.

[14] 202(R) Sqn Flying Order 2305, Annex F – 202(R) Sqn Outbrief.

Sortie Events

1.3.23. **Walk to the aircraft**. Aircraft Commander A and the Student Pilot walked to the aircraft and were joined by the remaining crew once the engines had been started. Pre-flight checks were conducted, followed by the abbreviated functional checks and Power Assurance Checks (PAC). Once these were complete, Aircraft Commander B walked to the aircraft and boarded.

Witness 2
Witness 4
Witness 8

1.3.24. **Seating positions**. Aircraft Commander A sat in the left hand cockpit seat and remained 'hands on'[15] the flying controls throughout the sortie. The Student Pilot sat in the right hand cockpit seat. The Student Crewman sat in the forward left hand cabin seat for take-off but was also on a dispatcher's harness.[16] Following take-off, the Student Crewman remained on the left hand side of the cabin to give relevant clearances. The Crewman Instructor was situated on the right hand side of the cabin on a dispatcher's harness throughout the sortie. Aircraft Commander B sat in the central, forward facing, cabin seat for take-off and was also on a dispatcher's harness. Once airborne, Aircraft Commander B moved to the right hand side rear cabin seat. Figure 2 depicts the respective crew seating positions.

Witness 4
Witness 2
Witness 3
Witness 5
Witness 8

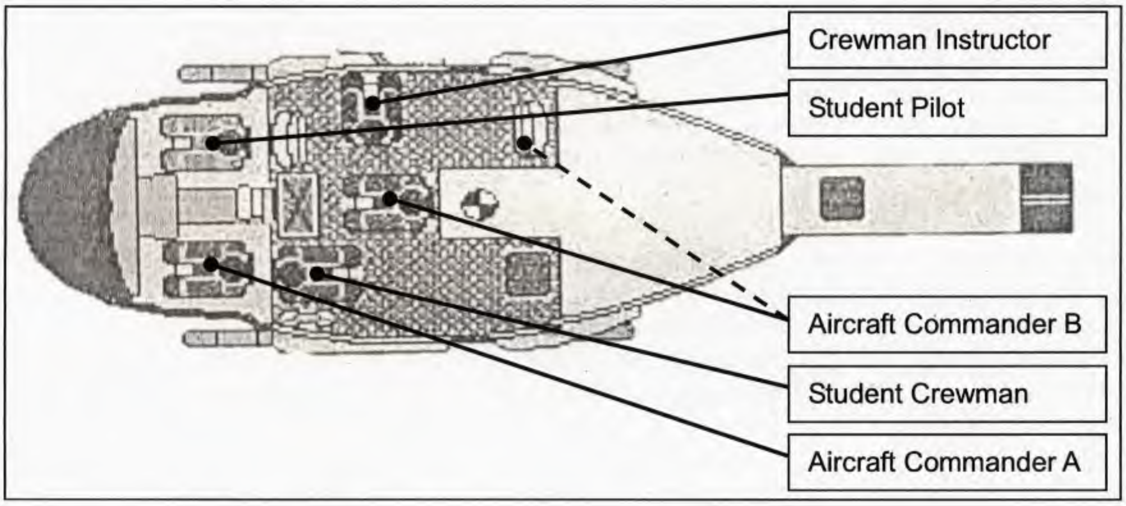


Figure 2 - Aircraft seating positions viewed from above.
(Picture Source: Easyweigh – modified)

1.3.25. **Take-off and departure**. On lift, torque was noted to be 75-80% and the aircraft departed RAF Valley via "East Gate"[17] with standard radio procedure used throughout: The crew communicated with "Valley Tower" on departure; then with "Valley Approach" on passing the Menai Straights.[18]

Witness 2
Witness 4

1.3.26. **Transit flight**. The transit to Yr Aran was via the Llanberis valley, climbing to approximately 1800 ft. A power check was carried out and it was noted that the aircraft

Witness 2

[15] 'Hands on' refers to which pilot is handling the aircraft.
[16] A dispatcher's harness fits around the crewmember's torso and allows secure movement via a variable length attachment to the airframe.
[17] Due to the mixed fixed wing and rotary operations, RAF Valley has a series of predetermined entry and exit gates for rotary traffic.
[18] Stretch of water separating Anglesey and the mainland.

was torque limited,[19] pre-landing checks were completed and airmanship points communicated to the student.[20] The last radio call to RAF Valley was made on "Valley Low Level", a quiet frequency, where 'operations normal'[21] calls are required every 45 minutes. The aircraft routed through the Llanberis valley during which identification of surface wind, funnelling, and surface wind versus wind at height comparisons were all discussed. The initial plan was to follow the Snowdon railway line as a steer towards Yr Aran, however the cloud base prohibited this. This prompted icing and 'inadvertent IMC'[22] considerations to be discussed while the aircraft routed clockwise around Snowdon to Yr Aran.

Witness 4
Exhibit 14
Witness 2
Witness 4

1.3.27. **Approach to the ridgeline**. On first sight of Yr Aran summit, a DHFS Squirrel helicopter was seen making an approach to the summit to drop off the Passenger. Aware that their aircraft was heavy, Aircraft Commander A elected to conduct an incremental assessment of conditions by making a separate approach to a lower point on the ridgeline to see how the aircraft felt. A 5-S recce[23] was conducted, a 'Bar-alt/Rad-alt' comparison made,[24] smoke was fired to assess the wind, and an academic approach flown to the 10 ft hover on the forward edge of the ridge. The demarcation line[25] was noted but did not affect the approach. Torque was noted to be 65% in the hover and the aircraft did not descend below 10 ft. As the aircraft transitioned away from the ridge, the Squirrel helicopter transmitted that it was departing.

Witness 4
Witness 4

1.3.28. **Approach to the pinnacle**. The crew remained visual with the Squirrel helicopter as it departed, until there was no longer a confliction. The aircraft was then flown overhead the peak of Yr Aran, where another 'Bar-alt/Rad-alt' comparison was made and another smoke canister deployed. Another 5-S recce was conducted and a circuit was flown, followed by a curved final approach from west to east along the ridge-line with wind remaining on the left until reaching the hover (Figure 3).

Exhibit 15
Exhibit 16

---

[19] A power check is conducted to confirm that within engine and torque limitations sufficient power can be generated by the engines. Torque is applied which increases engine power towards, but not above, engine temperature and speed limits while torque is monitored. In most temperate environments the torque limitation will be reached before engine limitations, this is described as being torque limited.
[20] Airmanship points included the MFTA layout and Caernarfon airstrip location and possible implications.
[21] An operations normal radio call is made to confirm that there are no problems and the sortie is continuing as planned and briefed.
[22] IMC or Instrument Meteorological Conditions are the weather conditions that necessitate flight by sole reference to the aircraft instruments. Entry is usually pre-meditated but inadvertent IMC can occur as a result of an emergency situation. Inadvertent IMC can also happen by accident when operating near cloud and in that case is considered an emergency situation.
[23] A 5-S recce is carried out prior to any field landing and includes size, shape, surrounds, surface and slope.
[24] The radio altimeter (Rad-alt) fluctuates while mountain flying due to the undulating terrain. The information it provides during an approach is therefore less useful to the pilot. The standard practice is to fly over the landing point and compare the radio altimeter reading to the barometric altimeter (Bar-alt) reading in order to get the exact height of the feature. The crew then use the Bar-alt figure as a reference while positioning the aircraft on an approach to a landing site.
[25] The demarcation line is where wind flow across the feature separates from a smooth laminar flow to turbulent air.

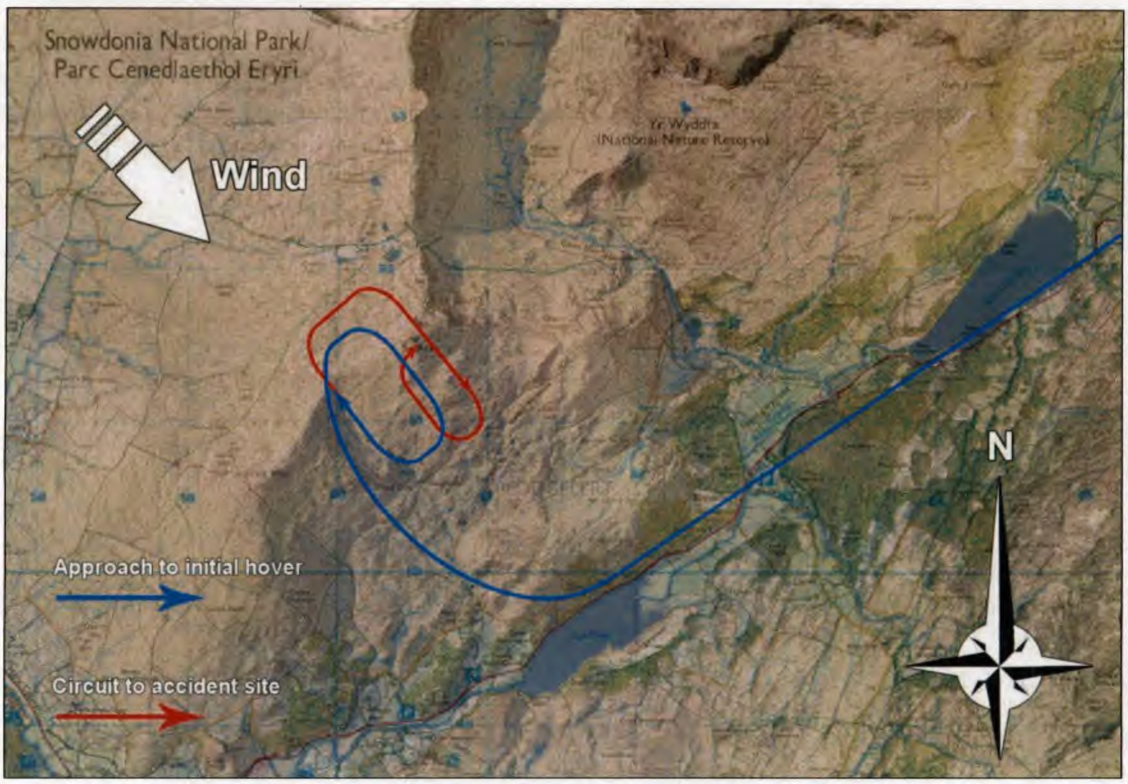


Figure 3 - Overview of Yr Aran and the aircraft flightpath.

1.3.29. The aircraft was flown on the upwind side of the ridge to stay in the up-draughting air. As planned, the aircraft slowed as it approached the landing site; wind from the left caused the aircraft to 'weather cock',[26] turning the nose of the aircraft to the left, into the wind. In the final part of the approach the aircraft was side-slipped to the right, with the tail being allowed to turn naturally down-wind.

1.3.30. **Manoeuvring in the hover**. The aircraft was brought to the hover on the leading edge of the ridge followed by confirmation of the torque figure. Aircraft Commander A selected a rocky outcrop on the left of the aircraft and distant mountains as reference features with which to hover.[27] The Crewman Instructor confirmed the intention to conduct a 'skids light'[28] landing and selected a suitable landing site in the low 2 o'clock of the aircraft. The aircraft was manoeuvred forward and right in the hover and clearance was given to descend to a low hover while updating the surface and slope aspects of the recce. Aircraft Commander A noted a slight rise in torque which was assessed as the increased shielding from up-draughting air. Some rocks were identified during the descent and at approximately 5 ft the tail was brought a little bit to the right to ensure that the skids were perpendicular to the slope. The Crewman Instructor gave several fine tuning marshalling

Exhibit 17
Witness 4
Exhibit 17
Witness 4
Exhibit 17

[26] 'Weather cocking' is a characteristic of most helicopters caused by the tail boom and the wind which tends to pivot the aircraft towards the wind. If the aircraft is hovered with wind from one side, it will naturally want to orientate into wind, this is weather cocking.
[27] Reference features or markers are usually distinctive enough to allow the pilot to judge movement of the aircraft and make fine adjustments to the position without looking at the instruments inside the cockpit.
[28] 'Skids light' means that as part of an expected sloping ground landing, the aircraft would not reduce its lift to zero and would remain 'power-on' at all times and able to make an immediate take off if needed.

commands to come half a unit to the left[29] to avoid a large rock. Witness 5

1.3.31. **Accident**. The rate of descent was normal as the front of the skids came into contact with the ground. Two sets of loud taps occurred after the skids touched the ground and severe vertical vibrations were felt through the airframe, enough to bounce the Crewman Instructor off the floor of the cabin. The Crewman Instructor suspected ground resonance, and initiated a missed landing procedure by calling for the pilot to come back up to the hover. Aircraft Commander A made a conscious decision that safe flight was no longer possible and a landing *in situ* was preferable. Aircraft Commander A remained 'hands on', while attempting to control the aircraft into a safe configuration. A fragment of the driveshaft coupling was ejected from the aircraft, to the right hand side in the 3 o'clock position, landing at the feet of the Passenger (Figure 4). With power removed from the main rotor blades, their speed reduced rapidly. Witness 4 Witness 5 Witness 4

Exhibit 18

Figure 4 - Fragment of driveshaft coupling found by the awaiting Passenger.
(Picture Source: Passenger)

1.3.32. Aircraft Commander A gave the order to shut down while simultaneously winding the throttles to idle and calling for the Student Pilot to activate the idle stops. The Student Pilot activated the idle stops allowing the throttles to be fully closed. After visually checking the aircraft for any obvious signs of damage to the tail, the Passenger picked up the fragment of driveshaft coupling and noticed the first sign of fire, emanating from the upper cowling just in front of the rotor mast. The Passenger indicated a fire to the crew Witness 4 Witness 2

[29] Horizontal voice marshalling instructions are given in units. The DHFS horizontal unit is 2 metres (Griffin Flying Guide, Exercise 14) so if a movement smaller than this is required the crewman request must either be a 'left/right one' followed almost immediately by a 'steady', or a 'half left/right'. This latter instruction is not included in the above reference but is used operationally to fine tune aircraft movement when required.

with standard hand signals. This information was communicated to Aircraft Commander A through the intercom. The number 2 engine T-handle[30] illuminated and was pulled by Aircraft Commander A. The Student Pilot also pulled both T-handles and Aircraft Commander A discharged both fire bottles into the engine compartment. The fire audio warning activated in-between the first and second engine shutting down but was not heard by the crew. The cockpit filled rapidly with thick smoke to the extent that the rotor brake could not be seen, which prevented completion of the shutdown checks. The extent of the fire approximately 5 minutes after initiation can be seen in (Figure 6).

Witness 1

Witness 2
Witness 4

Witness 2

Figure 5 - Aircraft fire approximately 5 minutes after the accident.[31]
(Picture Source: Aircraft Commander A)

Post Accident Events

1.3.33. **Egress from aircraft**. Aircraft Commander B first attempted to exit the aircraft after the onset of severe vibration but was restrained in the right hand cabin doorway by the dispatcher's harness, having forgotten to remove it. Aircraft Commander B was pulled back into the cabin by the Crewman Instructor who was concerned the aircraft might roll over. Shortly afterward, the harness was released and a successful exit was made to the right hand side of the aircraft. After exiting the aircraft, Aircraft Commander B noted that the tail rotor had already stopped while the main rotors were still turning. The Crewman Instructor initially tried to diagnose the fault and confirmed that the tail was intact. On initial exit the Crewman Instructor noted and picked up an unidentified yellow metal object on the cabin floor. On seeing the fire in the region of the main rotor mast, firefighting was prioritised and the object was placed back on to the cabin floor and not seen again. No

Witness 8

Witness 5

Witness 8

Witness 5

[30] A T-handle is a prominent cockpit console handle that signals by visual and audio means when a fire is detected in the aircraft engine bay. The handle is then pulled which, amongst other functions, closes the associated engine's fuel valve.
[31] Taken by Aircraft Commander A after the crew egressed, convened and moved away from the wreckage.

definitive instruction was given to abandon the aircraft; however the speed of onset of the vibration and rapidly deteriorating situation, combined with thick smoke, led the remaining crew members to make independent decisions to exit the aircraft almost simultaneously. The Student Crewman exited the aircraft at a similar time to the Student Pilot. Aircraft Commander A was momentarily restrained by his right hand shoulder strap, however, turning the Quick Release Fastener[32] a second time released the harness and an exit was made through the left hand cockpit door. The Crewman Instructor used the fire extinguisher beside the pilot seat in an attempt to extinguish the flames by reaching up to the top of the cowling. On seeing more extensive fire developing across the whole upper cowling and the lower rear portion of the cabin, the Crewman Instructor also moved away from the aircraft.

Witness 3
Witness 4
Witness 5

1.3.34. **Move to safety and crew recovery**. The crew initially moved a short distance away from the burning aircraft; several phone calls were made in this position to begin the notification processes. The Passenger called the DHFS Chief Flying Instructor (CFI), the Executive Flying Supervisor (EFS) and the Director Flying Training (DFT) while Aircraft Commander B called 202(R) Sqn Operations. The crew assessed that there was still a risk of injury due to the fire and the hissing and popping noises coming from the wreckage. The crew and Passenger then moved down the ridge and beyond line of sight of the aircraft. Two walkers were encountered as they descended who were advised to proceed no further up the hill. The same advice was repeated to 4 dry-stone wall builders shortly afterward. An air ambulance, "Helimed 61", arrived at the accident site at 1400 hrs and the crew were assessed for injuries. The first 4 were air-lifted to the Nant Peris Mountain Rescue hut in pairs. The SAR aircraft from St Athan, "Rescue 187", then arrived and recovered the remaining 2 people (Aircraft Commander A and Passenger) to the same location. Subsequently DHFS Squirrel aircraft transferred the crew and Passenger back to RAF Valley and RAF Shawbury respectively.

Witness 2
Witness 2
Exhibit 227
Witness 1

Post Occurrence Management

1.3.35. **202(R) Squadron response**. No radio calls were sent from the crew prior to egress, due to the rapid onset of the accident sequence. The initial notification to 202(R) Sqn came via mobile phone from Aircraft Commander B at 1342 hrs and Station Operations were notified by 202(R) Sqn Ops immediately after. 202(R) Sqn Ops room initially treated the accident as a 'downbird',[33] on the basis of the first information received, but later upgraded to a 'crash' once further information became available. The Duty Aviator notified civilian emergency services and Mountain Rescue at 1357 hrs. At 1415 hrs the DHFS EFS at RAF Shawbury was notified. At 1447 hrs the Duty Aviator spoke with 60(R) Sqn and recommended a recall of their Griffin aircraft as a precautionary measure in case of an aircraft type issue. This was agreed and all UK-based Griffin were on the ground by 1516 hrs. At 1608 hrs the Duty Executive was called across to the Station Emergency Coordination Cell (ECC) which had been activated and located initially within Station Operations. Examinations at the Medical Centre were completed by all crew members on their return and individual statements were made and relevant equipment quarantined.

Exhibit 19
Witness 9
Exhibit 19
Witness 9
Exhibit 20
Exhibit 19
Exhibit 21

1.3.36. **RAF Valley response**. ATC were made aware of a 'downbird' almost

[32] Quick Release Fastener (QRF) is the name given to the buckle on the five point harness that releases all straps simultaneously in the event of an emergency.
[33] Downbird is an "Aircraft being forced to land with a minor unserviceability or limiting event, away from base" SHY FOB Order 2425 Annex A

immediately by 202 Sqn; this was communicated around ATC and initially was not considered an emergency. Following confirmation that the crew were safe, the Senior Air Traffic Control Officer (SATCO), as Acting Officer Commanding Operations (OC Ops), began the notification process. ATC and OC Ops became aware of the magnitude of the situation after 1355 hrs when Helimed 61 arrived on scene and described ZJ241 as being destroyed by fire. At this point the incident was treated as a crash and the Crash Support and Major Incident Plan (CSMIP) was followed. It was decided between Squadron Leader Operations (SLOps) and SATCO that there were insufficient personnel to resource a separate ECC, therefore a pseudo ECC was set up in Station Operations. SLOps, as the qualified Post Crash Management Incident Officer (PCMIO), then deployed to the accident site. Witness 15 Witness 15 Exhibit 22

1.3.37. The Mountain Rescue Team Warrant Officer had been contacted via text from the civilian Llanberis Mountain Rescue Team Leader informing him of a crash in the Snowdonia area. After confirming via the Maritime and Coastguard Agency (MCA) and Aeronautical Rescue Coordination Centre (ARCC) that the incident involved a military aircraft and in lieu of any formal tasking, he then tasked RAF Valley and RAF Leeming Mountain Rescue Teams (MRT) to attend. The first members of these teams were flown to the site by "Rescue 936" (HM Coastguard S92 helicopter) by 1549 hrs to relieve the Llanberis team. The remaining Valley MRT walked to the site. Following arrival of the PCMIO at the Incident Command Post (ICP), it was decided that due to terrain and weather the MRT would form the guard force for the crash site. Exhibit 23 Exhibit 24

1.3.38. Over the following six days the ECC coordinated support for those in the field while the aircraft wreckage was catalogued and packed for removal by the Joint Aircraft Recovery and Transportation Squadron (JARTS). DHFS gave helicopter support in the form of a Squirrel helicopter for movement of people to the site and Mobile Air Operations Team (MAOT) personnel prepared for the arrival of a recovery aircraft. The RAF Regional Liaison Officer (RAFRLO) began communications with the landowner (The National Trust). The fuel samples taken at RAF Valley were declared clear on Friday 12 Aug 16. Exhibit 25

1.3.39. **Other responses**. The ARCC received its first notification of an incident at 1346 hrs but due to "Rescue 936", the Caernarvon based rescue helicopter, already undertaking another task, scrambled the St Athan based "Rescue 187". Exhibit 26

Accident Investigation

1.3.40. **Initial investigation**. DAIB operations investigators arrived at RAF Valley on the day of the accident having interviewed the Passenger earlier at RAF Shawbury, and interviewed all of the crew the following day. DAIB Engineering investigators arrived at the accident site with the Mountain Rescue Team and RAF Valley photographer in order to preserve perishable evidence such as oils and fuel samples. The cockpit, cabin and gearbox structures were destroyed by the fire with only the tail boom and tail rotor remaining intact. Several items were found outside the immediate area of the wreckage. Due to the collapse of the engine and gearbox, the CVR was buried and could not be retrieved until the main wreckage was removed on the 16 Aug 2016. The Service Inquiry Panel arrived on 17 Aug 16 and viewed the accident site for situational awareness. Exhibit 28

1.3.41. **Salvage operations**. Poor weather prevented wreckage recovery until Monday 15 Aug 16. The wreckage was contained within a relatively small area and this made identification easy, however the only method of recovery was by CH47 Chinook helicopter due to the remote location. Personnel from JARTS worked under the direction of the DAIB Engineering Investigators to cut the wreckage down to a size, shape and weight to enable relocation of the wreckage via underslung load. The remainder of the smaller components of the aircraft were collected into bags and labelled by location. The wreckage was ultimately relocated to MOD Boscombe Down. Exhibit 25

Figure 6 - Aircraft wreckage recovery.
(Picture Source: DAIB Engineering)

Damage to the aircraft, site and civilian property

1.3.42. **Damage to aircraft**. The damage to the aircraft was beyond economical repair. Exhibit 18

1.3.43. **Damage to the accident site**. The accident occurred on National Trust land which was also a Site of Special Scientific Interest (SSSI). There was a blackened patch of ground directly beneath the aircraft which did not extend beyond a few metres from the helicopter which also contained traces of oil and fuel. Molten metal components flowed a short distance down the hill before solidifying. This had to be dug out of the ground causing some superficial damage to the soil. The Recovery Site Clearance Certificate was signed-off on 26 Aug 16 when the accident site was surveyed by the National Trust. They deemed it preferable to leave the site as it was to allow it to regenerate, and also that there was no risk to public health. Exhibit 27

Intentionally Blank

PART 1.4

Analysis and Findings

Intentionally Blank

PART 1.4 – TABLE OF CONTENTS

INTRODUCTION **1**

METHODOLOGY **2**

Accident factors 2
Australian Transport Safety Bureau (ATSB) Analysis Model 2
Human Factors (HF) modelling 4
Available evidence 4
Services 6

BACKGROUND **8**

Context 8
Aircrew experience and crew composition 9
Planning and preparation 11
Authorisation 12
Supervision 13

DETERMINING THE CAUSE OF THE ACCIDENT **15**

Site analysis 15
Accident timeline 21
Main drive shaft coupling misalignment 29
Main gearbox movement 34
Main gearbox support case failure 39
Introduction to failure modes 49
Gearbox support case overload 49
Gearbox support case fatigue damage 58
Gearbox support case fatigue crack initiators 65
Main gearbox assembly and airframe history 66
Fire 72
Summary of determining the cause of the accident 78

ADDITIONAL FACTORS INVESTIGATED **79**

Weather 79
Landing site suitability 83
Workload 84
Structural integrity management 85

ORGANISATIONAL FACTORS **96**

Air safety management 96
Risk management and safety oversight 105
Military Registered Civilian Owned (MRCO) construct 109
Accident Overview 110

FACTORS NOT DIRECTLY RELATED TO THE ACCIDENT **112**

Crew composition 112
Knowledge of sloping ground limits 113
Flight Data Recorder (FDR) and Health Usage Monitoring System (HUMS) 113

Airframe configuration control 114
Automatic Flight Control System (AFCS) fault code management 114

POST OCCURRENCE MANAGEMENT 116

COST OF LOSS TO THE SERVICE 119

SUMMARY OF FINDINGS 120

PART 1.4 – ANALYSIS AND FINDINGS

All times local (Zulu plus 1 hour).

INTRODUCTION

1.4.1. On 9 August 2016 at approximately 1334 hours (hrs) a Griffin HT Mk1 (Griffin) helicopter, registration ZJ241, was involved in an accident on the peak of Yr Aran mountain in Snowdonia, North Wales. The accident occurred as the aircraft touched down next to the awaiting passenger and resulted in the loss of the aircraft by fire following assessed structural failure of the gearbox support case. However, the 5 crew and passenger escaped without injury. The Defence Accident Investigation Branch (DAIB) deployed to the scene and the Director General of the Defence Safety Authority convened this Service Inquiry on 16 Aug 2016 to investigate the circumstances surrounding the accident and to make recommendations in order to prevent reoccurrence.

1.4.2. ZJ241 was a civilian owned Bell 412 EP aircraft on the Military Aircraft Register (MAR). Cobham Helicopter Services (Cobham) were the owner and maintenance organisation for the aircraft, and provided the aircraft to the Defence Helicopter Flying School (DHFS) at RAF Shawbury and RAF Valley. The crew were a mixture of civilian, RAF and Royal Navy personnel who provided an account of the accident sequence. Although the aircraft was largely destroyed by fire, it was fitted with a Cockpit Voice Recorder (CVR) which was recovered despite being badly damaged. As a result, there was limited available evidence and the circumstances of this accident were not straightforward. However, the Panel was able to establish 2 possible reasons for the accident which were explored to provide recommendations to enhance Defence Air Safety.

Figure 1 - Bell 412 EP (Griffin HT Mk1), registration ZJ241.
(Picture Source: RAF Valley)

METHODOLOGY

Accident factors

1.4.3. Once an accident factor had been determined it was assigned to one of the following categories:

a. **Causal factor**. An event which in isolation or in combination with other factors and contextual details, led directly to the accident.

b. **Contributory factor**. A factor which made the accident more likely.

c. **Aggravating factor**. A factor which made the outcome worse.

d. **Other factor**. A factor which was none of the above, but was noteworthy in that it may cause or contribute to future accidents.

e. **Observations**. An issue that was not directly relevant to the accident but worthy of consideration to promote better working practice.

Australian Transport Safety Bureau (ATSB) Analysis Model

1.4.4. The ATSB model (Figure 2) was used for the Service Inquiry because of the complex interaction between a number of factors, the technical nature of the investigation and the importance of the sequence of events. The ATSB investigation analysis model is an adaptation of James Reason's[1] Swiss Cheese Model. It presents the components of the model, as a series of levels of potential safety factors. The model was broadly implemented from bottom to top during the investigation, asking a series of strategic questions for each level. Exhibit 213

[1] Reason, J. (1990). Human Error. New York: Cambridge University Press

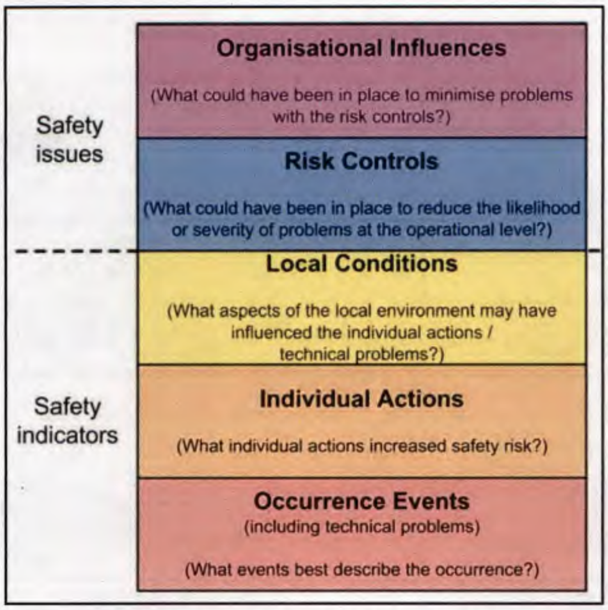


Figure 2 - ATSB accident model.[2]

1.4.5. Occurrence events are the key events that describe 'what happened' and include technical events. Individual actions are the observable behaviours of operational personnel, which include flight crew, crewmen and maintenance personnel. Local conditions are those conditions which exist in the immediate context or environment in which the event occurred. Risk controls are the measures put in place to facilitate and assure safe performance of the system and can be considered barriers in a 'bow tie analysis'.[3] Organisational influences are those conditions that establish, maintain or otherwise influence the effectiveness of an organisation's risk controls. An accident diagram was produced using the ATSB accident model to display the interactions between factors and other relevant events that were identified during the inquiry (Figure 52).

1.4.6. **Probability expressions**. The use of probability expressions in the Service Inquiry was modified from the ATSB approach (Figure 3). The purpose of formally introducing verbal probability expressions was to improve the consistency and communication of investigation findings. The choice of expression remained a matter of judgement by the Panel and provided an indication of meaning based on common usage and understanding. The terminology should therefore be thought of in terms of relative meaning within the report rather than a precise measurement of probability. Other expressions were not excluded from the discussion but avoided unless there was a specific requirement to articulate particular nuances. For a factor to be considered as contributory and potentially leading to a conclusion or recommendation, its probability was required to be at least 'likely' by the Panel.

[2] Figure 2 was sourced from https://www.atsb.gov.au/media/27767/ar2007053.pdf

[3] Bowties are one of many barrier risk models available to assist the identification and management of risk. For example: https://www.caa.co.uk/Safety-initiatives-and-resources/Working-with-industry/Bowtie/About-Bowtie/Introduction-to-bowtie/

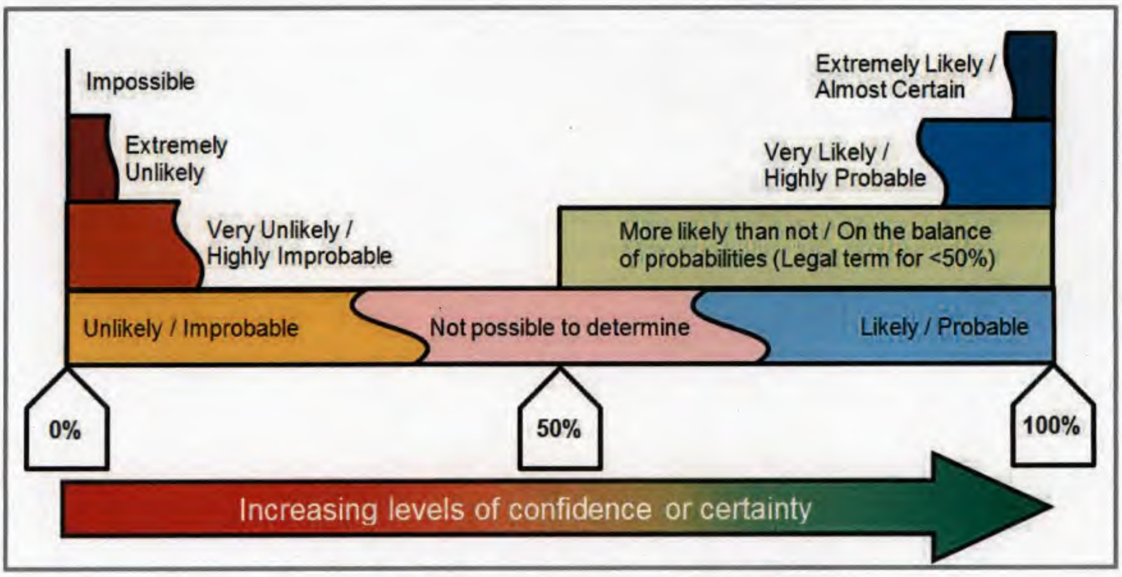


Figure 3 - Probability expressions used in this Service Inquiry.
(Source: DAIB)

Human Factors (HF) modelling

1.4.7. Specialist advice was provided by the Royal Air Force Centre for Aviation Medicine (RAFCAM) to ensure that HF aspects were suitably considered. This advice was provided based on the Accident Route Matrix (ARM) approach. The ARM was developed by RAFCAM based on the systematic and validated framework of the Human Factors Analysis Classification System (HFACS), which is based on James Reason's Swiss Cheese Model, and experience of providing HF advice to over 60 accident and incident investigations. Exhibit 29

1.4.8. RAFCAM adapted HFACS for use during the investigation, by analysing the type of HF issue, the time of effect, and the impact of that issue in the accident sequence. The aim of the ARM was to identify which issues, and at which point each issue, increased the risk of hazard entry, recovery, escape, and survival. The approach used in the SI considered the broad range of HF contributors to aviation accidents including: Organisational factors; the nature of the supervision and tasks undertaken; the equipment used; the operating environment as well as individual actions and the condition of operators involved in the accident. The conclusions from the HF report were incorporated into the broader investigation. Exhibit 29

Available evidence

1.4.9. The Panel had access to a significant volume of evidence which included:

1.4.10. **Interviews**. The Panel interviewed 24 people during the course of the investigation and recorded statements were taken. Witnesses included:

a. The crew and Passenger.

b. The Duty Executive.

c. The Chain of Command.

d. Defence Helicopter Flying School (DHFS) pilots.

e. 202(R) Sqn Engineers.

f. Civilian and Military Continuing Airworthiness Manager (CivCAM) and (MilCAM).

g. The Air Safety Manager (ASM).

h. The Type Airworthiness Authority (TAA).

i. A helicopter structural integrity specialist.

1.4.11. **Aircraft data**. Cockpit data included: Partial Cockpit Voice Recorder (CVR) data from the accident aircraft, ZJ241; comparative (non-accident) CVR recordings and "Vision 1000"[4] data from ZJ240 and ZJ241. The CVR normally provides a continuous record of the main rotor speed and sound from the cockpit area microphones, and intercom on 7 channels. High quality channels recorded the last 30 minutes of flight and the low quality channels and main rotor speed channel recorded the last 127 minutes.

1.4.12. **Photographic imagery**. Images taken by the crew, the awaiting Passenger, rescue services, members of the public and Defence Accident Investigation Branch (DAIB) investigators.

1.4.13. **Video imagery**. Video evidence from helicopter rescue services.

1.4.14. **Publications**. A range of publications including policy documents, flying logbooks, and other documentation within the Aircraft Document Set (ADS). Original Equipment Manufacturer (OEM) manuals and documents.

1.4.15. **Aircraft wreckage**. Physical examination of ZJ241 at the accident site, and once recovered, within a secure hangar.

1.4.16. **Equipment**. Physical examination of ground support, servicing equipment and vehicles.

1.4.17. **Visit to aircraft manufacturer**. The Panel visited Bell's accident and investigation department for specific engineering data and discussion. Bell provided a number of reports including factual observations of the wreckage, previous accident data, engineering data, technical documents, a CVR report and answered a number of technical queries.

1.4.18. **Specialist reports**. The Panel received the following reports:

a. Defence Accident Investigation Branch (DAIB) provided a safety

[4] Vision 1000 is a flight data recording solution that captures attitude, GPS position and cockpit imaging.

investigation report, including CVR technical analysis drawn from a number of experienced and competent independent experts and industry experts.

b. 1710 Naval Air Squadron (NAS) provided forensic, scientific and engineering reports which included: Spectral (frequency) analysis of the CVR; drive shaft report and analysis of other specific components.

c. RAFCAM provided a HF report.

d. 42 Engineer Regiment (Geographic) provided a detailed terrain survey to provide site slope data.

e. Pratt and Whitney provided a limited boroscope[5] analysis of the engine, CVR analysis, and responded to technical queries.

f. RAF Valley Aircraft Post Crash Management Incident Officer (APCMIO) provided a report.

1.4.19. **Expert advice**. The Panel consulted the following specialists:

a. Bell Air Accident Investigators.

b. Pratt & Whitney Accident Investigators.

c. Rotary Wing Test and Evaluation Squadron (RWTES) Griffin Test Pilots.

d. A helicopter structural integrity specialist.

e. Civilian Aviation Authority (CAA) staff.

1.4.20. **Griffin simulator**. A number of representative profiles were flown at RAF Shawbury in order to understand handling characteristics and emergency drills.

1.4.21. **Air safety documentary material**. Access to all flight safety related material extracted from the Military Aviation Authority (MAA) Manual of Air Safety, Air Safety Information Management System (ASIMS) and Defence Air Safety Occurrence Reports (DASORs). Previous UK and international accident reports were obtained from the National Transport Safety Board (NTSB), Canadian Armed Forces, ATSB and Spanish accident investigations.

Services

1.4.22. The Panel were assisted by the following personnel and agencies:

a. Duty Holders / Aircraft Operating Authority.

b. DAIB.

[5] A boroscope is an optical device consisting of a rigid or flexible tube with an eyepiece on one end.

c. RAFCAM.

d. 1710 NAS.

e. Civilian Air Accident Investigation Branch.

f. Bell Helicopter Textron.

g. Joint Aircraft Recovery and Transportation Squadron (JARTS).

h. RWTES.

i. QinetiQ.

j. Special Projects Multi-Air Platforms (SPMAP) Project Team.

k. CAA.

l. Heliwork Services Ltd.

BACKGROUND

Context

1.4.23. **Bell 412 EP history.** The Bell 412 is a derivative of the early design of the Bell UH-1H, or "Huey", which later became the twin engine version Bell 212. The Bell 412 allowed greater speed and range, providing wider civilian utility.[6] The Bell 412 EP was introduced as an Enhanced Performance model, which included some updates to the transmission, engines and flight systems, yet the structure and specifically the main gearbox support case remained the same as the early Bell 212. In response to a Canadian Defence requirement, Bell developed a sloping ground 'kit' to increase the sloping ground limit from 4° to 10° by reducing the life of some components.[7] The Griffin HAR Mk2 variant added a FLIR[8] turret and radar increasing its search and rescue capability. Annex G Exhibit 30

1.4.24. FBS Ltd / Bristows, originally purchased 9 Bell 412 EP (Griffin HT Mk1) aircraft in 1997, including ZJ241, and a further 2 were purchased in 2002, all of which were embodied with the slope landing enhancement. They were contracted for use by the DHFS at RAF Shawbury with three permanently based at RAF Valley for mountain and maritime training. Subsequently 4 HAR Mk2s were also purchased in 2002, 3 of which were stationed in Cyprus and one at MOD Boscombe Down at the time of the accident. Exhibit 31

1.4.25. **Aircraft utilisation**. The Bell 412 was chosen to fulfil the role of a twin engine training aircraft for DHFS, as it was capable of all the flight regimes required for basic and intermediate helicopter training. This included: instrument flying, general handling, sloping ground operations, medium and low level navigation, night flying, night vision device training, confined area operations, under-slung loads and formation flying. Additionally, when operating from RAF Valley it was also used for mountain flying, winching from decks, cliffs and the sea. The aircraft was to be flown in accordance with the Rotorcraft Flight Manual (RFM) provided by Bell helicopter. The RFM was derived from the design and test parameters. The design parameters were derived from the Design Usage Spectrum (which contain design usage assumptions), and are used to determine the limitations of the aircraft. Bell promulgated the information they considered relevant from this process to aircrew and engineers in the RFM and Maintenance Manual. Exhibit 46 Exhibit 198

1.4.26. **Military Registered Civilian-Owned (MRCO) aircraft**. The Griffin fleet is owned by Cobham and is on the Military Aircraft Register (MAR). The aircraft were transferred to the military register to enable military pilots to deviate from the Air Navigation Order, in particular to meet the need of DHFS flying. The MRCO construct was designed to enable more efficient training, operations and engineering for the MOD. Witness 22

---

[6] https://www.bellhelicopter.com

[7] Slope landing envelope expansion due to installation of Slope Landing Retrofit Kit, BHT-412-SI-62, Bell Rotorcraft Flight Manual Supplement , BHT-412-FMS-61.3 and 61.4 The kit reduces the life of the Rotor Mast from 10 000 hrs to 5000 hrs and the Main Rotor Yokes from 5000 to 4500 hrs.

[8] Forward Looking Infrared (FLIR) cameras sense infrared radiation, typically emitted from a heat source, to create an image.

1.4.27. **Operation on the military register**. MRCO aircraft are required to comply with both EASA regulations and Military Regulatory Publications (MRP) regulations. These describe the operation and maintenance of the aircraft, including the Duty Holder safety plans. The MRCO contract is owned by No 22 Gp and is overseen by the Type Airworthiness Authority (TAA), responsible for 'continued airworthiness',[9] within the Special Projects Multi-Air Platforms Project Team (SPMAP PT). The No 22 Gp MilCAM is responsible for 'continuing airworthiness'[10] supported by the Cobham CivCAM in accordance with CAA and MAA regulations. Air Officer Commanding (AOC) No 22 Gp acts as Operating Duty Holder (ODH). The ODH is legally accountable for the safe operation, continuing airworthiness and maintenance of systems in their area of responsibility and for ensuring that the risk to life is reduced to at least tolerable and As Low As Reasonably Practicable (ALARP). The contracting of maintenance and some training has shown other benefits, such as low capital costs, which make it an increasingly popular way of operating other MOD aircraft. For the DHFS contract it was decided in 1997 to translate the information from the RFM into the military format of documents. This comprised of an Aircrew Manual, Flight Reference Cards and the Release to Service (previously the Military Aircraft Release); these were translated by FB Heliservices (FBH) (now Cobham), DHFS Standards, and the Release to Service Authority respectively. This was to ensure that both military and civil requirements would be met and that military aircrew would be presented with a familiar document format.

Exhibit 32
Annex F
Exhibit 225
Witness 22

Aircrew experience and crew composition

1.4.28. **Aircraft Commander A**. The aircraft commander was a Qualified Helicopter Instructor (QHI). Aircraft Commander A had completed 2 operational SAR tours prior to the QHI course, followed by an instructional tour at RAF Shawbury. Aircraft Commander A completed a conversion to the Griffin helicopter and was awarded his Competent to Instruct (CtoI) in April 2015. Aircraft Commander A had 3044:15 flying hours of which 354:00 hours were on the Griffin and 490:00 were instructional.

Exhibit 33

1.4.29. **Student Pilot**. The Student Pilot completed the Single Engine Rotary Wing (SERW) course at RAF Shawbury and was part way through the Maritime OCU Lead-in Course (MOLIC). The accident sortie was the student's first mountain flying experience. He had a total of 190:20 flying hours of which 15:15 were on the Griffin.

Exhibit 34

1.4.30. **Crewman Instructor**. The Crewman Instructor was a Cobham employed Qualified Helicopter Crewman Instructor (QHCI). Previously a Royal Navy aircrewman, the Crewman Instructor joined the Search and Rescue Training Unit (now 202(R) Sqn) in 1997 and had a total of 7606:05 flying hours of which 2291:25 were instructional and 3795:40 on the Griffin.

Exhibit 35

1.4.31. **Student Crewman**. The Student Crewman had completed 22 sorties of the Joint Observer Lead-in Course (JOLIC). The course was the first exposure to rotary aircraft and the accident sortie was the first mountain flying instructional sortie of the course. The Student Crewman had a total of 110:50 flying hours, of which 32:10 were on the Griffin.

Exhibit 36

[9] Continued airworthiness encompasses all the actions associated with the upkeep of a type design and the associated approved data through life. Source: MAA02 glossary [MAA, 2016].
[10] Continuing airworthiness encompasses all of the processes that ensure, at any time in its operating life, the aircraft complies with the airworthiness requirements in force and is in a condition for safe operation. Source: EC1321/2014 Article 2 [EC, 2014].

1.4.32. **Aircraft Commander B**. Aircraft Commander B spent 7 years on 815 Naval Air Squadron flying the Lynx before completing the QHI course in November 2014 and then became an instructor at 202(R) Sqn. Aircraft Commander B had 2110:50 flying hours, 314:35 on the Griffin and 97:10 instructional. Exhibit 37

1.4.33. **Passenger**. The Passenger was a Qualified Helicopter Instructor. He had a total of 2190:00 flying hours which included mountain flying experience in the UK, Bosnia and Afghanistan. Exhibit 38

1.4.34. **Aircrew qualification, currency and competency**. All three instructors were qualified and within their Instructor Competency Check currencies. Recent crew flying hours and previous mountain flying sortie dates confirmed that all crew were current in accordance with regulations (Table 1). Exhibit 39 Exhibit 40 Exhibit 41

	Aircraft Cdr A	Aircraft Cdr B	Crewman Instructor	Student Pilot	Student Crewman
Hours flown in previous 31 days	15:15	20:00	07:35	08:25	15:25
Date of last mountain flying sortie	21-Mar-16	27-Apr-16	15-Apr-16	n/a	n/a

Table 1 - Crew currency data derived from STARS.[11]

1.4.35. **Aircrew fatigue**. The Panel considered the potential fatigue implications of the crew and other relevant individuals. The Sqn was running a period of night flying and in order to facilitate efficient programming, the aircrew were on night routine with the daily brief conducted at 1100 hrs. Operating a routine of this nature goes against the natural bodily circadian rhythm[12] and requires closer management. The accident sortie was at the start of a shift so issues arising from a long period of being awake were not present. All the crew positively asserted that they were fully rested and alert for the sortie and there was no evidence to the contrary. The Panel concluded that there were no aircrew fatigue related issues. Witness 4 Witness 3 Witness 2 Exhibit 29

1.4.36. **Summary of aircrew experience and crew composition**. The crew was a mixture of the two ends of the experience spectrum. The Sqn's main activity of teaching new pilots necessitated experienced pilots as instructors. All of the instructors had a wide experience that included multiple aircraft types and environments. In contrast, the students were not qualified on the aircraft type by virtue of their attendance on the course. The disparity between the levels of experience meant that their instructors might expect to complete more of the flying tasks than usual. The higher workload was an expected part of being an instructor, one that forms part of training and in the Panel's opinion was within the competency of the crew. The Panel concluded that aircrew experience and crew composition was reasonable for the content of the sortie and circumstances, and was **not a factor** in the accident.

[11] STARS is the computer program used for management of flying sorties and aircrew currencies.

[12] A circadian rhythm is a roughly 24 hour cycle in the physiological processes of living beings.

Planning and preparation

1.4.37. **Task**. The task was conceived during a DHFS Executive meeting and was kept secret from the Passenger who was finishing a tour of duty at DHFS. The task was designed to coincide with a pre-arranged meeting the Passenger was attending in Betws y Coed and was intended to be followed by a leaving meal. Aircraft Commander A also planned to attend the meeting. Exhibit 9 Witness 4

1.4.38. The DHFS Chief Flying Instructor confirmed that Staff Continuation Training (SCT) was being conducted in the mountains that would provide transit for the Passenger to the area in a DHFS Squirrel. In addition the date coincided with the mountain flying phase for 202(R) Sqn and they were able to support a passenger move within the Mountain Flying Training Area (MFTA) with negligible change to scheduled flying training. Exhibit 9 Witness 4

1.4.39. The Passenger would be dropped by Squirrel at a designated location within the MFTA and subsequently picked up by a Griffin to be flown to the meeting. Sortie planning for the Squirrel was conducted by another instructor at 660 Sqn and then by the Aircraft Commander of the Squirrel. Within 202(R) Sqn, co-ordination of the task and sortie planning was delegated to Aircraft Commander B, then the Duty Executive and lastly Aircraft Commander A who also flew the sortie. Despite a large number of different people being involved in the task planning and the unusual nature of the task, the Panel considered the manner in which it was to be conducted was reasonable. Witness 17 Witness 8

1.4.40. **Landing site booking**. Landing sites away from base were required to be authorised and the permission of the landowner obtained. As a result of a CFS(H) Exam Wing visit to 202(R) Sqn in 2012, this order was highlighted and a list of regularly used landing site coordinates were passed to the Defence Infrastructure Organisation (DIO) in order to approach land owners for written permission. This was completed and an MFTA map produced showing the approved sites. Previously there had been blanket consent from the National Trust as landowner for much of Snowdonia, for landings to take place, and anecdotally Yr Aran had been used as a landing site for many years. DIO confirmed that the site at Yr Aran was not included on the approved list at the time of the accident. This was not picked up by any of the crew on the day of the accident, 202(R) Sqn in general or DHFS prior to the accident. The Panel **observed** that if a landing site within the Mountain Flying Training Area is to be used frequently it should be included in the Defence Infrastructure Organisation approved list of landing sites and annotated on the appropriate maps. Exhibit 42 Witness 4 Witness 7 Exhibit 43 Witness 9 Witness 17

1.4.41. **Aircraft performance**. The Panel considered what implications aircraft performance planning had on the sortie and if aircraft performance had been calculated correctly.

1.4.42. Performance calculations are completed prior to every sortie in order to inform the crew about the state of the aircraft in different phases of flight. The figures were calculated using two different methods: The first uses the Flight Reference Card (FRC) Operating Data graphs, which are replicated and expanded in size in the Squadron Operations Room. The second uses a computer program called 'Easyweigh', which allows input of the variables (weather, fuel, aircraft fit etc.) to produce a set of performance data more quickly. The Student Pilot and Student Crewman completed the performance figures using the two methods respectively. Aircraft Commander B had also calculated the figures and compared them to both students' figures and found them to be similar. Aircraft Commander A calculated the performance figures using the FRC method and made a Exhibit 13 Witness 2 Witness 3 Witness 8 Witness 4 Witness 2 similar comparison. The figures were very close in all cases. Aircraft Commander A also commented that if there was any margin of uncertainty that one should always round down for the worst case scenario. Exhibit 12 Witness 4

1.4.43. The weather data used for the performance figures were from the previous Meteorological Aerodrome Report (METAR), which was the most up-to-date information available to the crew. Usually a wind factor is also added to make the performance figures more accurate but was not done so in this instance because mountain flying requires a zero wind figure to be used. This is prudent in all circumstances where the wind is not uniform or predictable such as mountain flying. The Panel noted that in all aspects of planning the safest approach was taken which demonstrated good practice. Exhibit 44 Exhibit 45

1.4.44. A common performance assessment standard for military aircraft is the Thrust Margin available, which represents 'spare' power expressed as a percentage. A 5% thrust margin is often used as the minimum performance requirement and allows the aircraft to climb vertically from a free-air hover with both engines operating and was required throughout the accident sortie. The calculated aircraft performance for the accident site conditions was such that the aircraft was capable of achieving a twin engine Outside Ground Effect (OGE) hover +5% Thrust Margin at 11300 lbs. The briefed take-off weight was 11250 lbs, and the weight at the time of the accident, based on standard fuel burn, was estimated to be 10850 lbs. Therefore, the crew had better performance than the minimum for safe flight by a margin of 450 lbs. The crew completed the daily Power Assurance Check (PAC) prior to lift in order to determine if the engines could produce the specification power. Both engines passed these checks. Exhibit 226 Exhibit 12 Exhibit 46 Exhibit 12 Witness 2 Exhibit 47

1.4.45. **Summary of planning and preparation**. The Panel concluded that the task and planning was reasonable despite the number of people involved. Although the crew identified that they would not have single engine performance the twin engine performance was better than required for the task. The performance figures were calculated correctly and pre-lift checks confirmed that both engines were capable of producing the specification power. The landing site booking process could be improved but had no bearing on the accident. The planning and preparation for the sortie met the activities' objectives and was **not a factor** in the accident.

Authorisation

1.4.46. The accident sortie was a DHFS tasking to a field landing site. The Panel considered whether the sortie was appropriately authorised and if this was a factor in the accident. The Regulatory Articles state that, *"independent authorization, rather than self-authorization, is encouraged."* At 202(R) Sqn all instructors have the power to self-authorise instructional sorties. As a result, the majority of sorties flown at 202(R) Sqn were self-authorised. The Panel considered this reasonable given the highly controlled nature of the flying syllabus. For Staff Continuation Training (SCT) or other non-syllabus sorties, the flight is usually authorised by another authorising officer to allow oversight and additional scrutiny of any non-syllabus activities. The 202(R) Sqn authorisation matrix stated that 5 people had delegated powers to authorise a DHFS tasking. This should have been the case for this sortie but for the added complication that there was also a field landing site involved. Exhibit 9 Exhibit 48 Exhibit 49 Witness 9 Witness 4 Witness 9 Exhibit 49

1.4.47. The authorisation matrix stated that the only person who could authorise a field landing site when not a DHFS tasking was Aircraft Commander A. This meant that because the sortie was a DHFS task, it could still be authorised by any one of the other 5 Exhibit 49 people, despite also being a field landing site. However, Aircraft Commander A believed that because it was a field landing site, that he should authorise the sortie. There was also a perceived choice between Aircraft Commander A authorising the sortie and then flying as a passenger, or self-authorising. The latter was chosen because it was preferable not to be a passenger on the same flight that he had just authorised. Self-authorisation was not strictly necessary and led to a crew change during the planning phase. It also created the need to swap aircraft commanders at the drop-off point. Whilst crew composition was affected by the authorisation process, it was comparable to any other instructional sortie and therefore had no direct effect on later events. Annex A Witness 4 Witness 4

1.4.48. The authorisation sheet showed that the sortie was split, such that the first part was a task and the second part was a training sortie. One of the aims of the task was to provide additional experience for the students during a profile that was similar to the follow-on training sortie and therefore posed no significant additional risk. Regulatory Article 2101 stated that in order to fly or operate UK military registered aircraft, aircrew should be qualified through award of appropriate military flying badge or in the case of a student, undergoing an Aviation Duty Holder approved training course and the duties to be authorised form part of a course of training. The Student Pilot and Student Crewman did not yet have a military flying badge. Therefore, they should have been under training, as part of the course syllabus, which was not the case during the task at the time of the accident. However, the Panel noted that the task sortie profiles were professionally flown demonstrations, the plan was reasonable for the circumstances, and there was no intention to act against the Regulatory Articles. Notwithstanding this, the students should not have been part of the crew until the instructional phase of the sortie. The regulations unnecessarily constrained what was an otherwise reasonable sortie profile and valuable training opportunity. Guidance material was not promulgated below the Regulatory Articles. Should the chain of command deem it appropriate or beneficial to include students on tasking sorties during a course of training, Alternative Acceptable Means of Compliance (AAMC) should be sought from the MAA. The Panel **observed** that students taking part in a flying task was beneficial to the students and future similar activity should not be unnecessarily constrained. Exhibit 8 Witness 4 Exhibit 50 Exhibit 51

1.4.49. **Summary of authorisation**. The Panel concluded that the students should not have been part of the tasking crew despite the reasonable nature of the activity. However, the Panel judged that it was a matter of coincidence that the accident happened during the task phase of the sortie and that the levels of authorisation were suitable. Therefore, the Panel concluded that a different authorisation would not have changed the outcome of the accident and that authorisation was **not a factor** in the accident.

Supervision

1.4.50. **DHFS supervision**. The RAF Shawbury Flying Order Book only detailed Shawbury local area procedures and did not specify orders for 202(R) Sqn at RAF Valley. 202(R) Sqn, although a DHFS unit, operated under the RAF Valley Flying Order Book (FOB) which had no amplification of Supervision under the 2000 series higher regulation. The DHFS Executive Flying Supervisor was responsible for the, *"routine oversight and supervision of all military airborne activity at RAF Shawbury"*, and was therefore not in the immediate management sphere of RAF Valley based aircraft. However, he was contacted soon after the accident and informed of known details. Exhibit 52 Exhibit 52

1.4.51. **202(R) Sqn supervision**. 202(R) Sqn supervision was primarily carried out by a Sqn Duty Executive, responsible for overall supervision of all flying conducted at 202(R) Exhibit 53

Sqn. As there were only 5 Duty Executives on the Sqn, the Duty Executive was supported by a Duty Aviator (DA) who carried out the daily running of the flying programme. The DA did not authorise sorties and was not formally responsible for supervision but did carry out many supervisory functions and received out/in-briefs and consulted the Duty Executive only where required. The 202(R) Sqn Duty Executive on the day of the accident was not required to authorise or receive an out-brief but was thoroughly aware of the tasking flight due to both the small number of personnel on 202(R) Sqn and his own planning of the sortie the previous day, when originally tasked to fly it. The Duty Executive had completed, and was in date for, the Flying Supervisors' Course.

Witness 9

Exhibit 41

1.4.52. **Sortie supervision**. Due to the small number of personnel on 202(R) Sqn and by virtue of the planning cycle, the Duty Executive had a thorough understanding of the sortie. The DA was given an 'out brief' by Aircraft Commander A separately, allowing independent scrutiny of the sortie. In the Panel's opinion, apart from the field landing site booking procedures, there was a good level of critical questioning in the supervisory chain.

Witness 9
Witness 4

1.4.53. **Summary of supervision**. The Panel concluded that supervision of 202(R) Sqn by DHFS was implicit in the RAF Shawbury Flying Order Book, despite the wording in the documents, and that the level of Sqn and sortie supervision was reasonable for the circumstances. The RAF Shawbury Flying Oder Book has since been updated and now contains specific 202(R) Sqn Duty Personnel orders. Supervision was therefore **not a factor** in the accident.

DETERMINING THE CAUSE OF THE ACCIDENT

1.4.54. Despite fire causing the ultimate destruction of the aircraft, the events leading to it were difficult to establish and determining the cause of the accident became the main focus of the Service Inquiry. The landing site and sloping ground provides context for much of the accident and is therefore analysed first along with the accident timeline, in particular because the angle of the slope was suspected to be out-of-limits. The first physical evidence of mechanical failure was the discovery of fragments of the driveshaft coupling. The damaged main rotor drive shaft coupling provided a basis for further analysis of the main rotor transmission system and specifically the main gearbox support case. Determining the sequence of events was also necessary to explain why mechanical failure occurred and what led to the fire. Although the Cockpit Voice Recorder (CVR) was significantly damaged by fire, analysis of the partial CVR data was achieved and combined with the technical analysis of the recovered damaged components to examine how mechanical failure occurred and the events that led to the fire. All these topics were analysed in detail in order to determine the cause of the accident.

Site analysis

1.4.55. **Accident site**. The aircraft wreckage had been removed from the hillside prior to the Panel's arrival due to the degrading environmental conditions and the need to preserve the evidence. Any immediately obvious and perishable evidence was retrieved by DAIB investigators who had been on-site for the preceding days. Other than witness accounts and photographs, evidence from the accident site initially provided the basis for the Panel's consideration. The accident site was situated on the summit of the mountain which was the shape of a hump-back ridgeline orientated north-east to south-west with a steep, rocky, north-west face. A picture of the mountain was taken by a rescue aircraft, 30 minutes after the accident, (Figure 4). Exhibit 22

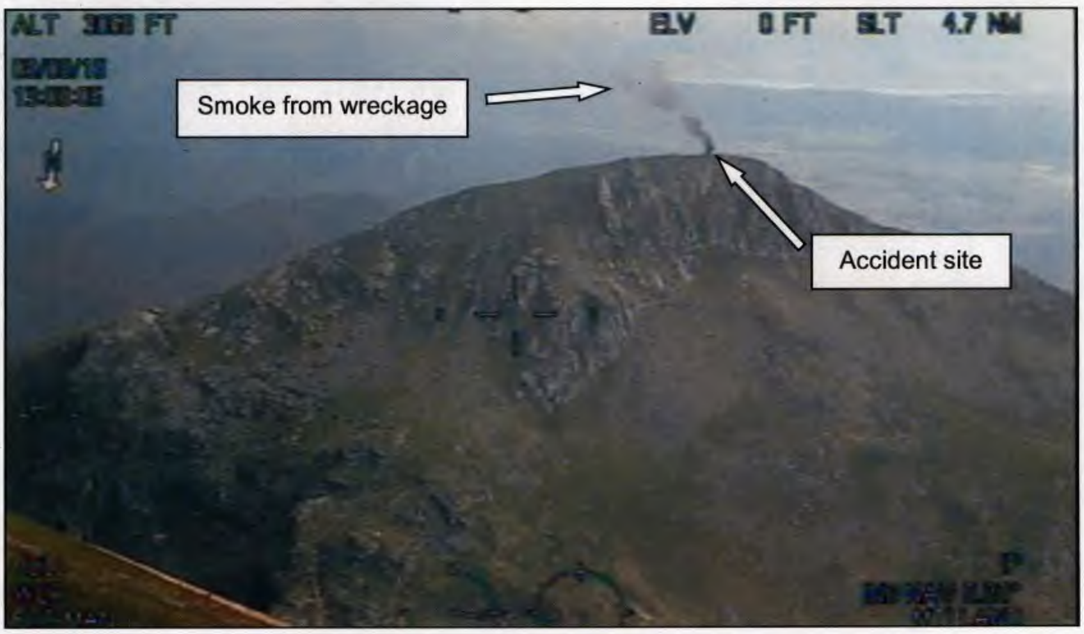


Figure 4 - Yr Aran viewed from the north.
(Picture Source: Maritime and Coastguard Agency)

1.4.56. The top of the mountain was mostly grass, interspersed with rocky outcrops and embedded smaller rocks within the vegetation. A number of rusty fence posts protruded but no longer had the original horizontal wires. The top was relatively flat but became steeper further away from the summit, except for one area of flatter ground to the south of the summit. An indistinct walker's path extended along the top of the ridgeline. A photo of the landing site was taken from the right hand cabin door on the final approach showing the position of the Passenger next to one of the fence posts (Figure 5). Exhibit 18

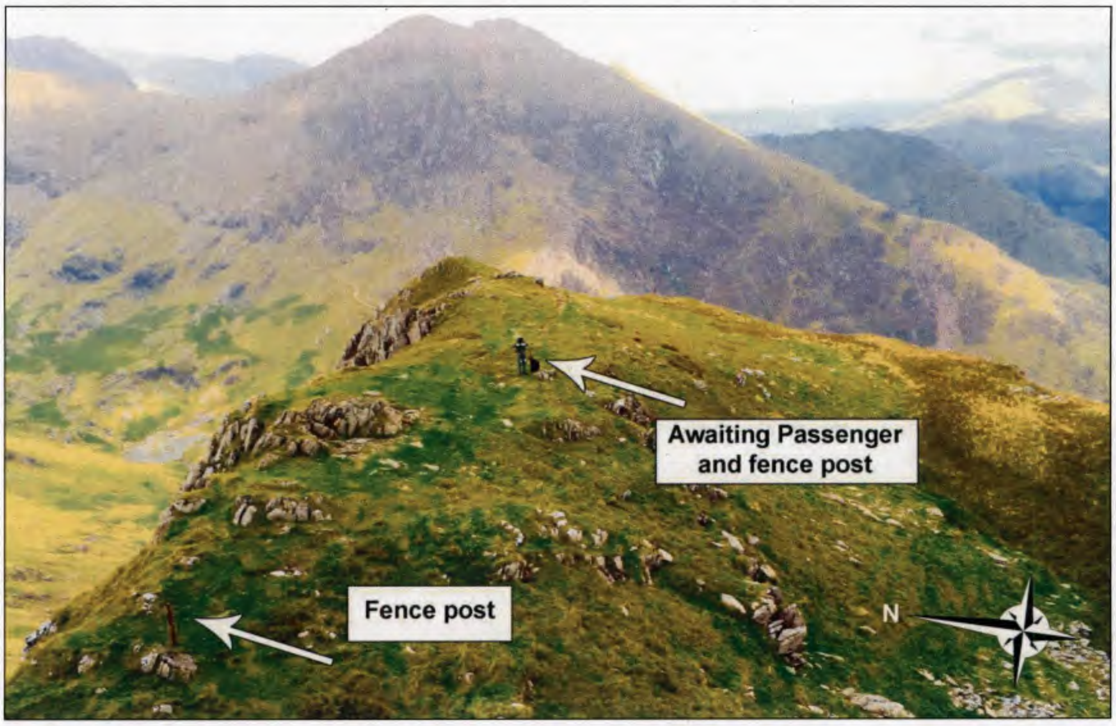


Figure 5 – Landing site, fence post and Passenger approximately 2 minutes before the accident.
(Picture Source: Aircraft Commander B)

1.4.57. The aircraft wreckage was located just below the top of the ridgeline, adjacent to a small rocky outcrop in the 10 o'clock position of the aircraft and a fence post in the 3 o'clock position on the right hand side of the aircraft (Figure 6). The aircraft remains were in one location with the main components relatively contained in the immediate surrounding area (Figure 7). Exhibit 18

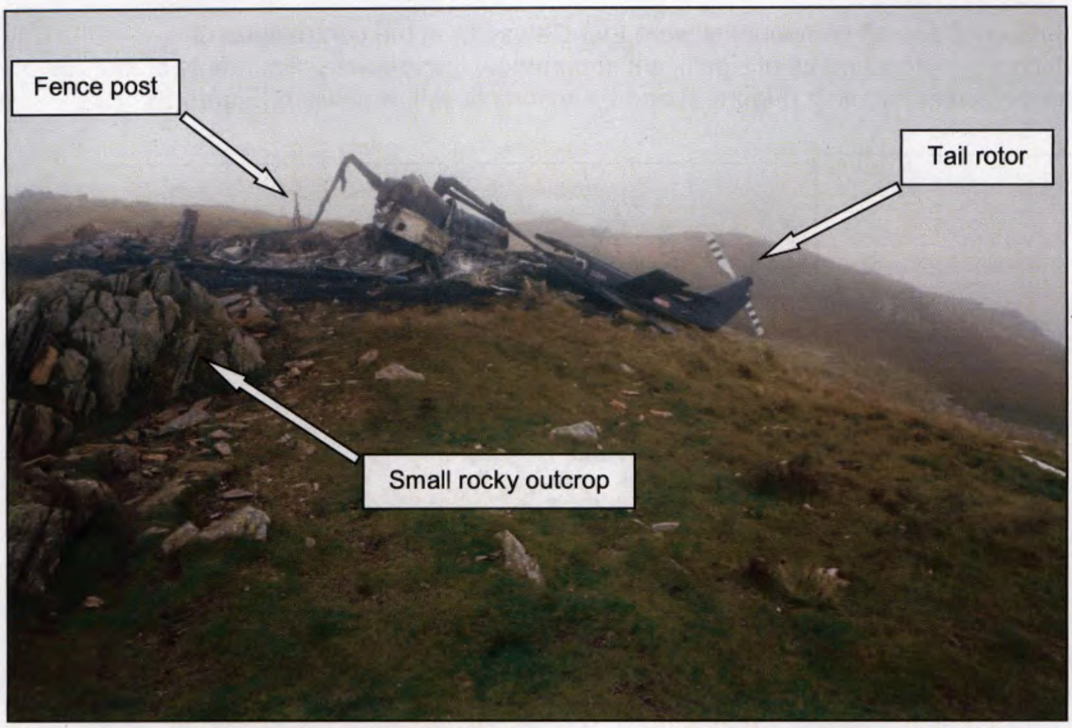


Figure 6 - Aircraft wreckage, adjacent to a small rocky outcrop.
(Picture Source: DAIB Engineering)

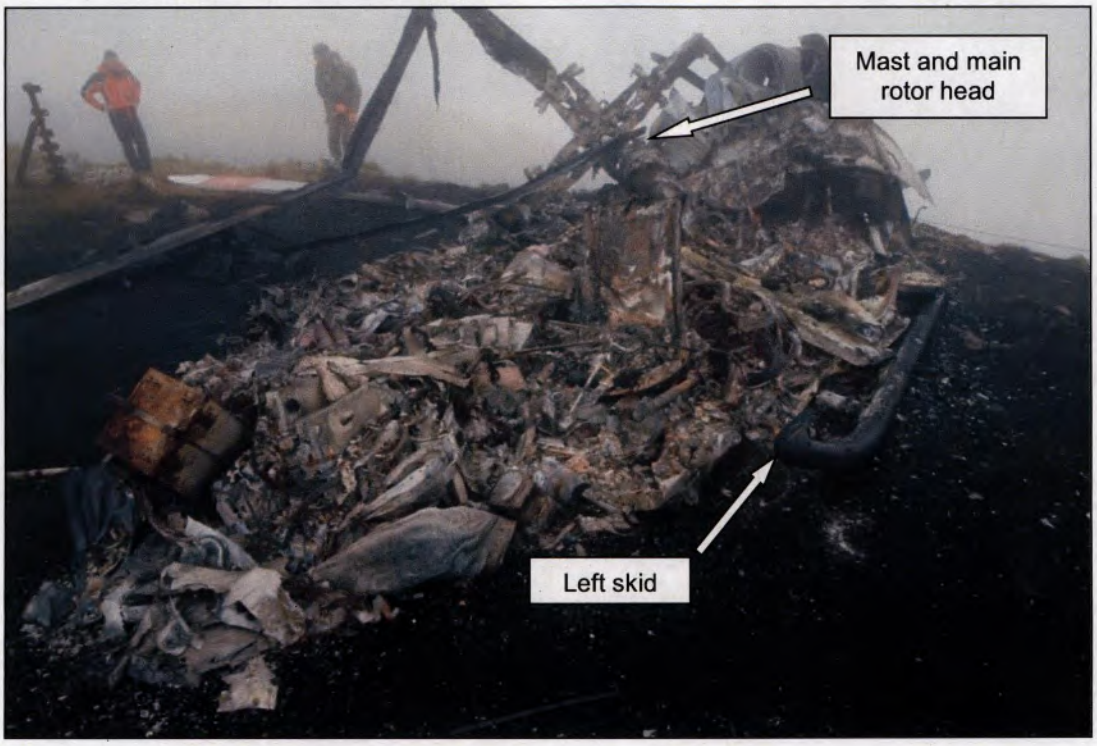


Figure 7 - Aircraft wreckage and immediate surrounding area.
(Picture Source: DAIB Engineering)

1.4.58. A number of aircraft components were found away from the central area of wreckage which were identified as of significant importance; these were 2 fragments of the driveshaft forward outer coupling (Figure 8) and 2 sections of yellow cowling (Figure 9). Exhibit 18

Figure 8 - Forward outer coupling fragments found in relation to the aircraft wreckage.
(Picture Source: DAIB report)

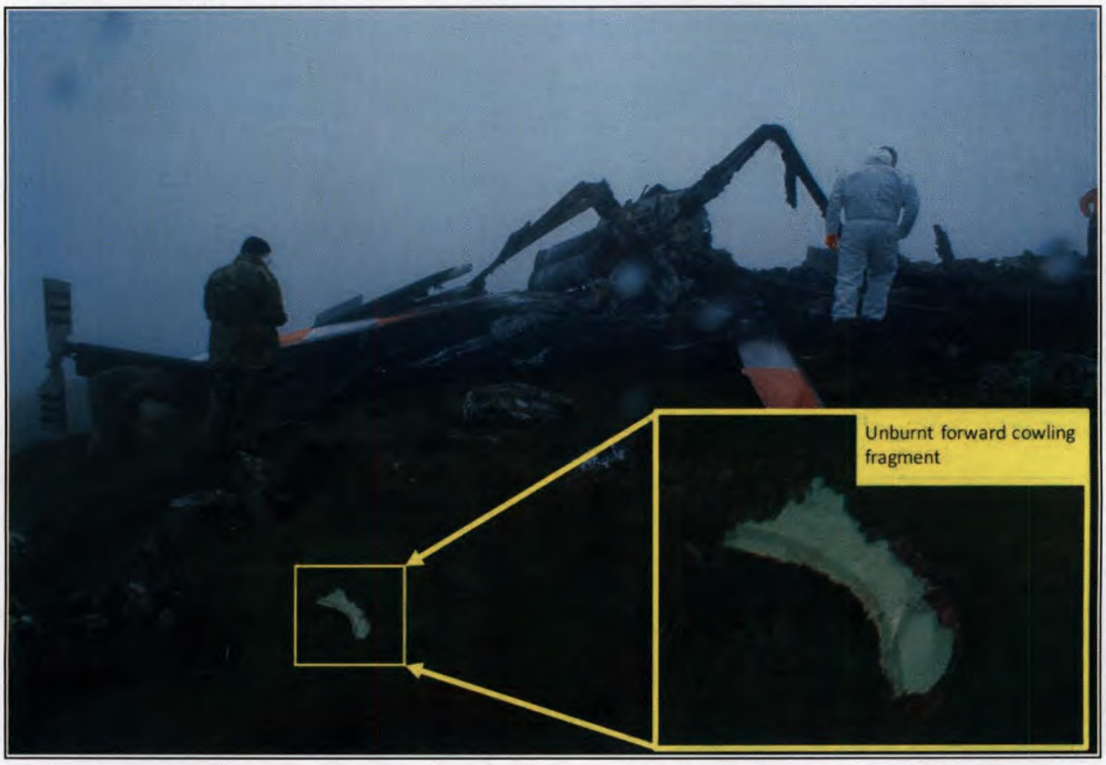


Figure 9 – One of the 2 fragments of aircraft cowling found to the rear right of the wreckage.
(Picture Source: DAIB report)

1.4.59. **Sloping ground**. The limited physical evidence from the accident site that could be analysed led the Panel to initially focus on the sloping ground until more detailed forensic analysis of the components could be completed. Informal measurements taken by DAIB determined that the sloping ground was close to the aircraft limits so the Panel sought to determine the exact slope angle where the aircraft came to rest. A geographic survey was carried out using LIDAR[13] to build a 3D computer model of the accident site (Figure 10). Exhibit 18 Exhibit 54 Exhibit 55

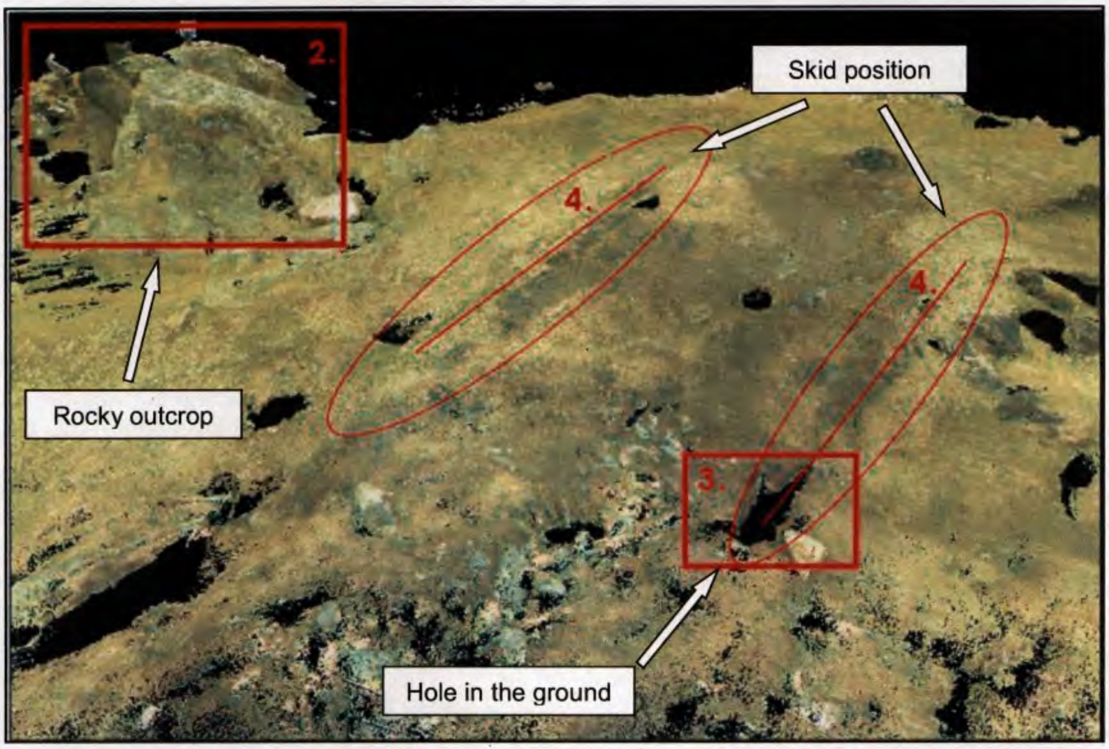


Figure 10 - Geographic survey of the accident site.
(Picture Source: 42 Engr Regt (Geo)) Exhibit 55

1.4.60. **Final resting position**. Through identification of the skid position (Figure 10, Number 4) and comparison with the computer model and geographic survey data, the final resting position of the aircraft was assessed. The LIDAR and photographic data showed roughly parallel lines close to the inter-skid distance. The rear of the right skid was found 'dug in' to the ground, such that it was prevented from moving further down the slope creating a small hole (Figure 10, Number 3). This hole contained rocks and some melt material that was removed during the site clearance, along with other surface materials, soil, stones etc. Therefore, the full cause and extent of the surface markings was not clear and consideration of the LIDAR plot accommodated all these factors when assessing the shape and angle of the pre-accident slope. The subsequent slope analysis provided the final resting position skid slope angles (Table 2). Exhibit 18 Exhibit 54 Exhibit 55 Exhibit 18

[13] Light Direction and Ranging (LIDAR) is a surveying method that uses a laser to create a digital 3D representation.

Orientation	Slope angle (degrees)
Left skid (nose up)	11.4°
Right skid (nose up)	10.6°
Front lateral (left skid high)	4.6°
Rear lateral (left skid high)	3.7°
Maximum combined slope angle[14]	12.3°

Exhibit 54

Table 2 – Angle of the skids in the final resting position.

1.4.61. **Estimated landing position**. The crew were concerned about slipping down the mountain and one witness stated that the aircraft moved from its initial landing position, slipping back down the hill before stopping. The Panel assessed it likely that the aircraft did move from its initial touchdown point but that it was not possible to determine by how far. The 3D slope picture and site analysis showed that almost any landing further upslope would have been less steep than the final resting position. Therefore, the Panel concluded that although the exact landing position could not be determined, the angle of the final resting position represented the maximum slope angle experienced during the accident.

Witness 8

Exhibit 55

1.4.62. **Sloping ground landing technique**. Sloping ground landings are conducted by hovering the aircraft to the point of initial contact. The aircraft is flown as a normal landing until first contact with the ground. The collective is lowered and into-slope cyclic is used to keep the rotor disc level while the aircraft pivots until the skids are fully in contact with the ground. To complete the landing, the aircraft stability is confirmed, after which the cyclic is returned to the central position before the collective is fully lowered. Alternatively, the aircraft can be held at the sloping ground limit or hovered 'skids light' with the aircraft lightly in contact with the ground. A *'missed landing'* is where the aircraft is returned to the hover in the event that the landing is unsuccessful for any reason.

Exhibit 56

1.4.63. **Sloping ground limits**. Sloping ground landings are limited to a maximum slope angle of 10° and 8° (Figure 11).

Exhibit 58

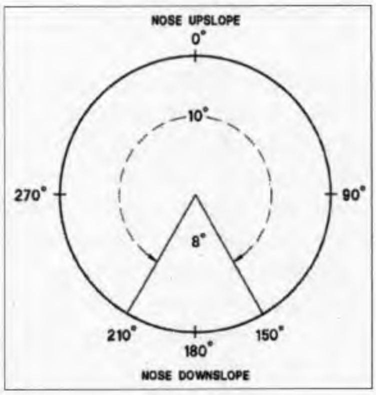


Figure 11 – Excerpt from the Bell 412 rotorcraft flight manual. *"Slope landings are limited to a maximum slope angle of 10° and 8° degrees. All headings indicate the direction of the nose of the helicopter".*

[14] The maximum combined slope angle was calculated using the worst case figures of 11.4 and 4.6

1.4.64. The crew's stated intention was to conduct a 'skids light' landing to pick up the Passenger. This meant the aircraft would be held in position prior to reaching any sloping ground limits. The full landing procedure would therefore not be required and the full extent of the slope would not be encountered. This was consistent with how sloping ground landings were taught at DHFS whereby once front-of-skid contact is made, the aircraft is slowly rotated while monitoring the slope angle with the Attitude and Direction Indicator (ADI). The Panel concluded that although the crew did not intend to land beyond the sloping ground limits, the maximum slope angle had been exceeded by up to 2.3° once in the final resting position. Exhibit 17 Exhibit 56

Accident timeline

1.4.65. The accident timeline was primarily established from events recorded from the partially recovered Cockpit Voice Recorder (CVR) transcript and supplemented with witness accounts. The crew provided statements on the day of the accident and were interviewed by the DAIB investigators the day after the accident. The Panel initially interviewed the crew a week after the accident and a second time approximately 2 months after the accident. All interviews and statements were collated to establish a preliminary sequence of events pending CVR data recovery. Exhibit 237 Exhibit 238 Exhibit 239 Exhibit 240 Exhibit 241

1.4.66. **Cockpit Voice Recorder (CVR) data recovery**. Once the CVR had been recovered by DAIB engineers it was relocated to the Air Accident Investigation Branch (AAIB) laboratory at Farnborough. The data recovery process was lengthy but necessary to obtain the maximum amount of information from the remains of the badly fire damaged casing. The CVR had been exposed to temperatures beyond its design limit,[15] resulting in significant internal damage to the memory module (Figure 12). Therefore, the CVR could not be downloaded by the AAIB in the usual way because the outer case was too badly burnt and the standard connectors were missing. Exhibit 18

Figure 12 – [Left] CVR condition on recovery. [Centre] Memory module assembly. [Right] Three layer integrated circuit board and loose components.

1.4.67. There were 39 chips in total inside the memory module; 2 chips had verifiable data, 18 chips provided usable information of variable quality and the remaining 19 chips suffered more extensive damage and produced no data. Low power X-rays determined the extent of the damage to the remaining 19 chips of which 9 had potentially recoverable data. The data on these 9 chips ultimately could not be recovered despite extended efforts to repair the damaged bond wires by Defence Science and Technology Laboratories. Exhibit 18 Exhibit 211

[15] The maximum internal indicators were set at 260° Celsius.

Some of the chips were too badly damaged to withstand the recovery process. The 6 that survived the recovery process were ultimately un-usable due to the damaged bond pads or connectors that would allow data to be extracted from the circuit board (Figure 13). CVR and "Vision 1000" in-cockpit video and audio recordings were obtained for comparison from non-accident aircraft and were downloaded in the usual manner. The CVR files that survived were sent to Bell, QinetiQ, 1710 Naval Air Squadron and Pratt & Whitney for further analysis. Activity to recover data from the damaged chips finally ceased on 1 June 2017. Recognised anomalies that presented problems with assessment of the CVR included: No audio data on one or more tracks, poor quality of the Cockpit Area Microphone (CAM) recording, pollution of CAM recording from the aircraft power supply and CVR power supply, erroneous memory management and level imbalance between tracks.[16] All of these anomalies were observed in the recording from ZJ241 and would therefore impinge upon the ability to recover accurate and useful information. Due to the extreme fire damage to the CVR and the extensive damage to the chips, DAIB assessed that recording on individual chips on the CVR Quality Rating Scale[17] was considered to be somewhere between "excellent" and "unusable". The Panel **observed** that exposure to conditions beyond the specification of the CVR did not preclude recovery of some useful data, albeit with difficulty, and that damage to future accident CVRs should not necessarily preclude attempts to recover the data. Additionally, aircraft would benefit from a CVR located away from potential fire sources. Exhibit 18

Figure 13 – [Left] Showing one of the damaged chips with partially de-packaged casing after recovery action and [Right] Showing a high magnification image of a damaged bond pad. (Picture Source: DSTL Chip Damage Analysis Report.)

[16] Bureau d'Enquetes et d'Analyses (BEA) study on detection of audio anomalies on CVR recordings: Dated Sep 2015.

[17] National Transportation Safety Board – Cockpit Voice Recorder Handbook for Aviation Accident investigations, Attachment D.

1.4.68. **Cockpit Voice Recorder (CVR) Spectrogram**. A spectrogram is a visual representation of the spectrum of frequencies of sound or other signals as they vary with time (Figure 14). The loss of data from the CVR chips manifested as a patchwork of short recordings of different lengths with resulting gaps (silences) in between. Each chip had a different periodicity of good data versus damage which meant that once combined some of the recordings reinforced each other and on occasions overlapped to reduce the number of data gaps.

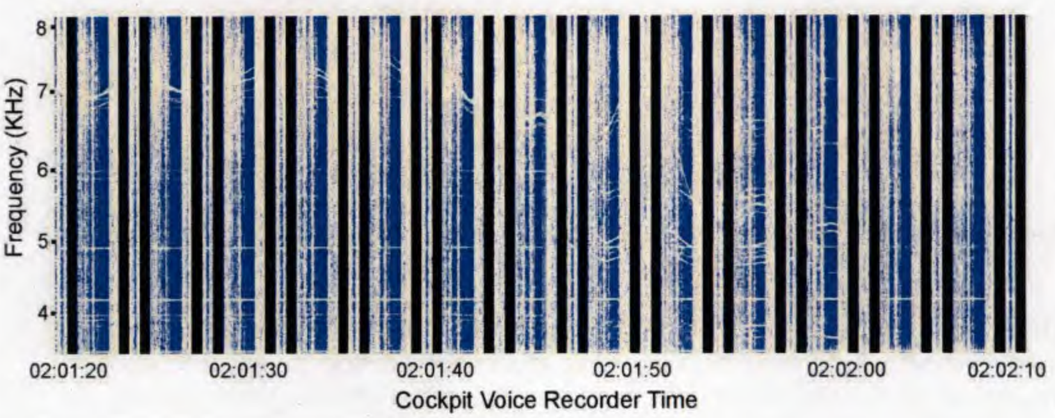


Figure 14 – Example of CVR spectrogram during the accident sequence (visually enhanced).
(Picture Source: QinetiQ)

1.4.69. DAIB, Bell, QinetiQ, 1710 Naval Air Squadron (NAS) and Pratt & Whitney all conducted an analysis of the CVR recordings and came to different conclusions. Subsequently the Air Accident Investigation Branch (AAIB), Bell, QinetiQ and 1710 NAS conducted an independent assessment of DAIB's CVR analysis report but were unable to validate its conclusions. The Panel concluded that given the differing interpretations of the spectrogram by all the different agencies, it was not possible to corroborate any individual interpretation of the spectrograms. In the Panel's opinion the DAIB CVR analysis of the engine speeds was considered to be the most credible representation of the engine performance (Figure 15) because of the amount of supporting evidence. However, due to the levels of uncertainty should also be treated with caution.

Exhibit 30
Exhibit 18
Exhibit 18

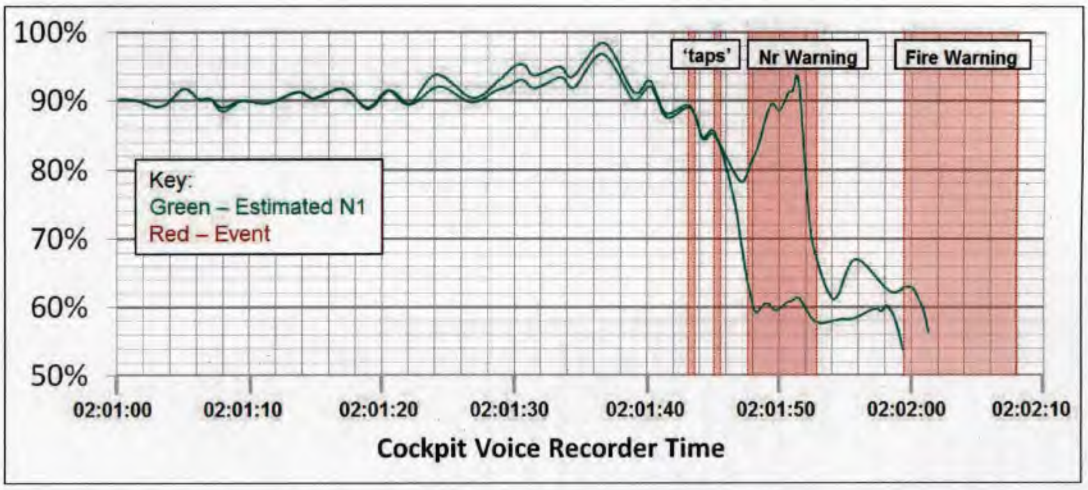


Figure 15 – Chart showing DAIB estimate of engine speed and other events derived from the spectrograms.

1.4.70. DAIB used the spectrograms to analyse engine speeds and other events during the accident and estimated that there was a peak in engine speed during the approach to land. DAIB's technical analysis of the engines in conjunction with a physical inspection by Pratt and Whitney concluded that the engines were responding to demands and operating correctly and within limits during the accident. Other events that were visible on the spectrogram were: a series of 'taps', audio warnings, a split in engine speed and engine shut down. The Panel then focused its analysis on the information that was audible on the CVR and recorded on the transcript.

1.4.71. **Cockpit Voice Recorder (CVR) transcript**. Analysis of the CVR audio files was conducted to translate the content of the CVR into a partial transcript of the accident. The crew also listened to a playback of the CVR in order to aid their memory recall and to help interpret difficult sections of the crew's speech. Information obtained by the crew then supplemented the content of the transcript. The information was thereafter treated with differing levels of confidence for subsequent analysis. Information that could be positively identified and agreed by all members of the Panel, and corroborated by the crew was viewed with a high degree of certainty. This was treated as 'almost certain', and annotated in black on the sequence of events (Table 3). Following advice from RAF Centre of Aviation Medicine (RAFCAM), information recalled or suggested by the crew only was viewed with medium confidence due to known difficulties regarding recollection of events post aviation accidents. This was treated as 'likely', and annotated in blue on the sequence of events. Information obtained from either source that was less certain due to lack of clarity or consensus of opinion was given a low confidence rating. This was mainly used for the purpose of context and treated as 'not possible to determine', and annotated in red on the sequence of events. The CVR timings relate to the longest CVR audio file and are used as a datum reference throughout.

Exhibit 18

Exhibit 205
Exhibit 206
Exhibit 207
Exhibit 208

Exhibit 29

1.4.72. **Cockpit Voice Recorder events**. For context, the Panel interpreted and summarised the content of the CVR transcript into a sequence of events, from the point the crew first discuss the approach to the accident site until they exit the aircraft. The CVR transcript also contained teaching points for the Student Pilot, discussion by the crew about the deployment of the smoke canister and how to get the Passenger into the aircraft. This information has been omitted to maintain clarity of the sequence of events. However, the transcription at the point at which the accident occurred contains all

Exhibit 17

recoverable data and includes direct quotes where necessary (Table 3).

CVR Time	Assessment of events based on audible CVR speech and crew recall	Audible CVR events
1:57:02	Crew discusses the approach and the safest method	
1:57:29	Pre landing checks	
1:57:36	Hoist master on	
1:57:42	Speed below 60 kts	
1:57:47	Fuel remaining discussion: 1680 lbs	
1:57:49	Side door open	
1:57:57	Overhead the pinnacle during recce circuit	
1:57:59	Smoke fired from cabin door	
1:58:01	Baralt / Radalt comparison	
1:58:20	Aircraft Commander A briefs the crew on intentions to conduct a curving approach along the ridgeline	
1:58:51	Crewman Instructor discusses the suitability of the landing site on the pinnacle and mentions the fence post	
1:59:12	Final approach initiated with wind from the left	
1:59:16	Aircraft Commander A describes the weathercock effect as the aircraft slows down	
1:59:21	Aircraft Commander A signals intention to approach to the leading edge of the pinnacle and asks for an update on the temperatures and pressures	
1:59:32	The Crewman Instructor describes the landing area again	
1:59:38	Aircraft Commander A identifies the fence post and the landing point	
1:59:51	Probable torque reading of 45%	
1:59:56	Aircraft hovers forward and right during short finals to stay in the up-drafting air	
2:00:04	Aircraft maintains height but continues forward and right	
2:00:07	Aircraft moves right only	
2:00:32	Aircraft establishes in the hover	
2:00:35	Probable Torque reading of 45%	
2:00:36	Aircraft in the hover on the leading edge of the ridge	
2:00:40	Crewman Instructor briefs the intention to go 'skids light' to get the Passenger in the cabin	
2:00:43	Crewman Instructor identifies a suitable area in the 2 o'clock position	
2:00:47	Crewman Instructor calls for right one and forward	
2:00:51	Aircraft maintains a hover	
2:00:52	Crewman Instructor updates the recce	
2:01:03	Crewman Instructor calls for descent	
2:01:10	Crewman Instructor indicates a further descent of 5 ft and then calls to maintain height	
2:01:13	Crewman Instructor calls for tail to come to the right to align the aircraft at 90 degrees to the slope	
2:01:18	Crewman Instructor requests to maintain tail position	
2:01:21	Confirmation of intention to go skids light	
2:01:24	Crewman Instructor calls for a movement of half a unit	
2:01:25	Crewman Instructor identifies a large rock	
2:01:29	Crewman Instructor calls to descend	

2:01:31		"…you go that's good…"
2:01:33	Aircraft in the low hover or light touch	"…skid…"
2:01:36	Crewman Instructor calls for a movement of half a unit	"…half a unit please boss…"
2:01:39		"…OK…"
2:01:40		"…left and…"
2:01:42.5	Aircraft is skids light	"…on…"
2:01:43	Aircraft rock-back	***'TAP TAP'***
2:01:44	Crewman Instructor confirms that the tail is clear	"…tail clear…"
2:01:45		***'TAP TAP TAP'***
2:01:45	Aircraft skids fully down	"…err…"
2.01:45.5	Crewman Instructor calls to come back up ***[urgently]***	"…up, up you go…"
2:01:49		**Low rotor speed warning ON**
2:01:52		**Low rotor speed warning OFF**
2:01:57	Aircraft Commander calls for idle stops	
2:01:59		**Fire warning ON**
2:02:00	Crewman Instructor identifies that something went bang	
2:02:06	Crew first identify the presence of fire	
2:02:08		**Fire warning OFF**
2:02:09	Crew further indication of a fire	
2:02:11	Crew exit the aircraft	

Table 3 – CVR transcribed and summarised sequence of events during the accident. Key: [Black] 'almost certain'; [Blue] 'likely'; [Red] 'not possible to determine'.

1.4.73. **Tail movement**. The Crewman Instructor gave instructions to move the tail right to achieve a perceived 90° angle to the slope, concluding with a tail steady call at 2:01:18. The geographic survey established the final resting position of the skids were on a heading of 348°, which was not at 90° to the slope. Achieving 90° to the slope would make the landing easier and was considered normal practice but not essential. Nevertheless, some lateral slope would have been acceptable in the circumstances and the difficulty of absolute slope assessment while airborne explains why there was a difference between the 90° angle to the slope heading and the final resting position. During interview, none of the crew recalled any yaw after the tail movement in the hover. The Passenger described the possibility of a slight shift of the aircraft, to the rear and to the left whilst on the ground, as the crew exited. Aircraft Commander A had a good marker to maintain position, and in the Panel's opinion would have noticed any significant movement. Therefore, the Panel concluded that the aircraft landed on a heading close to that of the final resting position of 348°, notwithstanding any movement of the aircraft during the subsequent aircraft fire.

Exhibit 17
Exhibit 61
Exhibit 56
Witness 1
Witness 4

1.4.74. **Low hover**. The sequence and timing of the crew conversation leading up to 2:01:33 all indicated that the aircraft was manoeuvred to a low hover or possible light touch at this point (Table 3). During interview, Aircraft Commander A described the aircraft feeling normal during the final descent from the hover, prior to a request from the Crewman Instructor to move left a half a unit. The crew also recalled that they were close to the ground or in the low hover from this point onwards. The next call on the CVR was to move half a unit at 2:01:36 and was coincident with DAIB's estimated peak in engine speed (Figure 15). The Panel judged that the peak was either due to arresting a rate of descent, the initiation of a climb prior to the lateral movement or a combination of both. The Panel concluded that a low hover was likely to have occurred between 2:01:33 and 2:01:36 before coming back up to manoeuvre and that it was not possible to determine if

Witness 4
Witness 5
Witness 2
Witness 8
Witness 3

the aircraft touched the ground during this period.

1.4.75. **Reposition**. The Crewman Instructor's call to move half a unit was almost certainly to come to the left as stated by witnesses at the CVR playback to the crew. Exhibit 17 Although a direction is missing from the CVR, the call is heard clearly and there was no concern in the tone of voice. The aircraft had not yet made its final touch down, because it would need to be airborne to make a movement of half a unit. Witness 4 The Panel assessed that lateral movement would have occurred after the call at 2:01:36. Aircraft Commander A also recalled a reposition following the Crewman Instructor's request and commented that Witness 8 during this reposition the aircraft sank slightly. Witness 4 Aircraft Commander A responded by raising the collective to give a comfortable rate of descent. The Panel concluded that there was a reposition to the left just after the instruction by the Crewman Instructor at 2:01:36.

1.4.76. **Skids light**. The Passenger, watching from outside, described an approach with Witness 1 nothing out of the ordinary to the point at which they went 'skids light'. Exhibit 17 There was an indication that contact was made with the ground at 2:01:40 when the words, *"left and"* are heard, then at 2:01:42.5 the word *"on"* is recorded. Witness 3 The Student Crewman stated he called that the left skid was on the ground, Witness 5 and that this was almost simultaneous to the Crewman Instructor's call of right skid on; Exhibit 17 the Crewman Instructor corroborated this. The Panel judged the speech on the CVR to be consistent with calls given to the pilot to inform Exhibit 205 him of the skid position. Exhibit 206 During the CVR playback to the crew the crew individually identified the initial skids light contact between 2:01:40 and 2:01:43. Exhibit 207 The Panel concluded that the calls were likely to be the Student Crewman or the Crewman Instructor providing Exhibit 208 information from their respective sides of the aircraft and that the aircraft went skids light between 2:01:40 and 2:01:43.

1.4.77. **Rock-back**. There were different recollections of a rock-back, or pivoting from the front of the skids, during the landing by the crew and Passenger. Witness 4 Aircraft Commander A described a slight rotation aft as the aircraft touched down with the aircraft returning to the level attitude. This was perceived as an aspect of a nose upslope landing and not unusual or abnormal. Witness 2 However, on correcting the aft rotation with collective, severe oscillations began. The Student Pilot described a perfectly normal sloping ground landing to the skids light position, with an initially gentle aft rotation. However, during this lowering, Witness 8 the rotation quickly increased before popping back up and severe vibration starting. Aircraft Commander B described a normally controlled and comfortable evolution during Witness 5 which shaking started instantaneously before the rear of the skids touched the ground. The Crewman Instructor described a little wobble on initial skid contact, stating that it did not feel unusual and that everything was as expected before the severe oscillations. The Student Crewman described a smooth landing, just like any other until the point of initial Witness 3 skid contact but that during the lowering of the skids, the back of the left skid came up and then jolted forward and down in a way that did not feel like a pilot input, accompanied by Witness 1 violent vibrations. The Passenger, watching from the outside, also noted that there may have been one or two rock-backs. Witness 1 The rock-back prompted the Passenger to check the tail rotor, which was undamaged, and then immediately notice that the cockpit occupants were being subjected to severe vibrations. The Panel concluded that the aircraft initially rocked back from the skids light position at some point after 2:01:42.5, returning to the hover attitude and then rocked back a second time before it came heavily fully down on the skids within a few seconds.

~~OFFICIAL SENSITIVE~~

1.4.78. **Skids fully down**. The first indication on the CVR that the crew had identified a problem with the aircraft was when the Crewman Instructor suspected ground resonance[18] (1.4.125) and called for the aircraft to come back up, at 2:01:45. There was also a preceding call from the Crewman Instructor to confirm that the tail was clear of obstructions at 2:01:44. Neither of these comments was conclusive in determining the position of the skids because both could have occurred before or after the skids made full contact with the ground. The Passenger described a hard landing at the point at which the rear of the skids came into contact with the ground. The Panel concluded that full skid contact must have occurred after the second rock-back.

Witness 5
Witness 8
Witness 1

1.4.79. **Audio warnings and *'taps'***. The *'taps'*, low rotor speed warning and fire warning are all present on the CVR audio but may extend beyond where they are heard due to the discontinuities and other acoustic events in the recordings. The low rotor speed warning and light activate at or below 95%, and the aircrew manual states that the audio warning activates at approximately 74% as the rotor speed increases and can be seen on the CVR spectrogram between 2:01:47.7 and 2:01:52.8. The fire warning activates when the fire wire in one of the engine bays senses excessive heat and is heard between 2:01:59 and 2:02:08. The *'taps'* were 2 sets of loud tapping sounds 1.6 seconds apart. They were the first audible indication of an abnormal event and occurred at 2:01:43 and 2:01:45.

Exhibit 17
Exhibit 62
Exhibit 62

1.4.80. **Departure from controlled flight**. The crew observed that there was a sudden onset of severe vertical oscillation. The marshalling commands and cadence of crew speech indicated a perception of a normal flight profile up until 2:01:44. Then at 2:01:45.5 the Crewman Instructor urgently called to come back up, suspecting ground resonance. During interview the Crewman Instructor observed that there was a rapid transition from being in control to having no control. The Crewman Instructor described severe vibration, a metallic cracking sound and a vertical bounce sensation that appeared to occur simultaneously. The Student Crewman described looking around at the Crewman Instructor and seeing the Crewman Instructor on all fours getting bounced up and down from the vibrations. In the Panel's opinion the sudden onset of severe oscillations represented the moment that the aircraft departed from controlled flight. The Panel concluded that severe oscillations developed between the speech on the CVR at 2:01:44 and 2:01:45.5 because of the change in tone of voice between the two comments and the urgency of the call to come back up.

Witness 5
Witness 5
Witness 3

1.4.81. **Decision to commit to land.** There was a period of 12 seconds between the Crewman Instructor's request to come back up to the hover at 2:01:45.5 and the next audible crew speech related to engine shut down at 2:01:57. All crew members stated during interview that Aircraft Commander A replied to the Crewman Instructor's request. Aircraft commander A did not believe that the aircraft was in a safe flying condition and elected to shut down *'in-situ'*. The Human Factors report assessed that it was likely that there was a period of assessment following the abrupt change to a new and unexpected situation. The lack of recovered data during this period combined with Human Factors may explain the relative lack of communication. The Panel concluded that the decision to commit to the landing site was made between 2:01:45.5 and 2:01:57.

Witness 5
Witness 3
Witness 8
Witness 2
Witness 4
Exhibit 29

1.4.82. **Idle stops**. 'Idle stops' are a safety switch on the right hand seat cockpit controls that prevent the engines from being shut down inadvertently. Aircraft Commander A called

Exhibit 18

[18] Ground resonance is a destructive oscillation that may be encountered if the rotor blades move on their lead-lag hinges, thus placing their combined centre of gravity toward one side of the rotor disc.

for idle stops at 2:01:57 indicating intent to shut down both engines. The throttles had already been turned to the idle position by this point but it was not possible to shut them down completely until the Student Pilot activated the switch. This was completed and the engines shut down. The fire warning sounded after the call for idle stops and therefore the decision to shut down was taken before confirming the presence of a fire. Witness 4 Witness 2

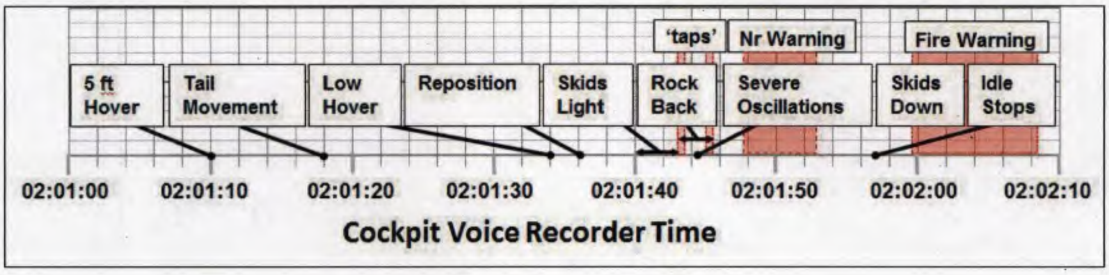


Figure 16 – Accident timeline.

Main drive shaft coupling misalignment

1.4.83. The first physical evidence of mechanical failure during the investigation was the discovery of a fragment of the main drive shaft forward outer coupling by the awaiting Passenger. During wreckage recovery the coupling was found to have detached and broken into multiple pieces; two of these pieces were found outside the main aircraft wreckage and were not damaged by the fire. One of those ejected was to the rear of the aircraft and the other landed at the feet of the Passenger waiting in the 3 o'clock position just outside the rotor disc. The Panel considered the cause of the failure of the drive shaft coupling and what effect this had on the accident. Exhibit 18

1.4.84. **Transmission components**. The engine-to-gearbox main drive shaft assembly is located between the two engines. There are two main drive shaft couplings, one located at either end of the main drive shaft. The drive shaft assembly (Item 4, Figure 17), is designed to transmit power between the engines (Item 5, Figure 17) and the main gearbox (Item 3, Figure 17) which in turn transmits power to the rotor blades (Item 1, Figure 17). The tail rotor drive shaft (Item 6, Figure 17) connects directly to the main gearbox and runs through the tail section to the tail rotor hub and blades (Item 7, Figure 17).

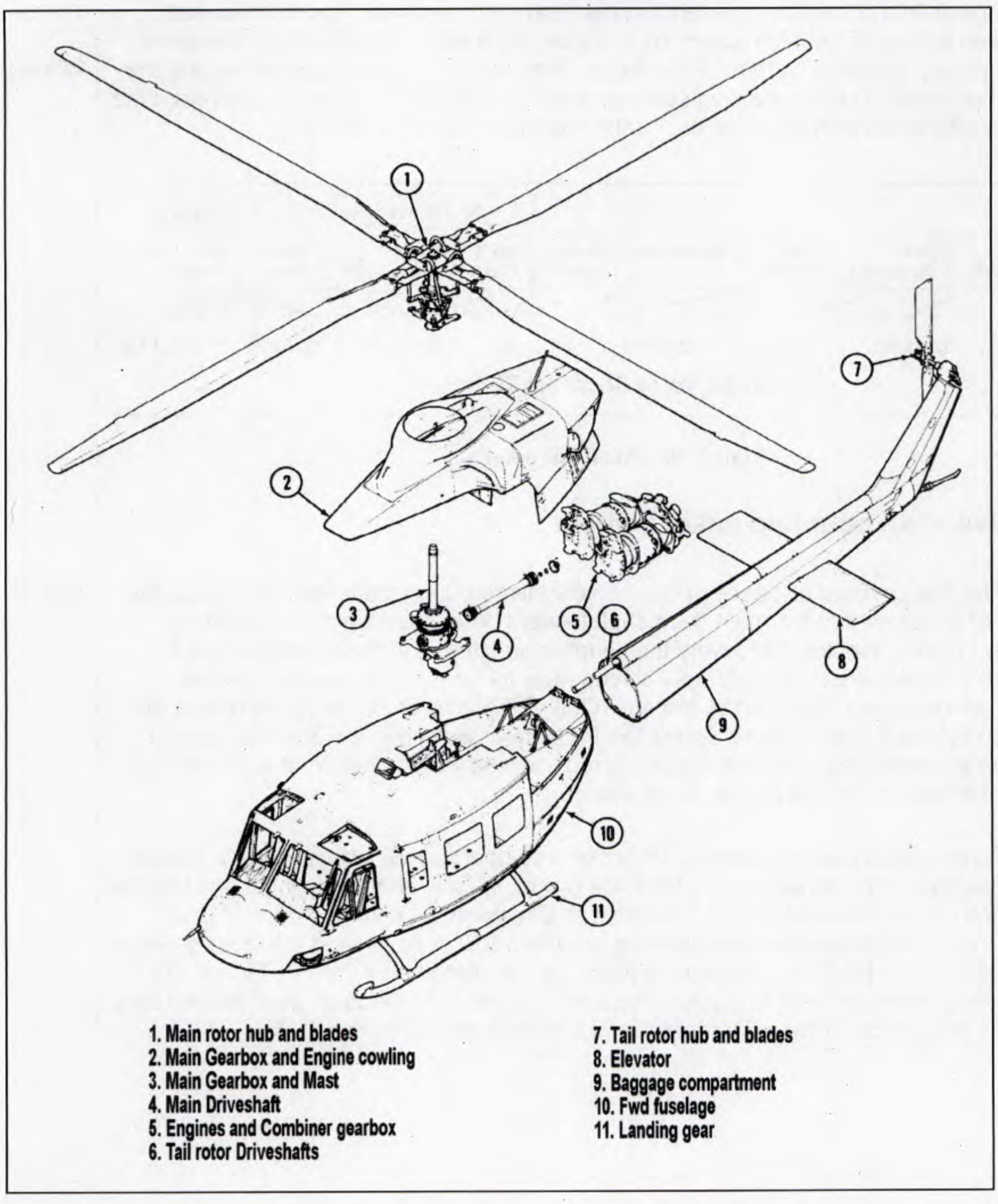


Figure 17 - Bell 412 aircraft major components' locations.
(Picture Source: Bell Maintenance Manual – modified)

1.4.85. **Main drive shaft and coupling assembly**. There is a coupling assembly at either end of the main drive shaft (Figure 18) and each consists of an inner and an outer coupling. Splined couplings are fitted at either end of the shaft to provide some flexibility between the rigidly mounted engines and combiner gearbox and the flexibly mounted[19] Exhibit 63

[19] The main gearbox is attached to the airframe with elastomeric mounts and can move by a small amount.

main gearbox transmission components. The inner coupling transmits torsional load to the outer coupling. The outer coupling is bolted to the main gearbox with 6 bolts via a boot assembly (Figure 19).

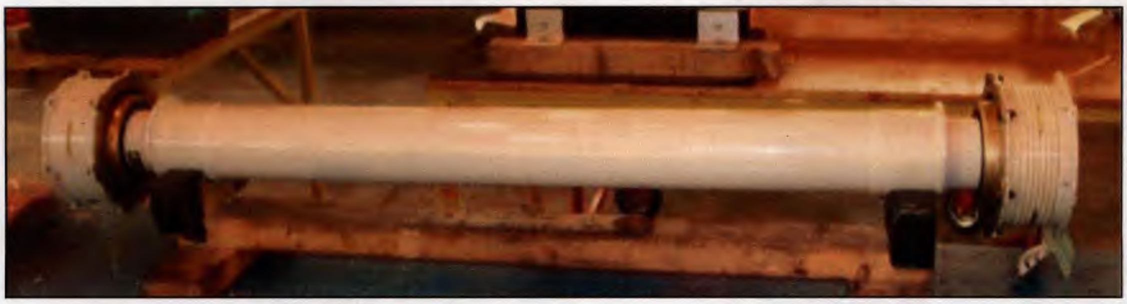


Figure 18 - Main drive shaft assembly.
(Picture Source: DAIB Engineering)

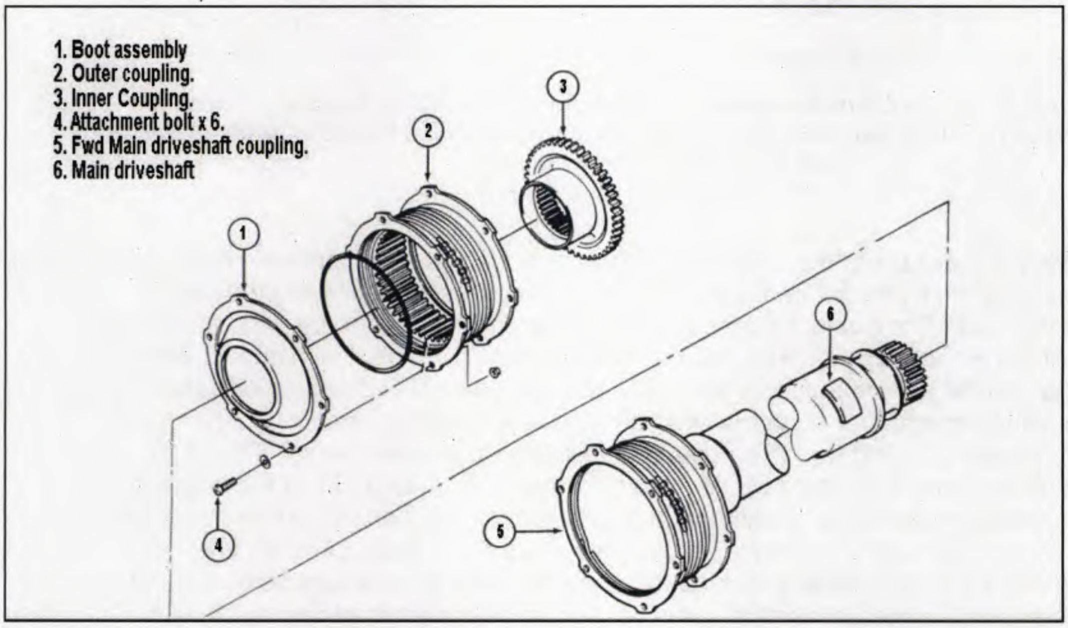


Figure 19 - Drive shaft coupling assembly.
(Picture Source: Bell Maintenance Manual – modified)

1.4.86. **Drive shaft coupling fracture surfaces**. The drive shaft couplings have red and yellow temperature plates that change colour to indicate if the coupling has overheated. The un-burnt fragments, referred to as 4001 and 4007 in (Figure 20), showed no evidence of overheating, indicating that they had been ejected before the fire. Therefore, overheating did not contribute to the failure of the forward outer coupling. The fragments recovered from the wreckage, referred to as 4006 and 4009 in (Figure 20), were subject to heat damage as a result of the fire. Forensic examination of the fracture surfaces revealed evidence of mixed mode overload failure on surfaces A, B and C (Figure 20). It was considered that as the outer coupling was still rotating, instantaneous crack propagation would have occurred under torsional loading, resulting in the initial 45 degree overload crack on surface D. It was not possible to analyse fracture surface E due to the fire damage. Exhibit 63

Exhibit 18

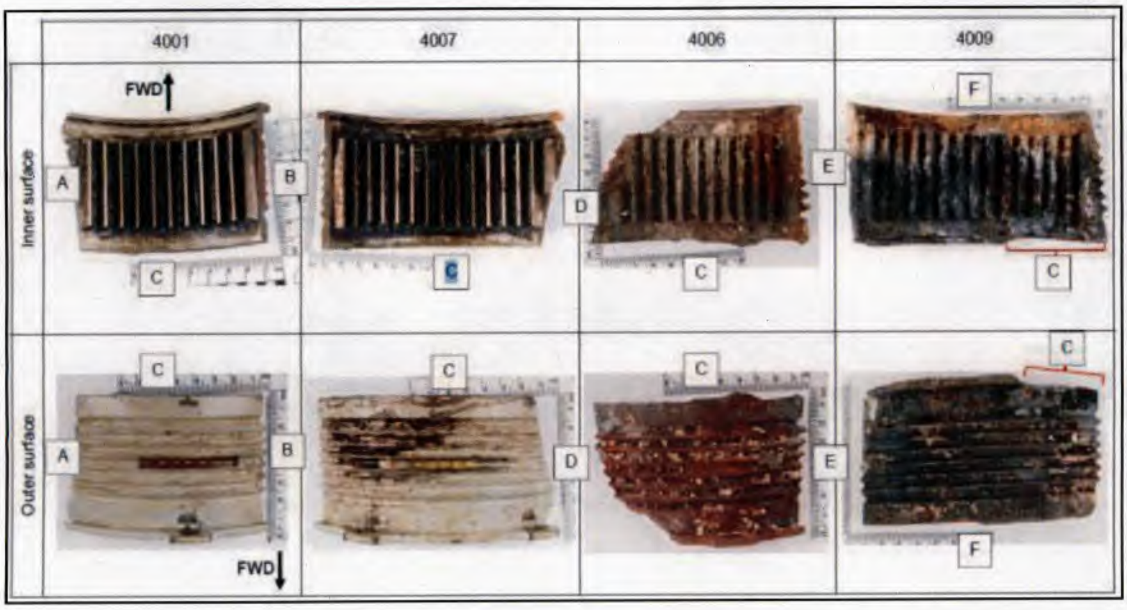


Figure 20 - The forward outer coupling as recovered from the accident site. The axial fracture surfaces are labelled (A,B,D and E) and the circumferential flange failures on the aft face (C) and the forward face (F).
(Picture Source: 1710 NAS)

1.4.87. **Forward inner coupling**. Forensic analysis by 1710 NAS determined that, *"The forward inner coupling was fractured with chunks missing, cracked, bent and the splines chipped"* (Figure 21). The fracture surfaces contained evidence of ductile overload caused by bending of the inner coupling. The chipped splines were consistent with impact during rotation of the shaft in a geometric lock due to a misalignment. This damage indicated that the inner coupling imparted an abnormal load on the outer coupling, resulting in the bursting of the outer coupling due to an overload failure at high strain rate.[20] The 1710 NAS report detailed that this action would have occurred very quickly and in the manner of an explosion, which explained the trajectory and final resting position of the outer coupling fragments. Despite not being able to analyse all the fracture surfaces in detail, enough evidence existed for 1710 NAS to conclude that the forward outer coupling failed through overload rather than fatigue and that this was consequential rather than causal. It was also determined that the cause of misalignment was due to an event forward of the coupling. This was supported by evidence that the inner coupling was found distorted at the forward end and that there was significantly less damage at the aft end of the shaft. The forward outer coupling was attached to the main gearbox input adaptor and it was therefore necessary to analyse this further to understand the cause of the misalignment. Exhibit 63

[20] The 'strain rate' is the change in deformation within a material with respect to time.

Figure 21 - Forward inner coupling including oil boot.
(Picture Source: 1710 NAS)

1.4.88. **Connection to the main gearbox input adaptor**. The Panel considered if there had been a problem with the connection of the drive shaft coupling to the main gearbox that had caused misalignment of the forward coupling. There were 6 nuts and bolts connecting the drive shaft coupling to the gearbox input adaptor. All but one bolt and washer were missing from the assembly and there was some deformation of the input adaptor flange (Figure 22). Exhibit 63

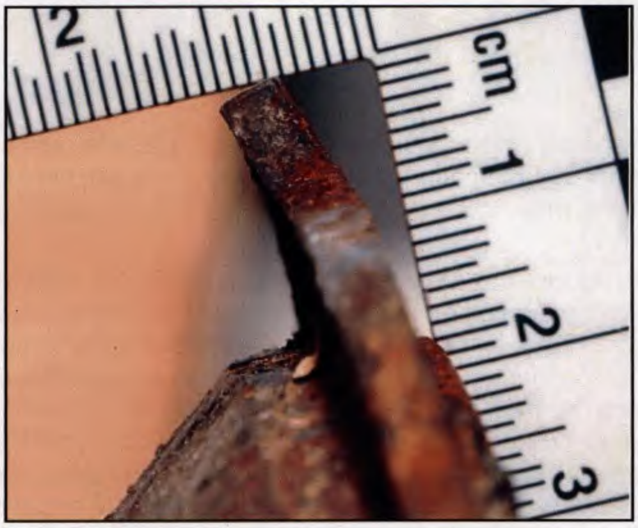


Figure 22 - Evidence of deformation of the main gearbox input adaptor flange.
(Picture Source: 1710 NAS)

1.4.89. 1710 NAS assessed that the bolts were more likely than not to have been fitted. The attachment of the nuts was last checked during a 25 hour inspection, 13:10 airframe hours before the accident. Had the bolts not been fitted or been loose it was very likely that there would have been vibration felt by the crew at an earlier stage of flight or in the hours since the last inspection. It was also considered very unlikely that the bolts were Exhibit 2 Exhibit 63 loose to an extent that could have accounted for the angular displacement of the forward coupling. This was due to the lack of physical evidence normally associated with movement between the two components such as fretting[21] between the mating surfaces.

1.4.90. **Timing of the main drive shaft failure**. In the event of a main driveshaft failure, power is immediately removed from the main rotors. Drag causes the main rotor speed to reduce to zero unless the aircraft can establish autorotation. As the accident occurred whilst close to the ground, achieving autorotation was not possible, therefore the main rotor speed would have reduced to zero without the ability to recover. When the main rotor speed audio warning was activated during the accident, the main rotor speed did not recover. Simulated drive shaft failures were analysed in the Griffin simulator at RAF Shawbury and although not an exact representation of the aircraft's behaviour, the low rotor speed audio warning repeatedly occurred within half a second of the main rotor drive shaft failure in sorties flown by DHFS standards. There were other factors may have caused the main rotor speed to reduce. Therefore, the Panel determined that the drive shaft coupling failure did not occur before half a second prior to the activation of the main rotor speed audio warning, but may have occurred after. The Panel concluded that the main rotor speed audio warning was almost certain to be the earliest timing, within half a second, of when the main drive shaft coupling failed.

Exhibit 64

1.4.91. **Summary of drive shaft coupling misalignment**. Analysis by 1710 NAS concluded that the drive shaft assembly failed in overload as a result of an angular displacement between the forward inner and outer coupling and that this occurred as a result of events forward of the coupling. The Panel concluded that failure of the forward outer coupling or its connection to the main gearbox was not the cause of the accident because they both occurred as a consequence of preceding events. Therefore, movement of the gearbox itself became the focus of the inquiry because it was the most likely preceding event that could cause misalignment of the coupling.

Exhibit 63

Main gearbox movement

1.4.92. The main gearbox assembly and associated components was the next major section of the transmission forward of the coupling and the Panel therefore considered how movement of this component may have caused misalignment of the coupling to occur.

1.4.93. **Main gearbox construction and purpose**. The main gearbox transfers drive from the main drive shaft through reduction gearing to the main rotor head and separately to the tail rotor drive shaft and ancillary systems. The main gearbox casing comprises a set of magnesium alloy castings connected to each other, including a support case that mounts the gearbox to the airframe. The main transmission gearing is contained within the main gearbox casing assembly (Figure 23). The support case is connected to the airframe by a lift link approximately 1/3 distance back from the forward edge of the support case. The lift link transmits the majority of the loads between the airframe and the gearbox support case and is mounted on spherical bearings at each end to allow small variations in pitch and roll movements during flight. The gearbox is further constrained by four corner mounts with elastomeric dampers designed to attenuate vibrations transmitted to the fuselage. Two friction dampers on the aft mounts were a legacy from the Bell 212, but

[21] Fretting is a special wear process that occurs at the contact area between two materials under load and subject to minute relative motion by vibration or some other force. Source: MAA Structural integrity handbook - 2015

were retained on the Bell 412 to provide low frequency pylon response stability. A number of ancillary components are mounted on the gearbox including aircraft hydraulic pumps, transmission oil pump, flying controls and the rotor brake. Exhibit 30

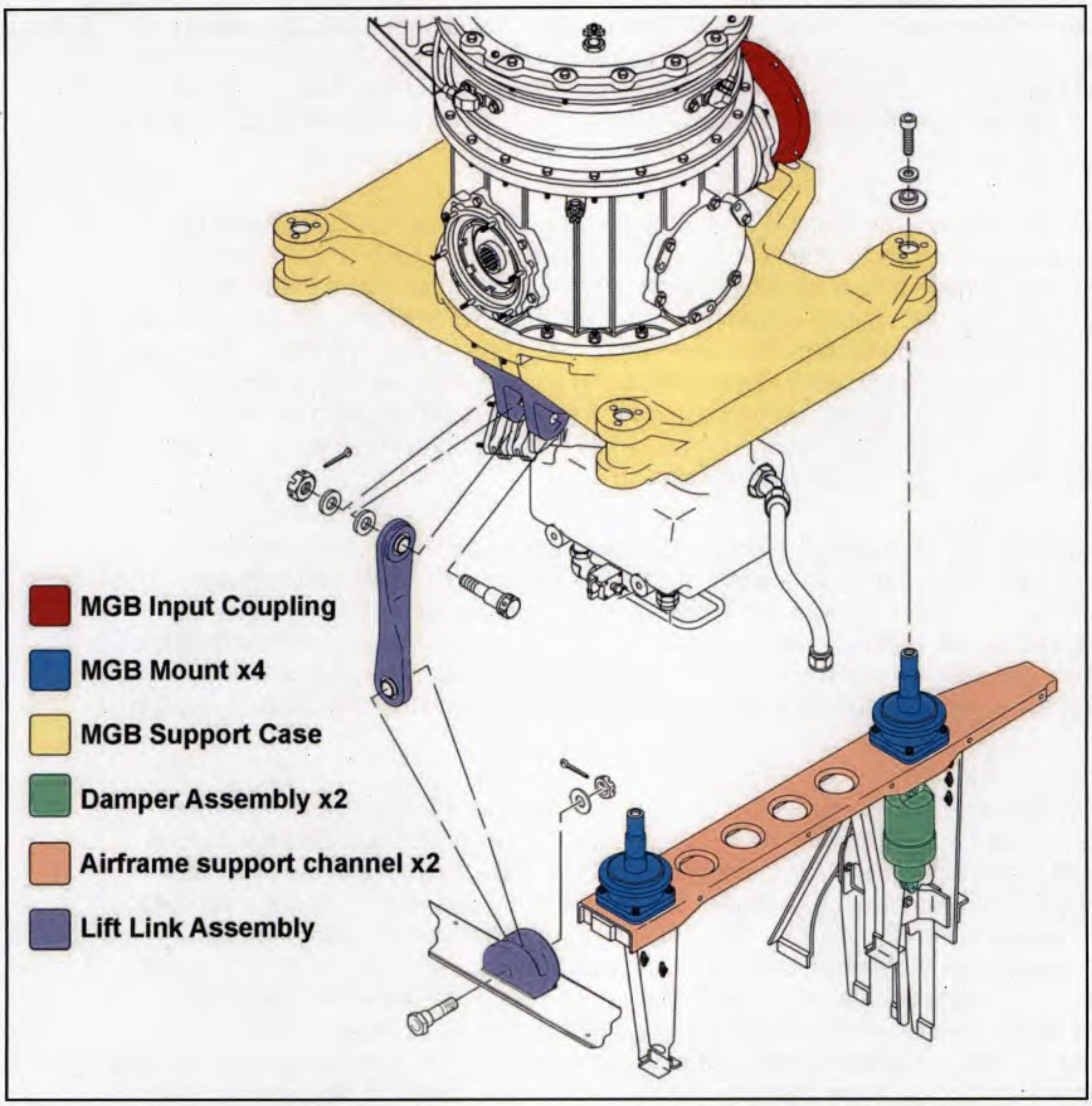


Figure 23 – Main gearbox assembly and associated components.
(Picture Source: Bell Maintenance Manual – modified)

1.4.94. **Main gearbox movement.** Following the 1710 NAS analysis that misalignment occurred due to events forward of the coupling, the Panel identified two possible causes which were; a movement of either the main gearbox input shaft relative to the main gearbox, or a movement of the main gearbox itself, beyond its normal alignment limits. The main gearbox input shaft showed no signs of gear wear or dislocation from the main gearbox. The Panel therefore concluded that the input shaft was not the cause of the forward outer coupling misalignment. Exhibit 63 Exhibit 18 Exhibit 214

1.4.95. It was necessary to establish the amount of gearbox movement that would cause damage to the coupling in order to determine if the gearbox had failed or caused damage through normal operation. Bell provided evidence that the maximum allowable misalignment between the inner and outer coupling was 7.5˚ before the two components 'lock' together and cause damage. During normal operation, limited main gearbox movement was possible through flexion or compression of the four isolation corner mounts that hold the main gearbox to the airframe. This movement was mechanically limited to 2˚ and was not enough to cause locking and bursting of the coupling. Therefore the Panel determined that angular movement between the main gearbox and the main drive shaft beyond the 7.5° limit would only be possible following failure of a component involved in gearbox mounting. Exhibit 65 Exhibit 65

1.4.96. Angular displacement of the aft end of the drive shaft was also considered to determine if a combination of relative movement would exceed the limits of the coupling. The aft end of the drive shaft is connected to the combiner gearbox which in turn is rigidly mounted to both engines. These components are bolted to the airframe and any flexibility is negligible by comparison to that of the main gearbox. The engines and their mountings remained intact, meaning that normal movement of a serviceable gearbox or combiner gearbox could not have caused misalignment of the forward outer coupling alone. Movement of the main gearbox beyond normal limits was the only remaining option that could cause misalignment of the forward coupling. Exhibit 18

1.4.97. **Consequential damage**. The gearbox was destroyed by fire, and prevented direct examination to confirm if a mechanical failure had occurred which would have enabled excessive forward movement. However, there was evidence of consequential damage caused by the gearbox moving forward. By analysing the consequential damage resulting from gearbox movement the Panel sought to determine if the gearbox could have moved a sufficient distance to cause misalignment of the main driveshaft forward coupling beyond 7.5°.

1.4.98. Two sections of aircraft cowling that surrounded the rotor mast were recovered without fire damage from the accident site (Figure 24). One section was damaged along the rotational plane, consistent with being struck by the 345 mm radius of the main rotor pitch change links. This damage area was cut in an anti-clockwise direction and intruded 110 mm into the cowling (Figure 24). The Panel determined that this meant that the section detached from the aircraft before the fire took hold and was the result of an event that preceded the collapse of aircraft due to fire. The Panel considered the possibility of the forward cowling becoming detached in flight first and then impacting the main rotor. The security of the cowling was checked during the daily inspection and on two successive pre-flight checks that day. More than one catch would have needed to be undone to allow it to move. Also proximity of the fragments to the aircraft and lack of other cowling fragments would not support a high energy impact. The Panel assessed that spontaneous cowling detachment was very unlikely. Pitch change link impact on the cowling was further supported by evidence from three previous accidents worldwide that had similar characteristics. In one of these accidents it was conclusively determined that the gearbox support case had fractured which allowed the main gearbox to move forward, impacting the cowling which caused similar damage to that identified with ZJ241 (Figure 25). In the same example the majority of the cowling remained intact and attached to the aircraft, demonstrating that the same outcome was possible in similar circumstances. Bell confirmed that pitch change link contact with the cowling cannot occur even with maximum forward cyclic applied. The Panel concluded that the pitch change links had impacted the cowling. Evidence of consequential damage to the cowling supported the conclusion that Exhibit 66 Exhibit 67 Exhibit 68 Exhibit 65 Exhibit 76 Exhibit 65 the main gearbox had moved forward during the accident.

Figure 24 – [Left] Cowling debris shown from above, overlaid on a serviceable component. [Right] Showing the relative position of the pitch change links to the cowling.
(Picture Source: DAIB Engineering)

Figure 25 - Forward upper cowling debris from similar Bell 412 accident, showing damage as a result of pitch change links impacting the cowling.
(Picture Source: Bell)

1.4.99. The Panel considered the effect of main gearbox movement on the tail rotor because of its connection to the base of the main gearbox. Evidence of damage to the tail rotor drive shaft would support the conclusion that the main gearbox moved beyond normal limits during the accident. Witnesses observed that the tail rotor slowed down much more quickly than the main rotor and was then seen to have stopped as the main rotor was still turning. The crew did not recollect any yaw during the incident and the Passenger did not report any significant visible yaw from the outside. The entire tail section was found separated from the main fuselage and recovered largely intact by DAIB investigators. Technical examination of the tail section provided no evidence of

Witness 1
Witness 4
Witness 8
Exhibit 18

component failure that would have caused a mechanical disconnection, leading to the conclusion that disconnection of the tail rotor drive must have occurred forward of the point of separation of the tail section, which was at the number 2 drive shaft just aft of the baggage locker. (Figure 17). The main rotor has greater momentum than the tail rotor therefore the tail rotor would have slowed more quickly than the main rotor once disconnected from the main gearbox. The Panel concluded that the tail rotor slowing more quickly than the main rotors indicated that the tail rotor disconnected during the accident sequence. Exhibit 18

1.4.100. The causes of tail rotor disconnection from the main gearbox, other than main gearbox movement, were either fire or severance caused by shrapnel from the damaged main drive shaft coupling. The fire had not had time to build by the time the tail rotor failed which made this option very unlikely. A redundant aft gearbox 212 attachment partly protected the tail rotor drive shaft from main driveshaft coupling fragment damage, also making this option unlikely (Figure 26). It was the Panel's opinion that movement of the gearbox most likely applied an excessive compressive axial force to the tail rotor output shaft and thus catastrophically damaged the tail rotor drive shaft, causing it to fail under load and separate from the main gearbox, allowing it to slow independently. The Panel assessed that disconnection of the tail rotor drive shaft was more likely than not as a result of gearbox movement.

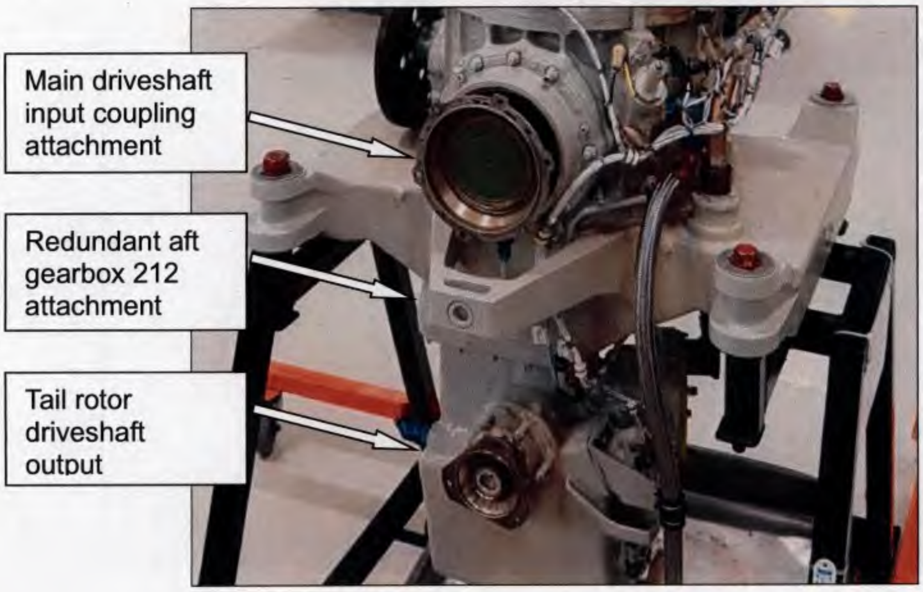


Figure 26 – Rear view of main gearbox uninstalled from aircraft
(Picture Source: SI Panel)

1.4.101. **Summary of main gearbox movement**. The main gearbox moved by an amount greater than 7.5° of misalignment at the forward outer coupling causing it to fail. Forward movement by this amount also caused consequential damage as the pitch change links cut through the forward upper cowling by 110 mm. The Panel concluded that the main gearbox moved forward during the accident by an amount greater than during normal operation. The Panel then sought to determine the cause of excessive main gearbox movement.

OFFICIAL SENSITIVE

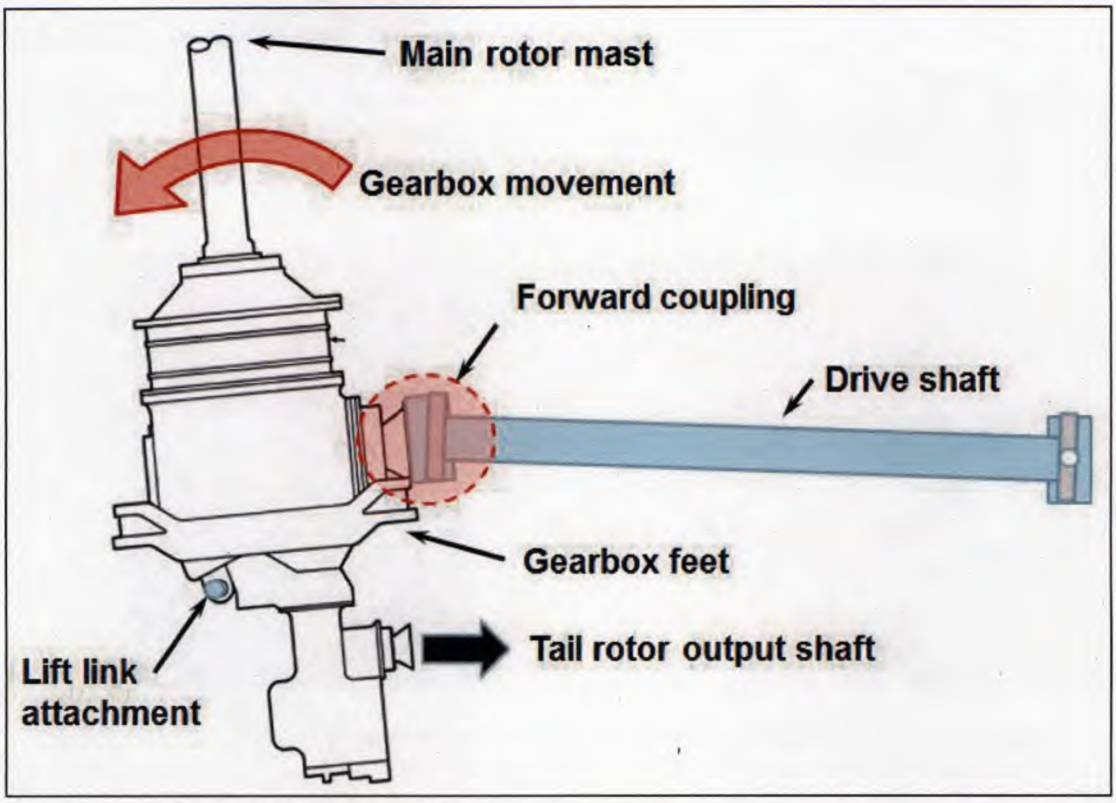


Figure 27 - Diagram showing gearbox movement and coupling misalignment.

Main gearbox support case failure

1.4.102. The Panel used a fault tree analysis to consider which components may have failed and caused excessive movement of the gearbox. The possibilities were failure of; the corner mounts, lift link, the airframe or the support case. Each of these options will be discussed, and compared against other similar examples, which support the Panel's conclusions regarding support case failure. Exhibit 18 Exhibit 66

1.4.103. **Support case corner mounts and lift link**. The lift link and 4 corner mounts connect the support case to the airframe (Figure 23). The remains of the corner mounts, which were significantly fire damaged, were examined by Bell and analysed by 1710 NAS for damage or incorrect fitment and deemed to be complete and correctly installed at the time of the accident (Figure 28). One of the corner mount bolts was found to be slightly bent, however forensic analysis determined that this was consequential damage. The lift link was also examined and assessed for damage and was observed to be complete and correctly assembled (Figure 28) and therefore discounted as a cause of main gearbox movement. Elastomeric de-bonding[22] within the corner mounts was considered as a potential cause of main gearbox movement because it was known to have occurred on other aircraft and would result in an additional movement of the main gearbox had it occurred. Bell confirmed that during normal operation, the gearbox was designed to move by up to 2°. However, Bell also confirmed that any additional movement of the gearbox Exhibit 18 Exhibit 203 Exhibit 65 Exhibit 203 Exhibit 65

[22] Elastomeric de-bonding is where the elastomeric components within the corner mounts become detached from the inside of the unit.

beyond 2° due to de-bonding would have been negligible and would not have produced enough misalignment to cause the coupling to fail. The corner mounts were significantly degraded by the fire. Therefore, it was not possible to determine if elastomeric de-bonding had occurred. The Panel concluded that movement of the main gearbox was not the result of failure or incorrect fitting of either the corner mounts or the lift link and was **not a factor** in the accident. Exhibit 65

Figure 28 - Fire damaged corner mount and lift link assembly.
(Picture Source: Bell Factual Observations Report ZJ241)

1.4.104. The remaining failure modes from the fault tree analysis were either; failure of the airframe or the support case that was attached to it. Given that both components had been destroyed by fire, and direct analysis was not possible, the Panel sought to determine the likelihood of which component had failed through analysis of the other layers of circumstantial evidence. Exhibit 18

1.4.105. **Airframe failure**. The Panel found one previous Bell 412 example of airframe failure, which had resulted in partial gearbox movement, enough to allow the main driveshaft coupling to misalign. The root cause was identified by Bell as incorrect bolts installed in the gearbox support case mounting points. Extensive fretting was found under 3 of the mounting points and overload features were found in all airframe fracture surfaces. Analysis by Bell and 1710 NAS confirmed that the mounting feet on ZJ241 were correctly assembled and the Panel assessed that this would therefore not have caused a similar airframe failure. The Panel also considered if a previous repair to the airframe had affected the structural integrity of the airframe surrounding the main gearbox feet and if this contributed to the accident. The last airframe inspection would have been during installation of the main gearbox, 404 airframe hours prior to the accident. It was difficult to establish the number of airframe repairs from the configuration control documents because they were not recorded in the aircraft's documents. However, through more detailed investigation, the Panel found that thirteen airframe repairs had been recorded, over the entire life of the aircraft. None of the repairs to the airframe were found to be in areas that could have resulted in structural weakness and consequent movement of the gearbox. The DAIB technical investigation assessed that due to the complexity of the structure and the redundant load paths, that the probability of failure of the airframe components that would enable the required freedom of movement was very low (Figure 29). Therefore, the Panel concluded that the airframe did not fail as a result of a previous airframe structural repair and that airframe failure was very unlikely because of the redundant load paths at

Exhibit 67
Exhibit 73
Exhibit 203
Exhibit 18
Exhibit 66
Exhibit 70
Exhibit 71
Exhibit 179
Exhibit 72
Exhibit 18

the attachment points. Airframe failure was **not a factor** in the accident.

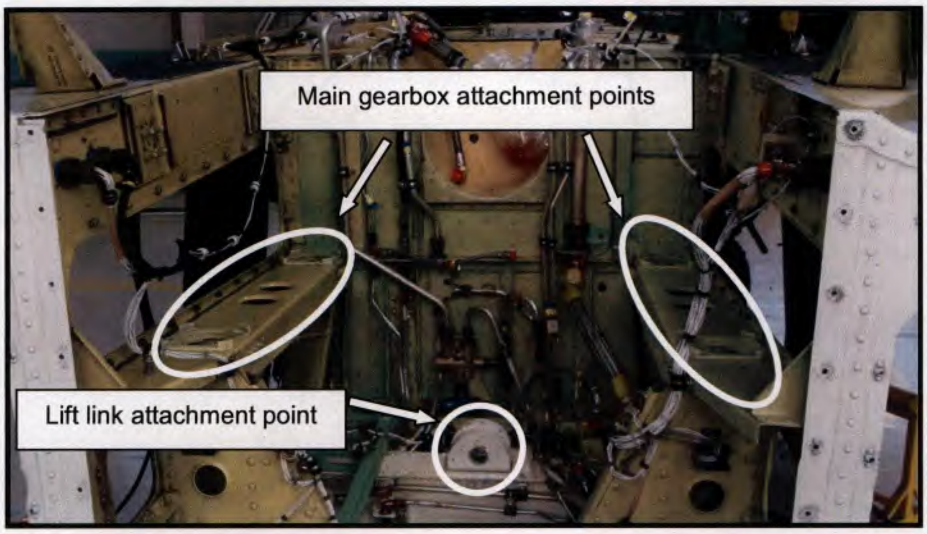


Figure 29 – View of the airframe structure and attachment points to the gearbox, view looking forwards.
(Picture Source: DAIB Engineering)

1.4.106. **Support case failure**. Finite element analysis[23] of the gearbox by Bell concluded that contact between the pitch change link and the forward upper cowling, following a failure of a single gearbox support case attachment leg, could only occur with very high forward cyclic input of greater than 75%. Bell also concluded that failure of a single leg would not provide sufficient misalignment to cause failure of the main driveshaft forward outer coupling in the accident. They concluded that the maximum misalignment with a single leg fracture and the cyclic fully forward would be 5.5° and that an additional secondary failure would be required in the support case or drive train for the main drive shaft coupling to fail. Therefore, the Panel assessed that the support case required at least 2 failure points to provide enough freedom of movement to misalign the main driveshaft coupling by greater than 7.5°. The Bell component repair and overhaul manual described the main gearbox support case as the area of critical load path on the main gearbox. The manual further described the critical areas on the support case that had the lowest tolerance to damage and therefore required even closer inspection. These areas were also the most vulnerable to corrosion, fatigue or mechanical damage (Figure 30).

Exhibit 30
Exhibit 30
Exhibit 30
Exhibit 70

[23] Finite Element Analysis is a computerised analysis method to envisage how a manufactured product will react to the physical world. The analysis can predict if the product is likely to break, tear, wear, or behave in the way it was designed.

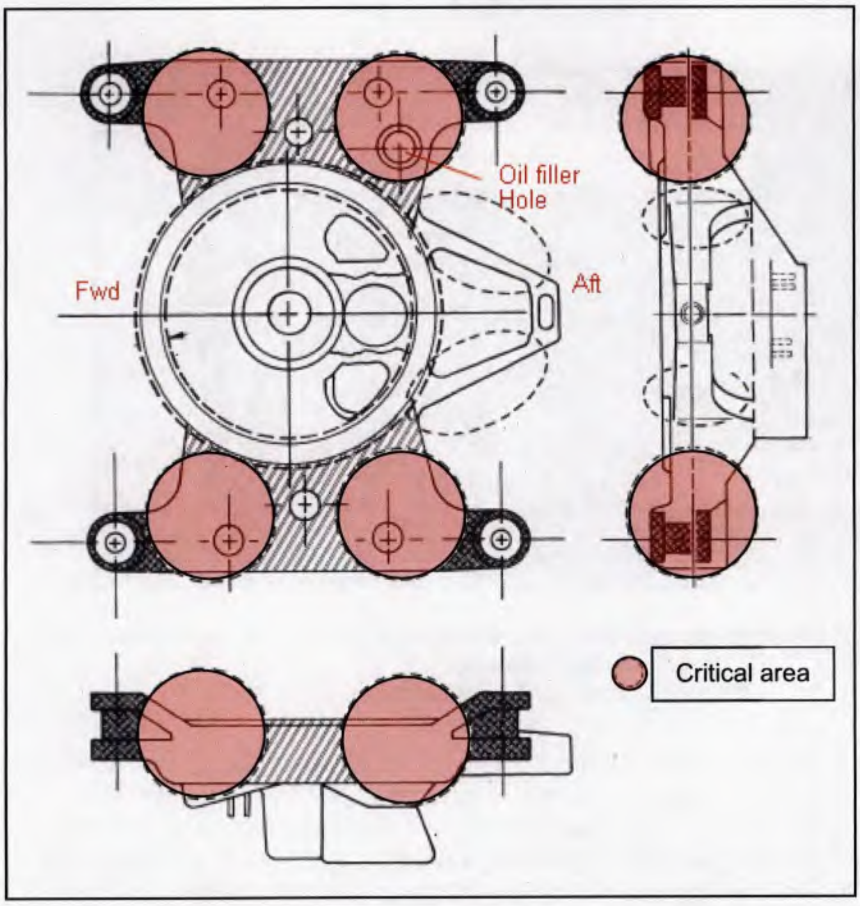


Figure 30 - Critical areas of main gearbox support case.
(Picture Source: Bell Component Repair & Overhaul Manual – annotated)

1.4.107. **Examples of support case failure**. The Panel found a total of 5 reported instances of main gearbox support case cracking: a British military aircraft support case fatigue crack in 2006; an incident (provided by Bell) where analysis of Health Usage and Monitoring System (HUMS) data led to the discovery of a support case crack in 2012; overload of a support case in Wollongong, Australia following severe vibration in 2008; a foreign military support case crack (Provided by Bell) in 2006; and an incident in Australia of a crack found in the support case following severe vibration in 2017. There were a further 2 instances of cracking within Canadian Forces' gearbox support cases, *"right hand transmission support cracked 5mm long" and "Cracked on forward right hand mount"*. Limited information prevented further analysis of the Canadian examples. The 5 non-Canadian incidents of cracking were all in or close to a critical area of the support case. Overlaying all of these incidents on a diagram of the support case demonstrated the most likely failure locations on ZJ241's support case because most of the cracks were almost coincident with each other (Figure 31). These incidents will now be individually discussed as case studies in support of determining the cause of the accident:

Exhibit 74
Exhibit 75
Exhibit 76
Exhibit 67
Exhibit 68

Exhibit 188

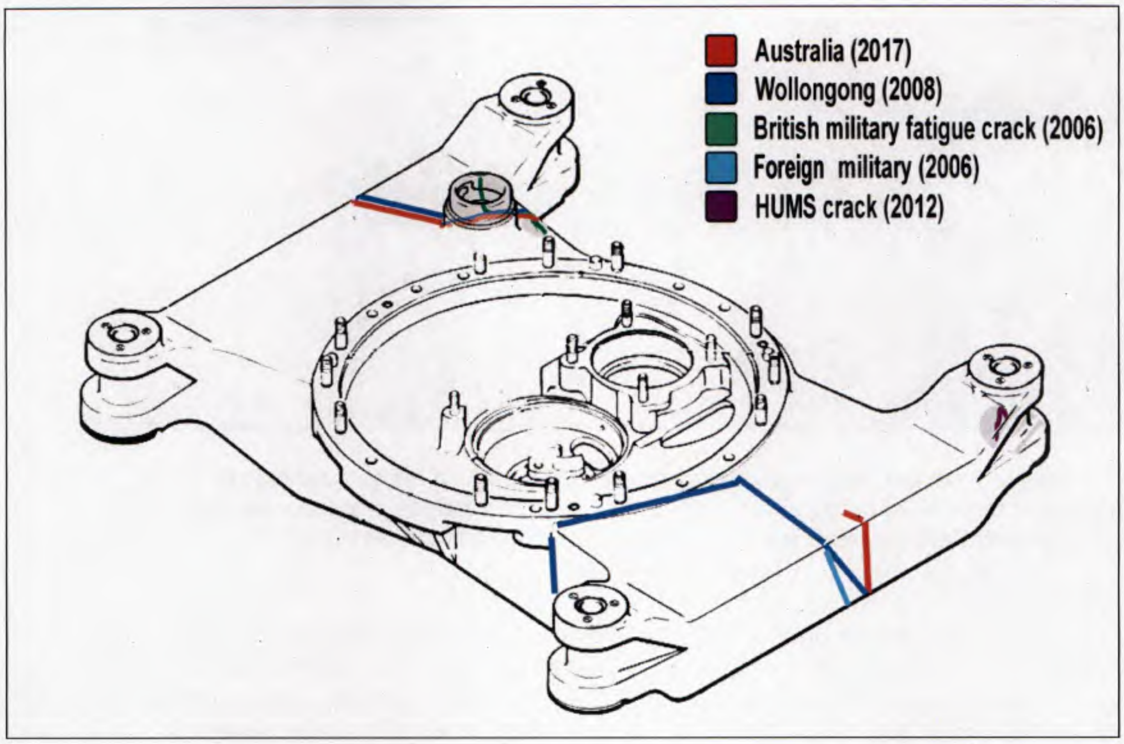


Figure 31 - Diagram showing the location of 5 previous support case failures.

a. **British military fatigue crack (2006)**. The fatigue crack, discovered on a support case in 2006, was significant because the incident occurred within the same aircraft tail number, ZJ241, albeit within a different gearbox and associated support case. This appeared to be more than a coincidence given the number of Bell 412 aircraft worldwide and was therefore considered by the Panel to be worthy of further investigation. The crack initiated from the fillet radius on the aft side of the oil filler hole on the rear right leg of the support case (Figure 32). The crack was found during a leak check ground run, following an in-flight engine failure on the previous sortie. Maintenance involved replacement of the engines and a number of ground runs prior to flight testing. A Bell lab report, following the incident, detailed that the cause of the crack was fatigue without any indication of a crack initiator. Bell's response confirmed that fatigue cracking could occur on main gearbox support cases and a structural integrity expert advised that this was 'loading severity'[24] driven. Exhibit 74 Exhibit 77 Exhibit 78

[24] 'Loading severity' is the combination of applied cycles and cycle magnitude.

Figure 32 – Images from the Bell engineering laboratory report on the fatigue crack found within the support case of ZJ241 in 2006. [Left] Location of the fatigue crack on the support case. [Right] Fatigue crack surface showing the initiation site in the circle.
(Picture Source: Bell)

b. The engine failure prior to the 2006 fatigue crack being discovered, that prompted maintenance on the gearbox, was a single engine failure in a 40 ft hover over the sea. This was one of only 2 airborne Griffin engine failures within the ASIMS database.[25] The 'flyaway'[26] recovery action would have involved lowering of the collective lever to minimise a reduction in main rotor speed and application of forward cyclic to achieve safe single engine speed. During this recovery the aircraft descended to 20 ft above the sea and rotor-speed was observed at 91%. The combined circumstances of the recovery action may have imparted a higher than normal stress on the support case. The aircraft was undergoing maintenance, and between the incident and the fatigue crack discovery, did not fly. The crack was discovered during maintenance several weeks after the engine failure. Despite 2 of the most serious flight safety events throughout the history of the aircraft occurring on the same aircraft and at the same time, a link was not made between the two events by the engineering organisation or flight safety staff. It was the Panel's opinion that this was due to the passage of time between the incident and discovery of the crack.

Exhibit 77

Exhibit 77

c. The root cause of the fatigue that led to the 2006 crack was not determined at the time. However, the first time Bell communicated a potential cause of the 2006 incident was during this Service Inquiry. Bell stated that the 2006 fatigue crack would either have been due to excessive long term vibration loading or flight outside the Rotor Flight Manual. The vibration records showed that the levels of vibration for the 2006 crack were within limits following each scheduled vibration analysis and at intermediate component changes. The records date back to 1999; therefore the Panel concluded that long term vibration loading was **not a factor**.

Exhibit 210

Exhibit 30

Exhibit 81

d. **HUMS crack (2012).** The location and operator of the HUMS crack in 2012 was not disclosed to the Service Inquiry but the details of the incident were

Exhibit 75

[25] As at 9 Aug 2016.

[26] 'Flyaway' is a term given to the immediate transition from hover to forward flight to offload rotor power.

released in order to help with the investigation. Bell provided an example of a support case crack in an attachment leg that was identified prior to failure by the use of a HUMS regime. The cause of the crack was not possible to determine but Bell stated that it may have been due to incorrect assembly of the upper and lower main gearbox cases during depth maintenance. The crack was found on the attachment leg at the rear left gearbox mount (Figure 33).

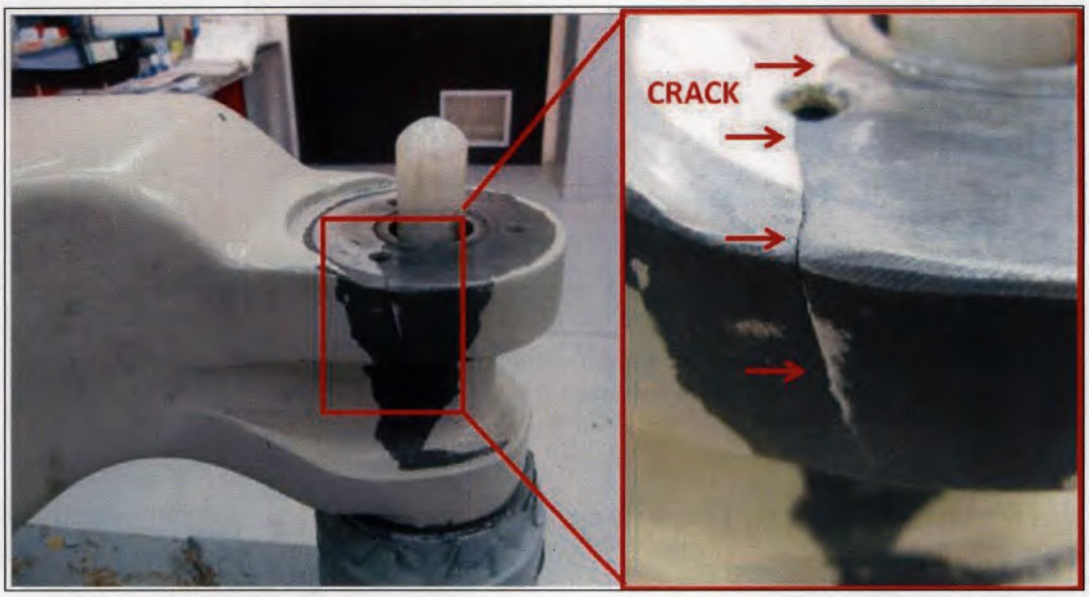


Figure 33 – HUMS support case crack (2012).
(Picture Source: Bell)

e. In the 2012 example, HUMS accelerometers detected unusually high levels of vibration. The level of vibration was undetected by the operator for at least 8 months and although it was unclear how many hours were flown during this period, none of the crew flying the aircraft detected anything unusual. It was brought to the operator's attention by Bell on review of the HUMS data. When the suspect support case was replaced by the operator, the level of vibration immediately reduced to below the acceptable threshold, confirming that HUMS had correctly identified an issue that led to the discovery of a fatigue crack in the support case (Figure 34 point A and point B).

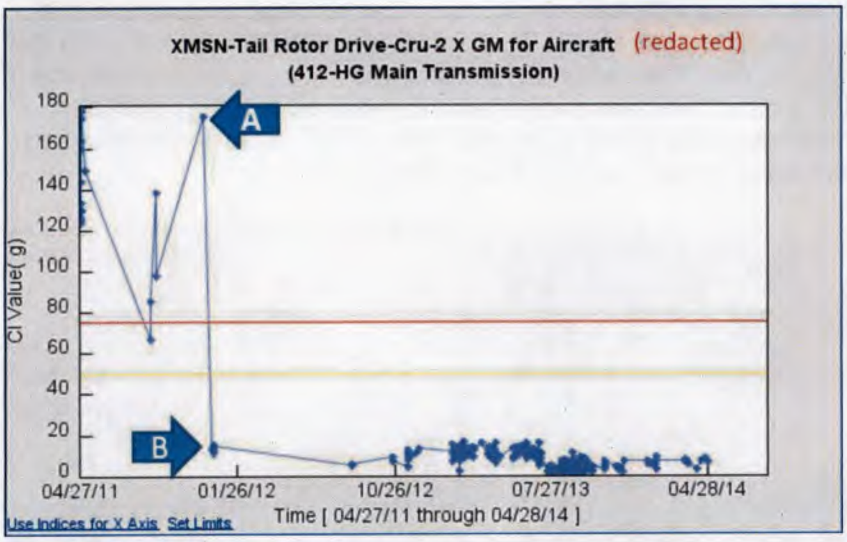


Figure 34 - HUMS data for the support case fatigue crack detected in 2012, showing significant decrease in vibration levels between point A and B after replacing the support case with a new component. The red line indicates a threshold level of vibration.
(Picture Source: Bell)

f. **Foreign military support case crack (2006)**. It was reported that shortly after landing on a grass pad and while light on the skids, the pilot felt the helicopter moving left and aft. In response, the pilot applied full right forward cyclic. The helicopter bounced forward approximately 34 ft and rotated slightly to the right. Airframe damage was limited to areas surrounding the gearbox. Amongst other damage, the forward pylon cowling was damaged consistent with main rotor pitch change link contact during the accident. The main drive shaft inner coupling was reported as becoming decoupled from the outer coupling and some chipped teeth were observed on the inner coupling. A large crack on the transmission support case in the vicinity of the right hand forward mounting leg was observed (Figure 35). The support case was sent to Bell Helicopter for laboratory examination. No features consistent with a fatigue failure mechanism were found on the crack's fracture surface; only features consistent with over-stress were observed. Extensive fretting was found under the left-hand forward pylon isolation mount between the mount spacer and channel. The two aft bolts fitted to the left-hand forward mount had longer grip lengths than required by the engineering drawing and exhibited contact damage from the bolts being tightened against the nut-plates. A total of three of the left-hand forward mount bolt locations had bolts installed that were not as specified, as well as one incorrectly specified bolt in the left-hand aft mount and two incorrectly specified bolts fitted to the right-hand aft mount.

Exhibit 67

Exhibit 30

Exhibit 73

Figure 35 – Foreign military support case crack (2006).
(Picture Source: Bell)

g. **Wollongong (2008).** While conducting training at Wollongong airfield the aircraft was landed on the runway and developed severe vertical airframe vibrations resulting in reduced pilot control. In an effort to mitigate the vibrations the aircraft was lifted back into the hover, however the vibrations increased in severity. The pilot lowered the collective to land again and the aircraft made a hard landing, resulting in damage to the gearbox. The fault was traced to excessive free-play introduced into the 'collective control run' at overhaul. This allowed extra vibration and lack of controllability issues to develop. The support case was fractured at the forward left and rear right corners (Figure 36). Exhibit 76

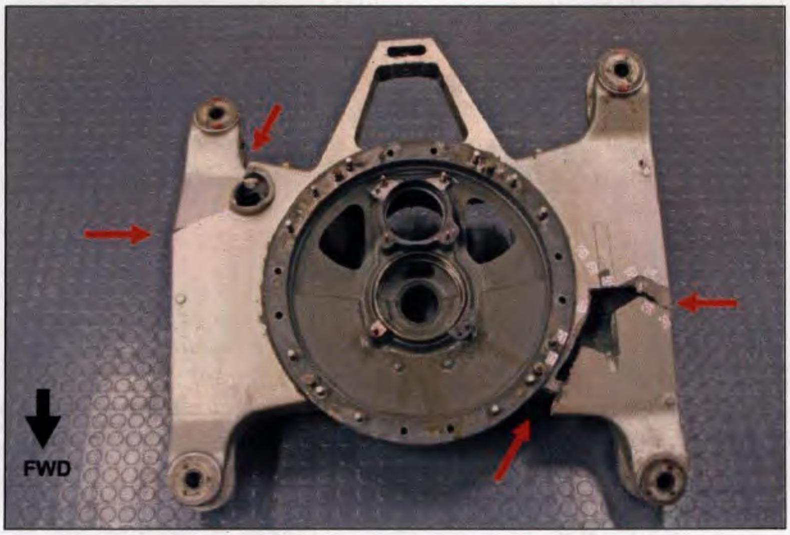


Figure 36 - Wollongong accident support case.
(Picture Source: Australian Transport Safety Bureau)

h. **Australia (2017).** Following uncommanded pitch changes during the previous flight, maintenance was carried out on the aircraft's autopilot system and ground checks were conducted to confirm the autopilot's serviceability. Aircraft start-up checks were completed without incident until the autopilot check commenced. At this point a vertical vibration began and quickly increased in intensity. The pilot raised the collective slightly to try to correct the situation however this increased the vibration further. The aircraft did not move laterally but continued "harsh bouncing" and the pilot believed that it did not leave the ground fully. The support case fractured due to overload forces at the rear right corner and on the left side in the vicinity of the rotor brake (Figure 37). Exhibit 68 Annex G

Figure 37 – Damage to the support case in the Australian accident (2017).

1.4.108. **Summary of support case failure**. The combination of the finite element analysis, consequential damage and similar historic failure locations all indicate that the support case failed. The first failure to occur in this incident was almost certainly on the support case because the only previous airframe failure in the vicinity of the support case had resulted from an incorrect fitting of the support case mountings. Notwithstanding this, there still needed to be a minimum of at least 2 failure points to allow the required freedom of movement to cause the consequential damage that was observed. The Panel assessed that once a single failure of the support case had occurred, a subsequent failure was then increasingly likely due to the reduced strength of the component.

1.4.109. The Panel concluded that based on the available evidence, it was almost certain that failure must have occurred in 2 or more locations on the support case and that these were likely to be in one or more of the critical areas and in a similar manner as the previously reported support case failures. The Panel concluded that structural failure of the support case enabled movement of the gearbox and misalignment of the driveshaft coupling by more than 7.5° and caused consequential damage that started a chain of events that ultimately led to the destruction of the aircraft by fire.

1.4.110. The *'taps'* recorded on the CVR, saturated the recording, indicating that they were loud and discrete events. The Panel judged that due to the similarity between the 2 sets of *'taps'* on the CVR they were from the same source. There were 2 major mechanical failures during the accident; the support case failure and the drive shaft coupling failure. Although there was no audible evidence of the driveshaft failure on the CVR, the timing of the driveshaft coupling failure was no earlier than half a second prior to when the main rotor speed audio warning activated, which occurred after the *'taps'*. Therefore, the *'taps'* were not the drive shaft coupling failure. The *'taps'* were the first audible manifestation of a mechanical failure but it was not possible to determine if there had been a mechanical failure prior to this event due to the incomplete CVR. Notwithstanding this, the Panel Exhibit 17 concluded that the gearbox support case failure was very likely to have been the source of the *'taps'* and coincident with the assessed departure from controlled flight.

Introduction to failure modes

1.4.111. Previous analysis has determined that there were 2 factors, with precedent, that may have led to structural failure of the support case: overload (1.4.112) or fatigue (1.4.141). To differentiate; fatigue is the cyclic loading of a material that leads to progressive cracking. The stress values that cause such damage are typically much less than the stress limit of the material, normally referred to as the static yield strength.[27] Once a fatigue crack initiates, stresses significantly less than the static yield strength may cause the remaining material to fail over a period of time. Comparatively, failure in overload is caused by applying a stress above the static yield strength of the material. An overload of the support case would indicate that the failure was a consequence of an external event during or prior to the accident, whereas fatigue cracking would be attributable to an inherent or pre-existing fault. Factors that contribute to each of these conditions are further analysed below, in order to establish the cause of the support case failure.

Gearbox support case overload

1.4.112. The support case was designed to sustain vertical and horizontal static loads up to 8g and in laboratory static tests performed to a considerably higher standard. The Panel identified and assessed a number of situations that could lead to a failure of the gearbox support case through overload. The potential factors were a number of different aspects of aircraft handling, the force of landing, vibration phenomena, and aircraft faults that could lead to any of the factors listed. They were considered in isolation on an otherwise serviceable support case for the purpose of determining if overload of the support case could have been the cause of the accident.

Exhibit 73
Exhibit 82

1.4.113. **Force of landing**. All crew members described a normal approach and rate of descent to a sloping ground landing until front-of-skid contact was made with the ground. Aircraft Commander B observed an entirely normal event. The Crewman Instructor described it as a normal and perfectly controlled sloping ground landing. The Passenger, an experienced helicopter pilot, standing just outside the rotor disc, also described a normal evolution to the point of initial contact. The Passenger further described the chronology of the landing as the rotation of the aircraft onto the ground that appeared heavy but not such that it was of concern. When asked to provide a subjective assessment of the force of landing the Passenger gave it 3 out of 10 (where 0 was a perfect landing and 10 was a write-off). Additionally, Aircraft Commander B recounted more severe landings as part of student training sorties. The Panel concluded that the approach and landing was normal up to the point of front-of-skids contact with the ground. The hardest part of the landing sequence was when the rear of the skids made contact with the ground.

Witness 2
Witness 3
Witness 4
Witness 8
Witness 5
Witness 1

Witness 1
Exhibit 201

Witness 8

1.4.114. The aircraft skids are designed to deform in the event of a crash to attenuate the loads transmitted to the airframe and protect aircraft components. The incident in

[27] The 'static yield strength' of a material is the maximum stress that can be applied before plastic deformation occurs.

Wollongong (Australia), 2008 resulted in overload of the support case following a severe vertical landing. In this incident the skids were deformed underneath the fuselage and bent outwards demonstrating how failure may occur as a result of a heavy landing. The inter-skid distance at the maximum all-up-mass was given as 2.8 m in the aircrew manual, and the LIDAR image of the crash site estimated this distance as 2.82 m at the rear of the skids and 2.96 m at the front of the skids. The skids were visibly intact after the crew had escaped and this was supported by photographic evidence and witness accounts. Subsequently, fire destroyed much of the skid frames and the fuselage collapsed. It was not possible to determine if the fuselage collapsing on the skids, post fire, had pushed them slightly apart or if this was an indication of the force of landing. DAIB conducted a *"conditional inspection – after hard landing"* on the available tail section in accordance with the Bell Maintenance Manual to identify if there was any damage that would indicate a hard landing. There was no structural damage evident in the tail rotor drive train or intermediate and tail rotor gearboxes, which indicated that a force of landing severe enough to cause structural damage was unlikely.

Exhibit 76
Exhibit 62
Exhibit 54
Exhibit 18
Witness 1
Exhibit 18
Exhibit 189

1.4.115. Advice sought from RAFCAM assessed the maximum vertical force that could have occurred during the accident as 3-4g, based on the medical assessment of typical injuries sustained during similar aircraft accidents such as whiplash and musculoskeletal injuries. Despite 2 crew members being unrestrained while lying down and leaning out of the cabin, the crew sustained no injuries during the accident which demonstrated that the landing was likely to be below this threshold. During the Australian accident (2017) example the crew sustained 2 minor back injuries and cuts and bruises, indicating that its severity was greater than the accident involving ZJ241. Although the assessed maximum severity of skid contact with the ground during the accident involving ZJ241 was higher than normal, it was significantly lower than the static design strength of the support case and supported the assertion that the landing was not severe enough to cause damage. There was no further evidence to suggest that the force of landing was in excess of the design parameters. Furthermore, the CVR indicated a slow and unhurried landing until the departure from controlled flight (1.4.80).

Exhibit 83
Exhibit 83
Exhibit 68
Exhibit 73

1.4.116. It was not possible to determine the exact force of the landing but based on the available evidence the Panel concluded that the force of the landing was unlikely to have been severe enough to overload the support case alone. However, when the aircraft came down heavily on the rear of the skids it would have transferred a loading through to the support case and may have contributed to the failure. The force of landing during the accident was harder than normal and increased the stress in the support case. This in conjunction with other factors made failure of the support case more likely and was therefore considered to be a **contributory factor**.

1.4.117. **Cyclic stirring**. The cyclic stick is the pilot's main control lever that affects the attitude of the helicopter. An Operations Safety Notice (OSN) issued in September 1976 by Bell describes how *'cyclic abuse'* can create a potential hazard of, *"engine to transmission drive shaft failure"*. The control movements that constitute 'cyclic abuse' are extremely large, fast cyclic displacements. The same situation could also be described as over controlling or cyclic 'stirring'. Pilots 'stirring' the cyclic during hover and slope landings could cause excessive main rotor movement. 'Stirring' the cyclic was normally only apparent during long line operations where a heavy load could set up a pendulum effect. Aircrew trying to overcome this effect may in fact exacerbate the amplitude as they try to position the load. Although the OSN did not relate to the Bell 412, the Panel considered if cyclic 'stirring' during a slope landing was analogous to the same effect whilst on the ground and if it could also have led to driveshaft and support case failure.

Exhibit 84
Exhibit 18

1.4.118. A study of DHFS training sortie reports revealed that 6 out of 672 reports mentioned the term, 'over-controlling' or a description of that type of handling. Of those 6, none indicated control inputs being severe enough to be unsafe. From the beginning of UK military flying instruction there was also a strong emphasis on making smooth control inputs, in particular with respect to 'outside ground effect' hover work. The Panel's and other crewmembers' assessments were that Aircraft Commander A was cautious during the approach to the pinnacle and that this approach was not consistent with 'over-controlling' or cyclic abuse. The Panel also judged that the general standard of aircraft handling was good during the sortie. This was further supported by a history of positive sortie reports in Aircraft Commander A's training record folder. The Panel concluded that cyclic abuse was not systemic within the UK Griffin fleet and was also exceptionally unlikely to have occurred prior to the onset of vibration during the accident, given that the approach to the landing site was slow and controlled. Cyclic stirring, as described in the OSN, did not occur prior to the landing. Therefore, its contribution to overload of the support case was **not a factor** in the accident. However, similar circumstances of forward cyclic may have occurred and are discussed next.

Exhibit 85
Exhibit 86

1.4.119. **Forward cyclic**. The Panel considered how much forward cyclic was applied and if this was a factor in the accident. Forward cyclic was applied during the landing as a result of the sloping ground and by an additional amount in reaction to the developing situation. Applying forward cyclic whilst on the ground induces a bending moment[28] in the mast and a resultant force through the support case. The greater the movement away from the central cyclic position, the greater the loading on the support case. Bell confirmed that the application of forward cyclic, even to the limit of cyclic movement, could not have caused a failure of the support case.

Witness 24
Exhibit 30

1.4.120. The technique for landing upon sloping ground required the handling pilot to lower the collective lever, allowing the aircraft to pivot, and carefully increase the into-slope cyclic to maintain a level disc attitude, (1.4.62). The required amount of cyclic depends on the angle of the slope. Other factors that also affect the amount of forward cyclic required include the surface condition and wind. For example a slippery surface or stronger headwind would both increase the amount of forward cyclic required to maintain position. Both these conditions are likely to have existed at the accident site and may therefore have resulted in an unknown additional cyclic displacement from optimum conditions.

Exhibit 56

1.4.121. The Student Pilot was not specifically being taught during the sortie so was primarily focused on the visual aspect of the approach and as a result was not 'following through',[29] so was not aware of the cyclic or collective position. The only remaining witness capable of assessing the position of the cyclic was the handling pilot, Aircraft Commander A. All crew members recall a normal nose up slope landing evolution up until the point that the front of the skids touched the slope. Once vibration began, Aircraft Commander A then experienced a very high workload as the aircraft became less controllable, possibly making recollection of events incomplete or inaccurate. Despite this, Aircraft Commander A distinctly recalled pushing the cyclic stick forward beyond its normal nose-up-slope position after shutting the throttles. In the Panel's opinion, the exposed and precipitous position, on a slope that was subsequently measured to be out of limits, was

Witness 3
Witness 5
Witness 4
Witness 2
Witness 8
Exhibit 29
Witness 4

[28] A 'bending moment' is the reaction induced in a structural element when a force is applied offset from a fulcrum or support causing the element to bend.

[29] 'Following through' is a technique used by instructors where a student puts their hands or feet on the controls without making any control inputs. This allows them to appreciate the control movements of a particular manoeuvre.

likely to have resulted in an instinctive preventative reaction to maintain the position of the aircraft. The instinctive reaction would likely have been beyond that considered normal during a sloping ground landing and therefore excessive. Due to the incomplete recollection of events and lack of evidence, the Panel could not determine the timing of the application of excessive forward cyclic, except that it was after the onset of vibration. However, the maximum position of the cyclic was between that expected during a normal sloping ground landing (consistent with the measured slope angle) and the forward limit of cyclic movement, but was not considered to be damage inducing by Bell. Witness 8 Witness 4 Exhibit 30

1.4.122. The Panel concluded that application of forward cyclic alone did not lead to overload failure of the support case, because even at maximum cyclic deflection, Bell confirmed that it would not cause failure. However, the application of forward cyclic did apply higher than normal stresses to the support case, due to the out of limit sloping ground, and the subsequent excessive forward cyclic movement. The level of this stress could not be determined but in combination with other factors would have made failure of a support case more likely. Therefore, application of forward cyclic during the accident was a **contributory factor**. Exhibit 30

1.4.123. **Effect of landing beyond the sloping ground limits**. Despite no intent to exceed the sloping ground limits the final resting position of the aircraft was on an absolute slope of 12.3° (refer to Table 2). Bell declined to provide the flight test report from the slope landing testing. However, Bell's original test flights on the aircraft up to a maximum of 12° validated the increase of sloping ground limits from 4° to 10°, and did not report that there were any handling issues during these tests. Therefore, handling issues resulting from a slope of up to 12° was unlikely. Almost any landing position, further up-slope was less steep than the final resting position. Therefore, it was likely to have been within the tested parameters at the point of touchdown. Notwithstanding operation beyond the tested parameters by 0.3° in the final resting position, it was exceptionally unlikely that a single controlled excursion up to 12° would cause damage to the aircraft, such as to destroy it. There was insufficient evidence to assess the effect of operating beyond 12°. However, any additional angle over 10° imparts increasing stresses to the aircraft that would have contributed to any subsequent mechanical failure. Additional stresses, applied to the support case, as a result of sloping ground greater than 10° was a **contributory factor**. Exhibit 30 Exhibit 87 Exhibit 30 Witness 24

1.4.124. **Severe oscillation**. Severe vibration was reported soon after the aircraft went *'skids light'* and this was the first indication to the crew that there was a problem with the aircraft. The reported vibrations were deemed *'oscillations'* due to their severity and relatively low frequency, which were not normally defined as 'vibration' from an engineering perspective. Vibration is normally associated with induced high frequencies within the aircraft. There were also a number of historic examples of reported severe vibration within the Griffin fleet and other foreign examples of severe oscillations. The causes of oscillations that were considered and examined are: ground resonance, ground bounce, an unexplained vibration phenomenon, and oscillations caused by component failure. The recovery actions for ground resonance or potentially for severe oscillations are one of 2 options: take off immediately or if the aircraft is not serviceable to fly, land fully and close the throttles. Either action should be carried out quickly to prevent destructive oscillations building. Adverse Rotorcraft Pilot Couplings (ARPCs)[30] were considered Witness 4 Witness 8 Witness 24 Exhibit 233

[30] Adverse Rotorcraft Pilot Couplings (ARPCs) are unwanted phenomena originating from anomalous and undesirable couplings between the pilot and the rotorcraft. Two subsets of oscillatory RPCs are Pilot Induced (or Involved) Oscillations (PIO) and Pilot Assisted (or Augmented) Oscillations (PAO): PIOs generally occur when the pilot, in response to some trigger event, applies control

throughout the analysis and although may have played a part following mechanical failure, there was no evidence that they occurred prior to the first indication of mechanical failure. The Panel sought to determine the source of the oscillation and if this was consequential or causal to the support case failure.

1.4.125. **Ground resonance**. Ground resonance is a destructive oscillation that may be encountered in all multi-blade rotorcraft when the blades move on their lead-lag hinges, thus displacing their combined centre of gravity towards one side of the rotor disc. When this occurs with the aircraft on the ground, and the offset centrifugal force[31] is at the natural frequency[32] of the landing gear, the resulting lateral oscillations can shake the aircraft to pieces.[33] Overload of the support case in these circumstances could occur.

1.4.126. Ground resonance in the Bell 412 occurs at 2 frequencies; 1.0 - 1.6Hz and 3.5Hz. Exhibit 65
The natural frequencies of the aircraft are kept separated from any oscillating frequencies to avoid frequency coalescence. The two components that were designed specifically to reduce the possibility of ground resonance in the Griffin were the lead-lag dampers and the skid gear. Bell stated that a possible cause of main rotor drive shaft coupling Exhibit 65
deflection, caused by gearbox movement, could have been damage to landing gear cross tubes either in the accident or as a result of previous heavy landings. Bell's concern was the effect that damaged landing gear would have on the aircraft's susceptibility to ground Exhibit 65
resonance, as the landing gear forms part of the mitigation against aircraft vibration coalescing with the aircraft's natural frequency. Although the skid gear was largely destroyed by fire, witness accounts indicated that the skids were intact before the onset of the fire. Witness 1
DAIB determined that excessive cross tube deflection due to heavy landing did not occur and indicated that maintenance processes were in place to ensure that cracking was not present in the critical areas of the landing gear. Bell stated that they had no knowledge of previous ground resonance occurrences on Bell 412 aircraft that led to an accident. Exhibit 30

1.4.127. The crew reported that severe vertical vibration occurred at an estimated 3.5 – 5 Hz by tapping the frequency of the oscillations on the table during their interviews. Although 3.5 Hz was at one of the ground resonant frequencies it was not in the expected lateral orientation. The crew reported other vibrations and noises but none of these matched the frequencies or direction normally associated with ground resonance. Witness 3
During the landing, both crewmen were looking at the skids and underside of the aircraft and did Witness 5
not report any anomaly with the aircraft during any part of the approach or initial touchdown. Specifically there was no evidence that severe oscillations, consistent with ground resonance, occurred prior to the first indication of failure. As the speed of the rotors reduced, later in the accident sequence, natural frequencies associated with ground resonance were encountered but any damage that may have been caused would have been consequential. Based on the available evidence, the Panel concluded that ground resonance was exceptionally unlikely to have initiated the accident because the sequence and timing of events, according to witness accounts, did not match the characteristics of

---

inputs to respond to that event which are then out of phase with the aircraft motion. In the most extreme cases, the pilot-vehicle system can become unstable. Pilot Assisted Oscillations (PAO), on the other hand, occur through an involuntary input to the aircraft control system via inertia of the pilot's limbs reacting to the motion of the aircraft. If this unintentional control input is in the correct sense and frequency to further excite the vehicle motion, the PAO can also become unstable.

[31] 'Centrifugal force' is the apparent force that tends to cause a component to go outward from the centre of rotation.

[32] 'Natural frequency' is the frequency at which a system tends to oscillate in the absence of any external force.

[33] Prouty "Helicopter Aerodynamics"

the phenomenon. Ground resonance did not lead to overload of the support case and was **not a factor** in the accident.

1.4.128. **Ground bounce.** Ground bounce is a phenomena that occurs on the Bell 412 and was described by Bell as:

> *"...the skid gear serves as an elastic foundation beneath the helicopter introducing a vertical 'bounce' natural frequency at ~5.6 Hz for the 412 with standard skid gear and ~5.5 Hz with high skid gear. Since the 412 main rotor 1/rev at 5.4 Hz (100% rpm) is slightly below this vertical natural frequency, 'ground bounce' might be observed particularly with the high skid gear. There should be adequate collective friction to prevent pilot-in-the-loop amplification of this vertical bounce. There is no aeromechanical mechanism that can lead to instability with 'ground bounce.' The pilot will sense ground bounce to be at the MR 1/rev frequency."* Exhibit 65

1.4.129. The Bell 412 had been previously described as quite bumpy on the ground, and that it was a known characteristic of the Bell 412 to exhibit 'ground bounce'. Anecdotal evidence also existed that ground bounce was a common feature of the Bell 412 worldwide. The crew reported vibrations prior to the rear of the skids making full contact with the ground and there was no evidence that ground bounce could occur unless the skids are fully in contact with the ground, which was further supported by statements in the maintenance manual. The severity of the phenomenon was described as a, *"ride quality factor at 1R"*, therefore not sufficient to cause instability or divergent vibration. Ground bounce is effectively 'set' at the level of the previous vibration analysis and degradation is a function of elastomeric bearing wear, therefore unlikely to change significantly during the course of a single sortie. The most prominent frequency during the accident, experienced by the crew was 3.5 - 5 Hz, below the frequency for ground bounce in a low skid aircraft and more severe. If ground bounce had occurred, it would not have been severe enough to cause overload of the support case. Based on the available evidence, the Panel concluded that it was very unlikely that ground bounce occurred, and even if it had, would not have caused damage to the support case. Therefore, ground bounce was **not a factor** in the accident.

Exhibit 88
Exhibit 76
Exhibit 88
Exhibit 89
Exhibit 90
Exhibit 90
Exhibit 30

1.4.130. **Unexplained severe oscillation events**. Three occasions existed within the UK MOD Griffin fleet, where reported severe oscillation whilst in contact with the ground was unexplained. In 2 of the 3 examples there was no evidence of an aircraft fault or rotor imbalance, and both incidents resulted in a, *'No Fault Found'* categorisation by the engineers following rotor track and balance. The third case was not investigated by engineers, as the aircraft commander believed it was a handling characteristic rather than an aircraft technical issue. Had it been investigated it is likely that a similar *'No Fault Found'* judgment would have been reached because the aircraft returned to flying without recurrence of the symptoms (Table 4).

Date	Aircraft and location	Event / Vibration	
16 Mar 15	RAF Shawbury ZJ707	Following a lateral slope landing, a nose-up sloping ground landing commenced. With the front of the skids in contact with the ground and ADI showing approximately 7-8 nose up, a vertical bounce that rapidly amplified began. After lifting, the vibrations decreased momentarily as the aircraft moved forward, then increased again in severity. An emergency landing was conducted including a Mayday call. Vibrations dissipated once on the ground. The main rotor hub was checked and hard landing checks completed followed by a handling check by a maintenance test pilot resulting in a 'No Fault Found'.	Exhibit 91 Exhibit 92
15 Apr 15	RAF Akrotiri ZJ706	On sloping ground, slightly left wing low, and 5-10 kt wind from 1 o'clock, vertical vibration started. The handling pilot attempted to find the 'sweet spot'.[34] Increasing vibration led to a take-off with an unsecured passenger in the cabin after pushing a second passenger away from the door. Vibration ceased as skids went light. The aircraft landed on a different heading, the vibration restarted but stopped when the cyclic was positioned in the 'sweet spot'. No engineering checks were completed as the aircrew were confident that this was not an airframe issue.	Exhibit 93
4 Oct 16	RAF Shawbury ZJ240	Whilst awaiting take-off from a field landing site with approximately 35% torque applied, the cyclic stick was displaced forward by a student and a considerable amount of vibration occurred taking no more than 3 seconds to build. Upon returning the cyclic to the central position and applying approximately 60% torque the vibration dissipated. A vibration analysis was carried out with, 'No Fault Found' and no adjustments required.	Exhibit 94

Table 4 - Vibration events within the MOD Griffin fleet.

1.4.131. The characteristics of unexplained severe oscillation events were forward cyclic and initiation whilst in contact with the ground. This suggests that they may be linked to, or an extension of, the similar but better understood phenomenon of ground bounce. In each of these events, oscillations were greater than that experienced during ground bounce. Also, there was an element of forward cyclic displacement or sloping ground in each one. However, the predominant circumstance that preceded excessive oscillation was the application of forward cyclic. Like ground bounce, it also occurred at a similar frequency to the rotors (1R or 5.4 Hz). Also like ground bounce, the severity was affected by the application of cyclic. The recovery action in 2 out of the 3 MOD incidents was to put the cyclic back to its central position and the vibration went away, or was at least reduced considerably, which was also consistent with ground bounce. In the other it continued in the air until the aircraft landed and was shut down. The phenomenon occurred infrequently but when it did occur it was not repeatable during fault diagnosis. Bell could not provide a complete explanation for the unexplained severe oscillations, however the general term, *"forced response"* was used to describe general induced vibration. The phenomenon is not fully understood by the designer and is not explained by any formal definition in any of the documentation. If the phenomenon were an extension of ground bounce, the assertion that ground bounce was a benign characteristic would no longer be true and should prompt further work to address the potential safety implications. Alternatively, if it were a separate phenomenon, then there exists an unexplained flight

Exhibit 30

[34] The 'sweet spot' is a term used to describe the point at which the controls induce the least vibration.

characteristic that operators should equally be aware of, to prevent future incidents. Severe oscillation leading to lack of control or increased workload did not appear on the ODHs risk management tool.[35] Lack of understanding of the phenomenon could cause aircrew to take inappropriate or incorrect action in future similar incidents, thereby resulting in more serious outcomes. However, the 3 unexplained severe oscillation events experienced by the MOD were all significant, not isolated, and had sufficient similarity to link them to each other. There was a lack of knowledge of unexplained severe oscillation whilst in contact with the ground. The severity of the potential impact on aircraft handling resulting from severe oscillations whilst in contact with the ground meant that the phenomenon could lead to other accidents and merited further investigation and was deemed an **other factor**. Exhibit 217

1.4.132. The Panel considered if the unexplained phenomenon had occurred during the accident. There were similarities between the accident and the other unexplained oscillation events. The onset of vertical oscillation was sudden and occurred soon after the front of the skids came into contact with the ground. The vertical oscillations experienced by the crew were approximately 1R frequency but this could not be confirmed as happening at the moment the aircraft went, *'skids light'*. Finally, some forward cyclic was applied during the sloping ground landing, as in the March 2015 event. The accident sequence did not exhibit enough similarity to allow the Panel to make a direct comparison to previous severe oscillation examples. However, in the 3 previous examples, support case failure did not occur. Therefore, if the unexplained phenomenon occurred during the accident, on the balance of probability it would not have initiated support case failure alone. Despite many similarities with the unexplained phenomenon, it was not possible to determine if the unexplained oscillations experienced by crews in previous incidents had occurred during the accident. Witness 5

1.4.133. Vibration phenomena in general were not widely understood and this was exacerbated by lack of information for aircrew and engineers in the aircraft document set. The maintenance manual refers to ground bounce only once and does not offer a definition. Ground resonance is not defined in any of the DHFS publications but is referred to where ground bounce would be more appropriate. Lack of available information regarding vibration phenomena had no direct impact on the accident but diminished the likelihood of accurate occurrence reporting, thus preventing constructive recommendations. In the Panel's opinion, it was important to distinguish between reporting a known phenomenon, and a general description of a vibration event. For example, aircrew should not report the known phenomenon 'ground resonance' if what they experienced was oscillations whilst in contact with the ground, as this could be misleading to any future follow up. The Panel also recognised that constraining the use of language in occurrence reporting may have unintended consequences. The Panel **observed** that lack of available information regarding vibration phenomenon diminished the likelihood of accurate occurrence reporting and continued education on technical and flight phenomenon may be the most effective method to improve future fault diagnosis. Exhibit 90 Exhibit 56

1.4.134. **Recommendation**. Bell should publish a definition for ground bounce and other Bell 412 specific vibration phenomena along with guidance for operators to reduce the likelihood of future incidents.

---

[35] The risk management tool is in the format of a *'bowtie'* that is commonly referred to as the unified risk register on other platforms.

1.4.135. **Automatic Flight Control System (AFCS)**. The AFCS enhances stability and controllability of the helicopter. It consists of 2 independent automatic systems. The AFCS has 2 modes; Stability Augmentation System (SAS) mode and Attitude retention (ATT) mode. One system failure is that if the AFCS is left in ATT mode during ground operations it can drive the cyclic to the limit stop in an auto-trim runaway condition. The AFCS was not in ATT mode during the accident as it was confirmed to be in SAS mode from the CVR transcript. This meant that it was not possible for the AFCS to interfere with the control positions, as SAS mode has limited authority of control input. The AFCS in SAS mode could slightly amplify vibrations in the helicopter, but could not be the source of severe oscillations. The Panel concluded that the AFCS was in SAS mode therefore the AFCS was **not a factor.**

Exhibit 181
Exhibit 18
Exhibit 17
Exhibit 73

1.4.136. **Flying control linkage**. The incident in Wollongong, 2008, involved severe vibration on the ground, resulting in the pilot taking avoiding action for the perceived ground resonance. As they lifted to the hover the aircraft became uncontrollable and landed heavily causing structural failure of the gearbox. It was caused by incorrect assembly of a flying control linkage. 500 hours had passed between maintenance taking place on their collective flying control system and the accident. Instructions were released by Bell in 2008 to ensure worldwide compliance of correct assembly, in accordance with the maintenance manual. ZJ241 had not had any maintenance on the collective system since the installation of the gearbox 400 airframe hours prior to the accident. Although the crew did not report any problems with the flying controls, there was not enough evidence to determine the serviceability of the flying control system as much of it was damaged in the fire.

Exhibit 76

1.4.137. **Main rotor head**. The main rotor head is a common source of aircraft vibration in any aircraft and requires engineering activity to track and balance the rotor blades so as to minimise adverse effects on the aircraft. This vibration is normally managed at a low level and rarely develops such that the crew feel uncomfortable. The remains of the main rotor head and blades were inspected by Bell and DAIB engineers. Technical analysis confirmed that the head, yoke and mast were intact, yet due to fire damage it was not possible to determine the serviceability of all components. The elastomeric bearings and pitch change rods could not be assessed as they had melted. However, Bell confirmed that it was not possible for the pitch change rods to have impacted the cowling prior to mechanical failure of the support case. There was no evidence to suggest that damage caused by anything other than the fire had occurred. Also, no unusual flying characteristics were reported prior to the accident, which would have been indicative of an out of adjustment blade track or balance. The Panel concluded that although not all the main rotor head components could be examined properly, a sudden onset of severe oscillation was unlikely to have been caused by the main rotor head.

Exhibit 214
Exhibit 18
Exhibit 30
Witness 4
Witness 5
Witness 8

1.4.138. **Summary of gearbox support case overload**. A number of factors contributed to a greater than expected load on the support case during the accident. The force of landing was the only directly attributable force that could have broken the support case through overload on its own and although the force of landing was higher than expected, there was no evidence that it was severe enough to break a materially sound support case. The angle of the slope played a part by increasing the stresses in the gearbox at the point the aircraft was fully on the ground but was unlikely to be large enough to have caused component failure directly. Equally, excessive forward cyclic that resulted from interaction with the ground did not cause overload in the support case, nevertheless excessive forward cyclic was likely to have occurred after the failure of the support case occurred.

1.4.139. Severe oscillations resulting from specific flight phenomena could not be ruled out as having occurred but the timing of severe oscillations during the accident was likely to be after the initial indication of mechanical failure. Therefore, severe oscillations were more likely than not the result of component failure rather than the cause of it. Severe oscillations were also present during other Bell 412 examples of support case overload and were used as a comparison with this accident. In each example the overload may have occurred as a result of the landing or the oscillations but in any event the accident appeared less severe than in the examples and therefore it was not possible for the Panel to determine if overload was possible in similar circumstances.

1.4.140. An analysis of the effects of a combination of any number of these factors was not possible because of the lack of quantitative data and the number of possible scenarios. In the Panel's opinion the worst case scenario that may have led to an overload was the simultaneous application of forward cyclic at the point at which the rear of the aircraft rocked back and made contact with the ground on a slope that was out of landing limits. It was also judged to be unlikely that these events all occurred at the same time. However, the Panel could not rule out that the support case may have failed in overload due to a combination of factors.

Gearbox support case fatigue damage

1.4.141. Fatigue is a process of progressive, permanent structural change occurring in a material that is subjected to fluctuating loads below the static yield strength of the material. Fatigue damage nucleates and grows on a microscopic scale until it manifests itself as cracking, the growth of which depends on material properties and geometry, the level, amplitude and frequency of fluctuating loads and the number of load cycles applied. Fatigue damage culminates in cracks that reduce the residual strength of the cracked structure and cause overload fracture if the residual strength falls below the applied stress. Exhibit 95 There are a number of mitigations that may be put in place to negate fatigue failure: design of the component such that the stresses experienced by it are below the fatigue limit[36] of the material, where an infinite number of cycles would not lead to failure; design the system to be fail safe so that once failure of a particular component occurs it does not affect the safety of the system; design the component with a safe life, also known as fatigue life, so that the component is replaced after a predetermined number of cycles; or design the component such that it is damage tolerant, which requires accurate prediction of crack growth rate and an inspection regime frequent enough that fatigue cracks cannot grow to a critical size in between inspections. Bell provided no data for the crack growth rate or critical size limits for potential cracks in the gearbox support case. In the opinion of a structural integrity expert, Bell used an engineering judgement variation of the damage tolerant methodology for the gearbox support case which was consistent with other helicopter design methodologies of the same era. Exhibit 78

1.4.142. Guidance from the Federal Aviation Administration (FAA) at the time the aircraft was being designed provided advice about fatigue analysis and testing. Fatigue substantiation of gearbox components should have had the same degree of structural reliability as the main rotors. However, caution was to be exercised in the application of fatigue analysis and methodology particularly when it involved large parts compared to test specimens; irregular shapes containing holes lugs and fillets; components subject to Exhibit 96

[36] Fatigue limits only apply to ferrous materials.

fretting and bolted components. No fatigue testing of actual parts was necessary if the stresses measured during ground and flight conditions were lower than the allowable stress levels. Bell stated that design and certification work did not reveal any airworthiness limitations with the gearbox support case. Also, Bell did not have a probability of failure for the lower support case, as it was not required to be calculated during the type certification process. A further fatigue substantiation report for sloping ground kit did not contain analysis of the gearbox support case. Exhibit 30

1.4.143. The gearbox of the Bell 412 is manufactured from magnesium alloy and therefore does not have an infinite fatigue life because of the inherent properties of the non-ferrous material. Components were therefore designed with a greater safety margin and issues that developed were addressed once the aircraft was in service. However, Bell did not conduct any fatigue assessment of the main gearbox casing, including the gearbox support case, to underpin its maintenance philosophy. This proved a reasonable approach given that the support case has since had relatively few fatigue events during its 36 year history. Therefore, the support case did not have a fatigue life, rather it was inspected at defined intervals and its serviceability determined, through an *'on condition'* maintenance philosophy and was reliant upon scheduled maintenance inspections to ascertain its serviceability through life, similar to a damage tolerant methodology. A fatigue significant event is one that accrues damage at a higher rate than normal use. The maintenance philosophy meant that it was difficult to quantify the effect of fatigue significant events on the main gearbox support case. The panel considered the factors that could have contributed to fatigue damage in the support case and the likelihood that fatigue occurred in the accident aircraft's support case. Exhibit 30 Exhibit 30 Exhibit 78

1.4.144. **Manoeuvre limits**. The Bell design limits for the Griffin were 50° angle of bank and pitch attitudes of 15° down or 30° up. The effect of exceeding these manoeuvre limits was unknown and represented the maximum values considered for certification of the aircraft. Between 1997 and 2003 the MOD were operating to the limits in the Rotorcraft Flight Manual (RFM) which only stated that, *"Aerobatic manoeuvres are prohibited"*. The limits that were adhered to by the MOD were 90° in pitch and 90° angle of bank. In February 2005, Bell provided numerical flight limitations and the Release to Service Authority (RTSA) identified that the aircraft had been exposed to flight regimes in excess of that expected by the design organisation. A DHFS report in September 2005 summarised the maximum exposure as an average of 7.25 hours per airframe over the total life of the aircraft. However, as definitive figures could not be obtained, the worst case scenario was reported to Bell by the TAA. The affected components were some of the main transmission and the majority of components above the main gearbox which included the support case. Bell's recovery plan in 2009 included replacement of all affected components but did not recommend replacement of the support case. Instead, the standard non-destructive inspection normally carried out at an overhaul was deemed adequate. The reason for this approach was given as the very low cycle nature of the loading which was within the static capabilities of the component. However, a helicopter structural integrity expert advised that low cycle fatigue still contributed to the overall fatigue damage accrual within the component. Regardless of the overhaul inspection any fatigue significant event would make the support case more likely to suffer the effects of fatigue during its lifetime. Exhibit 97 Exhibit 120 Exhibit 97 Annex H Witness 24

1.4.145. The flight test parameters for manoeuvre limits was less than the MOD aircraft usage over the period. Therefore, Bell could not substantiate the impact on the airworthiness of affected components resulting from exceeding the manoeuvre limits. In addition, the only way to quantify the impact on the support case would be to conduct a fatigue analysis. Bell declined to conduct this analysis in 2006 at the time the issue was Exhibit 97 raised due to the time and cost of the activity, and MOD also declined to fund the research. This meant that the stresses imparted to the support case as a result of exceeding the manoeuvre limits were unknown. Bell subsequently confirmed during this Service Inquiry that flight outside the design parameters would cause fatigue and that this may have led to a fatigue crack in the support case. The Panel concluded that flight outside the design limits occurred as a result of the information provided in the RFM and caused additional unknown fatigue damage to the support case and made a fatigue crack more likely and was therefore a **contributory factor**. Exhibit 30

1.4.146. **Rate of sloping ground landings**. The enhanced slope landing limits for the aircraft were added to the aircraft on request from the Canadian Forces to increase the sloping ground limits from 4° to 10°. A fatigue substantiation report for the enhanced slope landing kit was produced to validate the changed use of the aircraft and contained the underlying assumptions made by the design organisation about the expected usage spectrum. The top level assumption in the fatigue substantiation report was that there were a limited number of slope landings per hour. Of these slope landings, a high proportion was also conservatively assumed to be in the worst case scenario, of between 5° – 10°. The affected components were cited as the mast, the lower cone seat and the yoke but not the support case. Bell considered these assumptions to be conservative estimates and confirmed that slope landings within the expanded sloping ground limits were considered fatigue significant events because of the increased bending moment in the mast. However, any increase to the bending moment in the mast also imparts an additional un-quantified fatigue load on the support case but this was not included in the fatigue substantiation report for the sloping ground kit. Exhibit 30 Exhibit 87 Exhibit 30

1.4.147. A historic study was conducted of flying hours and the number of sloping ground landings, for the 12 month period (September 2015 to August 2016), on 60 Sqn aircraft. The study was based on crewman currency information recorded on STARS.[37] There was no evidence for the number of slope landings conducted by 202 Sqn or 84 Sqn aircraft because they did not record crewman currencies in a similar way. The number of slope landings conducted by aircraft at 60 Sqn showed that the minimum number of slope landings per hour was 0.30, averaged across all aircraft, and that the highest rate for an individual aircraft was 0.41 (Table 5). The Panel identified that the rate of sloping ground landings was not uniform across the fleet and that some of the affected components may have changed aircraft tail numbers during their life. This made the rate of slope landings on any given component more difficult to predict, and more likely to be higher on some individual components. The Panel were also informed by crewmen at 60 Sqn that not all sloping ground landings were recorded. Once crewman reached their slope landing quota, the number of landings may not have been recorded. Where multiple landings in the same location took place, only one landing may have been recorded because each landing did not represent a full currency cycle for the crewman. The data collected therefore represented the minimum number of slope landings because of the way in which the crewman recorded the number of slope landings. Additionally, in the Panel's opinion, when conducting dedicated sloping ground sorties, angles towards the upper sloping ground limit were more likely to occur. The training syllabus at DHFS for sorties involving slope landings did not change significantly throughout the entire period of the contract and therefore the figures obtained over the period of a year could reasonably be extrapolated to provide a basis for long term use of the aircraft between 1997 and 2016. Exhibit 212 Exhibit 100 Exhibit 100

[37] STARS is the computer program used for management of flying sorties and aircrew currencies.

Aircraft Location	Aircraft Tail Number	Number of Slope Landings	Total number of landings away from main base	Flying Hours	Minimum Rate of Slope Landings	Maximum Rate of Slope Landings
60 Sqn	ZJ234	210	1036	508:00	0.41	2.04
	ZJ235	204	1422	588:45	0.35	2.42
	ZJ236	195	1265	524:25	0.37	2.41
	ZJ237	177	1455	627:25	0.28	2.32
	ZJ238	101	1153	551:45	0.18	2.09
	ZJ240	125	796	452:00	0.28	1.76
	ZJ705	2	375	226:55	0.01	1.65
	ZJ707	145	1125	428:45	0.34	2.62
	ZJ708	75	603	386:00	0.19	1.56
202 Sqn	ZJ239	-	283	323:00	-	0.88
	ZJ241	-	294	404:40	-	0.73
	ZJ242	-	325	306:40	-	1.06
84 Sqn	ZJ703	-	375	313:55	-	1.19
	ZJ704	-	433	273:25	-	1.58
	ZJ706	-	545	445:30	-	1.22
AVERAGE	-	-	-	-	**0.30**	**1.70**

Table 5 - Number of slope landings per flying hour for the period (Sep 15 – Aug 16)[38]

1.4.148. As part of the same study, a worst case scenario for the number of slope landings was calculated from the total number of landings conducted by all aircraft. Pilots are required to record the total number of landings for a sortie in the technical log. The Panel assumed that one landing per sortie must be the final landing at a level airfield. Therefore, the total number of landings minus the total number of sorties provided the maximum potential number of slope landings.

1.4.149. The Panel concluded that the minimum average rate of 0.3 slope landings per hour was greater than the design assumption specified by Bell in the design usage spectrum. Also that the average potential maximum rate of 1.7 slope landings per hour was significantly more. It was also likely that this had been the case since the introduction of the aircraft and that the increase in fatigue damage accrual was therefore long term. By comparison, the Canadian Forces recorded their rate of slope landings, which were: 0.1 slope landings per hour for 5° and over, 0.7 slope landings per hour for 2° - 5°, and a total of 3.3 landings per hour for all landings. The Panel further concluded that the rate of sloping ground landings was likely to have caused additional un-quantified low cycle fatigue damage to the support case. This was because no assessment was made of fatigue in the support case, many of the slope landings were fatigue significant events and bending moments in the mast also imparted an additional unknown fatigue load on the support case. During the entire life of the aircraft, there was a higher rate of sloping ground landings than assumed by the designer in the design usage spectrum that led to unknown fatigue damage in the support case and was a **contributory factor**. Exhibit 190

1.4.150. **Combined slope**. The Bell RFM stated that slope landings are limited to a maximum absolute slope angle of 10°, (refer to Figure 11). There was no further guidance from Bell about how to apply this limit. The Panel found that in specific circumstances this limit may be unwittingly exceeded when referring to the aircraft instruments alone. Should aircrew choose to conduct a combined slope landing with both a nose up and lateral element, the combined maximum slope angle would be greater than either of the two Exhibit 58

[38] Slope landing data was collected from STARS and recorded by Crewman at 60 Sqn for the purpose of currency monitoring. The average rate of slope landings represent the minimum and maximum possible rate of slope landings carried out in the period. The maximum rate of slope landings assume that one landing per sortie is at a level airfield and therefore cannot be a slope landing (total number of landings – total number of sorties). ZJ705 was discounted from the calculation of the average because it had been detached for the majority of the period, therefore slope landings were not recorded and the data was unreliable.

components. In the most extreme circumstance, the crew could execute a 10° nose up and 10° lateral slope landing and be on a combined slope angle of 14.1° (Table 6). Even if aircrew were aware of the effect of combined slope angles, cockpit instrumentation would not have provided the required information to calculate the effect of the combined slopes without a manual calculation during flight or reference to further information (Table 6). There was no evidence to indicate how often the slope landing limit may have been exceeded or by how much. However, in the Panel's opinion, unwitting instances of exceeding the sloping ground limits throughout the aircraft's life was very likely to have occurred but it seemed reasonable that it was infrequent due to the obscure circumstance that would lead to such a landing. Notwithstanding this, for any landing at the limit in one direction, any slope in the second direction, would cause the limit to be exceeded, albeit by a small amount. The effect of a combined slope landing was not directly considered by the crew during the accident because the landing was only intended to be skids light. Therefore, during the accident the crew never got to the stage where they were assessing the angle of the slope using cockpit instruments and the angle of the final resting position was not affected by any such assessment of the slope by the crew. However, it did have a broader impact on the slope landing history of the aircraft. The fact that the slope limit could be unwittingly exceeded whilst referring to cockpit instruments alone could have an impact on other Griffin aircraft or other aircraft fleets. The Panel concluded that the relationship between the lateral, longitudinal and absolute sloping ground limits resulting from a combined slope landing could impact any other helicopter. Unwittingly exceeding the sloping ground limit on any aircraft due to a combined slope landing was an **other factor**.

1.4.151. **Recommendation**. Director Helicopters should commission a study into how combined slope landings are assessed with reference to cockpit instruments, for all helicopter types, to ensure that aircraft do not stray outside the design limits intended by the Original Equipment Manufacturer (OEM).

		Lateral slope angle in degrees									
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Longitudinal slope angle in degrees	**1**	1.4	2.2	3.2	4.1	5.1	6.1	7.1	8.1	9.1	10.0
	2	2.2	2.8	3.6	4.5	5.4	6.3	7.3	8.2	9.2	10.2
	3	3.2	3.6	4.2	5.0	5.8	6.7	7.6	8.5	9.5	10.4
	4	4.1	4.5	5.0	5.7	6.4	7.2	8.1	8.9	9.8	10.8
	5	5.1	5.4	5.8	6.4	7.1	7.8	8.6	9.4	10.3	11.2
	6	6.1	6.3	6.7	7.2	7.8	8.5	9.2	10.0	10.8	11.6
	7	7.1	7.3	7.6	8.1	8.6	9.2	9.9	10.6	11.4	12.2
	8	8.1	8.2	8.5	8.9	9.4	10.0	10.6	11.3	12.0	12.8
	9	9.1	9.2	9.5	9.8	10.3	10.8	11.4	12.0	12.7	13.4
	10	10.0	10.2	10.4	10.8	11.2	11.6	12.2	12.8	13.4	14.1

Table 6 - Combined slope angles for all orientations of longitudinal and lateral slope landings.

1.4.152. **Effect of combined slope landings on fatigue**. It was likely that there were a small number of historic examples where the absolute slope landing limit of 10° had been unwittingly exceeded (1.4.150). There was no evidence for the frequency or magnitude of

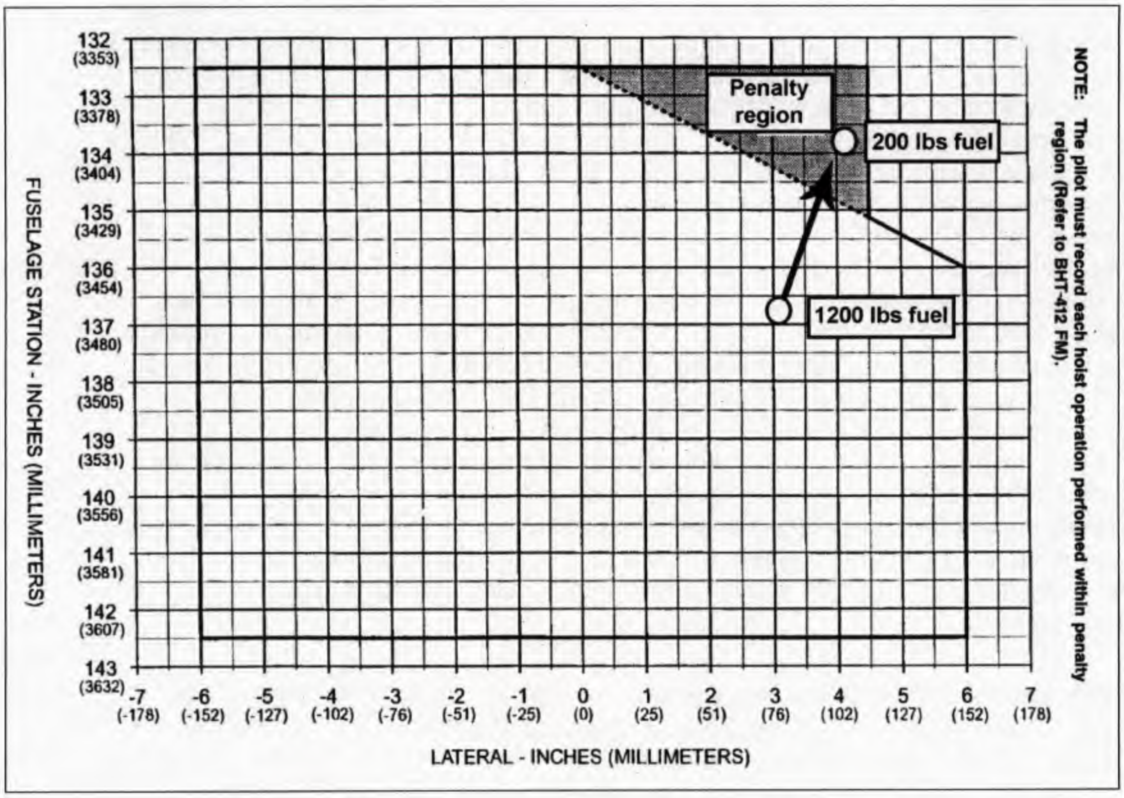


Figure 38 - Representative example centre of gravity calculation for hoist operations (5 crew members) showing entry into the penalty region for a typical winching sortie.

1.4.154. The Panel concluded that aircraft at RAF Valley were subjected to hoist operations within the penalty region. Although the effects of these operations were quantified for certain components, they would have increased the bending moment in the mast and so imparted an additional un-quantified and unrecorded fatigue load on the support case. Consequently, it was the Panel's judgement that hoist operations within the penalty region were likely to have accrued additional un-quantified fatigue consumption in the support case and was therefore a **contributory factor**.

1.4.155. **Summary of gearbox support case fatigue damage.** The Panel concluded that on different occasions and for different reasons, the Griffin fleet were operated: outside the design parameters, outside the design usage spectrum, and in high stress scenarios within the design limits. All these scenarios will be referred to as fatiguing conditions throughout the remainder of this report. Each fatiguing condition would have had a different impact on the fatigue loading on the support case. The combined likely number of excursions over an extended period of time led the Panel to conclude that the combined load spectrum on the support case was higher than it should have been for Griffin aircraft. It was likely to be higher than for other Bell 412 aircraft worldwide, due to the introduction of the slope landing 'kit'. The Canadian Forces also used the slope landing kit, however excursions within the UK Griffin fleet would also have been higher than for the Canadian Forces because of the higher rate of slope landings. Therefore, the Panel concluded that it was more likely than not that some UK MOD Griffin aircraft had among the highest fatigue loading on the support case of any Bell 412 aircraft in the world. However, to establish if fatigue was a factor, further analysis on fatigue crack initiators and the gearbox and airframe history was necessary and is analysed next.

potential historic excursions beyond the limit but it was the Panel's opinion that the number of excursions slightly over the 10° limit would be greater than the number of excursions up to the maximum of 14.1°. Nevertheless, Bell did not provide load spectrum data or calculations to determine the severity of operating beyond the limit or subsequent maintenance penalties. Therefore, it was not possible to assess the impact of combined slope landing activity. However, Bell did confirm that slope landings beyond 5° were considered fatigue significant events because of the increased bending moment in the mast. As previously discussed, any increase to the bending moment in the mast also imparts an additional un-quantified fatigue load on the support case. The effect of combined slope landings would not have had an impact on the number of fatigue cycles on the support case, but would have increased the magnitude of the stress imparted to the support case during the landings that were already being conducted. Any combined slope landing that led to unwittingly exceed the sloping ground limit would have imparted an additional unknown load on the main gearbox support case. The Panel concluded that combined slope landings beyond the 10° limit were likely to have occurred during the life of ZJ241 and contributed to additional fatigue damage in the support case due to the higher stresses imparted at these slope angles. Although the number of excursions could not be determined, their cumulative effect was still present. Fatigue damage on ZJ241's support case resulting from the effect of historic combined slope landings was a **contributory factor**.

Exhibit 65
Witness 24

1.4.153. **Hoist centre of gravity penalty region**. During the course of the Inquiry, the Panel were made aware that during a period of time, estimated to start in 2011 until August 2015, some aircraft flown at RAF Valley, including ZJ241, were subjected to a number of unrecorded fatigue significant events, whilst operating the hoist. At lower fuel states, it would have been possible for the aircraft to have been operated within the hoist centre of gravity penalty region (Figure 38), discussed further at (1.4.223). The operators assessed that this was likely to have occurred at an average of 4 times per month per aircraft. The penalty for this operation was applied to the same fatigue significant components as for the slope landing kit; the mast, the lower cone seat and the yoke.[39] There is a penalty incurred of 4 hours per excursion into the zone for each affected component. Reassessment and recovery of component lives was carried out by Cobham during the course of the Service Inquiry as a result of the issue being identified by the Panel, after being directed to by the Military Continuing Airworthiness Manager. The hoist centre of gravity penalty region represented a calculated use of the aircraft outside the normal operating limits but within the overall design limits and therefore did not constitute an unknown loading on the aircraft. However, Bell did not have data on the impact of operating within the penalty region on the support case, despite the purpose of the penalty region to account for the increased bending moment through the mast which translates to an un-quantified effect on the support case. Therefore, the Panel judged that operation within the penalty region did represent a higher than normal loading on the support case. As hoist operations moved the CofG further away from the ideal position, fatigue consumption is likely to have been higher and as no calculations were made it was not possible to quantify these effects. However, the total number of cycles over the 4 year period would have increased the fatigue consumption on the affected support cases.

Exhibit 219
Exhibit 101
Exhibit 101
Exhibit 102
Exhibit 223
Exhibit 122
Exhibit 141
Exhibit 30

[39] Main Rotor Mast (serial number: 412-040-101-133); Yoke (serial number: 412-010-101-127); Lower Cone Seat (serial number: 412-018-056-105)

Gearbox support case fatigue crack initiators

1.4.156. The panel considered the initiators that could lead to a fatigue crack that were identified as potentially applicable to the accident by a helicopter structural specialist, 1710 NAS and Bell Helicopter. Gearbox support case fatigue crack initiators were identified as those that could have led to a fatigue crack or made the gearbox more susceptible to fatigue damage accrued through usage. It was not necessary for any of the initiators to be present for a fatigue crack to propagate but would make it more likely.

1.4.157. **Metallurgical imperfections**. The Panel considered if metallurgical imperfections could have been a factor in fatigue initiation. The gearbox support case is formed using a casting method. This method can be susceptible to microscopic imperfections and metallurgical build anomalies, which can lead to fatigue. However, X-ray examination during production acceptance checks were reported to have mitigated this potential fatigue initiator. These imperfections can arise within the material during in-service conditions and may not always be visible during scheduled maintenance. During the visual inspection conducted at 13:10 airframe hours prior to the accident, the Panel was almost certain that any internal cracking would not have been identified. The Panel further determined that any sub surface cracking would not have been observable using the prescribed PFD technique[40] during overhaul at 404:40 airframe hours prior to the accident. However, a structural expert stated that occurrences of metallurgical imperfections on high integrity components were very rare. Based on the available evidence the Panel concluded that metallurgical imperfection were very unlikely and was therefore **not a factor** in the accident.

Exhibit 78
Exhibit 70
Exhibit 78
Exhibit 105

1.4.158. **Mechanical damage and corrosion**. The main gearbox was made of magnesium alloy, which is susceptible to corrosion, particularly in a salt laden environment. The aircraft at RAF Valley were subjected to a corrosive environment by virtue of the course syllabus that included winching sorties over the sea. Mechanical damage was considered a precursor to corrosion and instances of either were treated in the same way. The surface paint was designed to protect the underlying metal and although there was no physical evidence to rule out the presence of mechanical damage, routine visual checks carried out 9:35 airframe hours prior to the accident reduced the likelihood that mechanical damage was present and undetected. Corrosion had not previously been identified as a direct cause of cracking in any Bell 412 support case but could not be ruled out as an initiator to gearbox fatigue cracking in this accident. Bell identified that pitting corrosion was of particular concern in the critical areas of the support case. The work sheet from the last overhaul of the gearbox fitted to ZJ241 detailed work carried out to replace components due to pitting, corrosion and mechanical damage. This supported the possibility that pitting or corrosion could have occurred, for which there is no inspection between overhauls. The panel judged that mechanical damage was less likely to have been present than corrosion due to the recent check which would most likely have detected any damage. However, it was not possible to determine if corrosion was present as an initiator to fatigue cracking on the accident support case.

Exhibit 103
Exhibit 70
Exhibit 70
Exhibit 192

1.4.159. **Fretting and wear**. Fretting is a special wear process that occurs at the contact area between two materials under load and subject to minute relative motion by vibration or some other force. Fretting and wear occurred on the foreign military accident in 2006 (1.4.107.f). Although it was found in-between the support case and the airframe, it was

Exhibit 95
Exhibit 73

[40] Penetrant Flaw Detection (PFD) is a technique used to locate surface cracks by using a liquid to make small cracks visible.

determined that it did not directly lead to damage of the support case. The cause of the fretting was identified as incorrect assembly of the corner mounts to the airframe. The destruction of the support case in the fire in the case of ZJ241 meant that most components could not be checked for incorrect assembly. However, the corner mounts, although fire damaged, were found to be assembled correctly (1.4.103), and the Panel concluded that based on the available evidence, it was very unlikely that incorrect assembly elsewhere on the gearbox caused fatigue cracking in the critical area of concern. Fretting and wear was therefore **not a factor** in the accident.

Exhibit 18

Exhibit 63
Exhibit 214

Main gearbox assembly and airframe history

1.4.160. **Support case maintenance history**. Neither the main gearbox nor its associated support case have a fatigue life. The airworthiness of both components is determined 'on condition' through scheduled maintenance. Within a broader maintenance package, Bell specified that the gearbox condition was checked at 25 hr intervals, 3000 hr special inspection, and 5000 hr (now 6000) overhaul. Cobham introduced a 300 hr inspection for the support case to supplement this schedule after the discovery of a fatigue crack in the support case in 2006 (Table 7). Cobham also conducted a daily inspection as part of their aircraft maintenance program. In considering the serviceability of the support case, the main gearbox maintenance documents were examined to ascertain that correct maintenance practices and processes had been followed and that no pre-existing conditions were a factor in the accident (Table 7).

Exhibit 189

Exhibit 2

Component	Ser. No.	Component life and type of maintenance	Airframe Hours	Aircraft Maintenance Program, main gearbox Inspection details
Main gearbox (412-040-004-109)	A-213	Component life	10229:20	
Support case (212-040-054-109)	A3320	Component life	7253:10 (14 years, 5 months)	
		Hours since 5000-hour overhaul	404:40	Penetrant Flaw Detection (PFD) inspection
		Hours since 300-hour 'B' check	97:40	Inspect Main Transmission Support Casing for cracks. Pay particular attention to the area around the Oil Filler Boss.
		Hours since 25-hour 'A' check	13:10 (3 August 2016)	Check Transmission casings, as visible, with side access panels removed, for damage, condition and evidence of leaks.
		Hours since Daily Inspection (not required by Bell)	0:00 (8 August 2016, 2300Hrs)	Check if in good condition. Check all flexible hoses and tubes for correct routing and evidence of chafing.

Table 7 – Summary of main gearbox component life and maintenance history.

1.4.161. Prior to the main gearbox (serial number A-213) complete with support case being fitted to ZJ241, it underwent a major overhaul, conducted by Bristows. The gearbox was fitted to ZJ241 on 21 September 2015 and had flown 404:40 airframe hours since last overhaul, which involved stripping the gearbox surface paint and Penetrant Flaw Detection

Exhibit 192
Exhibit 70

(PFD) Non-Destructive Testing (NDT) technique.[41] The overhaul revealed some areas of pitting, corrosion and mechanical damage that required the replacement of some parts. A scheduled main gearbox casing check was carried out every 25 hours in accordance with Bell maintenance manuals, which described the inspection of the support case as, *"visible, with side access panels removed, for damage, condition and evidence of leaks"*. This was last carried out on 3 Aug 16, 13:10 airframe hours before the accident. The level of aircraft strip, detailed for this crack inspection, was not specific and could be open to interpretation. The maintainer was directed first to the maintenance manual, then to the component repair and overhaul manual for the inspection criteria. The overhaul manual was designed for maintenance at an overhaul facility and presumed that the gearbox was uninstalled and stripped of all paint prior to the inspection. Reference to the overhaul manual did not include the required preceding maintenance activity and it was not clear if the preceding activity was necessary to make a timely discovery of any crack in the support case. Clarification of the activities required by the maintenance manual and the component repair and overhaul manual may help to ensure the inspection of critical components are carried out in the manner intended by the design organisation in future. It was the Panel's opinion that the detail of the 25 hr maintenance inspection was insufficient to prevent cracks being missed and clarification of the inspection criteria and method would improve the chance of a crack or surface flaw being spotted. The Panel considered, in consultation with 1710 NAS and Defence Science and Technology Laboratories (DSTL), whether NDT techniques could be introduced as part of scheduled maintenance to reduce the risk of fatigue cracking being missed in-between overhaul inspections. The Panel judged that other techniques were possible, although it would require a more detailed analysis of likely crack sources and propagation.

Exhibit 193

Exhibit 104

Exhibit 104

Exhibit 105

1.4.162. The Panel concluded that the gearbox had been correctly inspected in accordance with the maintenance manual. It was installed in a serviceable condition and there were no areas of concern during scheduled maintenance prior to the accident that could have indicated the presence of a pre-existing condition. However, the Panel determined that the description of the support case inspection was not specific enough to ensure that it was carried out with sufficient detail and did not take account of the level of component strip required for it to be fully effective. The description and method of inspection of the main gearbox support case could make detection of a crack less likely and contribute to a future accident and was therefore deemed an **other factor**. The Panel further concluded that NDT techniques should be considered but that a more detailed analysis was required on the use of NDT techniques on the Griffin support case.

1.4.163. **Recommendation**. The Type Airworthiness Authority should implement an appropriate Non Destructive Testing technique in consultation with fatigue experts to mitigate the effects of fatigue damage to the affected support cases by increasing the likelihood of detecting a fatigue crack.

1.4.164. **Recommendation**. The Type Airworthiness Authority should ensure that for 25-hour airworthiness critical inspections for cracking, the level of aircraft strip, access of the area to be inspected, light source and tooling used, should be more explicit, in order to mitigate the effects of fatigue damage to the effected support cases by increasing the likelihood of detecting a fatigue crack.

[41] Non Destructive Testing techniques are a range of methods to determine the condition of equipment without causing damage.

1.4.165. **Gearbox installation history**. There was only one previous support case failure in UK MOD service and it also occurred on ZJ241. This led the Panel to further investigate the gearbox and airframe history for ZJ241 and cross reference this to the fatiguing conditions (1.4.155) discovered throughout the course of the inquiry, in order to establish if there was any significant correlation. The Panel analysed all 6 gearboxes fitted to ZJ241 throughout its life. The original gearbox (A-297) flew on ZJ241 until 2005 but was briefly replaced by the gearbox involved in the accident (A-213) which was fitted and removed without flying in 2002, for unknown reasons. The 2006 fatigue crack gearbox (A-295) had the support case replaced and was returned to service after the incident. A further 3 gearboxes were fitted in-between the two incidents, and finally the gearbox involved in the accident was re-fitted in 2015. The accident gearbox had been fitted on a total of 6 aircraft during its life including ZJ241 (Figure 39).

Exhibit 74

Exhibit 109

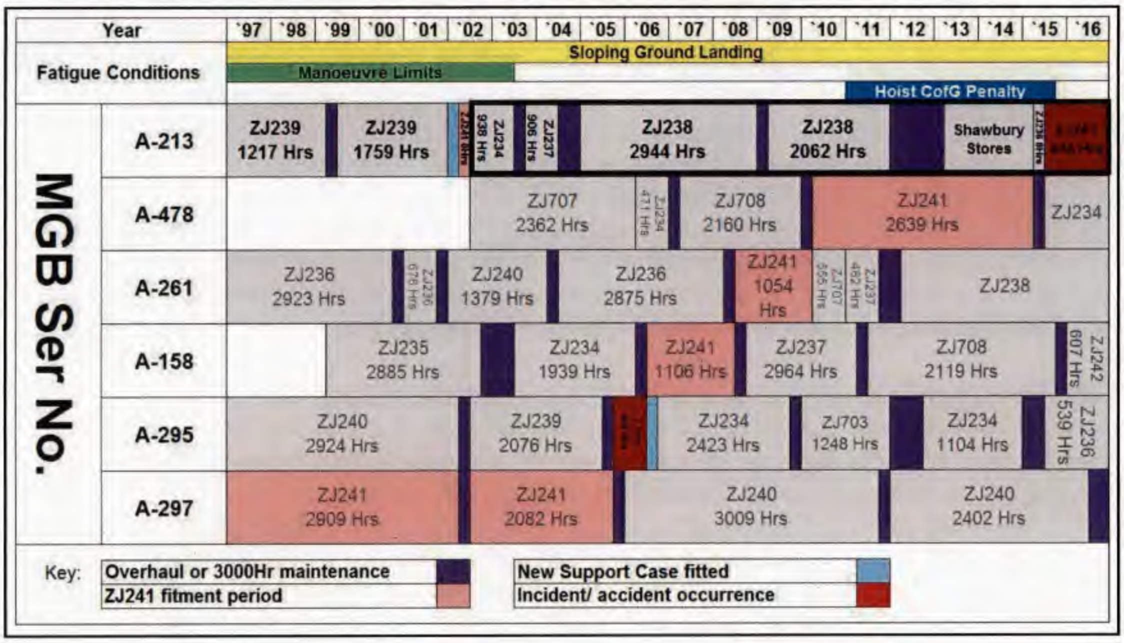


Figure 39 - ZJ241 gearbox installation history.

1.4.166. **Gearbox storage conditions**. Between 2013 – 2015, the accident gearbox (A-213) was stored in the bonded store at RAF Shawbury for approximately 2 years prior to being fitted to ZJ241 in 2015. The panel considered if the storage of the gearbox had an influence on its condition prior to fitment to the aircraft. Cobham stated that the gearbox was inhibited and secured in accordance with Bell's instructions. The Bonded store at RAF Shawbury was subject to quality assurance audits and complied with regulations. The panel concluded that the storage conditions of the gearbox prior to the accident was **not a factor.**

Exhibit 106

Exhibit 220

1.4.167. **Support case replacement**. At the end of 2001, the accident gearbox A-213, an airworthiness traceable item, was removed from ZJ239 for a routine overhaul. During overhaul it was discovered that the support case needed refurbishment so it was replaced with a new (zero hours) support case. The panel sought to ascertain why the support case required refurbishment and if it subsequently replaced another support case on a different gearbox. Cobham confirmed that the most likely reason for the support case replacement was that the time taken to repair would extend past the output date of the gearbox overhaul and so was replaced to expedite return of the gearbox to Cobham. However, the

Exhibit 107

Exhibit 108

reason for the replacement could not be confirmed because Bristows, the overhaul agent, no longer had the work documents. Moreover, the location of the support case following the suspected repair could not be ascertained as the item was not tracked. Tracking of components with an 'on condition' maintenance philosophy was not considered necessary. Bristows were also the overhaul agent for a number of operators other than the UK MOD and it was not possible to determine if the support case, removed from gearbox A-213, was subsequently fitted to a gearbox of another operator. The Panel determined that the support case that was previously fitted to A-213 had been subjected to 2 of the fatiguing conditions (the manoeuvre limits issue, and high rate of sloping ground landings). An unknown amount of fatigue damage accrued on the support case of A-213 within the period of 2976 airframe hours and for approximately 4 years. The Panel could not determine the location of A-213's original support case therefore the 'interchangeability' of parts within the global fleet of aircraft may also be affected by a component with unknown fatigue damage. The Panel concluded that the support case, from gearbox A-213, that was replaced in 2001, could not be located. The 'interchangeability' of 'on-condition' aircraft components within the global fleet meant that it was very likely that the original support case fitted to gearbox A-213 was now installed on another gearbox, potentially with another operator and been subjected to an unsubstantiated level of fatigue damage. The 'interchangeability' of UK MOD gearbox support cases was deemed an **other factor**. The Panel **observed** that the potential for fatigue damage within the components necessitated their need to be identified as a Structurally Significant Item (SSI)[42] and be traced accordingly throughout life in order to maintain the 'interchangeability' of parts within the global fleet.

1.4.168. **Recommendation**. The Federal Aviation Administration in conjunction with Bristows should ensure that all interchangeable gearbox support cases, from UK MOD registered Bell 412 aircraft, potentially affected by fatigue damage, are located and monitored appropriately.

1.4.169. **Inherent fault with the airframe of ZJ241**. The Panel considered if there was an inherent fault with ZJ241 that led to both incidents and whether the aircraft could have induced fatigue damage into 2 different gearboxes at different times. The Panel judged that if there was an inherent fault with the airframe that it was likely that all previous gearboxes would also have been affected by the same conditions. Gearbox A-297, fitted to ZJ241 for nearly 5000 hours prior to the first incident, subsequently flew for a further 5000 hours without issue. Gearbox A-478 was fitted for 2600 hours on ZJ241 without an issue. Two of the 4 gearboxes not involved in an incident were fitted to ZJ241 for a significantly longer period of time and airframe hours than either of the support cases involved in the incidents and neither of these gearboxes has experienced fatigue issues since fitment to ZJ241. The panel concluded that there was not enough available evidence to determine if any potential fatigue crack in the gearbox support case was a consequence of an inherent fault in the airframe of ZJ241. Exhibit 109

1.4.170. **Support case depth maintenance**. Both UK support case failures occurred at under 500 hours since their previous gearbox overhaul. At the time of the accident, scheduled depth maintenance occurred at 3000 and 5000 hours (now 6000 hours). The difference between the inspections was mainly that the 5000 hr inspection used a PFD technique, used on a paint stripped gearbox to determine surface flaws on the gearbox Exhibit 109 Exhibit 70

[42] A Structurally Significant Item (SSI) is any item or assembly, which contributes significantly to carrying flight, ground, pressure or control loads and whose failure could affect the Structural Integrity necessary for the continued safe and controlled flight of the aircraft.

structure. Fatigue cracks may have been identified by this technique and both gearboxes had a 5000 hr overhaul within 500 hours of their respective failures. PFD can only detect surface flaws and not internal fatigue damage/cracks that have not propagated to, or formed at the surface. The PFD technique could not have detected the presence of fatigue damage accrued within the gearbox in either case unless a fatigue induced surface crack was present. The 2006 incident was analysed by Bell and assessed as a fatigue failure but no further analysis was carried out and a striation count[43] was not conducted. Therefore, it was not possible to determine the length of time that the fatigue crack had been present. However, any surface flaw should have been evident at the 5000 hr overhaul, during the PFD inspection. Therefore, it was very likely that the fatigue crack in 2006 initiated within the 404:40 flying hours since overhaul. The accident gearbox, A-213, was also subject to the PFD inspection prior to the accident, and a 300 hour inspection for cracking (implemented by Cobham following the 2006 incident). Therefore, if there was a fatigue crack present in the accident support case it was also very likely to have initiated in the time since overhaul. The Panel concluded that the PFD inspection did not exclude the existence of a sub-surface fatigue crack or fatigue damage in the support case.

Exhibit 30
Exhibit 105
Exhibit 74
Exhibit 110
Exhibit 104

1.4.171. **Assessment of fatigue damage accrual**. Cobham stated that the support case was not tracked separately as a sub-component in their system. Therefore, it was not possible to determine the precise history of gearbox support cases. However, they were likely to have remained with the same gearbox in most cases and there was only one known instance of a support case being changed. Therefore, the assessment of fatigue damage is presented through the history of the main gearbox assembly, which includes the support case. The gearboxes in both the 2006 incident and the 2016 accident experienced flight in fatiguing conditions along with every other gearbox in the fleet. The Panel sought to determine if there was a correlation between the fatiguing conditions the gearboxes experienced, and the respective incidents. The only data that was available was the calendar life and flying hours for each gearbox over the lifetime of each gearbox. Fatiguing conditions affect gearboxes dependent on the number of load cycles and load cycle magnitude, ie, the number and severity of sloping ground landings or excursions outside the design manoeuvre limits. Quantitative data was not available and therefore no direct correlation could be made between exposure to fatiguing events and individual gearbox fatigue damage accrual. Nevertheless, the aircraft history indicated the general exposure to the fatigue conditions and circumstances leading up to the 2006 incident and 2016 accident.

Exhibit 107
Exhibit 78
Exhibit 78

a. Gearbox A-295 was exposed to the manoeuvre limits issue (1.4.144) over a period of 6 years and the rate of sloping ground landing issue over 9 years before it failed in 2006 (Figure 39). It was not possible to determine the loading severity of these conditions on the support case but Bell considered that exceeding the manoeuvre limits was one of two possible factors previously discussed in the fatigue crack incident in 2006 (1.4.107.c). The Panel assessed that exceeding the manoeuvre limits was the more likely of the 2 factors. A-295, was exposed to the maximum period of fatiguing conditions but this did not explain why other gearboxes may also have experienced similar loading but did not present similar fatigue cracks.

b. The accident gearbox, A-213, was only exposed to the manoeuvre limits issue for approximately 1 year due to its support case replacement in 2002. A-

[43] A striation count is a method for determining the number of fatigue load cycles prior to failure.

213 was also exposed to the hoist CofG issue (1.4.153) for approximately 1 year due to the gearbox being in storage, and an excessive number of sloping ground landings for 14 years (Figure 39). Although the magnitude of the hoist CofG issue could be determined for specified components, it was not possible to determine the loading severity of any of these issues on the support case.

1.4.172. The Panel concluded that although A-295 was exposed to the maximum period of fatiguing conditions, and this may have led to the fatigue crack, it did not explain why other gearboxes that also experienced similar loading did not present similar fatigue cracks. The exposure of all gearboxes was similar to, or greater than both gearboxes involved in the incident in 2006 and the 2016 accident. There is a random element to fatigue crack initiation and the sample size of affected gearboxes was relatively small. Based on the available data the Panel could not determine a correlation between exposure to fatiguing events and either incident.

1.4.173. **Calculation of gearbox support case accrual of fatigue damage**. Notwithstanding the lack of available data, a helicopter structural integrity expert specialising in structural integrity assurance for a number of helicopter platforms, conducted an assessment based on a number of comparative assumptions to account for the lack of access to proprietary design data. The analysis primarily focussed on aircraft usage during the manoeuvre limits issue and an increase to the number of sloping ground landings and the effect of these on the fatigue life of the support case. The analysis used standard fatigue evaluation procedures with an appropriate stress cycle curve for magnesium alloy. This analysis led to a qualitative judgement that the component life becomes extremely sensitive to variations in the load. Furthermore that there were potentially some damaging loads within the usage spectrum and therefore a more detailed fatigue analysis of specific features of the gearbox support casing should be seriously considered. After applying standard life and strength safety factors, the life that was calculated would indicate that the support case may require an overall fatigue life as a result of the extra fatigue damage accrued. The Panel concluded that the gearbox support case may be sensitive to fatigue damage and that due to the UK MODs historic usage, a fatigue analysis should be considered with a view to applying a fatigue life to the affected UK MOD gearbox support cases.

Witness 24

Witness 24

1.4.174. **Summary of all gearbox fatigue factors**. The Panel concluded that potentially damaging fatigue loads occurred in the support case as a result of a number of fatiguing conditions and the level of fatigue damage was above that assumed by the designer because of operation outside the design parameters. However, it was not possible to determine if fatigue damage led to any fatigue cracks in the support case because the support case melted in the fire. It was not possible to determine if fatigue initiators were present at the time of the accident, although this was not necessary for a fatigue crack to exist, similar to the UK MOD fatigue crack in 2006. The aircraft maintenance programme provided an adequate means to identify fatigue cracking in a gearbox casing if flown as designed. The Panel assessed that more detailed inspections were needed to identify and therefore mitigate the increased risk of cracking in a fatigue damaged gearbox. Sufficient data was not available to allow calculation of the effect of exposure to fatiguing conditions in order to predict future gearbox support case failures. However, it was proposed that fatigue damaged gearbox support cases may require a fatigue life in order to assure continued use. Notwithstanding the difficulty in assessing the condition of all gearbox support cases, it was the Panel's opinion that the gearbox support case should be assessed as a SSI by the TAA due to its historic susceptibility to fatigue within the UK MOD and controlled appropriately in accordance with the Military Regulatory Publications. Unquantified fatigue damage in the support case made initiation of a fatigue crack in the support case more likely and was a **contributory factor**.

1.4.175. **Recommendation**. Director Helicopters should assure structural integrity and type airworthiness of the Griffin platform such that the residual risk to life is tolerable and ALARP, while on the military register, with respect to:

a. The gearbox support cases that were fatigue damaged by any of the fatiguing conditions described within the Service Inquiry.

b. All components within the fatigue substantiation report for the sloping ground kit that were affected by rates of sloping ground landings above Bell's design assumptions.

1.4.176. **Recommendation**. The Federal Aviation Administration in conjunction with Bell should investigate the long term airworthiness of the gearbox support cases that were fatigue damaged by any of the fatiguing conditions described within the Service Inquiry and all components affected by rates of sloping ground landings above Bell's design assumptions.

Fire

1.4.177. Fire destroyed most of the aircraft fuselage and burned for approximately 4 hours after the crew left the aircraft. Technical analysis determined that, had the fire been prevented or stopped before it was out of control, the aircraft may have been repairable and the accident may have been classified as an incident rather than an accident. There were 5 main indications of fire during the accident; flames in the vicinity of the rotor mast, fire bursting out from below the tail section and fuselage 'transportation joint', the main fuselage fire, the cockpit fire warning audio and the illumination of the No.2 'T-Handle'. The Panel sought to establish the cause of the fire and if an effective barrier to the fire could have minimised the level of damage. Each of the components of the fire is discussed below to establish the progression of the fire and its implications (Figure 40). Exhibit 18 Exhibit 18 Witness 5 Witness 4

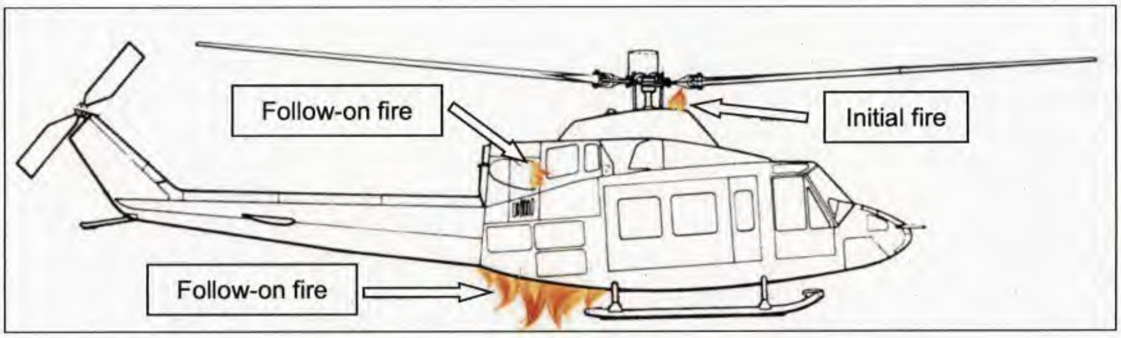


Figure 40 – Illustration of the fire locations as observed by Witness 5.

1.4.178. The fire was first seen in the vicinity of the rotor mast by the Passenger who signalled to alert the crew. The presence of a fire was acknowledged by the crew at this point. A fire warning was visible and audible on the CVR around this time, indicating that fire of sufficient heat was also present in the vicinity of at least one engine bay. The No 2 engine 'T-Handle' illuminated and the front crew emptied both fire bottles into the No 2 engine bay. The crew were further made aware of the fire when smoke entered the cockpit from above, this prompted the front crew to egress the aircraft. This also meant Witness 1 Witness 4 Witness 2 Exhibit 112 that the engine fire and emergency shut down drills were not fully completed and consequently the aircraft power supply and fuel booster pumps were left on. The Crewman Instructor attempted to fight the fire at the top of the rotor mast cowling by leaning out of the starboard cabin door with the aircraft fitted fire extinguisher, however there was no impact on the fire (Figure 41).

Figure 41 – Approximate location of the fire and Crewman Instructor's view while discharging the fire extinguisher.
(Picture Source: Crewman Instructor)

1.4.179. The Crewman Instructor began to feel heat emanating from the starboard lower rear fuselage area while trying to tackle the fire at the rotor mast and once the extinguisher was emptied, hastily retreated. The crew saw a large amount of what appeared to be burning fuel flowing from the lower rear of the fuselage on the starboard side of the aircraft. It was a matter of minutes after this that the entire aircraft was engulfed in flames, (Figure 42).

Witness 5
Witness 8
Witness 3

Figure 42 - Aircraft fire approximately 5 minutes after the accident.
(Picture Source: Aircraft Commander A)

1.4.180. **Fuel source.** DAIB technical analysis concluded that there would have been approximately 1640 lbs of fuel on board at the time of the accident, which was verified by a fuel check on the CVR of 1680 lbs just prior to the accident. DAIB technical analysis also highlighted a number of likely options that may have contributed to the fire's fuel source, which included gearbox oil, hydraulic fluid, aircraft fuel and the aircraft structure. The void that surrounds the main gearbox, which extends vertically through the aircraft and is referred to as the *'hell hole',* also facilitates the routing of fuel pipelines from the fuel tanks to the engines. A firewall protects the fuel tanks from the engine and a metal bulkhead separates them from the *'hell hole'*. An example of main gearbox movement during a previous accident showed how the gearbox of a previous foreign military accident in 2006 simultaneously impacted both engines' fuel pipelines and throttle control rods as the gearbox's sump[44] moved aft. The UK military fuel pipe configuration and layout is very similar (Figure 43).

Exhibit 18
Exhibit 17
Exhibit 18
Exhibit 67

[44] The 'gearbox sump' is the bottom of the gearbox where oil is collected.

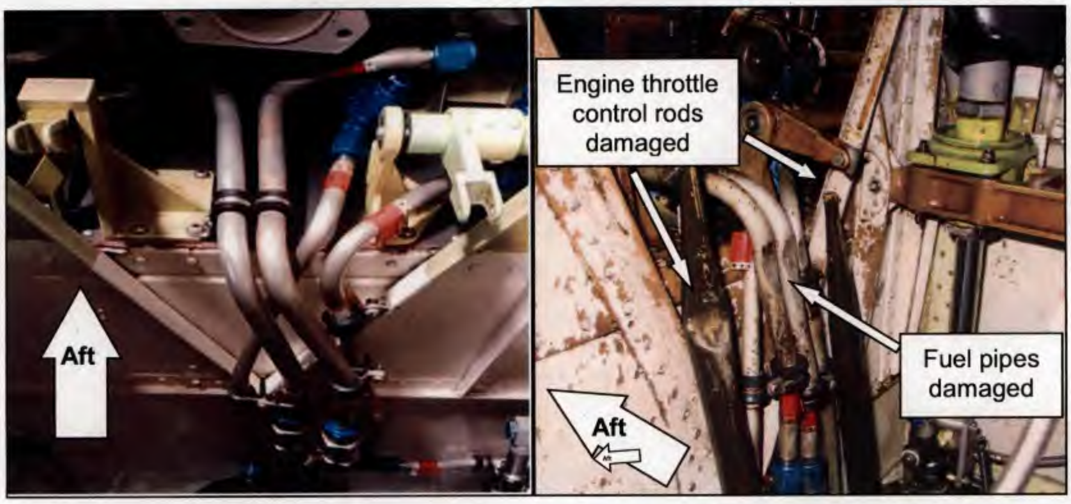


Figure 43 – [Left] MOD Griffin fuel pipe configuration with engine throttle control rods removed. [Right] Foreign military accident (2006).
(Picture Source: Left – SI Panel, Right – Bell)

The fuel pipelines and throttle control rods within the '*hell hole*' were judged by the Panel as almost certain to have been damaged as a consequence of support case failure and subsequent gearbox movement during the accident. The fuel pipelines and throttle control rods were likely to have been damaged at the beginning of the accident sequence following movement of the gearbox and may explain why the engine speeds are seen to split around 2:01:46 (Figure 15). The fire was likely to have developed in the vicinity of the main gearbox and the *'hell hole'*, and blown upwards to be visible at the top of the cowling as a result of fuel spillage from the damaged pipelines. There was a significant quantity of fuel remaining in the fuel tanks that could have been fed via the booster pumps into the *'hell hole'*, sustaining the fire leading to complete destruction of the aircraft. The proximity and concentration of the engine controls and services into the confined space at the rear of the *'hell hole'* provided a particular susceptibility to unrestrained motion of the gearbox. The follow-on fire emanating from the lower rear fuselage was likely to be the result of the contents of the fuel tank being released (Figure 44). In addition to the fire risk, the panel assessed that the configuration of the pipelines represented a single point of failure because structural failure and subsequent movement of the gearbox could cause loss of fuel to both engines. The FAA stated that the aircraft was subject to FAR 21.101 (Product Change Rule) or 'grandfather rights', thus any 412 derivatives only had to meet the certification basis at the time of their original Type Certification. The Panel did not conduct an assessment of the past and present regulations but noted that the Griffin safety case at the time of the accident was based on the Bell 412 Type Certificate. The Panel **observed** that there was a potential difference between the safety standards at the time of application for a Type Certificate and the safety standards in current regulation and that the safety case for older aircraft should take this into consideration for the risks to remain tolerable and as low as reasonably practicable.

Exhibit 18

Figure 44 – Fire approximately one hour after the incident
(Picture Source: Passenger)

1.4.181. The Panel concluded that the initial combustible fuel source was likely to be from the fuel pipelines in the vicinity of the 'hell hole'. The Panel further concluded that the location of the fuel pipelines, directly behind the gearbox sump, represented a single point of failure in the event of gearbox movement because any damage to this area would affect the fuel supply to both engines and was a **contributory factor**.

1.4.182. **Recommendation**. The Type Airworthiness Authority should identify the hazards associated with a single point of failure, due to excessive movement of the main gearbox. This should consider the routing of fuel pipelines and engine control rods with respect to engine fuel starvation and risk of fire, in order to articulate the risks to life to the ODH.

1.4.183. **Ignition sources.** DAIB technical analysis stated that the ignition source was likely to have been either from an electrical source, hot components or metal on metal contact. Likely causes were; projectiles associated with the drive shaft forward outer coupling, frictional sparks associated with excessive misalignment of a rotating component or component failure including movement of the gearbox. One further possible consequence of support case failure and main gearbox movement was that the rotor brake made contact with the support case after it moved forward. If this occurred it would have provided an ignition source in the same area that the fire was first spotted. Two previous accidents showed the likely consequence of rotor brake interaction with the support case (Figure 45). Exhibit 18

Exhibit 76
Exhibit 68

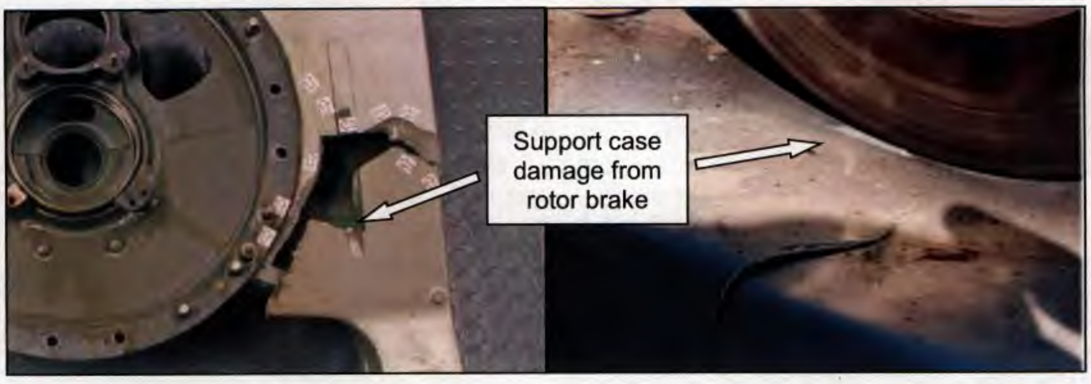


Figure 45 - Two examples of rotor brake contact with main gearbox support cases during an accident.

1.4.184. The crew reported a sound during the accident that was described as a chainsaw chewing through concrete. The Panel judged that this was more likely than not due to a high speed rotating metal component like the rotor brake making contact with another metallic object such as the support case. The rotor brake position on the gearbox provided approximately 2 mm of clearance between the brake disc and the support case. This has no adverse effect during normal operation. However, previous incidents have shown that during gearbox support case structural failure, this small rotor brake clearance may cause the disc to impact the case (Figure 45), presenting an ignition source and therefore increasing the potential risk of fire. The Panel concluded that the most likely ignition source was metal on metal contact. Metal on metal contact occurred as a result of the ejection of the forward outer coupling through the aircraft and was also likely to have occurred as a result of rotor brake interaction with the support case. Witness 5

1.4.185. **Firefighting.** A 2 kg Halon[45] fire extinguisher was provided in the aircraft for firefighting and is consistent with that on other platforms of a similar size. The extinguisher did not have a record of its weight on the inspection record, as required by the Aircraft Maintenance Program (AMP). Although it was not possible to determine the exact contents, it was very unlikely that this extinguisher would have been adequate to contain or put out the entire fire. The Panel judged that the fire extinguisher provided was not designed to tackle the magnitude of the fire at the time it was used in the accident. The scale of the fire was initially perceived to be much less and the limited attempt to fight the fire was the most that could have been expected in the circumstances. Although the aircraft-fitted fire bottles were discharged into the No.2 engine compartment by the crew in response to the 'T-handle' illumination their effectiveness could not be determined. There were no firefighting appliances located near the landing area as it was a remote location which posed a risk to the sortie and was implied by the nature of the task. The Panel judged that the risk taken as a result of the lack of fire protection at the landing site was reasonable given the exceptionally unlikely combination of factors that would need to align for the risk to materialise. However, the Panel concluded that the lack of firefighting facilities at the landing site made the outcome significantly worse through an inability to respond to the fire and was an **aggravating factor**.

Exhibit 112

Exhibit 104

Witness 2
Witness 4

[45] Halon fire extinguishers are used for wood, paper, liquid grease and electrical equipment. (Halon 1301, liquefied gas, pressurised to 100 psi with dry Nitrogen)

1.4.186. **Summary of fire.** The Panel concluded that gearbox movement created the conditions that provided a fuel and ignition source to start an enduring fire that led to the complete destruction of the fuselage. The relative position of various components such as the fuel pipelines and the rotor brake made the fire more likely in the circumstances. The crew were unable to complete a full shutdown before they egressed and consequently the booster pumps were not isolated and the aircraft fuel system would have continued to provide fuel, at pressure, into the fire. Incomplete shut down checks led to the fuel booster pumps remaining on, which increased the severity and the duration of the fire and made the outcome of the accident worse, and was therefore considered an **aggravating factor**. The location of the accident, and thus the lack of firefighting facilities, made the outcome of the accident significantly worse. However, even with good firefighting facilities available at an airfield, the speed with which the fire engulfed the aircraft may still have prevented the fire from being extinguished in time to recover the aircraft. Therefore, notwithstanding structural failure of the gearbox support case, the fire itself was also part of the cause of the accident because it directly caused the destruction of the aircraft.

Summary of determining the cause of the accident

1.4.187. The Panel concluded that structural failure of the main gearbox support case in 2 or more locations was a causal factor in the accident. The freedom of movement afforded by the breaks in the support case allowed the gearbox to move forward on its remaining mounts. The main drive shaft forward inner and outer coupling misaligned as the gearbox rotated forwards. The coupling locked at its limit of movement and failed in the manner of an explosion sending fragments into and outside the aircraft.

1.4.188. The cause of the gearbox support case failure was either through overload or fatigue. Each was examined separately but neither could be ruled out. However, the support case was fatigue damaged, beyond a level assumed during design, because of excessive usage throughout the aircraft's life. The circumstances of the landing prior to and during the accident sequence exerted additional loads on the support case that may have led to overload or contributed to a pre-existing fatigue crack. It was the Panel's opinion that a pre-existing fatigue crack had initiated and the high stress scenario during the landing sequence accelerated the growth of the fatigue crack to the point of failure. Once the residual strength of the material was reduced, it may have been overloaded at a stress below the certified static strength of the gearbox.

1.4.189. Fire was likely to have developed in the vicinity of the *'hell hole'* and drawn up through the aircraft so as to be visible in front of the main rotor mast. The ignition source of the fire was most likely through metal on metal contact of either the main drive shaft coupling fragments being ejected, or from interaction of the rotor brake on the support case as it failed. Regardless of the origin of the fire, the release of aircraft fuel increased its intensity and precipitated the uncontrollable destruction of the aircraft. The Panel concluded that although the gearbox support case failure directly led to the fire it may not have rendered the aircraft beyond repair. However, the severity of the accident was predominantly determined by the severity of the fire and therefore an uncontrollable aircraft fire was also a causal factor in the accident.

1.4.190. The Panel could not determine with certainty whether the gearbox support case failed in overload or fatigue, but it was almost certain that structural failure of the support case in 2 or more locations led to unrestrained motion of the gearbox and was a **causal factor**.

1.4.191. The presence of an uncontrollable aircraft fire, following mechanical failure, led to the destruction of the aircraft and was a **causal factor**.

ADDITIONAL FACTORS INVESTIGATED

Weather

1.4.192. The Panel sought to determine the local weather on Yr Aran during the moments leading up to the accident. This was necessary due to the difficulties associated with mountain flying and lack of local weather reporting in the mountains and at the accident site. The effect of the weather on the aircraft handling characteristics was considered and an assessment was made of the impact on the accident. A military guide to mountain flying described mountain winds:

> *"**Mountain winds**. By far the most important weather factor in mountain operations is the wind. Over open country the assessment of wind strength and direction and its effect on flying presents few problems. In the mountains the wind flow may be modified markedly, with significant upward and downward movement as well as horizontal variations, depending on the nature of the air mass and the incidence of topographical friction."*[46]

1.4.193. **Wind speed and direction**. The wind strength and direction on Yr Aran was affected by the surrounding mountains and topography. The Aircraft Commander of the Squirrel helicopter, the Passenger and Crewman Instructor provided an assessment of the wind speed and direction in the vicinity of the accident site (Table 8). The range of wind speeds given by these witnesses were between 10-25 kt. The most accurate forecast of the wind was assessed to be the RAF Valley area forecast which was 20 kt at 2000 ft. The height of the accident site was 448 ft higher than the forecast height and as wind strength usually increases with height, could have been slightly more than the forecast wind in this instance. The Meterological Aerodrome Report (METAR)[47] at RAF Valley and Capel Curig weather station were noted, but not considered significant due to the measurements being taken too far from the accident site and in a different geographic environment, therefore subject to local modifications by the surrounding terrain. A maximum gust of 26 kt was given by the mountain weather forecast, which was the highest of all the wind speed forecasts. A gust of this strength was judged to be very unlikely as the figure represented a temporary condition throughout the entire period of the forecast. Based on the available evidence the Panel concluded that the general wind speed in the local area was approximately 20 kt and between 300° - 310° at the time of the accident. This was likely to be greater on the windward side of the mountain, and relatively still next to the ground at the accident site.

Witness 17
Witness 4
Witness 5
Witness 1
Exhibit 10
Exhibit 113
Exhibit 11

[46] AP 3456 Helicopters. Chapter 16 Mountain Flying and Winter Operations.

[47] A METAR is an aviation routine weather report issued hourly or half-hourly intervals. It is a description of meteorological elements observed at an airport at a specific time.

Weather Report	Wind direction	Wind speed (kt)	Comments
RAF Valley area forecast 25Km radius	310°	20	Forecast valid at 2000ft AMSL
Witness - Passenger on Yr Aran	300°	10-15 G+5	Estimate based on experience
Witness - Aircraft Commander (Squirrel)	-	15-ish	Estimate based on experience
Witness - Crewman Instructor	310°	-	Estimate based on memory
RAF Valley cross section 2000ft upper wind forecast	310°	20	Forecast valid at 2000ft AMSL
RAF Valley TAF 1050Z	300°	14	
Mountain Weather Forecast Tuesday 9 Aug (above 500m/1640ft)	NW	Max 17 – 22 Gust 26	Converted from Mph (Max 20-25 Gusts 30)
RAF Valley METAR actual at 1250Z	270°	15	Surface wind
Capel Curig weather station	250°	7	Location in a valley 13Km NE of Yr Aran

Table 8 - Reported and calculated wind strength on 9 Aug.

1.4.194. **Demarcation line and turbulence**. The demarcation line is where the airflow (wind) travelling over a feature breaks away from a smooth laminar flow and so turbulence results (Figure 46).[48]

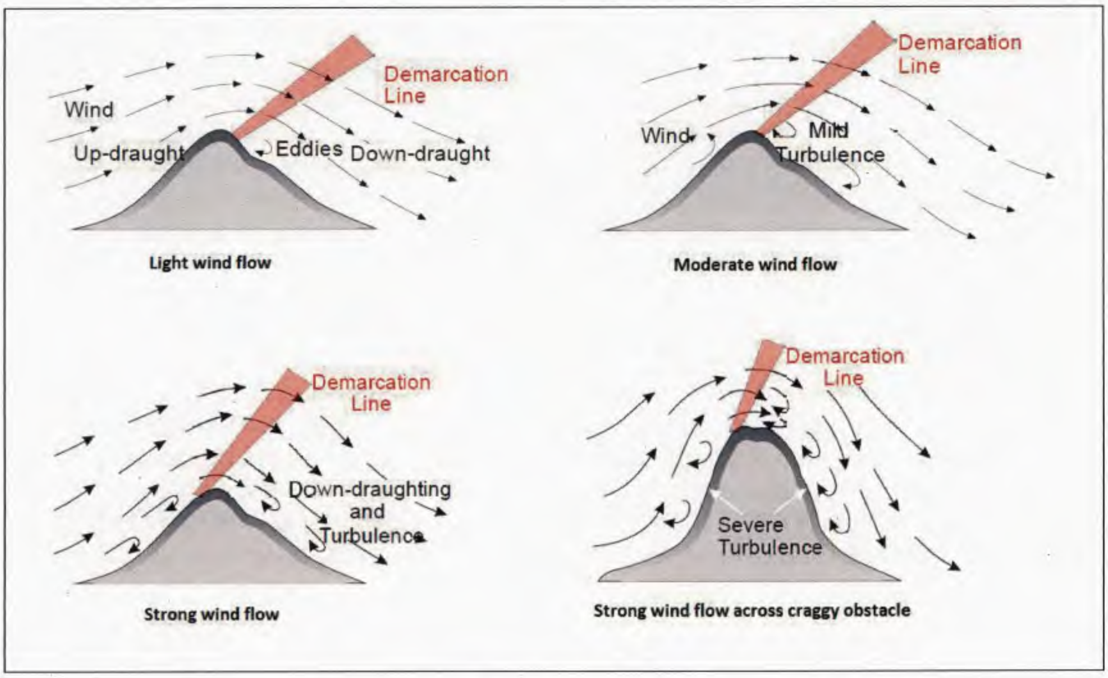


Figure 46 - Wind patterns over features with varying strengths
(Picture source: AP3456.49)

[48] AP 3456 Central Flying School Manual of Flying. Volume 12, Chapter 16

[49] AP 3456 Volume 12: Helicopters. Chapter 16 Mountain Flying and Winter Operations.

"When a wind flow is interrupted by an obstacle such as an isolated hill or pinnacle, it will divide and accelerate over and to each side, causing up-draughts to windward, and turbulent down-draughts with eddies in the converging air on the lee side. The intensity of these disturbances will depend on the speed of the wind and the cragginess of the obstacle, varying from mild up-and down-draughting over gentle slopes to more volatile vertical and horizontal mixing when strong winds encounter rough, irregular features. This is illustrated in [...][Figure 46]*, showing an increasing risk of severe up and down draughts, with localized reverse flows which, in extreme cases, may exceed the normal maximum rates of climb and descent of a helicopter. The demarcation line between up-draughting and down-draughting air will, typically, become steeper and move towards the windward edge of the feature as wind speed increases."*

1.4.195. The profile of Yr Aran shows a steeper craggy section on the windward side of the hill which would have increased the steepness of this demarcation line (Figure 47).

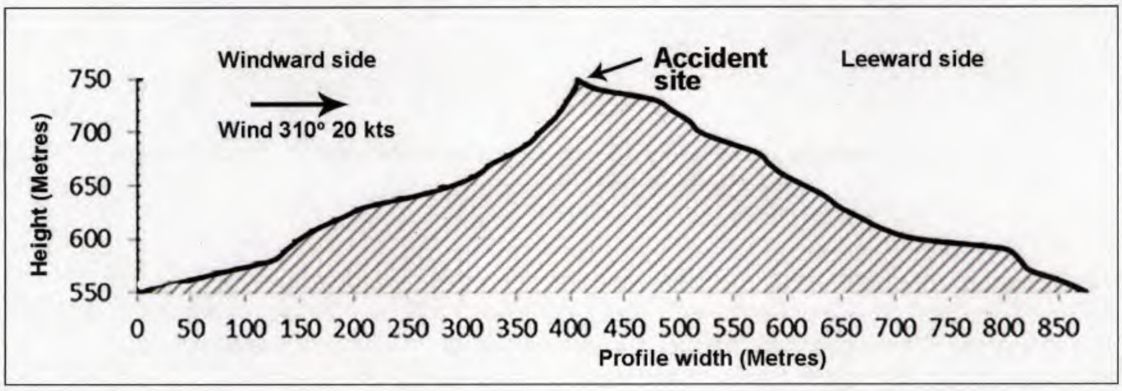


Figure 47 - Profile through the summit of Yr Aran, on the heading of the wind.

1.4.196. The hill was also part of a ridgeline that provided a 'wall' feature for the wind to divert over. This created a complex three dimensional demarcation 'plane'. Aircraft Commander A described going through the demarcation line quite smoothly during the first approach to the lower point on the same ridge and that the approach was absolutely normal. While not a perfect comparison to the actual accident site, the orientation of the ridge to the wind was similar in both cases. Both the Instructor Crewman and Student Pilot noted that the smoke canister fired during the recce, while slightly down-draughting on the lee-side of the hill, did not indicate turbulence (Figure 48).

Witness 4

Witness 5
Witness 2

Figure 48 – Photo of smoke (taken approximately 15 seconds after deployment), fired during recce to the pinnacle.
(Picture Source: Aircraft Commander B)

1.4.197. The Crewman Instructor described the wind flow on the leeward side of the mountain as down drafting air but not turbulent, just the line of the flow of air going across the top of the mountain. The Crewman Instructor was focused on the task at the time and as such the Panel judged this to be the most accurate assessment of the level of turbulence. The Aircraft Commander of the Squirrel stated the conditions were not overly turbulent during the approach to the pinnacle, in an aircraft that weighed less than half that of the Griffin and therefore more susceptible to turbulence. The Passenger (flying the Squirrel), hadn't noted any particular turbulence or demarcation line issues, having flown through the demarcation line on a direct approach into wind, perpendicular to the ridgeline. Turbulence, rather than absolute wind strength, during the landing would have had more effect on aircraft handling. This is because any changes to wind speed vary the lift created by the main rotor blades which in turn require handling inputs to maintain the helicopter in a steady position. Handling would also have been more sensitive once in the skids light position due to the pitch response rate during a nose upslope landing. Therefore variations in wind speed combined with pitch response rate would have increased the difficulty of the landing. The crew did not experience any unusual weather and there was no evidence that handling of the aircraft was adversely affected leading up to the accident. In addition, the Panel assessed that the conditions at the time of the accident were within the competency of the crew.

Witness 5
Witness 17
Witness 1
Exhibit 89

1.4.198. **Wind limits**. The maximum allowable cross wind or tail wind component in the hover was 35 kts. Local orders further restricted activities that could be conducted in different conditions. Wind above 25 kts required Duty Executive approval for flights in the Mountain Flying Training Area (MFTA). In addition to these limits, the aims of the sortie, other meteorological factors, experience of the crew, the activities to be conducted and the turn back options would all need to be discussed and considered. The go/no go criteria would then be at the discretion of the Aircraft Commander and the authoriser. The Panel concluded that the wind was within limits because it was below the least restrictive limits for mountain flying, and of the remaining considerations for flight over 25 kts, all had all

Exhibit 62
Exhibit 114
Exhibit 194

been appropriately considered or were not relevant for this particular sortie.

1.4.199. **Summary of weather**. The Panel concluded that handling would have been more sensitive than usual because of the variations in wind speed combined with the slope landing. However, the Panel further concluded that despite this, the wind was within limits to operate the aircraft and there was no evidence of unusual or turbulent conditions, such that would adversely affect normal operation of the aircraft. The weather was therefore **not a factor**.

Landing site suitability

1.4.200. The general landing area, on Yr Aran, was initially selected by Aircraft Commander B during the planning phase. It was chosen due to its classic shape as a pinnacle, its impressive nature and because it has a low volume of use by the general public. The pinnacle was described as the most classic looking pinnacle that was infrequently visited by walkers. The mountain has a number of possible landing points. A variety of options exist along the summit ridge, Area A and B (Figure 49) and a lower shelf of flatter ground immediately to the south of the ridge, Area C (Figure 49) which was also often used by members of 202(R) Sqn. The grid of the landing site (SH605516) was accurate to 100m and therefore not a specific point on the top of the mountain, this left an element of interpretation to the crew flying the approach regarding the exact landing point. The crew were free to choose the best location for the conditions at the time which included, but was not limited to, the 3 areas (Figure 49).

Witness 8
Witness 8
Witness 9
Witness 5
Exhibit 115

Figure 49 - Landing areas on Yr Aran.
(Picture Source: Aircraft Commander B)

1.4.201. As the wind was perpendicular to the ridge all landing points on the ridgeline would have had comparable wind conditions. Area C was much further down the lee side of the mountain and therefore would be subject to greater risk of turbulence and down draughting air than the windward side of the mountain (Figure 49). Due to the increased

Witness 5
Witness 8

power demand, Area C would also have presented fewer escape opportunities and required an earlier commitment to land in the event of an emergency. For these reasons, the Panel assessed that landing areas on the ridge would have been more suitable for the conditions on the day of the accident. This was supported by the decision of the Squirrel Pilot to land the Squirrel helicopter at Area B, immediately prior to the accident. This demonstrated the suitability of an alternative landing point further along the ridge on the day of the accident, in the same conditions, noting that this was a different aircraft type and slightly different position, therefore not a direct comparison. The Passenger remained beside the drop-off position in area B, halfway along the ridgeline, next to a metal post, leaving landing options to either side. The ridgeline has varying degrees of sloping ground that although difficult to estimate from the air, remain suitable to attempt, using the 'skids light' method described at 1.4.62. Aircraft Commander A elected to land in Area A, next to the Passenger. The Panel assessed that this would have placed fewer initial references to his side, although it afforded good views for the Instructor Crewman and as a lesser consideration, good views for the Student Pilot. Aircraft Commander A stated that once in the 10 ft hover, there were sufficient references on his left hand side to allow a descent to land. Witness 17 Witness 1 Exhibit 17 Witness 4

1.4.202. **Summary of landing site suitability**. In the Panel's opinion there were sufficient suitable landing areas to attempt a slope landing on either side of the Passenger and that the captaincy decision to land on the left hand side was reasonable in the circumstances. Therefore, notwithstanding the conclusion that the final resting position was out of limits (1.4.64), the suitability of the landing site for the skids light type of landing selected and for the circumstances on the day was **not a factor** in the accident.

Workload

1.4.203. **Working with a student**. The circumstances of the sortie were not dissimilar to many other sorties conducted by instructors at 202(R) Sqn. However, the 3 main areas that the Panel determined contributed to workload were the inexperienced student, the pinnacle landing and the emergency situation that developed. Cockpit workload was considered by the Centre for Aviation Medicine (RAFCAM) Human Factors specialists,

> *"under normal situations, workload in a helicopter cockpit is increased by: looking outside the window to focus on the demands of the flight or tasks whilst simultaneously looking inside the cockpit to attend to the aircraft instruments and controls, listening to multiple audio inputs eg crewman communication, audio warnings, and concurrently building situation awareness".* Exhibit 29

1.4.204. Once in the hover, the handling pilot's attention would primarily have been external, scanning the rocky outcrop and distant attitude markers. The handling pilot's visual scan should also include glances at interior flight instruments, for example to check the ADI. With two experienced pilots, these internal instruments are normally monitored by the non-handling pilot, however a student pilot in the right hand seat is more likely to focus outside the cockpit and the instructor's focus was necessarily divided between the two activities, therefore workload was higher than with another qualified pilot but normal for an experienced instructor. Exhibit 29 Exhibit 56

1.4.205. **Landing on a pinnacle**. Landing on a pinnacle is a period of relatively high workload for the handling pilot. This would have been exacerbated when accompanied by a student pilot who can be expected to be concentrating on external cues and is unlikely to have additional capacity for simultaneously scanning internal instruments. During the approach to the hover over the pinnacle there were limited close references for the handling pilot to use and he was using a combination of better cross cockpit references on the right and distant markers (the facing hill in the distance). Aircraft Commander A described how the combination of the two markers aided the approach and once the rocky outcrop that sits at the top of Yr Aran on the left hand side of the aircraft became visible it was an excellent marker in the ten o'clock position. The combination of clear instructions from the Crewman and the availability of markers did not suggest that workload was higher than normal for the type of landing being conducted. Witness 4

1.4.206. **Dealing with an emergency situation**. As soon as an emergency situation develops, the human factors report stated, *"workload and level of arousal is increased which reduces attentional [sic] resources and the ability to focus on anything more than a small set of cues. This might explain why, during the accident sequence, Aircraft Commander A appears to have been focused on trying to understand what was happening and control the aircraft"*. Unfamiliarity with the task and time shortage are the two top risk factors influencing human error rate. These factors multiply the possibility of a human error occurring by a factor of 17 and 11 respectively. Both factors were present when dealing with the nature of the emergency that confronted the crew, which was unusual and rapid. This explains why slight omissions were made in the attempted hazard recovery phase of the accident and that only one of the crew heard the low rotor warning which was misidentified as the fire warning. Exhibit 29 Witness 8

1.4.207. **Summary of workload**. The Panel concluded that the workload of Aircraft Commander A was normal for the circumstances leading up to the accident. Notwithstanding this, the handling pilot's attention was primarily focussed on maintaining the aircraft position during the landing and less on the instruments. Following failure of the gearbox support case (an unforeseen emergency), workload for the entire crew was significantly increased and may have led to omissions. However, the Panel judged that the shutdown checks were not completed due to thick smoke entering the cabin rather than due to a high workload, therefore workload was **not a factor**.

Structural integrity management

1.4.208. The Military Aviation Authority (MAA) produces Regulatory Articles (RA) on structural integrity management in order to maintain airworthiness. The RAs state that structural integrity management should be applicable to all new and legacy aircraft types, regardless of procurement model. Structural integrity may be compromised by overload, fatigue, fretting and wear, accidental damage, environmental damage, or procedural error in design, manufacturing, maintenance and supply. The Regulatory Articles explain how threats to structural integrity should be managed through the Establish-Sustain-Validate-Recover-Exploit (ESVRE) management framework which was also echoed in the Griffin airworthiness strategy. Exhibit 116 Exhibit 143

1.4.209. **Establishing structural integrity**. Structural integrity is established in order to demonstrate that the aircraft is airworthy to operate under the Release to Service (RTS) document and the assumptions made within the Statement of Operating Intent and Use (SOIU). The RTS for Griffin aircraft is a limitations document, signed by the Assistant Chief of the Air Staff, that states, *"The RTS describes the approved Air System configuration(s), the operating envelope, limitations, design standard, standard of operational software and the parameters within which the Air System SC [safety case] has been established, and to which the Air System or equipment may be flown in Service regulated flying."* The RTS does not include performance targets. The Panel found that Exhibit 116 Annex F Exhibit 224 Exhibit 117 historic work to advise the importance of structural integrity and the ESVRE principles was provided as far back as 1998. The panel also found reference to Air Publications (AP) dating back to 1993 that stipulated similar instruction to that of the current Regulatory Articles (RA) regarding structural integrity. However, it was not apparent how this activity was carried forward by the SPMAP PT, as they did not establish structural integrity as required by the Military Regulatory Publications (MRP). Instead they relied upon a generic SPMAP PT airworthiness strategy, which covered multiple aircraft, to provide the necessary guidance. This approach was considered by D-Hels in 2011 as a reasonable holding position following the introduction of the MRP. The Griffin Airworthiness Strategy initial issue was in August 2015 and the absence of a Griffin specific Structural Integrity Strategy document and the associated integrity working group prior to this meant that the framework to manage threats to structural integrity, in an MRP compliant manner, was not in place. This also meant that the key stakeholders and their responsibilities for structural integrity were not identified. Consequently, during the service life of the platform, threats were not treated in a planned and coordinated manner. In support of addressing the threats to structural integrity an SOIU is designed to convey the intended usage of the aircraft to the Design Organisation (DO). It provided an indication of the flight conditions and sortie types so that the impact on the aircraft fatigue life consumption could be deduced accurately. When the Griffin was first introduced there was no usage data for the duration of every flight condition. However, this was anticipated and advice was sought from operators and information was obtained from flight authorisation sheets. The empirical data obtained from operators and authorisation sheets was included with the first iteration of the Griffin SOIU, published in March 1998. The original SOIU identified sloping ground landings up to 10° as part of the aircraft usage spectrum and it showed that there was no expected flight time within the 5° – 10° sloping ground range. Following the introduction of a new aircraft type there is a need to capture actual, accurate usage data early in the service of the aircraft to support the original usage assumptions and to establish structural integrity, yet this was not conducted for the Griffin until 2005, approximately 7 years after it had first been introduced. An intermediate SOIU, published in December 2002, contradictorily acknowledged that landings were conducted up to 10° but recorded the number of landings to be zero. Sloping ground landings were not included in an SOIU after 2002 and were subsumed into the term 'ground condition'. The Panel judged that anomalies in the SOIU regarding sloping ground landings, and lack of data capture in the early life of the aircraft, should have prompted further investigation to ensure that structural integrity was fully established.

Exhibit 209
Exhibit 117
Exhibit 116
Exhibit 169
Exhibit 118
Exhibit 117
Exhibit 135
Exhibit 222

1.4.210. An independent review of the draft Military Aircraft Release (MAR) (now RTS) by Defence Test and Evaluation Organisation (DTEO) (now QinetiQ) in 1997 queried the lack of information related to Angle of Bank (AOB) limitations. The statement in the Griffin RFM in 1997 stated that, *"aerobatic manoeuvres are prohibited"* but did not provide any published limits associated with the statement. In order to infer numerical manoeuvre limits, an assumption was made by the Release to Service Authority (RTSA) that Bell users would be compliant with FAA code of federal regulations section 14 order 91.303. This defined aerobatic manoeuvres as *"an intentional manoeuvre involving an abrupt change in an aircraft's attitude, an abnormal attitude or abnormal acceleration, not necessary for normal flight"*. This was further supported by the FAA general aviation operations inspectors' handbook, order 8700.1 chap 49 which stated, *"when pitch angle exceeds a positive or negative 90° angle from the horizon, and/or when the bank diverges from level flight in excess of 90°"*. Therefore, during the period 1997 – 2003, the RTSA published limits regarding manoeuvres for Griffin aircraft that were derived from the RFM,

Exhibit 118
Exhibit 119
Exhibit 80
Exhibit 120
Exhibit 121

FAA and other documents.[50] Between 2000 – 2003 the RTSA introduced the MOD definition of aerobatic manoeuvres as, *"Intentionally performed manoeuvres which involve angles of pitch or bank greater than 90° to the horizon or yawing through angles of greater than 20°."* The RTSA used this definition as it did not contradict the definition provided by Bell within the RFM. Bell stated that the initial parameters defined by the RTSA were based on assumptions that would not have been supported, had they been reviewed with Bell at the time. FAA regulations mandated, since 1978, that the RFM must contain the operating limitations under which the aircraft was type certified. Bell stated that the manoeuvre limits were considered as part of the certification of the Bell 412, yet numerical manoeuvre limits were not included in the RFM. Therefore, the Panel judged that numerical manoeuvre limits should have been included since certification of the aircraft, which would have prevented ambiguity, leading to misunderstanding of the definition of aerobatic manoeuvres. An RTS update in 2003 prompted the RTSA to question Bell via FBH (now Cobham) regarding the lack of published limits, which prompted Bell to revise the RFM. The RTSA reduced the limits in the RTS accordingly as a protective measure. In 2005, FBH (now Cobham) advised that the limits were set at 50° angle of bank, 30° pitch up and 15° pitch down, which prompted an airworthiness recovery exercise by the TAA. Bell updated the RFM on the 31 October 2007, to include, *"Intentional manoeuvring resulting in roll attitudes in excess of 50° angle of bank, or pitch attitudes lower than 15° nose down or higher than 30° nose up are prohibited."* The Panel concluded that although the first edition of the MAR correctly translated the information from the RFM, it did not articulate the correct design limits because they were not available. The independent review in 1997 by DTEO (now QinetiQ) identified a lack of specific manoeuvre limits but this did not result in the issue being resolved at the time. There were some errors in the first iterations of the SOIU and the RTS that directly affected the establishment of structural integrity; this meant it was possible for military operators to fly outside the design envelope of the aircraft due to the published limits in the RTS.

Exhibit 121
Exhibit 199
Exhibit 216
Exhibit 97
Exhibit 80
Exhibit 121
Exhibit 199
Exhibit 80

1.4.211. **Recommendation**. The Federal Aviation Administration should determine if the Bell 412 Rotorcraft Flight Manual (RFM) adequately represented the limits under which the aircraft was type certified, and should consider amending regulations to ensure that design limits are better represented in the RFM.

1.4.212. **Sustaining structural integrity**. Part of structural integrity management is sustaining structural integrity throughout the fleet's life. Although there are many ways to sustain structural integrity, the following factors are discussed: monitoring fatigue significant events, aging aircraft and environmental damage, and corrosion control.

a. **Monitoring fatigue significant events**. Structural integrity is sustained by monitoring, measuring and countering threats to airworthiness. It has already been established that the rate of sloping ground landings for some of the fleet was greater than Bell's design assumption. The fatigue substantiation report for the slope landing kit also described the affected components as being the mast, lower cone seat and the yoke. The Panel noted that Bell did not require the operator to record fatigue significant slope landings and to impose a maximum number for each component or to instigate a Retirement Index Number (RIN)[51] for

Exhibit 116
Exhibit 212
Exhibit 87

[50] The predecessor to the regulations at the time of the accident were; JSP 318 [military flying regulations] and JSP 550 [UK MOD military aviation policy, regulation and directives].

[51] Retirement Index Numbers are used to record fatiguing events on so that the component may be retired early if there are a significant number of fatiguing events over the life of the component.

each slope landing recorded against each component. Instead, they chose to reduce the component life, RIN or both for the mast, yoke and the lower cone seat, on the basis that the number of slope landings remained within their assumptions. The Panel judged that this was reasonable for civil operators that did not have access to the design assumptions. Bell also continue to support the use of their components, provided the operation of the aircraft stays within the RFM. However, the military regulations stipulated, since 1997, that the project team should ensure that military aircraft do not exceed the rate of fatigue significant events specified in the design assumptions and Design Usage Spectrum (DUS) which the SPMAP PT had access to. The number of slope landings was not recorded in the Technical Log and consequently could not be quantified in the SOIU from which structural integrity should be monitored. This is in contrast to the Canadian Forces, who record sloping ground landings and use HUMS to monitor fatigue. The Panel judged that the high rate of sloping ground landings almost certainly caused additional unknown fatigue damage to those components detailed in the fatigue substantiation report (the mast, the lower cone seat and the yoke). Had sloping ground landings been assessed as fatiguing and monitored, any associated threats to structural integrity would have been mitigated by simple counter measures such as a reduction in the number of slope landings or a reduction in the severity, ie, steepness of those landings. The lack of monitoring of fatigue significant slope landings during the aircraft's service life prevented the TAA from sustaining structural integrity by comparing this usage to the design assumptions. An Independent Structural Airworthiness Advisor (ISAA) is a key stakeholder in establishing and sustaining structural integrity. The Panel could find no evidence that an ISAA was present at structural integrity working groups and this reduced the likelihood of detecting issues related to sustaining structural integrity. The Panel concluded that the sustainment of structural integrity required data on all fatigue significant events within the SOIU, including the number of sloping ground landings, to be available and monitored appropriately so that they could be periodically reviewed. An assessment of fatigue significant events required an ISAA. However, the Panel found no record of this type of assessment.

Exhibit 058
Exhibit 102
Exhibit 143
Exhibit 209
Exhibit 2
Exhibit 117
Exhibit 190
Exhibit 116
Witness 22

b. **Recommendation**. Type Airworthiness Authority should record all fatigue significant events within the Design Usage Spectrum and ensure that they are monitored and validated within the Statement of Operating Intent and Use, to maintain structural integrity throughout the life of the aircraft.

c. **Ageing aircraft and environmental damage management**. Part of structural integrity management is the process of conducting an ageing aircraft audit to identify environmental damage. RA 5723 states that at 15 years or 50% of planned life an aircraft should undergo an ageing aircraft audit. The Griffin fleet fell into the category of ageing aircraft by 2008, as defined by the MRP. Despite this an ageing aircraft audit was not conducted, increasing the possibility that threats due to Environmental Damage (ED) were not identified. The Regulatory Articles state:

Exhibit 126

"As aircraft age, ED [Environmental Damage] becomes more widespread and is more likely to occur concurrently with other forms of damage such as fatigue cracking. ED degrades Structural Integrity and if uncontrolled will reduce the inherent ability of the structure to sustain loads in the presence of other forms of damage."

Exhibit 126

d. The DHFS aircraft were not considered 'old' compared to the global fleet leader in terms of airframe hours, as discussed during the Platform Safety Environmental Working Group (PSEWG). There was a qualitative discussion with Bell and other operators that included the type of operation and location. However, there was no quantitative comparison between the fleet leader and the Griffin fleet. The MOD fleet of Griffin aircraft are not the same as the global fleet because they were fitted with the enhanced slope landing kit and routinely landed on slopes up to 10° compared to the normal global limit of 4°. They were also configured differently and may not operate in the same environmental conditions. In the Panel's opinion comparison to the global fleet should not be relied upon as the sole means by which to mitigate the risks associated with ageing aircraft because the comparison is not direct. Despite the DHFS fleet leader being 19 years old at the time of the accident, no ageing aircraft audit was planned or conducted by the Project Team and they made no application for Alternative Acceptable Means of Compliance (AAMC), waiver or exemption to RA 5723. The Project Team relied on Bell civil regulatory compliance and a valid civilian Type Certificate as the sole mitigation against compliance with the regulation and to assure longer term airworthiness. An ageing aircraft audit would have informed the PT of associated risks and most likely have taken comparable civil derivatives into account. The Panel concluded that the lack of ageing aircraft audit reduced the likelihood of identifying fatigue damage in the support case.

Exhibit 127
Exhibit 228
Exhibit 126
Exhibit 128
Exhibit 143

e. **Corrosion control**. Part of structural integrity management is sustaining structural integrity through corrosion control. The Griffin SOIU indicates, "*fleet managers at all levels are to ensure that wherever possible, individual aircraft experience as wide a range of roles as possible"* in order to avoid, *"limiting an airframe to one type of flying only"*. It also describes the relative difference between the operating areas for the Griffin. Specifically, it notes that, *"Both mountain and maritime training and SAR operational flights for the aircraft involve operations over salt water. This environment has the potential to increase instances of corrosion damage, particularly for unprotected items of structure."* However, the Griffin Military Continuing Airworthiness Management Exposition (CAME)[52] specifies which aircraft tail numbers are to operate in each location. This fixes specific aircraft to specific environments for extended periods of time contradicting guidance given in the SOIU. RAF Valley operations are predominantly in the maritime environment and therefore aircraft at this location will be significantly more exposed to corrosive conditions. The Panel **observed** that rotating aircraft between operating locations would share the level of exposure to potential corrosion amongst the fleet but equally may have to be balanced with other important considerations such as maintenance planning and role fit.

Exhibit 130
Exhibit 130
Exhibit 131

f. The Bell corrosion control guide gives advice on how corrosion could be prevented and states that the operator should create a, *"reliable corrosion control program that must take into consideration factors such as geographical location, and specific operational environments"*. A Corrosion Control Program is not mentioned in the SPMAP PT's Support Policy Statement.[53] The Cobham owned

Exhibit 103
Exhibit 132

[52] The Continuing Airworthiness Management Exposition (CAME) is the document that explains how continuing airworthiness will be carried out for the Griffin fleet.

[53] The Support Policy Statement is also known as the aircraft publication, 'Topic 2' as mandated by military publications

Aircraft Maintenance Program refers to the Bell corrosion guide but does not explicitly address the requirement to differentiate between different environments. A generic maintenance practice was provided in the form of a 3-month, out of phase 'Corrosion Check'. This Corrosion Check gives comprehensive direction for protection around the engines, tail and fuselage, however, no additional protection of the main gearbox was mandated in Cobham's Aircraft Maintenance Programme. Bell stated that other Bell 412 maritime operators do provide greater corrosion protection for the main gearbox components. Therefore, the Panel concluded that specifying geographic locations of the 4 aircraft at RAF Valley exposed them to a more salt laden environment than the aircraft at RAF Shawbury. A Corrosion Control Program should have been implemented to account for the difference in environment between the two locations. The lack of additional geographically specific corrosion control on the main gearbox components could have led to the initiation of a fatigue crack in the support case. However, due to the level of destruction of the airframe, it was not possible to determine if other airframe corrosion was present, but the lack of explicit corrosion control for the gearbox support case may lead to fatigue crack initiation in other support cases, and was therefore an **other factor**.

Exhibit 104
Exhibit 104
Exhibit 30
Exhibit 131
Annex C

g. **Recommendation**. The Type Airworthiness Authority should provide a corrosion control policy, in the Support Policy Statement, based on the specific environment and aircraft usage, which should take account of best practice within other Bell 412 maritime user communities.

1.4.213. **Validation of structural integrity**. The Regulatory Articles state that a triennial review of the SOIU should be completed by an appointed competent organisation using aircraft usage data to carry out a quantitative update. The review process is to ensure that aircraft usage remains within the design parameters, the DUS and assumptions, and to highlight any changes in usage. The Griffin SOIU states that:

Exhibit 116

"By reviewing this SOI/SOIU, the Designer is ensuring that these fatigue significant manoeuvres are not being carried out at a greater rate than that assumed in the Design and Usage Spectrum (DUS), and that the published component fatigue lives are still valid."

Exhibit 133

1.4.214. This methodology required that the correct data was validated by the Designer in order to assess the implication of any changes to the aircraft usage. However, the only triennial review of the SOIU was carried out in 2006 using the results from the Manual Data Recording Exercise (MDRE) in 2005. The data capture exercise was approximately 6 years out of date and the triennial review was approximately 7 years out of date at the time of the accident. The fatigue substantiation report for the slope landing kit detailed Bell's sloping ground landing assumptions. The sloping ground assumptions were only one aspect of the entire DUS and did not represent an aircraft limit. Therefore, sloping ground assumptions were not published by Bell in the RFM. Notwithstanding this, the sloping ground assumptions did represent an engineering assumption that had an impact on fatigue and therefore structural integrity. The Panel determined that the rate of sloping ground landings should have been validated during the SOIU review process and required further investigation once usage reached the design assumptions. The SPMAP PT did have access to the fatigue substantiation report (including the design assumptions) from when the aircraft was purchased. Therefore, threats to structural integrity as a result of the number of slope landings should have been identified through the SOIU review process. The MDRE exercise in 2005 did not capture any sloping ground landing data as a discrete event so proper validation was not possible. The lack of SOIU review at the time of the

Exhibit 134
Exhibit 135
Exhibit 87
Exhibit 122
Exhibit 87
Exhibit 135

accident was also highlighted by the TAA in June 2016 just prior to the accident:

> *"The requirement under the MAA Aircraft Usage Validation Programme is that the usage of the aircraft as described in the SOI is validated by an appointed competent organisation to compare the In Service usage to the Design Usage Spectrum and subsequently provide a statement of acceptance or advice on the continuing Structural Integrity of the aircraft. There is potential that this validation will not be completed in a timely manner. The approved design of the aircraft requires that the sum of the Average Probabilities per Flight Hour of all Catastrophic Failure Conditions caused by systems is of the order of 10-7 [1 in 10,000,000] or less. The classification of risk associated with the lack of validation of usage by the TCH is therefore classified as Catastrophic / incredible, although this is not believed to be a credible risk."* Exhibit 127

1.4.215. However, the Duty Holder chain did not hold any risks associated with lack of SOIU review or ageing aircraft audit in the unified bowtie risk management tool. The Panel concluded that following the MDRE exercise in 2005 there was a dilution of the importance of monitoring sloping ground landings and other fatigue significant events during the service life of the aircraft. This led to a lack of validation of fatigue significant events and a potentially undetected and unrecorded excessive rate of sloping ground landings which may have compromised structural integrity. Exhibit 167

1.4.216. Although not formally contracted, Bell did review the SOIU in 2009. However, the Panel opined that Bell may not have been fully aware of the purpose of the review because sloping ground data was not present and angle of bank data was outside of the aircraft operating limits, neither of which was commented on by Bell. The Panel would have expected the angle of bank and sloping ground data or lack of it, to have been commented on in order for it to be compared to proprietary design information. Cobham as the Civil Continuing Airworthiness Management Organisation (CAMO) had no requirement to have access to the proprietary design assumptions and could not assist in this function. Additionally, Civil regulations did not require a process of validating design usage. However, as the Co-ordinating Design Organisation (CDO), Cobham were required to coordinate DO activity on behalf of the TAA. The SOIU review was therefore not directly contracted with Bell and was carried out as part of a technical support contract between Bell and Cobham. The TAA stated that the project team had no direct contract with Bell to routinely carry out SOIU reviews and therefore the TAA could not be compliant with Regulatory Article RA 5720. This partly explained why the queries to Bell regarding validation of the SOIU were difficult and time consuming throughout the life of the UK Griffin fleet. The Panel **observed** that formalising a direct relationship with the Original Equipment Manufacturer (OEM) regarding SOIU review should improve the quality of the validation activity and reduce the risk of errors in structural integrity management. Exhibit 134 Exhibit 135 Witness 22 Witness 22 Witness 22 Exhibit 116

1.4.217. **Recovery of structural integrity**. The Panel sought to understand if structural integrity was recovered effectively following the manoeuvre limits issue in 2005 (1.4.144) and whether this was a factor in the accident. It was not until 2007 that Bell included manoeuvre limits in the RFM and 2009 that Bell responded with a formal recovery action plan for the MOD Griffin fleet. The issue of structural integrity of MOD aircraft was revalidated in 2012 upon completion of a component replacement programme. In the Panel's opinion the time that it took to initiate recovery action of an airworthiness issue, following discovery in 2005 to production of a formal action plan in 2009 (4 years), was unreasonably long. Exhibit 121 Exhibit 97

1.4.218. A component replacement program was devised by Bell Helicopter to replace all life limited parts, located above the main transmission, with the exception of the main rotor droop restraint system. Bell's recovery plan also assessed the susceptibility of the gearbox support case to fatigue and concluded that the very low-cycle nature of the loading was within the static capabilities of the gearbox. However, Bell recommended: Exhibit 97

> *"The standard non-destructive inspection per the 412/412EP CR&O manual for the transmission [gearbox] cases should be adequate. However, both mast bearings should be replaced due to the unknown high cycle loading at potentially high mast bending loads."* Exhibit 97

1.4.219. Non-destructive inspections were sub-contracted by FBH (now Cobham), at cost to the UK MOD. Even though the loading was within the static capability of the gearbox, as stated by Bell, an independent structural integrity expert advised the Panel that low cycle fatigue would still contribute to fatigue damage in the gearbox. Consequently, the Panel concluded that the overhaul inspections recommended by Bell would not have been sufficient to assess the level of fatigue damage or predict future failure. The gearbox inspections could only identify the presence or otherwise of a crack at the time of the inspection. In addition, Bell did not communicate a possible cause of the 2006 fatigue crack until this Service Inquiry when a possible cause was cited as exceeding the manoeuvre limits. Thus, Bell recognised that exceeding the manoeuvre limits would have contributed to fatigue damage accrual within the support case. Witness 22 Witness 24 Exhibit 30

1.4.220. Cobham, as holders of the civil Part M approval (Continuing Airworthiness Management Organisation), made enquiries to Bell regarding follow-up action to the 2006 fatigue crack. Although Bell provided a summary laboratory report, they declined to provide the full laboratory report, and also declined to return the original gearbox support case following another formal request. A Mandatory Occurrence Report (MOR) was raised by FBH (now Cobham) to the CAA, due to the unsafe condition of the aircraft. The FAA stated that 14 CFR 21.3 require failures, malfunctions and defects to be reported to the FAA within 24 hours of determining a reportable event, however, it also allows for reports not to be filed if the failure was caused by improper maintenance or use; and the regulation allows the design approval holder to make that decision. Bell determined that the cause of gearbox support case failure was a fatigue crack in the full lab report dated 7 Feb 2007 but did not raise a report to the FAA within 24 hours. In response to the Service Inquiry Bell stated *"FAR Part 21.3 reporting does not apply to failures caused by improper use"* and that this particular failure was not a reportable event. However, Bell did not communicate the potential root cause of the 2006 fatigue crack until prompted during this Service Inquiry and the Panel could find no evidence that Bell had determined the cause, other than fatigue, at the time that a FAR 21 report was required. There was no Airworthiness Directive (AD), Alert Service Bulletin (ASB) or amendment to maintenance practices promulgated by Bell, the FAA or the CAA following this incident. In-lieu of other mitigation, FBH (now Cobham) took the internal measure of introducing an extra visual check of the oil filler neck during all 300-hour inspections. Bell stated that the issue was unique to the UK MOD fleet and therefore an AD or ASB was not appropriate and no further cracks that were found in other gearbox support cases were attributed to fatigue since the UK MOD fatigue crack in 2006. However, this mitigation was not known in 2006 and the Panel could not find a correlation between exposure to fatigue damaging conditions and the timing of the initiation of a fatigue crack (1.4.171). Annex F Exhibit 136 Exhibit 137 Exhibit 163 Exhibit 231 Exhibit 138 Exhibit 74 Exhibit 199 Exhibit 97 Exhibit 104 Exhibit 199

1.4.221. The Panel concluded that Cobham and the TAA, in consultation with Bell, recovered structural integrity of all components other than the support case, and made reasonable efforts to recover structural integrity of the support case itself. Subsequently, Bell advised the Service Inquiry that the fatigue crack from 2006 suggested a usage spectrum that was outside the normal flight regime. The Panel concluded that although Bell assisted the MOD in recovery of structural integrity, they did not inform the FAA or other Bell 412 users of the potential to inadvertently exceed the manoeuvre limits before 2007 when the RFM was changed. It was the Panel's opinion that numerical manoeuvre limits should have been included in the RFM since the certification of the aircraft, and also defining aerobatic manoeuvres in the RFM. This would have removed ambiguity in the interpretation of the document. Bell stated that some other helicopter manufacturers do not always include specific manoeuvre limits and did not agree that there was a potential world-wide fleet issue that required action because they were not aware of operators flying the aircraft beyond the design limits. However, the Panel also assessed that other military and civilian operators may have inadvertently exceeded design limits during the period prior to 2007 due to the lack of published manoeuvre limits and definition of aerobatics in the RFM. Exhibit 30 Exhibit 199 Annex G

1.4.222. **Recommendation**. The Federal Aviation Administration in conjunction with Bell should ensure that all Bell 412 users were not affected by the lack of manoeuvre limits in the Rotorcraft Flight Manual prior to 2007 and take necessary action in order to assure structural integrity of all affected components.

1.4.223. **Responsibility for structural integrity**. The TAA is ultimately accountable for structural integrity. However, given the complexity of relationships within the MRCO construct, the Panel sought to determine if others understood their responsibility for structural integrity, which may have contributed to the hoist penalty region CofG issue (1.4.153). In 2005 the RTSA changed the cabin configuration of the aircraft, operating at RAF Valley, to include the 10 man quarter door life raft, in addition to the 5 person life raft and other equipment. The precipitating factor in the hoist Centre of Gravity (CofG) penalty excursions was predominantly the periodic removal of the existing 5 person life raft from 2011 onwards that meant that the likelihood of flying within the hoist CofG penalty region was increased. Until March 2014, aircrew were referred by the RTS to a hoist penalty region graph within the Aircrew Manual stating, *"Pilots are to be aware of when hoist operations result in operating within the Penalty Area* [...] *This will result in a reduced rotor components life."* No amplification instructions were given and there was no specific facility (other than logging a fault) to record penalty life in the aircraft tech log. Lack of a tech log reporting facility had not been an issue prior to 2011 because cabin configuration would have required a fuel load just above the minimum landing allowance, which made entry into the penalty region almost impossible. In March 2014 the RTS added the following instruction, *"Excursions into the penalty area are to be reported to the appropriate maintenance authority."* Aircrew did not recognise that the RTS prohibited the removal of the 5 person life raft or that once they did they were potentially operating in the penalty region. Entry into the penalty region prior to removal of the 5 person life raft was almost impossible and in the Panel's opinion normalised behaviour had developed. Exhibit 116 Exhibit 101 Exhibit 232 Exhibit 62

1.4.224. An email seeking clarification of engineering procedures and the reporting of time spent in the penalty region was sent from 202(R) Sqn to Cobham's training manager on 4 August 2015 containing the following: Exhibit 101

> *"The sortie's [sic] where the penalty region is a problem occurs on about a third of our winching sorties. Each affected sortie results in one to two winch lifts in the penalty region [. . .] Currently there is no provision in the Hoist or Tech log to record winch lifts in the penalty region, so we have no idea how much life we have taken off the gearbox."* Exhibit 101

1.4.225. The response from Cobham's [redacted] to the [redacted] was:

> *"There is no risk, this is a known and controlled issue and highlighted that both crews and engineers were made aware of in February this year [sic]. Providing crews undertake WB [weight and balance] correctly and highlight appropriately when they are operating in the penalty area we remain within a controlled and managed environment. [. . .] We have also assumed the worse [sic] and checked component records and even if they have ignored the requirements of the RFM we are okay. We also have an amendment coming out to the hoist technical log that will make any recording easier."* Exhibit 101

1.4.226. Cobham assured themselves that airworthiness was not compromised at that time, having checked component records. However, despite knowing the aircraft had been operated in the penalty region, only estimates of those excursions were available and correction to component lives could not therefore be completed. OC 202(R) wrote back to the Cobham engineering manager requesting amplification of the assumptions made and details of the worst case scenario. There was no further correspondence and the issue remained unresolved. Cobham stated that the reason component lives were not amended was because: Exhibit 124 Exhibit 101 Annex C

> *"In the absence of any clear instruction from the operator on either the authorised SRP [Sector Record Page] or hoist tech log, or from the Mil CAMO responsible for continuing airworthiness, the component life's [sic] were not amended. It should be noted that it is not common practice within civil regulations to amend aircraft component life's [sic] based on estimates or non-verified figures. At no time were the figures verified nor were instructions received from the TAA or Mil CAMO to apply any penalty factor as a result of hoist operations in the penalty area."* Exhibit 141

1.4.227. The issue was not communicated to the MilCAM or the TAA who therefore had no way of intervening. RA 1124 (CAA oversight of military registered aircraft) and CAP 562 leaflet B40 asserts that the MilCAM retains primary responsibility for continuing airworthiness for all MRCO aircraft and components operated by the MOD.[54] Component lives were rectified by Cobham once the issue was raised again by this Service Inquiry in July 2017 when specific figures were received from the Mil CAM/TAA.[55] However, the risk to airworthiness had not changed since it was first raised. Cobham's assertion that even if operators had ignored the RFM in the worst case scenario that, *"we are ok"* was only true at that point in time. Cobham did not seek clarification from OC 202(R) Sqn or seek to resolve the airworthiness issue. The MilCAM and CivCAM were both present at standard engineering meetings within 6 months of the issue being raised in 2015 but the meeting minutes contained no evidence of discussion regarding the matter. Exhibit 124 Exhibit 101 Exhibit 32 Exhibit 142 Exhibit 195 Exhibit 172 Exhibit 151 Exhibit 161

1.4.228. The Panel concluded that removal of the 5 person life raft made entry into the hoist CofG penalty region possible and that aircrew should have realised that they were operating within this region prior to August 2015. The Panel also concluded that despite the reported figures for the hoist CofG issue being estimates, Cobham should have taken

---

[54] Leaflet B40 is a complimentary CAA regulation that explains the responsibilities within a MRCO contract in order to comply with Civil regulations.

[55] Griffin ZJ241 – Urgent Safety Advice dated 31 Mar 17

action to escalate the issue in order to amend component lives. Although Cobham acted correctly and in line with their maintenance program, it was the Panel's opinion that they did not respond within the spirit of their responsibility for structural integrity as defined by military regulations. It was also the Panel's opinion that the CFI could have communicated the issue to the MilCAM for engineering input in order to resolve the issue. Although OC 202(R) Sqn tried to raise the matter, aircrew did not recognise or report the issue, as detailed in the RTS because of normalised behaviour. The hoist CofG issue was an example of the challenges faced between civil and military organisations within the MRCO construct and highlighted that responsibility for structural integrity extended to a greater number of people than the TAA who was directly accountable.

Exhibit 142

Annex C

1.4.229. **Summary of structural integrity management**. The Panel concluded that there were lapses in structural integrity management throughout the life of the Griffin, beginning with the manoeuvre limits issue in 1997 when structural integrity was not established due to incorrect information in the RFM. The TAA relied upon an Airworthiness Strategy to convey compliance with the requirements of structural integrity management. The absence of a defined stakeholder community led to ineffective communication to address and recover events such as exceeding limits, fatigue, corrosion, and configuration that severely inhibited the route to effective structural integrity management. Furthermore, the Griffin airworthiness strategy stated that type airworthiness would be achieved by maintaining structural integrity. The Regulatory Articles provided a framework specifically designed to ensure that military structural integrity management conformed to a minimum level of engineering practice. The TAA was non-compliant with the Regulatory Articles or their equivalent preceding instructions since 2009.

Exhibit 143

Witness 22

Exhibit 143

Exhibit 32
Exhibit 144
Exhibit 116

1.4.230. The SOIU and the RTS had errors in their first iterations that directly affected the establishment of structural integrity. The lack of ageing aircraft audit reduced the likelihood of identifying fatigue damage in the support case. The lack of additional geographically specific Corrosion Control on the main gearbox components could have led to the initiation of a fatigue crack in the support case. Following the MDRE exercise in 2005 there was a dilution of the importance of monitoring sloping ground landings and other fatigue significant events during the service life of the aircraft. This led to a lack of validation of fatigue significant events and a potentially undetected and unrecorded excessive rate of sloping ground landings. An assessment of fatigue significant events required an ISAA in order to identify threats to structural integrity, however, the Panel found no record of this type of assessment. Overhaul inspections recommended by Bell would not be sufficient to assess the level of fatigue damage in the support case and did not represent a full recovery of structural integrity following the manoeuvre limits issue in 2005. The Panel concluded that the lack of a compliant structural integrity strategy undermined the ability to treat threats to structural integrity effectively and was a **contributory factor**.

1.4.231. **Recommendation**. The Type Airworthiness Authority (TAA) should retain the services of an Independent Structural Airworthiness Advisor to assess the impact of fatiguing conditions, assure structural integrity management activity and to advise the TAA on airworthiness risks arising from structural integrity concerns.

ORGANISATIONAL FACTORS

1.4.232. There were a number of historic and unexplained vibration incidents that led the Panel to initially investigate air safety management processes to determine why they had not been resolved. There were a number of factors that contributed to the accident that were influenced by the organisation. The resultant line of enquiry expanded to include Air safety management, trend analysis, risk management and safety oversight, and the MRCO construct. Air Safety Management Systems (ASMS) and the MAA air safety culture model were used as frameworks during the assessment. MAA oversight and approval department and a DSTL data analyst were also consulted. The complex and interrelated civil and MOD policy and regulations for all MRCO aircraft meant that factors identified for Griffin operations could equally apply to other MRCO aircraft that follow similar processes. Exhibit 89 Exhibit 91 Exhibit 92 Exhibit 93 Exhibit 94 Exhibit 145

Air safety management

1.4.233. Air safety management within the MOD is managed by the Aviation Duty Holder system. The MOD's Air Safety Information Management System (ASIMS) is a web based application to support the reporting, management and analysis of air safety occurrences, investigations and recommendations. The civilian occurrence reporting system is mandated by European regulations to be through ECCAIRS.[56] Within the civilian sector, each operating organisation also has an internal occurrence management system. In Cobham's case their safety process, SP-01, details the management of safety related data, but the MRP oblige operators of MRCO aircraft to use ASIMS as the reporting system for all air safety occurrences. The different types of air safety reports are as follows: Exhibit 149 Exhibit 146 Exhibit 147 Exhibit 148

a. **Defence Air Safety Occurrence Report (DASOR)**. DASORs are the occurrence report forms submitted through ASIMS. DASOR management using ASIMS is the DDH's primary occurrence reporting tool. DASORs are raised on the ASIMS website or in hard copy where ASIMS access is not available. It is the reporting method for all air safety related occurrences including reporting of potential air safety hazard observations. Exhibit 149

b. **SF-01A**. SF-01As are Cobham's occurrence management report forms. They are otherwise referred to as a Hazard Report (HzR), Ground Occurrence Report (GOR) or Flight Occurrence Report (FOR). Exhibit 147

c. **Mandatory Occurrence Report (MOR)**. MORs are used to communicate occurrences that fall within set criteria to the CAA and EASA. Occurrence reporting in the UK and the rest of Europe is governed by European Regulations. An 'occurrence' means any safety related event which, if not corrected or addressed, could endanger an aircraft, its occupants or any other person. The purpose of occurrence reporting is to improve aviation safety by ensuring that relevant safety information relating to civil aviation is reported, collated, stored, protected, exchanged, disseminated, and analysed. The criterion for civilian Exhibit 150 Exhibit 146

[56] European Co-ordination Centre for Accident and Incident Reporting Systems (ECCAIRS)

reporting is different from military reporting.

1.4.234. **Air safety information flows**. An analysis of the air safety information flows across DHFS and other Griffin organisations is represented in (Figure 50). The model is based on the ASIMS user manual but includes the additional necessary pathways that occur as a result of the MRCO construct. Exhibit 149

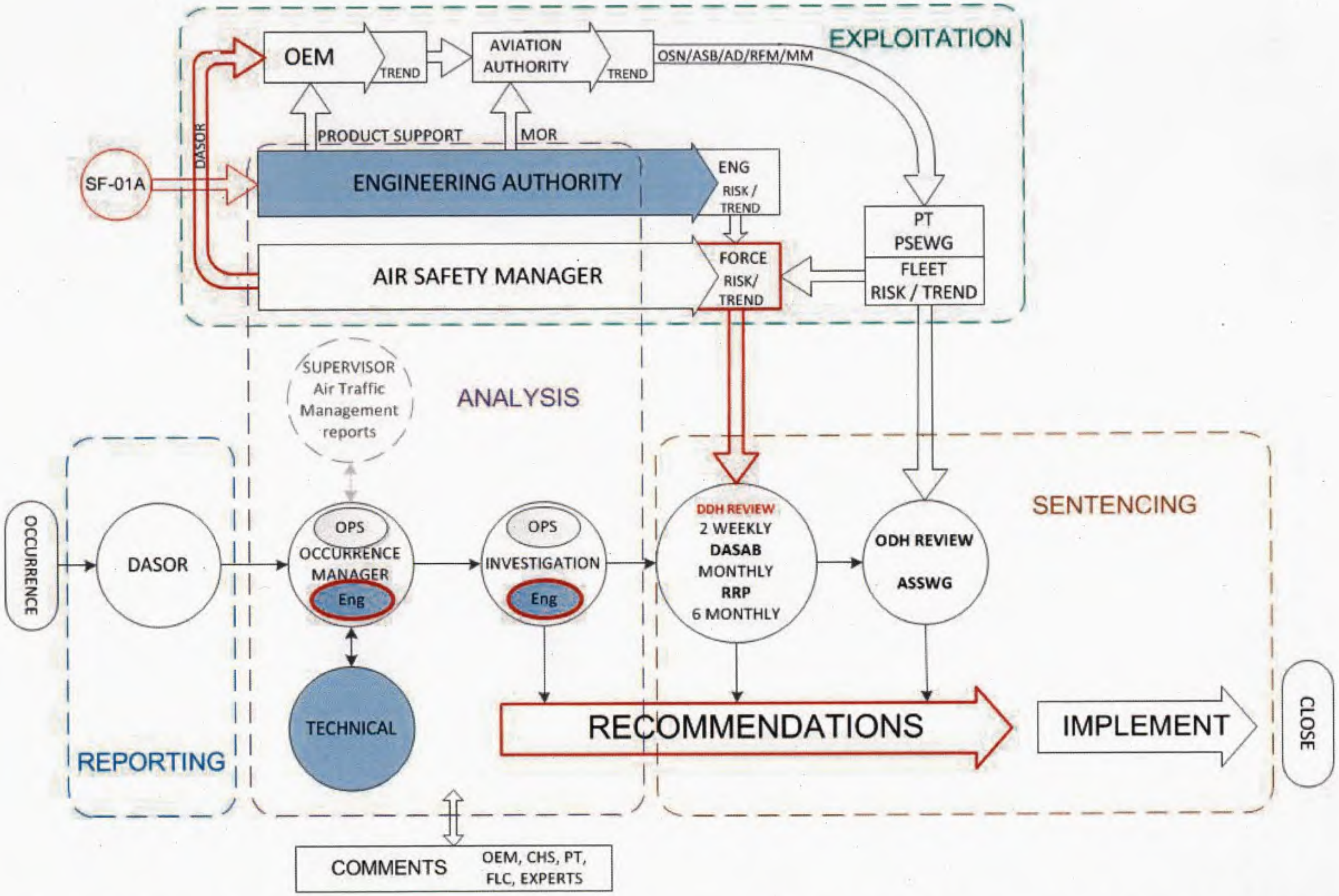


Figure 50 - Analysis of air safety information flow for Griffin aircraft. Areas identified by the Panel for improvement are highlighted in red.

1.4.235. **Reporting**. Reporting of air occurrences using ASIMS was well established at
RAF Shawbury and RAF Valley. Ground occurrences were being reported, yet there was Witness 10
confusion within engineering over whether a DASOR or an SF-01A should be raised. Witness 11
Paper SF-01A forms were being used and they were available around the engineering
office in containers. SF-01A reports were mostly used for reporting engineering ground Witness 14
occurrences, which would then require duplication on a DASOR, to enable the DDH to
manage any risk associated with the engineering occurrences. Further to this, the
Cobham Maintenance Organisation Exposition (MOE) referred to the Maintenance Error
Management System (MEMS) and Maintenance Error review board to manage SF-01A. Exhibit 151
This process was aligned with the MOD Defence Aviation Error Management System
(DAEMS) process for error management. A Civil Part 145 organisation, such as Cobham, Exhibit 145
was required by Civil regulation to have its own error management system. This Exhibit 150
introduced two separate reporting procedures at the lowest level. An MAA audit in 2016
observed the number of reporting systems in use and stated that it would be beneficial to Exhibit 152
mandate the use of a single system in future contracts. The Panel judged that two Exhibit 153
separate reporting systems could result in missed information or inhibit the ability to link air
safety occurrences. There was limited access to ASIMS amongst 202(R) Sqn engineers
due to only one available computer terminal in the engineering building. The MOD
computer system was not regularly used by the engineers other than the senior 202(R) Witness 14
Sqn engineer and the Panel did not find evidence that hard copy DASOR forms were used
by individual technicians.

1.4.236. An important indicator of an effective reporting culture is that there is confidence, Exhibit 145
at all levels, in the Air Safety/Error Management reporting system. During the Service
Inquiry the Panel was made aware of an unresolved historic situation with the hoist CofG
penalty region that led to the reduction in component life due to the incorrect recording of
aircraft usage. The hoist penalty CofG issue needed to be communicated to a wider Exhibit 124
audience for it to be resolved. This incident was reported on a number of occasions by
senior management but only via e-mail. It was the Panel's opinion that this informal
method of reporting may have contributed to the issue not being resolved at the time,
because information was not promulgated more widely, and through miscommunication
and misunderstanding of the information. The unresolved issue resulted in component
lives being incorrect for a period of 4 years. The use of a DASOR would have formally
highlighted the airworthiness concern to a wider air safety audience. The absence of a
formal report, and that the issue remained unresolved was a negative indicator of an Exhibit 145
effective reporting culture. The Panel concluded that a number of individuals should have
known to formally report an airworthiness concern via a DASOR. The lack of access to
computer terminals, and thus DASOR occurrence reporting forms, may have contributed
to a lack of reporting of occurrences on ASIMS by the maintenance organisation. The lack
of formal reporting of an airworthiness concern was an **other factor**.

1.4.237. **Recommendation**. The Operating Duty Holder should ensure that the contracted maintenance organisation is appropriately resourced to use the Air Safety Information Management System as the primary reporting and occurrence management system in accordance with RA 1410, to ensure that all air safety occurrences are appropriately managed.

1.4.238. **Occurrence management**. The Air Safety Manager (ASM) at DHFS was the Exhibit 154
Occurrence Manager for the majority of all DHFS occurrences. Unit Flight Safety Officers
carried out the remainder of Occurrence Management activity. The Panel found during a
sample check that the technical sections of DASORs were often incomplete and in the Exhibit 160
Panel's opinion the investigation, findings and recommendations sections lacked comment Exhibit 159
in instances where it would have been appropriate. Occurrence managers at DHFS were

all air safety qualified but none were engineers. Instead, they were exclusively operators. There were no Cobham or engineering ASIMS occurrence managers, nor was there any stated requirement for any. At the time of the Inquiry, Version 3 of ASIMS required each DASOR to be investigated, but did not dictate the level of investigation required. This requirement placed an administrative burden on the air safety organisation, which would be proportional to the number of investigators available. The Panel noted that the occurrence manager was usually nominated as the investigator. In most cases the Panel judged that this was reasonable provided that the content of the DASOR was not significant. For others, the lack of a separate investigator represented a missed opportunity for the occurrence manager to question the comments of the investigator and created additional workload. In the majority of cases this was also the DHFS ASM, which resulted in the loss of a further layer of potential independence and oversight. The ASM was authorised to close low risk DASORs on behalf of the DDH, without consultation, which was a routine activity. Of particular note was that among the most common outcomes on Griffin DASORs was a 'no fault found' classification. None of the 'no fault found' DASORs drew recommendations from the DDH or action from the TAA or engineering organisation. The Human Factors report also commented that the workload of the ASM was relatively high and that a reliance on the ASM as the conduit of all DASOR information could increase the risk of an issue not being raised to a higher authority or acted upon. A DSTL report concluded that much of the ASM's focus was on processing 'Airprox'[57] DASORs, which at a busy training airfield was understandable as these related directly to one of the greatest risks owned by the ODH. Yet, this provided further evidence of under resourcing in the management of DASORs. The Panel concluded that the workload of the ASM was high and this was partly due to a lack of engineering occurrence managers. The Panel also concluded that a high workload and lack of engineering occurrence managers would make effective oversight and quality control of all DASORs more difficult and hinder the DDH's ability to question engineering practice and challenge norms. Lack of engineering occurrence managers for technical DASORs may lead to lack of oversight and quality control of occurrence reports and was an **other factor**.

Exhibit 154
Exhibit 154
Exhibit 154
Exhibit 161
Exhibit 29
Exhibit 155
Exhibit 29

1.4.239. **Recommendation**. The Delivery Duty Holder of the Defence Helicopter Flying School should ensure that there is an appropriate balance of engineering and operator competencies between nominated occurrence managers and investigators within the organisation, to improve the management of engineering related DASORs.

1.4.240. The DDH review group was the first point at which air safety and airworthiness risks were managed and sentenced. The ASMP did not articulate a requirement for sub-unit occurrence managers to attend the fortnightly DDH review group meeting. Good practice from other forces demonstrated that the DDH review group benefited from the attendance of engineering and operations occurrence managers from each sub unit to explain the content of DASORs and take actions from the DDH.

Exhibit 156
Exhibit 157
Exhibit 158

1.4.241. **DASOR Recommendations**. The MAA Manual of Air Safety states that DASORs provide an invaluable source of data, particularly when they are comprehensively completed with the inclusion of causal factors and recommendations that can be analysed further. Recommendations on ASIMS are a searchable audit trail and therefore contribute to data trending and exploitation. A review of Flying Training Squadrons (FTS) within No 22 Gp and Joint Helicopter Command's use of recommendations, conducted by the Panel confirmed that DHFS had the fewest number of recommendations as a percentage of the

Exhibit 145
Exhibit 149
Exhibit 159

[57] Airprox – an occurrence where aircraft fly within an unsafe distance of each other.

total number of DASORs raised (Table 9). This finding supported a qualitative review of
individual DASORs that found that DDH comments and external comments were being Exhibit 159
used on a number of occasions in lieu of recommendations. The ASM indicated that the
reason for this in most cases was that corrective action was carried out prior to closure of Witness 18
the DASOR. The actions, if formally logged as recommendations, should be used as
guidance and communicated to other fleets to prevent future occurrences. When Exhibit 145
recommendations were made, it could be seen that individuals were held accountable for
implementing changes directed by the DDH. Implementing change prior to a
recommendation being raised could have unintended consequences to overall air safety
and may cause the Duty Holders to be unaware of how risks were being dealt with.

ODH	No 22 Gp						JHC					
DDH	DHFS	1FTS	2FTS	3FTS	4FTS	No 22 Gp Average	CHF	Wattisham	Odiham	Benson	Yeovilton	JHC Average
Total DASORs Raised	450	242	125	660	256	346.6	246	294	831	503	345	443.8
Total DASORs containing recommendations	13	25	11	34	24	21.4	72	85	101	60	66	76.8
Percentage of DASORs containing recommendations	2.8	10.3	8.8	5.1	9.4	6.17%	29.3	28.9	12.2	11.9	19.1	17.3%

Table 9 – Number of DASORs containing recommendations.

1.4.242. The Panel assessed that DHFS was closing DASORs on a number of occasions
where recommendations should have been made. The Panel judged that this could lead
to repeated mistakes being made within the organisation and a missed opportunity to
share positive safety improvements with other organisations. Closing DASORs without
making a recommendation where a recommendation would have been effective may lead Exhibit 145
to repeat errors amongst DHFS operators and the wider Griffin fleet and was an **other
factor**.

1.4.243. **DHFS trend analysis**. The ASM at DHFS did not carry out any formal trend Witness 18
analysis other than from collective corporate memory within the organisation. The ASMs
terms of reference stated that lessons from other units should be promulgated within Exhibit 154
DHFS. This requirement was non-specific and there was no other mention of a
requirement to conduct data trending within the DHFS Air Safety Management Plan. A
DSTL report showed that ASIMS statistical analysis was not used by DHFS, the Project Exhibit 155
Team or Cobham to provide trend analysis. It further commented that the lack of ASIMS
functionality to normalise events against flying hours in its trending capabilities precluded
its use on many occasions because meaningful comparisons could not be made. This
required each organisation to use a bespoke procedure. It was also found that there was
no training or guidance on effective methods of exploitation of data from ASIMS; experts Exhibit 149
from a number of organisations used the system in different ways for the same purpose.
Cobham conduct a bespoke analysis of component failure and tech log entries for
presentation at the Airworthiness Review Board but the Panel found no evidence that this Exhibit 161
information was combined with DASOR information for a holistic organisational trend

analysis. The Panel **observed** that improving the functionality of ASIMS to allow occurrence events to be normalised against flying hours, would provide an essential quantitative trend analysis tool for all DASORs.

1.4.244. A study was conducted by DSTL to identify if there were any predictors of gearbox failure within the available data that might have been identified during routine safety management reviews. The study indicated that it was not possible to have predicted the accident from the available information. The study did highlight that a trend in magnetic chip faults (the most reported technical occurrence for Griffin) in DASORs was present (Figure 51). However, it was not an accurate predictor of main gearbox failures or rejections. The man hours expended to investigate magnetic chip faults, in association with the sorties lost as a result, show that this was an area where efficiencies could have been made through trend analysis. A sample of the DASORs showed that action to identify magnetic chips as a potential issue or consider reliability improvements had not been taken. Additionally, the DASORs had not been linked with each other and no recommendations were found. This suggested to the Panel that either ASIMS was not the primary source of trending for the issue, that the issue was not deemed safety related or the issue was not recognised. Further, the DSTL report found that SPMAP PT safety team had procedures for trending, but identified that it had a weakness in identification of connections between potentially related DASORs and also in determining when a number of DASORs formed a meaningful pattern. The DSTL report determined that identifying an underlying issue within a collection of random events in the data was left to engineering qualitative judgement.

Exhibit 155

Exhibit 196

Exhibit 155

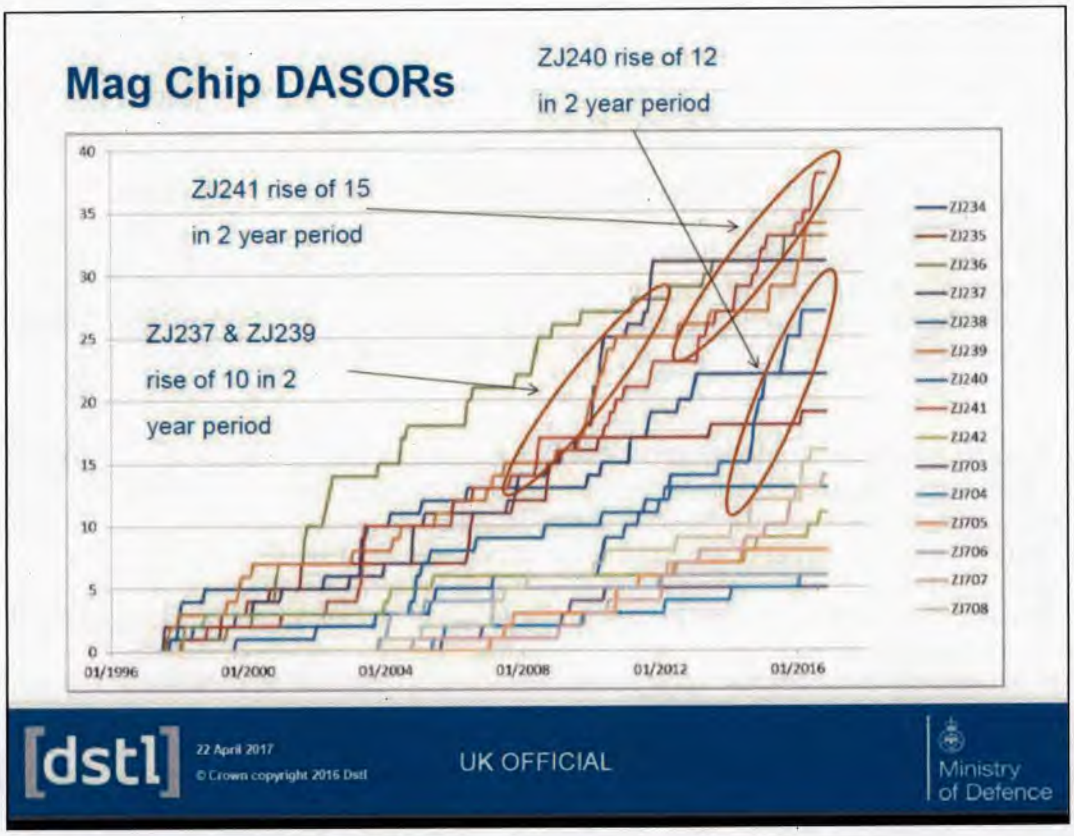


Figure 51 - DASORs containing magnetic chip faults.
(Picture Source: DSTL)

1.4.245. The Panel concluded that trend analysis at DHFS and SPMAP PT was qualitative with the exception of the information provided by Cobham, who used quantitative data from a component replacement perspective. It relied solely upon the maintenance organisation and could have resulted in missed opportunities to identify safety issues or improvements.

1.4.246. **CAA trend analysis**. The criteria for initiating MORs resulted in 93 MORs being generated since the start of the Cobham contract in 1997. This was a small proportion of the total number of DASORs (2629 records) submitted and exemplified the difference in reporting criteria. Consequently there was insufficient data to undertake meaningful trend analysis by the civilian regulator. Although the maintenance organisation correctly raised MORs, there were instances of MORs or OEM product support requests that had not been cross referenced with a DASOR and further demonstrated the complexity of operating two streams of reporting. The use of ASIMS to formally track and trend air safety information required that, once initiated, DASORs were the prime source of all related reports and corrective action. Recommendations and lessons identified that were derived from an investigation could be deficient without the correct information all being in one place. The Panel concluded that the relatively low number of MORs would be unlikely to trigger the discovery of a trend through the CAAs internal system and that this should not be relied upon for the purpose of wider trend analysis. The CAA indicated, during discussion, an aspiration to encourage voluntary occurrence reports in addition to those that met the criteria of an MOR. The purpose of voluntary reports would be to improve their ability to identify wider trends at a National or European level and thus prevent potential future accidents. The proposal for the collection of voluntary reports would be applied in the spirit of EASA regulation 996/2010. In the Panels opinion the lack of DASOR data being sent to, and observed by, the CAA and OEM did not represent effective data exploitation or reflect a coherent 'data feedback loop'.

Exhibit 162
Exhibit 148
Exhibit 139
Exhibit 146

1.4.247. **Bell trend analysis**. EASA and FAA specify that a reporting mechanism should be created by the Type Certificate Holder (TCH), in this case Bell, and occurrences should be communicated using this mechanism. In addition, FAR 21 requires the TCH to act upon failures detailed in a NTSB aviation safety report authored by the aircraft operator. The requirement for reporting to the NTSB was not dictated in any ASMP. The FAA and EASA regulations did not align and it was not clear how Bell would be informed of safety occurrences. Both Cobham and Bell's safety departments described to the panel that the primary method of safety related data collection was through product support. The product support methodology is naturally biased towards collecting information on equipment failures which form the majority of safety related data that was acted upon by Bell. Additional information was sometimes collected from the operators when it was volunteered or following direct interaction during a safety investigation. Generally, the information compiled was incomplete or missing. The Panel found it difficult to obtain safety related occurrence information from Bell in order to conduct worldwide trending from an operator perspective. It was only as a result of informal links with other international organisations and collaboration with the Bell flight safety investigation team that any information was forthcoming. One example of this was the lack of available data on vibration phenomena. A Bell statement indicated that they were not aware of vibration issues that had been experienced by the Griffin fleet, despite 40 DASORS on the subject, some of which Bell had responded to via product support. These occurrences were known to occur amongst other Bell 412 users, yet not considered by Bell as a safety issue due to the lack of direct reporting or access to the data. In the example of vibration, Bell had not collated any information as it was neither requested by, nor reported to Bell. There was no formal mechanism for Bell to be aware of occurrences that did not result in a broken part, yet could still be hazardous to the operator. A reporting mechanism was

Exhibit 150
Exhibit 163
Exhibit 162
Exhibit 30

required by Federal regulations FAR Part 21.137, as part of in-service feedback. This would allow Bell to determine if any changes to the instructions for Continued Airworthiness were necessary. Considering that 'no fault found' reports were the second highest outcome on Griffin DASORs, Bell were unaware of almost all those reported occurrences, even though both the TAA and the Part M organisation consider reliability study as the responsibility of Bell, as the TCH. Pratt & Whitney as a separate OEM only received occurrence related information that pertained to fault conditions with the engines. Neither of the OEMs shared data with each other and this additional lack of collaboration could have had further implications in the event that airframe or engine faults may be linked to each other. The Panel concluded that Bell did not communicate effectively to users how to ensure that safety related occurrence reports should be transferred to the Type Certificate Holder such that they would be formally recorded. The Product Support Enquiry system was the primary conduit for this information but did not appear to effectively communicate all flight safety related data with Bell safety department. Efforts to maintain a local database provided some useful information but the Panel **observed** that a more cohesive data management and trending system would enable the most effective data exploitation by all Bell users. Exhibit 164 Exhibit 196

1.4.248. **TAA reliance on trend analysis.** The Project Team indicated that many of their safety assessments against full compliance with military regulation were on the premise that Bell as the Type Certificate Holder (TCH) conducted reliability trending and structural / systems integrity verification work. The Bell 412 user community spans many nations, with a large number of different reporting strategies. The operator of most interest to the Panel was the National Defence Government of Canada, due to their similarity in usage to the UK military and the maturity of their reporting process. The Panel found no evidence that Bell had ready access to these Nation's safety reports and thus had a reduced ability to act on potential technical issues and operator errors. The only organisation capable of conducting a truly global trend analysis of operational safety data was Bell, but the Panel judged that it had neither adequate information available nor the ability to deal with it. The Panel concluded that comprehensive worldwide data trending by the Original Equipment Manufacturer (OEM) was an essential part of the MOD air safety argument, as stated in the Airworthiness Strategy for the Griffin. Therefore, reliance on the OEM was not an effective strategy because the Panel judged that Bell's trend analysis was not as good as required by the TAA's responsibilities detailed in Regulatory Article RA 1015. Exhibit 165 Exhibit 143 Witness 22 Exhibit 143 Exhibit 144

1.4.249. **Military data sharing.** The facility to distribute relevant DASORs exists within ASIMS and could be used to distribute voluntary reports to info addressees. The Panel noted that although ASIMS should only contain unclassified data, filtering operationally sensitive DASORs would be prudent and that reporting every occurrence was not relevant given the total number of DASORs produced, but that targeted distribution within specified criteria would be beneficial. This could be completed by ASMs on a routine basis. It was the Panel's opinion that for the MOD to fully embrace a culture of open communication it should commit to voluntarily release occurrence reports to EASA and OEMs, where the data could be used by another agency and wider trending of aviation occurrences would improve air safety within the MOD or those other agencies. Exhibit 149 Exhibit 145

1.4.250. **Recommendation**. Director Military Aviation Authority should provide guidance on the routine voluntary release of occurrence reports, in addition to Mandatory Occurrence Reports, to civilian regulators and Original Equipment Manufacturers, in order to facilitate wider trending of occurrences on civilian aircraft.

1.4.251. **Summary of Air safety management**. The Panel concluded that air safety management of MRCO platforms was complex due to the number of interconnecting agencies. Air safety information flows (Figure 50) were further complicated by the number of reporting systems, the lack of access to ASIMS computer terminals and lack of ASIMS occurrence managers within the maintenance organisation. Trend analysis by all organisations had significant scope for improvement but the Panel opined that the most important of potential improvements was an ability to routinely normalise occurrence events against flying hours. More widely, a reliance on external agencies to provide trend analysis and safety assurance was not an effective strategy unless policy or contracts formalised this communication. The confluence of all air safety and airworthiness risks were managed at the DDH review group meeting and recommendations for improvements sentenced. Despite much activity to improve flight safety, DHFS had the lowest proportion of DASORs that contained recommendations and were sometimes closed where a recommendation should have been made. Although there were a number of observations and other factors resulting from air safety management, none directly contributed to the accident and therefore air safety management was **not a factor** in the accident.

Risk management and safety oversight

1.4.252. **Risk management**. Cobham's safety policy described both Cobham and MOD reporting systems. The existence of two processes reduced the visibility of engineering safety issues to the Duty Holder chain and allowed Cobham to manage engineering occurrences internally without formal ownership by the DDH. Oversight of Cobham processes were not included in the DHFS safety policy documents and although the MilCAM and ASM attended meetings where Cobham investigations were discussed, the resolution and implementation of the outcome were still owned by Cobham. Both DDH and MilCAM stated that their only method of implementing recommendations within the maintenance organisation was via informal negotiations or through a cessation of flying. The available options were at the extreme ends of the spectrum and relied on good will, or were not practical. For the MilCAM or DDH to formally implement changes to engineering manpower, training or financial resources, any unresolved issues were required to be elevated to the ODH. During a CAMO audit in 2017, the MAA also highlighted a lack of detailed formal access to the DDH in the Mil CAME. Additionally, an MAA air safety audit of No 22 Gp in 2016, also commented on the lack of contractual and formalised leverage for air safety in MRCO platforms. The Panel concluded that there was no contractual leverage or formal method of implementing air safety changes on a short term basis. The DDH's ability to oversee and manage risks within the maintenance organisation was thus diluted unless all occurrences were managed using ASIMS and authority to implement change within the maintenance organisation were provided within the DDHs terms of reference. The complexities of risk management in the maintenance organisation, specific to MRCO platforms, would benefit from being addressed in policy.

Exhibit 147
Exhibit 154
Exhibit 161
Witness 1
Witness 21
Exhibit 166
Exhibit 152
Exhibit 153
Exhibit 154

1.4.253. The Panel identified that the TAA had been non-compliant with respect to RA 5720 (Structural Integrity) and RA 5723 (Ageing Aircraft) or the preceding equivalent instructions since 2009. However, the ODH had not recorded any risks regarding the non-compliance of regulations RA 5720 and RA 5723 or the consequences of that non-compliance. The issue was formally raised to the ODH in February 2013 at an Air System Safety Working Group (ASSWG) but the TAA assured the ODH that compliance with civilian regulations meant that the platform was airworthy. Many other platforms had complied with the same Regulatory Articles but the SPMAP PT was under resourced and this was cited as one of the main reasons that they did not apply for an Alternative Acceptable Means of Compliance (AAMC). Nevertheless, the risk resulting from non-compliance was not highlighted to the ODH and therefore the standard safety statement was recorded in the minutes by the ODH and the TAA that, all equipment risks, all current and foreseeable risks to life and the aggregated risk to all parties, were tolerable and As

Exhibit 116
Exhibit 126
Annex F
Exhibit 209
Exhibit 202
Exhibit 168
Exhibit 145
Exhibit 169
Witness22
Exhibit 167
Exhibit 145

Low As Reasonably Practicable (ALARP). The TAA identified non-compliance of regulations as a platform integrity risk. In such circumstances that the risk was not articulated properly, the risk could not be tolerated because it was not recognised. The Panel concluded that non-compliance with regulations did not by itself constitute a separate risk to life because compliance with civilian regulations provided a minimum level of safety assurance. However, military regulations provided an additional level of safety that was deemed appropriate for the MOD and which was based on good engineering practice. It was the Panel's opinion that there was a risk to life associated with non-compliance with structural integrity regulation. An opportunity was missed to manage the risk associated with fatigue damage accrual by accurately monitoring the aircraft usage and taking action to mitigate previous aircraft usage. Exhibit 127 Exhibit 169 Witness 24

1.4.254. The risks associated with a delay in the SOIU review was assessed by the TAA in May 2016, two and a half months before the accident. A panel of suitably qualified and experienced people chaired by the TAA discussed the possible consequences of failure of a Structurally Significant Item. The possible causes of failure were assessed as: The aircraft consistently flown in a concentrated area of the flight spectrum but within the Release to Service (RTS), the aircraft exceeded the operating parameters during its operating life and the aircraft flown outside the RTS. All of these potential causes occurred in the accident to a greater or lesser extent with the number of sloping ground landings, the manoeuvre limits, the hoist centre of gravity issue and the combined slope angles. The conclusion of this assessment was that there was *"no reasonably foreseeable accident sequence resulting from these causes"*. Even without the benefit of hindsight from this accident, the report negated to include the fatigue crack incident from 2006 in the analysis and that historic fatigue damage could not be ignored. An expert in structural integrity was not present at the meeting as either an Independent Structural Airworthiness Advisor or Independent Technical Evaluator to articulate the risks associated with fatigue in the Griffin, as was required by the Regulatory Articles. During a review of sample data for the Service Inquiry a helicopter structural integrity expert advised that there appeared to be routine usage of aircraft at high 'all up mass' at RAF Valley. Also, that although usage remained within the RTS and RFM limits, operating in a concentrated area of the spectrum, particularly with high 'all up mass', could have an effect on structural integrity. Since the Manual Data Recording Exercise (MDRE) in 2005, a number of modifications had been added to the aircraft; due to the lack of usage validation through the SOIU, their quantitative effect on usage was unknown. The Panel concluded that the assessment of risk was made without access to all of the relevant data. The ODH would therefore benefit from a re-assessment of airworthiness risk, taking into account the circumstances of the accident, the missing SOIU data and all the current and historic fatiguing conditions. The assessment should be carried out based on the failure of related structurally significant items but specifically the gearbox support case. Exhibit 170 Witness 24 Exhibit 116 Witness 24 Exhibit 95 Exhibit 135

1.4.255. **Safety oversight**. The introduction of MAA regulations in 2011 prompted a review of compliance by SPMAP PT and key activities were prioritised. The MAA first conducted an audit of SPMAP in 2012, where they identified 11 major Corrective Action Reports (CARs) and 1 minor CAR; Corrective Action Plans (CAPs) were subsequently received in relation to these 12 CARs. Although none of the audits made specific reference to non-compliance with the MRP for Griffin, one of the major CARs was that SPMAP had not sought MAA endorsement for any of its AAMC approaches to managing MRCO aircraft; e.g. structural integrity and risk management. Following the 2012 audit, SPMAP were put on an enhanced audit cycle with further audits being conducted in 2013, 2014, and 2016. It was agreed between D-Hels and the MAA that the establishment and publication of Airworthiness Strategies would be the optimum way of articulating what was done at that time within the existing resource. D-Hels directed a dedicated 1-Star to drive Annex J the development of Airworthiness Strategies (using Bell 212 aircraft as the pilot) that would capture what was being done and permit clearer stakeholder understanding. It was also agreed to review the MRP in segments and focus on the intent of the MRP (safety objectives/outcomes) and not necessarily on the explicit wording. Review of the 5000 Series was initially held in abeyance, and key activities were addressed in sequence; Airworthiness Strategies, Integrity Management Plans, Configuration Management Plans and Integrity Working Groups. It was understood by SPMAP PT and the Helicopter Operating Centre (Hels OC) that the maintenance and management of the aircraft should always be at least as good as that expected of a civil operator, thus meeting the Secretary of State's overarching responsibility under the Health and Safety at Work Act. However, a gap analysis by De Havilland Ltd in 2008, a study in 2013 and independent advice from a helicopter structural expert during the inquiry all indicated that although civilian regulations did cover much of that required by the military, some of the structural integrity military regulations plugged holes in the civil regulations in a MRCO context. There were a number of other reasons why full compliance with the MRP did not take place and progress towards compliance was slow: Contractual difficulties; resource levels within the PT to support MRCO platforms to deliver an MRP-compliant solution (leading to a heavy reliance on industry and contracted support); Industry Type Certificate Holders (TCH) were not willing to provide access to Intellectual Property Rights to facilitate 3rd party review/scrutiny/decision making; and a desire to use civilian equivalence in place of military compliance. The Panel judged that additional resources should have been allocated to achieve compliance and the risk associated with non-compliance should have been identified, articulated and accepted at the appropriate level. The MAA did not include the compliance with RA 5720 or Griffin specific processes during the audit of SPMAP in 2016 as compliance with structural integrity regulations was perceived to be an on-going issue, being discussed at a higher level between DE&S Director Helicopters (D-Hels) and MAA Director Technical (D-Tech). Although there was an enhanced audit regime for the broader SPMAP, there were missed opportunities to ensure compliance, for Griffin, as part of a formal CAR. Additionally, the lack of a CAR was accepted as assurance by D-Hels during a working group that the Project Team was compliant with MAA regulation. The Panel concluded that compliance with civilian regulation would provide a generally safe air system and was a reasonable approach when considering the resource constraints on the project team. Nevertheless, the TAA had a responsibility to comply with the regulation or apply for AAMC or waiver against regulatory non-compliance in the 5 years that followed the introduction of the MRP. Ultimately, the perceived long term discussions between D-Hels and D-Tech led to an organisational paralysis that prevented the resolution of the issue in the form of a CAR, AAMC or waiver.

Exhibit 169
Exhibit 234
Exhibit 235
Witness 24
Exhibit 236
Exhibit 169
Exhibit 236
Exhibit 171
Exhibit 236
Exhibit 169
Exhibit 116

1.4.256. **Summary of risk management and safety oversight**. Although civilian regulations provided a minimum level of safety assurance required by the Secretary of State for Defence under the Health and Safety at Work Act, the military regulations provided an additional level of safety that was deemed appropriate for MOD aircraft and which was based on good engineering practice. Therefore, non-compliance with structural integrity regulation should have been highlighted by a CAR, and resources provided to the TAA to achieve compliance. Alternatively, the TAA should have applied for an AAMC or waiver and the associated risk identified and accepted at the appropriate level. Part of the reason for the risks not being recognised was that the assessment of risk was made without access to all of the relevant data. The Panel concluded that the risks associated with non-compliance with the structural integrity regulations were not properly identified by the TAA and not effectively communicated to the ODH. Equally, the ODH missed an opportunity to manage the risks associated with non-compliance by not recognising it as an issue and requesting further information. Compliance with civilian regulation alone was widely used to justify non-compliance with military regulation and became a cultural norm that was also tacitly accepted by the regulator for Griffin aircraft. The lack of effective risk management associated with the consequences of non-compliance with the MRP, and robust safety oversight was a **contributory factor**.

1.4.257. **Recommendation**. Director Military Aviation Authority should re-assert a robust enforcement of compliance with 5000 series Regulatory Articles for Military Registered Civil Owned aircraft and ensure that all non-compliance is tracked to enable more effective Duty Holder mitigation of the consequences of non-compliance.

Military Registered Civilian Owned (MRCO) construct

1.4.258. The Panel considered the Military Registered Civilian Owned (MRCO) interfaces following the review of a number of key documents that appeared to point to this as an area of difficulty in the MRCO construct. The Panel sought to establish if the civil/ military interface was a factor in the accident.

1.4.259. During a review of the air safety related documents for each organisation, it was apparent that each MRCO stakeholder was compliant within their respective area of interest; however the complexities of the MRCO construct required implementation of an integrated approach by each air safety responsible organisation to achieve overall air safety for the platform. The Panel reviewed ASMPs from other flying organisations and found that by comparison the DHFS ASMP was brief, lacked depth and did not fully describe the relationships with interfacing organisations even when viewed in the context of the document hierarchy. The complex nature of the MRCO construct was not evaluated in the DHFS Air Safety Management Plan (ASMP). Regulations state that a key enabler to the effective delivery of operational capability is safety management which *"ensures a systematic, pro-active and auditable approach to the management of air safety risks to achieve an acceptable level of safety. Central to safety management is the intellectual activity and decision making which is enabled by the necessary organizational structures, accountabilities, policies and procedures."* An MAA audit found that No 22 Gp ASMPs did not define a unified, coherent process for the sharing of safety information between contractors and the military. Further, whilst information exchange was taking place, the process by which it was occurring was not defined in the majority of contracts. The Panel **observed** that the lack of detail in the ASMP was evidence of a vague civil-military interface and that the lack of definition and formal commitment to integration could lead to a shift in attitudes over time, dependent on individual personalities within the leadership.

Exhibit 154
Exhibit 147
Exhibit 172
Exhibit 151
Exhibit 131
Exhibit 143
Exhibit 156
Exhibit 157
Exhibit 158
Exhibit 154

Exhibit153
Exhibit152
Exhibit 173

1.4.260. **Recommendation**. The Operating Duty Holder should revise relevant air safety policy documents and subordinate Air Safety Management Plans in order to formalise all civil-military interfaces, interactions and responsibilities within their area of Responsibility.

1.4.261. The premise of MRCO aircraft is that contracted organisations provide a civilian aircraft in order to reduce the capital costs in roles where a bespoke military platform was not required. There was a widely accepted belief that platform safety was assured solely by compliance with civilian regulations. However, for this to be correct the aircraft would need to be operated entirely as a civilian aircraft, as intended by the Design Organisation. As this report has identified there will always be differences between military and civilian flying whilst operated on the military register. Therefore, it was not possible to completely assure safety by compliance with the civilian regulations. The purpose of structural integrity management and specifically the SOIU should have been to capture these differences throughout the life of the aircraft and instigate additional activity where required. The process of validating design usage was not required by civilian regulation and was not included in contractual arrangements. Therefore, the TCH was not willing to provide access to intellectual property to facilitate third party review / scrutiny / decision making. There were no established resources to support MRCO platforms to deliver an MRP-compliant solution and each validation exercise required costing and approval. Therefore, the risks associated with non-compliance as a result of budgetary constraints should have been articulated and accepted at the appropriate level. A gap analysis of civil

Witness 22

Exhibit 169

Exhibit 116

Exhibit 169

and military regulations that mitigate hazards to the structural airworthiness MRCO aircraft was conducted in 2008 by De Havilland Support Ltd. They concluded the following:

> *"Overall, the MRCO process outlined in JSP 553* [legacy regulations] *seems to form a firm platform for the military use of this type of aircraft. However, there are many nuances in the application of civil regulations that may not be readily apparent to the staff of an IPT. The lack of consolidated legislation, updated to show the current approved amendment state, continues to pose a significant hazard. In terms of continuing airworthiness, there could well be issues of the accuracy of aircraft records and the field embodiment of generic repairs or modifications which might affect both airframe and systems. Care is also needed at the outset of aircraft selection to ensure that the basis of certification of a type is fully understood. The severity of use of military aircraft may often be greater than that of a civil type and care must be taken to ensure that the SOIU properly reflects the actual use of the aircraft. Moreover, OLM may well be needed to check that the design loads are not being exceeded. Military regulations have specific requirements for AAA* [Aging Aircraft Audit] *but in the civil requirements a less rigorous process applies and only (at present) to large aircraft."* Exhibit 234

1.4.262. The conclusions that De Havilland Support Ltd came to, appear to echo much of the issues found by this Service Inquiry. In addition, a study in 2013 highlighted those risks in MRCO arrangements that could be mitigated by the use of robust business processes that constitute the continued airworthiness of each platform. The gap analysis studies did not include a comparison to the FAA regulations. The panel concluded that these independent studies showed that the role of policy for continued airworthiness was crucial in mitigating the risks involved in the MRCO construct. The Panel **observed** that implementation of policy for continued airworthiness through the 5000 series of MAA regulations provided the necessary framework to account for the military delta between the MRP and EASA regulations. Exhibit 235

Accident Overview

1.4.263. The accident diagram (Figure 52) displays the interaction between the different factors and events that occurred during the accident using the ATSB model. It predominantly shows that there were a complex set of occurrence events and a large number of organisational influences and missing risk controls. It also demonstrates that there was no single activity in isolation that could have easily prevented the accident.

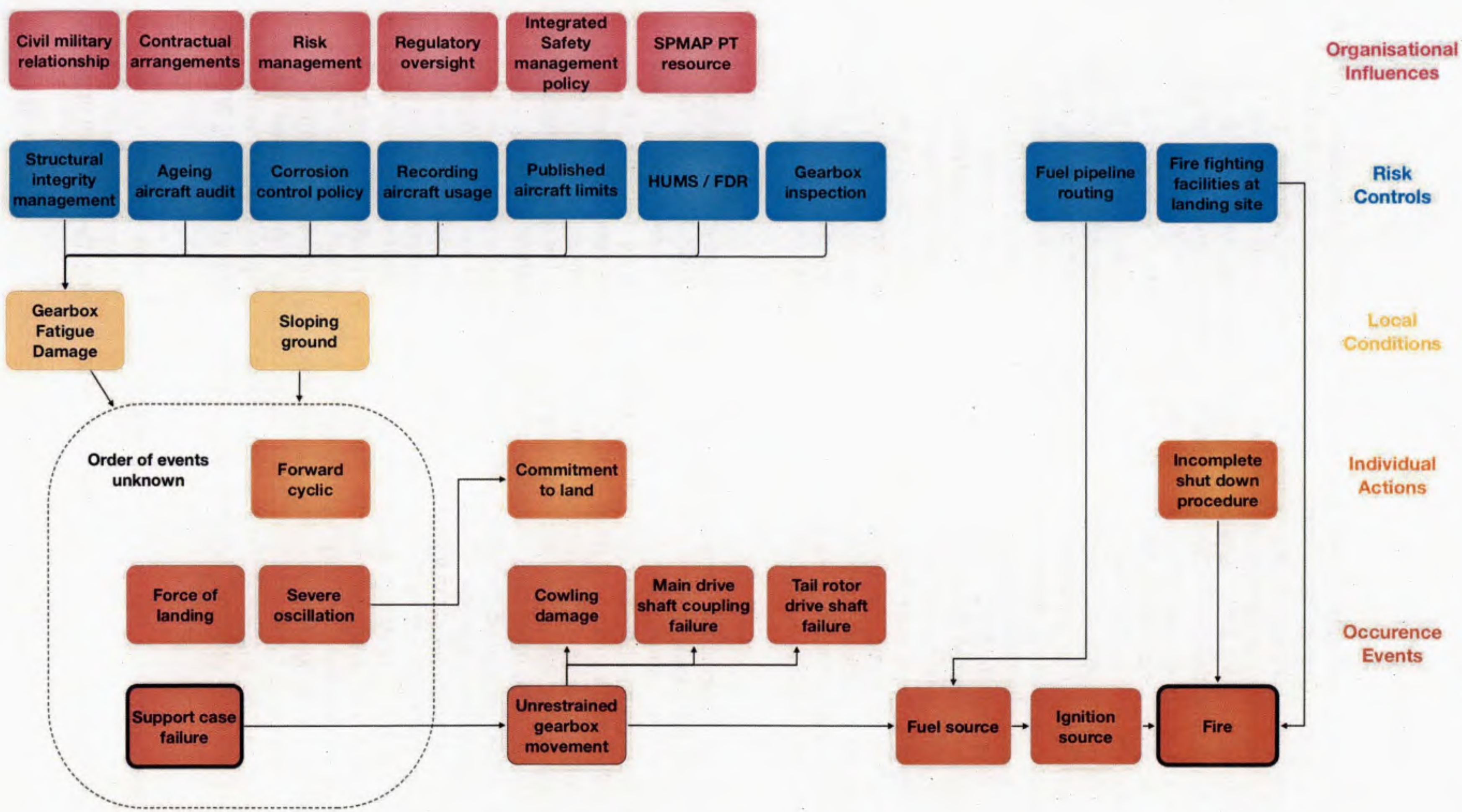


Figure 52 – Accident overview using the ATSB model.

FACTORS NOT DIRECTLY RELATED TO THE ACCIDENT

Crew composition

1.4.264. It was discussed at para (1.4.48) that the regulations did not allow DHFS students to operate the aircraft on non-syllabus sorties. The RAF Shawbury Flying Order Book included supernumerary crew as an acceptable means of complying with this. However, the MAA Master Glossary considers supernumerary crew as, "temporarily attached to an Air System crew for the purpose of carrying out a specific duty **not** *[emphasis added]* involved with flying/operating the Air System." Therefore, supernumerary crew cannot operate an aircraft and there was no option under regulation for DHFS students to operate the aircraft on anything other than syllabus sorties. The RTS stated, *"Limitation: Min flight crew is one pilot who is to occupy the RHS"*. Hence, the Griffin was cleared for flight with a solo pilot in the right hand seat. The statement in the RTS was based on information provided in the Bell flight manual which stated, *"The minimum flight crew consists of one pilot who shall operate helicopter from right crew seat [. . .] the left crew seat may be used for an additional pilot when approved dual controls are installed"*. While this did not preclude the main pilot from flying in the left hand seat, this configuration relied on a right hand seat occupant operating the aircraft too. Therefore, neither of the students should have been part of the crew during the task phase of the sortie and Aircraft Commander A should have operated the aircraft from the right hand seat during the task. It was the Panel's opinion that the primary focus at 202(R) Sqn was the reasonable intent to provide maximum exposure of students to flying and that student placement in the right hand seat was normalised to the extent that it wasn't considered in the planning of the task. The similarity of the task profile to a syllabus mountain flying sortie did not prompt this to be questioned.

Exhibit 174

Exhibit 175

Exhibit 224

Exhibit 122

1.4.265. The aircraft controls are designed for the primary pilot to be in the right hand seat of the aircraft, hence the lack of some switches on the left hand collective lever. On completion of their first 3 sorties, MOLIC students carried out a simulator sortie in which they practiced emergency shut-down procedures, but did not carry out engine fire extinguisher drills in that sortie. As a result MOLIC students were operating the aircraft with limited training in the use of the fire extinguishers. Where training and experience is limited, there is a greater risk of error in performance of the task. Therefore, in an incident where a student has to be relied on to discharge the fire extinguishers, there was an increased risk of carrying out an incorrect procedure which subsequently reduces the chance of successful fire extinction. The left-hand-seat pilot must lean over to operate any of the switches in the right hand crew seat. In a situation where the left-hand-seat must remain hands on, this might not be possible and a challenge / response would be required to operate the switches. This was the method used during the accident and the Panel concluded that it likely delayed completion of the shut down by a matter of seconds. The Panel further concluded that this delay had little impact on the overall outcome of the accident because the timing of the shutdown did not affect any subsequent events. Control switch differences between left and right hand cockpit controls increased the risk of carrying out an incorrect procedure in situations where an inexperienced crewmember is required to operate the switches. Crew composition and seating position was an **other factor**.

Exhibit 29

Exhibit 29

1.4.266. **Recommendation**. The Delivery Duty Holder should revise crew composition policy for Defence Helicopter Flying School aircrew under training, with respect to seating position and participation in non-syllabus tasking, in order to clarify the policy on operating with students.

Knowledge of sloping ground limits

1.4.267. A selection of Griffin aircrew were asked about the sloping ground limits. None of them recalled the limits completely correctly. A feature of the Griffin, and its skidded landing gear, is that on a level surface the fuselage sits approximately 3-4° nose up. The stated limits apply to the slope the aircraft lands on, rather than the indication in the cockpit. Therefore on a 10° nose up slope, the ADI in the cockpit will show 13-14° with collective fully lowered. Clarification was offered in March 2015 by DHFS standards about the difference between 'real' and ADI slope limits, following a previous incident during a sloping ground landing (1.4.133). Discretion was given to individual squadrons whether to brief the information or to add it to the 'hot poop'.[58] 202(R) Sqn opted for the latter on 14 March 15, while 60 Sqn briefed their crews but did not amend any written instruction or written guide. The difference between ADI and actual slope angle was not explicitly mentioned in the Griffin flying guide or the instructor guide to flying. Answers provided by aircrew regarding sloping ground limits were on the safe side of the limit in all cases except in the nose down attitude. Therefore, unless attempting to land on a steep nose down slope (which was rare), aircraft were unlikely to have gone beyond the enhanced sloping ground limits as a result of lack of aircrew knowledge of limits. Better knowledge of the limits would not have changed the selection of the landing site nor would it have changed the decision making process during the accident, as a 'skids light' landing had already been briefed. The Panel concluded that the apparent lack of understanding of the sloping ground limits was mostly due to the use of the ADI as the sole reference with which to apply the limit, and confusion may have originated from the lack of clarity in the DHFS Griffin flying guide. The Panel **observed** that Griffin aircrew should have known the sloping ground limits and would benefit from clarification in the Griffin Flying Guide on how to apply the sloping ground limits using the available cockpit instrumentation.

Witness 2
Witness 3
Witness 5
Witness 8

Exhibit 62
Exhibit 177

Exhibit 176
Exhibit 91

Exhibit 178
Exhibit 56

Witness 4

Flight Data Recorder (FDR) and Health Usage Monitoring System (HUMS)

1.4.268. No Flight Data Recorder (FDR) was fitted to the aircraft and the 'Vision 1000' data was not recoverable as it was not crash-worthy and was destroyed in the fire. The lack of a data recording device prevented the Panel from determining the exact position of all the flying controls but in particular the position of the cyclic. In the Panel's opinion, even limited but accurate data related to the attitude of the aircraft, and the position and timing of application of the flying controls would more likely than not have provided a definitive answer for the cause of the accident or reduced the time taken to investigate. It was also the Panel's opinion that an FDR would have made technical analysis of one of the most likely aircraft fault categorisations, 'no fault found' and specifically vibration incidents, easier to diagnose, thus reducing recurring fault trends.

Exhibit 18

1.4.269. HUMS was not specifically designed to detect structural damage but in the HUMS crack example in 2012 it was more effective than the scheduled visual inspection regime which did not detect the issue. The observed level of vibration was above threshold for the entire time that the fault was present. Therefore, the probability of early detection of

Exhibit 75

[58] 'hot poop' is a method of promulgating the most recent information essential for pilots to read prior to flight.

structural damage to large components using accelerometers was good, providing an appropriate condition indicator was established. The Panel concluded that if HUMS or a similar system could be calibrated to detect a fatigue crack before it was apparent to the crew or engineers during scheduled maintenance that this would be a significant improvement to flight safety where it was deemed that there was a likelihood of a fatigue crack developing in fatigue damaged components. Witness 24

1.4.270. **Summary of Flight Data Recorder and Health Usage Monitoring System**. The lack of a crash tolerant FDR and HUMS reduced the ability of the maintenance organisation to more effectively detect and diagnose faults. Also, these systems act as barriers to mitigate the risk to life associated with damaged components that may lead to structural failure of an SSI. The lack of a crash worthy FDR and HUMS could result in other similar events not being identified and investigated and was deemed an **other factor**.

1.4.271. **Recommendation**. The Director Military Aviation Authority should review regulatory guidance for retrospectively fitting Flight Data Recorders and Health Usage Monitoring Systems on legacy aircraft in order to improve the maintainability and safety of aircraft components.

Airframe configuration control

1.4.272. Configuration control is the recording of repairs, any airframe modification work and the control of serial numbers and modification states of the aircraft components. Whenever the airframe is modified or repaired its details are updated in the modification and repair record book (CAP395). The modification and repair record book of ZJ241, detailed seven airframe repairs over the life of the aircraft. Additionally, a damage register highlighted a number of repair requests sent to Bell Product Support. These repairs, where applicable, were carried out and recorded as a Non Routine Inspections (NRI), yet no formal record was made against the airframe in the modification and repair record book. The Regulatory Articles state that, *"Structural Configuration Control information is to be recorded in sufficient detail to allow retrieval and analysis so as to inform structural integrity decisions"*. Cobham use a Repair Request Spread-sheet to record all repair requests that are generated. This spread-sheet did not document airframe repairs and did not form part of the official Aircraft Document Set. The spread-sheet records were only kept from 2012 and historic records were time consuming to access. In the opinion of the Panel, airframe repair record keeping was not detailed and accurate enough to assess individual airframe structural integrity by tail number and that airframe repairs, not specified as a standard repair, in accordance with Bell technical documentation, should still be recorded against the airframe in the modification and repair record book. Inaccurate airframe repair record keeping could lead to loss of configuration control and other accidents and was therefore deemed an **other factor**. Exhibit 179 Exhibit 71 Exhibit 179 Exhibit 116 Exhibit 72

Automatic Flight Control System (AFCS) fault code management

1.4.273. The Panel sought to understand if an AFCS fault code (E56) that was reported to the engineers on the morning of the accident could have caused the sever oscillations experienced by ZJ241; this fault code (E56) was identified as a storage limit error and cleared prior to flight. There was no evidence to explain what led to the AFCS fault code memory being full; additionally, the Panel identified that it required over one hundred entries to be full. There were no entries in the aircraft tech log pertaining to AFCS fault code 'unserviceability' and a DASOR had not been raised. The Panel noted that there Witness 7 Exhibit 2 were no instructions for aircrew in either the FRCs or the Aircrew Manual on what to do in the event of an error code. The aircrew manual detailed a list of over 100 possible error codes, with no associated 'actions on'. The Flight Reference Cards (FRCs) detailed a procedure for dealing with auto trim failure and indicate that an error code would be present but not how to diagnose it. The aircraft had not exhibited any abnormal flying characteristics prior to the accident according to the crew, nor did it have a history of such behaviour. The maintenance manual details that the system has a method of *"verifying pilot reported error codes on a flight by flight basis or verifying system integrity on a regular basis. This regular basis may be in conjunction with normal periodic helicopter inspections. Since a particular error code may be stored repeatedly, trends may be spotted in system and/or component performance. These trends may prove helpful in diagnosing chronic problems."* The aircraft maintenance program does not contain a regular check for error codes and there was no reference to this check for the benefit of system integrity in either the airworthiness strategy or Topic 2(R) series. The panel concluded that the presence of error code E56 could have indicated a fault in the control system but that this AFCS fault alone could not have contributed to the severe oscillation of the aircraft. The ability to understand trends or chronic problems in AFCS could be diminished by the lack of engineering and aircrew instructions for reporting and checking fault codes. The lack of AFCS fault code management was deemed an **other factor**.

Exhibit 62
Exhibit 180
Exhibit 2
Exhibit 181
Exhibit 104
Exhibit 143
Exhibit 182

1.4.274. **Recommendation**. The Type Airworthiness Authority should implement policy and procedures for recording and acting upon Automatic Flight Control System error codes in order to validate system integrity as detailed by the Bell maintenance manual.

POST OCCURRENCE MANAGEMENT

1.4.275. **Survival and injury.** All 5 crew and Passenger survived with no injuries. The two front-seat crew suffered minor smoke inhalation but were assessed medically fit at RAF Valley Medical Centre later on the day of the accident. Exhibit 183 Exhibit 184

1.4.276. **Post Crash Management (PCM)**. RAF Valley PCM began with 202(R) Sqn's receipt of Aircraft Commander B's phone call which was passed immediately to the Duty Executive and Air Traffic Control (ATC). It was not possible to determine exactly what message was passed but 202(R) Sqn Operations believed that the aircraft had landed and all crewmembers evacuated after a fire broke out. The magnitude of the fire was not immediately conveyed and both 202(R) Sqn Operations and RAF Valley ATC initially treated the situation as a 'downbird' rather than a 'crash' which started a different, more limited response. The RAF Valley Crash Support and Major Incident Plan (CSMIP) stated that in the event of a *'crash'* an *"Emergency State 3 will be tannoyed [sic] if the crash occurs more than 5nm from RAF Valley"*. There was no record of the *'tannoy'*[59] taking place. Some areas on station remained unaware of the situation and reacted with less urgency to requests for assistance The severity of the accident was confirmed by the North Wales Air Ambulance Helimed aircraft and communicated to ATC so the Senior Air Traffic Control Officer (SATCO) quickly upgraded the *'Downbird'* to a *'Crash'*. The natural description of the accident was that an, *"aircraft landed"* which did not match the categorisation and response that was required from the emergency services. The Panel concluded that lack of clarity about the incident/accident categorisation led to a delay in certain PCM activities being initiated. However, the minor delay had no material effect on the outcome of the response in this event but could make a difference in other circumstances and was therefore an **other factor**. Exhibit 185 Exhibit 185 Exhibit 52 Exhibit 186 Witness 15

1.4.277. It was unclear when the information that the accident had been upgraded to a 'crash' reached 202(R) Operations due to the high volume of telephone calls that blocked the line. In any case the Duty Executive independently made the decision to treat the incident as a 'crash'. Senior officers were notified directly by the crew and Passenger and so news of the accident was promulgated extremely quickly. 202(R) Sqn and RAF Valley Station Operations fielded multiple requests for information from a number of different military and civilian organisations including higher headquarters and organisations outside the chain of command. From the amount of phone calls received, the Panel judged there to be an additional sensitivity and attention from external agencies due to the civilian registration of the aircraft. This contributed to the high number of telephone calls to the Squadron Operations room at an already busy time and slowed outgoing information. Witness 15 Witness 9 Witness 9 Witness 15

1.4.278. 202(R) Sqn Operations began collating information and running through the 'Downbird' plan before 'upgrading' to the CSMIP. There was a misunderstanding following a missed radio call which created uncertainty about the number of people on the hill at the accident site. The STARS database was used by 202(R) Sqn Operations which meant the Squadron no longer booked out with ATC, this would have included the planned aircraft Persons On Board (POB) figure. However, ATC did not have sight of STARS and were reliant on the aircraft radio calls for this information. The POB number was an important piece of information for PCM activity and would have been a more important factor if there Witness 9 Witness 9

[59] 'Tannoy' is a trade mark of a sound amplifying apparatus used as a public address system.

had been casualties. The Panel **observed** that a more robust method of communicating the POB figure would have prevented confusion of casualty numbers. Impounding 'live' documents such as the authorisation sheets, aircraft documents and other evidence was standard practice but the custodian of those documents was not specified, which led to a brief dispute between operations and engineering staff about the most appropriate storage location. The Panel **observed** that a clear procedure for the quarantine of all air safety documents, evidence or electronic devices was required to prevent the uncertainty that transpired during the event. The use of other Griffin aircraft to support the movement of people to and from the accident site was initially discounted due to the uncertainty surrounding the cause of the accident. Use of the unit's other type, the AW139, was also rejected until fuel contamination was discounted. 202(R) Sqn personnel had recently completed 2 practice crash exercises involving simulated aircraft crashes on the airfield which positively impacted 202(R) Sqn's ability to respond in an effective and co-ordinated manner.

Witness 9
Witness 6
Exhibit 218

1.4.279. RAF Valley was in the midst of a major runway repair which necessitated all fixed wing aircraft and corresponding personnel to be detached to RAF St Athan in South Wales. The combination of relocated personnel and summer leave meant that RAF Valley ATC and Operations were at minimum manning. Both the RAF Valley Station Commander and the Officer Commanding Operations (OC Ops) were away. The Senior Air Traffic Control Officer (SATCO) was also performing the job of OC Ops and subsequently became the Emergency Coordination Cell (ECC) Commander when this was convened at 1430. The lack of personnel meant that there were insufficient personnel to create a separate ECC and resulted in much 'double-hatting' of personnel filling two roles simultaneously. Additionally there were no personnel nominated for contingency roles and responsibilities such as the Post Crash Management Incident Officer (PCMIO) and PCMIO's assistant. In accordance with the CSMIP, once the pseudo ECC was set up in Station Operations it assumed command of the incident and began working through the plan, however there was great difficulty in the ECC contacting 202(R) Ops due to almost continuous phone engagement at 202(R) Sqn. It was also realised that due to 202(R) Sqn being a DHFS lodger unit at RAF Valley, two independent crash plans were being followed.

Witness 15
Exhibit 22
Witness 15
Witness 15

1.4.280. At approximately 1600 hrs a convening of available station executives including the 202(R) Sqn Duty Executive allowed a face to face exchange of information, following which the PCMIO was deployed to site. Due to the exposed location it was decided that only trained RAF Mountain Rescue personnel were suitable to guard the site and their capabilities in cordoning, controlling and communication via Airwave radio in the mountainous environment proved invaluable. The removal of the wreckage and returning of the landscape to its previous condition involved a number of agencies including: The Mobile Air Operations Team (MAOT); Joint Aircraft Recovery and Transportation Squadron (JARTS; RAF Regional Liaison Officer (RAFRLO) and the Defence Accident Investigation Branch (DAIB). Poor weather delayed the removal of the wreckage from the hillside by Chinook under-slung load until Monday 15 August 16.

Exhibit 22
Exhibit 173
Exhibit 27
Exhibit 27
Exhibit 22

1.4.281. **Summary of Post Occurrence Management**. Although understandable given the accident occurred during a landing evolution, the ambiguity of the accident classification between 'down-bird' and 'crash' caused confusion during the initial stages of PCM. The Panel noted the importance of clear and accurate reporting in minimising ambiguity. 202(R) Sqn dealt with the initial situation that presented itself particularly well which was almost certainly due to the recent contingency planning exercises emphasising the benefit of conducting this type of practice activity. It was also likely that 202(R) Sqn's communication influx may have led to a decreased level of situational awareness and ability to take over control of the situation by Station Operations. The crash plan procedures of both 202(R) Sqn and RAF Valley Station Operations were followed and adequate. However, the Panel **observed** that where a detached Sqn is hosted by a larger organisation both parties would benefit from a combined review of the crash plan to ensure cohesion, particularly in regard to lines of communication. The Panel also **observed** the importance of contingency awareness when operating on minimum manning, highlighted by the Station's inability to operate a separate ECC. Finally the Panel **observed** that the capabilities of the RAF Mountain Rescue Service in the remote location were instrumental in enabling successful Post Occurrence Management.

COST OF LOSS TO THE SERVICE

1.4.282. The Panel considered financial implications of the accident to the MOD. Using the MRCO construct to provide aircraft to the MOD, Cobham was contracted by No 22 Gp to provide aircraft availability for flying training to DHFS. Cobham were able to utilise their subsidiary companies, FB Leasing services and FB Heliservices (FBH) Limited, for aircraft provision and manpower and equipment facility to fulfil the contract.

1.4.283. **Aircraft cost.** A statement received from Cobham details that *"ZJ-241 was insured under FBH's aviation hull insurance and FBH were liable for (and paid) all insurance premiums associated with the aircraft. The UK MOD had no financial interest in the aircraft and therefore did not receive any proceeds (or share any losses) associated with this aircraft and its subsequent loss."* Therefore, the MOD did not incur any cost for the loss of the aircraft due to the accident. Exhibit 187

1.4.284. **DHFS training shortfall.** The Panel also considered the cost to DHFS training and any related contractual constraints with Cobham. The Griffin fleet had been grounded as a precautionary measure for 6 weeks due to the accident in order to carry out safety checks. DHFS flying training had been postponed during this period. A further statement from Cobham specifies that, *"FBH's Contract with the UK MOD is to provide a level of flying hours on Bell 412 helicopters (with a financial mechanism to repay the MOD for any under fly). Following the loss of ZJ-241, FBH has worked closely with the UK MOD to determine how best to fulfil the contractual requirements, given the relatively short time left on the Contract (certainly not enough time to procure, modify and certify a replacement aircraft))."* Cobham implemented a number of measures to ensure efficiencies were made, allowing them to recover the training loss by 2018. No additional financial cost was sustained by the MOD, yet the cost to Cobham was detailed as approximately £[redacted] for the provision of training equipment. Exhibit 187

SUMMARY OF FINDINGS

1.4.285. **Causal factors**.

a. The Panel could not determine with certainty whether the gearbox support case failed in overload or fatigue, but it was almost certain that structural failure of the support case in 2 or more locations led to unrestrained motion of the gearbox and was a **causal factor**. 1.4.190

b. The presence of an uncontrollable aircraft fire, following mechanical failure, led to the destruction of the aircraft and was a **causal factor**. 1.4.191

1.4.286. **Contributory factors**. The following factors were contributory to the accident:

a. The force of landing during the accident was harder than normal and increased the stress in the support case. This in conjunction with other factors made failure of the support case more likely and was therefore considered to be a **contributory factor**. 1.4.116

b. Application of forward cyclic did apply higher than normal stresses to the support case, due to the out of limit sloping ground, and the subsequent excessive forward cyclic movement. The level of this stress could not be determined but in combination with other factors would have made failure of a support case more likely. Therefore, application of forward cyclic during the accident was a **contributory factor**. 1.4.122

c. Any additional angle over 10° imparts increasing stresses to the aircraft that would have contributed to any subsequent mechanical failure. Additional stresses, applied to the support case, as a result of sloping ground greater than 10° was a **contributory factor**. 1.4.123

d. Flight outside the design limits occurred as a result of the information provided in the RFM and caused additional unknown fatigue damage to the support case and made a fatigue crack more likely and was therefore a **contributory factor**. 1.4.145

e. During the entire life of the aircraft, there was a higher rate of sloping ground landings than assumed by the designer in the design usage spectrum that led to unknown fatigue damage in the support case and was a **contributory factor**. 1.4.149

f. Combined slope landings beyond the 10° limit were likely to have occurred during the life of ZJ241 and contributed to additional fatigue damage in the support case due to the higher stresses imparted at these slope angles. Although the number of excursions could not be determined, their cumulative effect was still present. Fatigue damage on ZJ241's support case resulting from the effect of historic combined slope landings was a **contributory factor**. 1.4.152

g. Aircraft at RAF Valley were subjected to unrecorded fatigue significant events as a result of hoist operations. Although the effects of these operations were quantified for certain components, they would have increased the bending 1.4.154

moment in the mast and so imparted an additional un-quantified and unrecorded fatigue load on the support case. Consequently, it was the Panel's judgement that hoist operations within the penalty region were likely to have accrued additional un-quantified fatigue consumption in the support case and was therefore a **contributory factor**.

h. Unquantified fatigue damage in the support case made initiation of a fatigue crack in the support case more likely and was a **contributory factor**. 1.4.174

i. The location of the fuel pipelines, directly behind the gearbox sump, represented a single point of failure in the event of gearbox movement because any damage to this area would affect the fuel supply to both engines and was a **contributory factor**. 1.4.181

j. The SOIU and the RTS had errors in their first iterations that directly affected the establishment of structural integrity. The lack of ageing aircraft audit reduced the likelihood of identifying fatigue damage in the support case. The lack of additional geographically specific Corrosion Control on the main gearbox components could have led to the initiation of a fatigue crack in the support case. Following the MDRE exercise in 2005 there was a dilution of the importance of monitoring sloping ground landings and other fatigue significant events during the service life of the aircraft. This led to a lack of validation of fatigue significant events and a potentially undetected and unrecorded excessive rate of sloping ground landings. An assessment of fatigue significant events required an ISAA in order to identify threats to structural integrity, however, the Panel found no record of this type of assessment. Overhaul inspections recommended by Bell would not be sufficient to assess the level of fatigue damage in the support case and did not represent a full recovery of structural integrity following the manoeuvre limits issue in 2005. The Panel concluded that the lack of a compliant structural integrity strategy undermined the ability to treat threats to structural integrity effectively and was a **contributory factor**. 1.4.230

k. The Panel concluded that the risks associated with non-compliance with the structural integrity regulations were not properly identified by the TAA and not effectively communicated to the ODH. Equally, the ODH missed an opportunity to manage the risks associated with non-compliance by not recognising it as an issue and requesting further information. Compliance with civilian regulation alone was widely used to justify non-compliance with military regulation and became a cultural norm that was also tacitly accepted by the regulator for Griffin aircraft. The lack of effective risk management associated with the consequences of non-compliance with the MRP, and robust safety oversight was a **contributory factor**. 1.4.256

1.4.287. **Aggravating factor**. The following factors were aggravating to the outcome of the accident:

a. The lack of firefighting facilities at the landing site made the outcome significantly worse through an inability to respond to the fire and was an **aggravating factor**. 1.4.185

b. Incomplete shut down checks led to the fuel booster pumps remaining on, which increased the severity and the duration of the fire and made the outcome of 1.4.186

the accident worse, and was therefore considered an **aggravating factor**.

1.4.288. **Other factors**. The following other factors were identified during the investigation of the accident:

a. The severity of the potential impact on aircraft handling resulting from severe oscillations whilst in contact with the ground meant that the phenomenon could lead to other accidents and merited further investigation and was deemed an **other factor**. 1.4.131

b. The relationship between the lateral, longitudinal and absolute sloping ground limits resulting from a combined slope landing could impact any other helicopter. Unwittingly exceeding the sloping ground limit on any aircraft due to a combined slope landing was an **other factor**. 1.4.150

c. The 'interchangeability' of 'on-condition' aircraft components within the global fleet meant that it was very likely that the original support case fitted to gearbox A-213 was now installed on another gearbox, potentially with another operator and been subjected to an unsubstantiated level of fatigue damage. The 'interchangeability' of UK MOD gearbox support cases was deemed an **other factor**. 1.4.167

d. The lack of explicit corrosion control for the gearbox support case may lead to fatigue crack initiation in other support cases, and was therefore an **other factor**. 1.4.212.f

e. The lack of access to computer terminals, and thus DASOR occurrence reporting forms, may have contributed to a lack of reporting of occurrences on ASIMS by the maintenance organisation. The lack of formal reporting of an airworthiness concern was an **other factor**. 1.4.236

f. Lack of engineering occurrence managers would make effective oversight and quality control of all DASORs more difficult and hinder the DDH's ability to question engineering practice and challenge norms. Lack of engineering occurrence managers for technical DASORs may lead to lack of oversight and quality control of occurrence reports and was an **other factor**. 1.4.238

g. Closing DASORs without making a recommendation where a recommendation would have been effective may lead to repeat errors amongst DHFS operators and the wider Griffin fleet and was an **other factor**. 1.4.242

h. The description of the support case inspection was not specific enough to ensure that it was carried out with sufficient detail and did not take account of the level of component strip required for it to be fully effective. The description and method of inspection of the main gearbox support case could make detection of a crack less likely and contribute to a future accident and was therefore deemed an **other factor**. 1.4.162

i. Control switch differences between left and right hand cockpit controls increased the risk of carrying out an incorrect procedure in situations where an inexperienced crewmember is required to operate the switches. Crew 1.4.265

composition and seating position was an **other factor**.

j. The lack of a crash tolerant FDR and HUMS reduced the ability of the maintenance organisation to more effectively detect and diagnose faults. Also, these systems act as barriers to mitigate the risk to life associated with damaged components that may lead to structural failure of an SSI. The lack of a crash worthy FDR and HUMS could result in other similar events not being identified and investigated and was deemed an **other factor**. 1.4.269

k. Airframe repair record keeping was not robust enough to quickly assess individual airframe structural integrity by tail number and that airframe repairs, not specified as a standard repair, in accordance with Bell technical documentation, should still be recorded against the airframe in the modification and repair record book. Inaccurate airframe repair record keeping could lead to loss of configuration control and other accidents and was therefore deemed an **other factor**. 1.4.272

l. The ability to understand trends or chronic problems in AFCS could be diminished by the lack of engineering and aircrew instructions for reporting and checking fault codes. Lack of AFCS fault code management was an **other factor**. 1.4.273

m. Lack of clarity about the incident/accident categorisation led to a delay in certain PCM activities being initiated. However, the minor delay had no material effect on the outcome of the response in this event but could make a difference in other circumstances and was therefore an **other factor**. 1.4.276

1.4.289. **Observations**. The Panel made the following observations during the investigation of the accident:

a. The Panel **observed** that if a landing site within the Mountain Flying Training Area is to be used frequently it should be included in the Defence Infrastructure Organisation approved list of landing sites and annotated on the appropriate maps. 1.4.40

b. The Panel **observed** that students taking part in a flying task was beneficial to the students and future similar activity should not be unnecessarily constrained. 1.4.48

c. Recognised anomalies that presented problems with assessment of the CVR included: No audio data on one or more tracks, poor quality of the Cockpit Area Microphone (CAM) recording, pollution of CAM recording from the aircraft power supply and CVR power supply, erroneous memory management and level imbalance between tracks.[60] All of these anomalies were observed in the recording from ZJ241 and would therefore impinge upon the ability to recover accurate and useful information. Due to the extreme fire damage to the CVR and the extensive damage to the chips, DAIB assessed that recording on individual chips on the CVR Quality Rating Scale[61] was considered to be somewhere 1.4.67

[60] Bureau d'Enquetes et d'Analyses (BEA) study on detection of audio anomalies on CVR recordings: Dated Sep 2015.

[61] National Transportation Safety Board – Cockpit Voice Recorder Handbook for Aviation Accident investigations, Attachment D.

between "excellent" and "unusable". The Panel **observed** that exposure to conditions beyond the specification of the CVR did not preclude recovery of some useful data, albeit with difficulty, and that damage to future accident CVRs should not necessarily preclude attempts to recover the data. Additionally, aircraft would benefit from a CVR located away from potential fire sources.

d. The Panel **observed** that lack of available information regarding vibration phenomenon diminished the likelihood of accurate occurrence reporting and continued education on technical and flight phenomenon may be the most effective method to improve future fault diagnosis. 1.4.133

e. The Panel **observed** that the potential for fatigue damage within the components necessitated their need to be identified as a Structurally Significant Item (SSI) and be traced accordingly throughout life in order to maintain the 'interchangeability' of parts within the global fleet. 1.4.167

f. The Panel **observed** that there was a potential difference between the safety standards at the time of application for a Type Certificate and the safety standards in current regulation and that the safety case for older aircraft should take this into consideration for the risks to remain tolerable and as low as reasonably practicable. 1.4.180

g. The Panel **observed** that rotating aircraft between operating locations would share the level of exposure to potential corrosion amongst the fleet but equally may have to be balanced with other important considerations such as maintenance planning and role fit. 1.4.212.e

h. The Panel **observed** that formalising a direct relationship with the Original Equipment Manufacturer (OEM) regarding SOIU review should improve the quality of the validation activity and reduce the risk of errors in structural integrity management. 1.4.216

i. The Panel **observed** that improving the functionality of ASIMS to allow occurrence events to be normalised against flying hours, would provide an essential quantitative trend analysis tool for all DASORs. 1.4.243

j. Bell did not communicate effectively to users how to ensure that safety related occurrence reports should be transferred to the Type Certificate Holder such that they would be formally recorded. The Product Support Enquiry system was the primary conduit for this information but did not appear to effectively communicate all flight safety related data with Bell safety department. Efforts to maintain a local database provided some useful information but the Panel **observed** that a more cohesive data management and trending system would enable the most effective data exploitation by all Bell users. 1.4.247

k. The Panel **observed** that the lack of detail in the ASMP was evidence of a vague civil-military interface and that the lack of definition and formal commitment to integration could lead to a shift in attitudes over time, dependent on individual personalities within the leadership. 1.4.259

l. Conclusions that De Havilland Support Ltd came to, appear to echo much 1.4.262

of the issues found by this Service Inquiry. In addition, a study in 2013 highlighted those risks in MRCO arrangements that could be mitigated by the use of robust business processes that constitute the continued airworthiness of each platform. The gap analysis studies did not include a comparison to the FAA regulations. The panel concluded that these independent studies showed that the role of policy for continued airworthiness was crucial in mitigating the risks involved in the MRCO construct. The Panel **observed** that implementation of policy for continued airworthiness through the 5000 series of MAA regulations provided the necessary framework to account for the military delta between the MRP and EASA regulations.

m. The Panel **observed** that Griffin aircrew should have known the sloping ground limits and would benefit from clarification in the Griffin Flying Guide on how to apply the sloping ground limits using the available cockpit instrumentation. 1.4.267

n. The STARS database was used by 202(R) Sqn Operations which meant the Squadron no longer booked out with ATC, this would have included the planned aircraft Persons On Board (POB) figure. However, ATC did not have sight of STARS and were reliant on the aircraft radio calls for this information. The POB number was an important piece of information for PCM activity and would have been a more important factor if there had been casualties. The Panel **observed** that a more robust method of communicating the POB figure would have prevented confusion of casualty numbers. 1.4.278

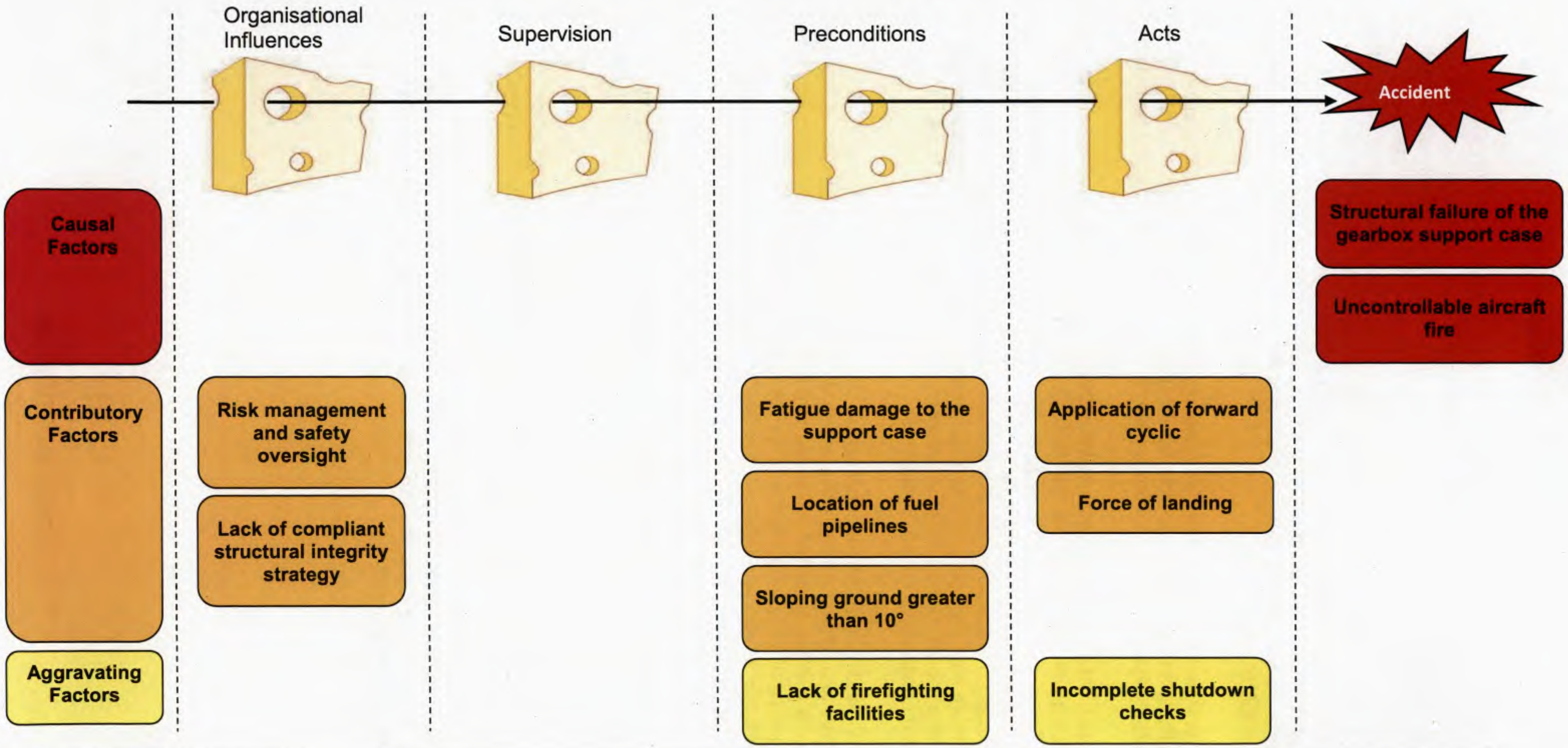
o. Impounding 'live' documents such as the authorisation sheets, aircraft documents and other evidence was standard practice but the custodian of those documents was not specified, which led to a brief dispute between operations and engineering staff about the most appropriate storage location. The Panel **observed** that a clear procedure for the quarantine of all air safety documents, evidence or electronic devices was required to prevent the uncertainty that transpired during the event. 1.4.278

p. The Panel **observed** that where a detached Sqn is hosted by a larger organisation both parties would benefit from a combined review of the crash plan to ensure cohesion, particularly in regard to lines of communication. 1.4.281

q. The Panel **observed** the importance of contingency awareness when operating on minimum manning, highlighted by the Station's inability to operate a separate ECC. 1.4.281

r. The Panel **observed** that the capabilities of the RAF Mountain Rescue Service in the remote location were instrumental in enabling successful Post Occurrence Management. 1.4.281

"SWISS CHEESE"[62] REPRESENTATION OF THE ACCIDENT INVOLVING GRIFFIN ZJ241 ON 9 AUG 16



62 The original source for the Swiss Cheese illustration is: "Swiss Cheese" Model – James Reason, 1990. The book reference is: Reason, J. (1990) Human Error. Cambridge: University Press, Cambridge

PART 1.5

Recommendations

Intentionally Blank

PART 1.5 – RECOMMENDATIONS

Introduction. The following recommendations are made, in order to enhance Defence Air Safety:

Recommendations		**Analysis Reference**
1.5.1.	**Recommendations to Director Military Aviation Authority (D-MAA):**	
	a. Director Military Aviation Authority should re-assert a robust enforcement of compliance with 5000 series Regulatory Articles for Military Registered Civil Owned aircraft and ensure that all non-compliance is tracked to enable more effective Duty Holder mitigation of the consequences of non-compliance.	1.4.257
	b. Director Military Aviation Authority should provide guidance on the routine voluntary release of occurrence reports, in addition to Mandatory Occurrence Reports, to civilian regulators and Original Equipment Manufacturers, in order to facilitate wider trending of occurrences on civilian aircraft.	1.4.250
	c. The Director Military Aviation Authority should review regulatory guidance for retrospectively fitting Flight Data Recorders and Health Usage Monitoring Systems on legacy aircraft in order to improve the maintainability and safety of aircraft components.	1.4.271
1.5.2.	**Recommendations to AOC 22 Gp Operating Duty Holder (ODH):**	
	a. The Operating Duty Holder should revise relevant air safety policy documents and subordinate Air Safety Management Plans in order to formalise all civil-military interfaces, interactions and responsibilities within their area of Responsibility.	1.4.260
	b. The Operating Duty Holder should ensure that the contracted maintenance organisation is appropriately resourced to use the Air Safety Information Management System as the primary reporting and occurrence management system in accordance with RA 1410, to ensure that all air safety occurrences are appropriately managed.	1.4.237
1.5.3.	**Recommendations to Director Helicopters (D-Hels) DE&S:**	
	a. Director Helicopters should commission a study into how combined slope landings are assessed with reference to cockpit instruments, for all helicopter types, to ensure that aircraft do not stray outside the design limits intended by the Original Equipment Manufacturer (OEM).	1.4.151

	b. Director Helicopters should assure structural integrity and type airworthiness of the Griffin platform such that the residual risk to life is tolerable and ALARP, while on the military register, with respect to: (1). The gearbox support cases that were fatigue damaged by any of the fatiguing conditions described within the Service Inquiry. (2). All components within the fatigue substantiation report for the sloping ground kit that were affected by rates of sloping ground landings above Bell's design assumptions.	1.4.175
1.5.4.	**Recommendations to the Griffin Delivery Duty Holders (DDH):**	
	a. The Delivery Duty Holder of the Defence Helicopter Flying School should ensure that there is an appropriate balance of engineering and operator competencies between nominated occurrence managers and investigators within the organisation, to improve the management of engineering related DASORs.	1.4.239
	b. The Delivery Duty Holder should revise crew composition policy for Defence Helicopter Flying School aircrew under training, with respect to seating position and participation in non-syllabus tasking, in order to clarify the policy on operating with students.	1.4.266
1.5.5.	**Recommendations to SPMAP RW Type Airworthiness Authority (TAA):**	
	a. The Type Airworthiness Authority should provide a corrosion control policy, in the Support Policy Statement, based on the specific environment and aircraft usage, which should take account of best practice within other Bell 412 maritime user communities.	1.4.212.g
	b. The Type Airworthiness Authority should implement an appropriate Non Destructive Testing technique in consultation with fatigue experts to mitigate the effects of fatigue damage to the affected support cases by increasing the likelihood of detecting a fatigue crack.	1.4.163
	c. The Type Airworthiness Authority should ensure that for 25-hour airworthiness critical inspections for cracking, the level of aircraft strip, access of the area to be inspected, light source and tooling used, should be more explicit, in order to mitigate the effects of fatigue damage to the effected support cases by increasing the likelihood of detecting a fatigue crack.	1.4.164
	d. Type Airworthiness Authority should record all fatigue significant events within the Design Usage Spectrum and ensure that they are monitored and validated within the Statement of Operating Intent and Use, to maintain structural integrity throughout the life of the aircraft.	1.4.212.b
	e. The Type Airworthiness Authority should implement policy and procedures for recording and acting upon Automatic Flight Control System error codes in order to validate system integrity as detailed by the Bell maintenance manual.	1.4.274

	f. The Type Airworthiness Authority should identify the hazards associated with a single point of failure, due to excessive movement of the main gearbox. This should consider the routing of fuel pipelines and engine control rods with respect to engine fuel starvation and risk of fire, in order to articulate the risks to life to the ODH.	1.4.182
	g. The Type Airworthiness Authority (TAA) should retain the services of an Independent Structural Airworthiness Advisor to assess the impact of fatiguing conditions, assure structural integrity management activity and to advise the TAA on airworthiness risks arising from structural integrity concerns.	1.4.231
1.5.6.	**Recommendations to Bell Helicopter Textron:**	
	a. Bell should publish a definition for ground bounce and other Bell 412 specific vibration phenomena along with guidance for operators to reduce the likelihood of future incidents.	1.4.134
1.5.7.	**Recommendations to the Federal Aviation Administration (FAA):**	
	a. The Federal Aviation Administration in conjunction with Bell should investigate the long term airworthiness of the gearbox support cases that were fatigue damaged by any of the fatiguing conditions described within the Service Inquiry and all components affected by rates of sloping ground landings above Bell's design assumptions.	1.4.176
	b. The Federal Aviation Administration in conjunction with Bristows should ensure that all interchangeable gearbox support cases, from UK MOD registered Bell 412 aircraft, potentially affected by fatigue damage, are located and monitored appropriately.	1.4.168
	c. The Federal Aviation Administration in conjunction with Bell should ensure that all Bell 412 users were not affected by the lack of manoeuvre limits in the Rotorcraft Flight Manual prior to 2007 and take necessary action in order to assure structural integrity of all affected components.	1.4.222
	d. The Federal Aviation Administration should determine if the Bell 412 Rotorcraft Flight Manual (RFM) adequately represented the limits under which the aircraft was type certified, and should consider amending regulations to ensure that design limits are better represented in the RFM.	1.4.211

Intentionally Blank

PART 1.6

Convening Authority Comments

PART 1.6 – CONVENING AUTHORITY COMMENTS

Introduction

1.6.1. During the early afternoon of 9 August 2016, whilst attempting to land on a peak in Snowdonia, a Griffin HT Mk1 Helicopter from the Defence Helicopter Flying School (DHFS), suffered an accident that led to its complete destruction. Thankfully all of the 5 persons on board escaped without significant injury. Although this was an unremarkable sortie in terms of its complexity and conducted in benign weather conditions, Griffin ZJ241 was an accident waiting to happen. It only took an attempted landing on a slope, which was outside the aircraft's permitted limits, to initiate a sequence of events that led to its destruction. Once this sequence had started, there was nothing the aircrew could have reasonably done to prevent the accident from occurring. Indeed, I would suggest the immediate actions taken by Aircraft Commander A and his decision to land the aircraft, reduced the likelihood of more serious injury and possibly loss of life.

1.6.2. This has been a particularly difficult Service Inquiry (SI) that has taken some 20 months to conclude. I am grateful for the depth of analysis and logic the President and his Panel have applied in meeting their Terms of Reference (TORs). With only minimal physical evidence available at the accident site, the SI has relied heavily on and made best use of the verbal and documented evidence available at time of writing. I agree with the Panel's findings and support fully the recommendations that flow logically from these. In addition to complying with the Urgent Safety Advice[1] and Safety Advice[2] provided to Duty Holders during the course of the Inquiry, I am satisfied that meeting these recommendations in full will help prevent a reoccurrence of this type of accident.

1.6.3. The findings of this SI will be relevant beyond the specifics relating to the Griffin helicopter.[3] The SI highlights the imperative of understanding and operating within aircraft design limitations, the importance of Structural Integrity and its management in demonstrating airworthiness under a Release to Service (RTS) and in accordance with assumptions made within the Statement of Operating Intent and Use (SOIU). Its conclusions are relevant to current and future Military Registered Contractor Owned (MRCO) constructs, to the role and responsibilities of the Type Airworthiness Authority (TAA) and on military/civilian Air Safety management and Culture interfaces. It also raises issues concerning the effectiveness of the MAA in ensuring compliance with mandated regulation.

1.6.4. Technical Failure essentially caused this accident. Whilst this might appear simple to identify, understanding why this happened and how preceding events and practices conspired to allow it to do so, is far more complex. As a level of understanding is necessary to give appropriate perspective to the recommendations made, I will structure my comments accordingly. I will start with *'what caused the accident'* and comment on key evidence and analysis that led to the Panel's

[1] Urgent Safety Advice (USA) Issued. 20160812- Drive Shaft Forward Outer Coupling Failure – 12 Aug 16, 20160901 - Update to USA regarding failure and indicating Consequential Damage – 1 Sep 16 and 20161201 - Structural Failure of Gearbox Mounting – 1 Dec 16.

[2] Safety Advice (SA) Issued. 20170124 - Sloping Landing Safety Letter – 24 Jan 17, 20170404 - Hoist Centre of Gravity Safety Letter – 4 Apr 17, 20170614 - Airworthiness Concerns Letter to DComOps, HQ Air Command – 14 Jun 17.

[3] UK MOD use of the Griffin is limited and set to reduce, to only those few aircraft operated by 84 Squadron RAF, in line with the end of the DHFS contract. From 1 April 2018, a new Military Flying Training System (MFTS) contract will deliver student pilot training. For Rotary Wing training, MFTS will use Airbus helicopters. The findings of this SI will remain relevant particularly, should the MOD consider bringing additional Griffin onto the military register in the future.

conclusions. I will then comment on the Panel's conclusions as to *'what led to the accident happening'*. This latter section is potentially the most complex to understand, but draws from it important recommendations. As ever, understanding context is an essential pre-requisite.

Context

1.6.5. The Griffin helicopter is a variant of the Bell 412 Enhanced Performance (EP) model, manufactured by Bell Helicopter Textron (the Original Equipment Manufacturer (OEM) and the Design Organisation). The Bell 412 was first produced in 1981 and remains in extensive use worldwide by civilian and military users. The UK MOD chose the Griffin to fulfil a training role for basic and intermediate student pilot training as part of the DHFS. All aircraft had an Enhanced Sloping Ground Landing Kit (ESGLK) embodied.[4] The Griffin fleet[5] is owned and maintained by Cobham Helicopter Services (Cobham) – formally FB Heliservices (FBH)/Bristows – and operated under a MRCO contract.

The MRCO Construct

1.6.6. The MOD chose the MRCO construct, as it avoided the capital outlay of aircraft purchase and offered significant efficiencies in maintaining the fleet and its through-life costs. It permitted the use of what was essentially a variant of a mass-produced civilian aircraft, whilst allowing necessary deviation from the Air Navigation Order, to meet military flying training needs.

1.6.7. MRCO aircraft are required to comply with MOD Military Aviation Authority (MAA) Military Regulatory Publications (MRP) and follow European Aviation Safety Agency (EASA) regulations. At the time of the accident, Griffin ZJ241 held a valid Military Airworthiness Review Certificate (MARC) which is equivalent to the civilian Airworthiness Review Certificate (ARC). For the DHFS Griffin fleet, the MRCO contract is owned by AOC 22 Gp (who is also the Operating Duty Holder) and is overseen by the TAA, who is responsible for 'Type Airworthiness' and therefore owns the Aircraft Documentation Set. The TAA works within the Special Projects Multi-Air Platform Project Team (SPMAP), which forms part of the Defence Equipment and Support (DE&S). Together Cobham and 22 Gp are responsible for day-to-day 'Continuing Airworthiness'.

1.6.8. Bell Helicopter provided a Rotorcraft Flight Manual (RFM) for the aircraft. The RFM set the limits within which the aircraft was to be operated. These were taken from design and test parameters, with design parameters derived from the Design Usage Spectrum (DUS). Bell also provided a Maintenance Manual (MM). For the DHFS contract, the RFM and MM were translated by FBH (now Cobham) in conjunction with DHFS Standards and the Release to Service Authority (RTSA), into a military format, to standardise the document sets and assist understanding.[6]

What Caused the Accident

1.6.9. The Panel identified two Causal Factors, which were sequential. The first was a structural failure of the Main Rotor Gear Box (MRGB) Support Case (SC) in two or more locations, leading to unrestrained motion of the gearbox. This was followed by (second) an uncontrolled aircraft fire, which led to ZJ241's destruction.

---

[4] In response to a Canadian military request, Bell developed an ESGLK. This increased the sloping ground limits from 4 to 10 degrees and reduced specific component life.

[5] FBH/Cobham purchased a total of 15 x Bell 412s, with varying specifications, between 1997 and 2002.

[6] These comprised the Flight Reference Cards, the Aircrew Manual and the Release to Service.

First Causal Factor – Failure of the Main Rotor Gear Box (MRGB) Support Case (SC)

1.6.10. The Panel arrived at its conclusions following in-depth analysis of remaining evidence that had survived the fire and witness testimony. The aircraft's Cockpit Voice Recorder (CVR) was badly damaged by fire, but analysis of the audio files yielded a partial transcript of the accident. Corroboration with aircrew testimony led to the determination of the most likely sequence of events and an accident timeline. This timeline was further analysed in conjunction with landing-site characteristics, aircrew inputs and fragments of the drive-shaft outer coupling, which had been ejected from the aircraft during the accident sequence. With expert advice from 1710 Naval Air Squadron, the Panel determined that the forward outer-coupling failed through overload, owing to misalignment and that this was consequential rather than causal.[7] It was further determined the misalignment, owing to the level of movement (being greater than 7.5 degrees), must have been caused by a failure in the MRGB SC. Through methodical fault-tree analysis, the use of a combination of finite element analysis[8], consideration of consequential damage and evidence from similar historical failure locations, the Panel concluded that it was the MRGB SC that had failed and had done so in a minimum of 2 locations.

1.6.11. To understand why this had happened, it was necessary to determine if the failure had been caused by Overload[9] and/or Fatigue[10]. A failure in overload would indicate an external event during or prior to the accident, whereas Fatigue cracking would be attributable to an inherent or pre-existing fault. This accident was not unique within the global Griffin fleet. During their investigation, the Panel found a total of five previously reported historical cases of MRGB SC cracking[11]. All of these concerned international fleets except for one previous UK MOD incident, which occurred on the same aircraft, ZJ241, in 2006.

1.6.12. The Panel considered a number of events in determining if failure had been caused by overload. These included the force of the landing[12], the application of forward cyclic during the landing[13] and the effect of landing beyond the Sloping Ground Limits (SGL) of the aircraft.[14] The Panel concluded that, although many of these events were Contributory Factors[15], it was unlikely any one would have been sufficient alone to cause the MRGB SC to have failed through overload.

---

[7] This damage was determined as Consequential owing to the characteristics of damage sustained by the cowling surrounding the rotor mast, which survived the subsequent fire and witness testimony of the tail rotor slowing down more quickly than the main rotor during the accident. The Panel's analysis was supported by 3 previous accidents, in different countries, having similar characteristics.

[8] Finite Element Analysis is a computerised analysis method to envisage how a manufactured product will react to the physical world. The analysis can predict if the product is likely to break, tear, wear, or behave in the way it was designed.

[9] Applying a stress above the static yield strength of the material causes failure in overload.

[10] Fatigue is a process of progressive, permanent structural change occurring in a material that is subjected to fluctuating loads below the static yield strength of the material. The manifestation can lead to progressive cracking.

[11] In 2006, a UK Military Sales Case fatigue crack. This occurred on the same aircraft (ZJ241) and was classified as a fatigue crack by subsequent Bell analysis. In 2006, a Foreign Military Sales (FMS) case crack. In 2008, following overload of the Support Case on an aircraft in Wollongong, Australia. In 2012, from Health Usage and Monitoring System (HUMS) information provided by Bell, and in 2017, a Support Case crack found following severe vibration.

[12] The force of the landing during the accident was harder than normal and would have increased the stress transmitted to the MRGB Support Case.

[13] Forward cyclic is commonly used during a landing on sloping ground. Its application when the aircraft is on the ground induces a bending moment on the rotor mast and a resultant force through the MRGB Support Case. However, Bell confirmed that even a maximum application for forward cyclic could not cause a failure of the Support Case.

[14] There is no evidence to suggest the pilot intended to land fully on the slope, which exceeded the aircraft's limitations (12.3 degrees vice 10 degree limitation), but in its final resting position, it was beyond limits.

[15] A Contributory Factor is a factor which made the accident more likely.

Being unable to analyse the combined effect of these events, owing to a lack of quantitative data, and the number of possible scenario permutations, the Panel could not rule out failure of the MRGB Support Case in overload.

1.6.13. Fatigue damage culminates in cracking that can reduce the residual strength of a structure making it more susceptible to failure. For key aircraft components, the impact of fatigue damage can be mitigated until an acceptable probability of failure is achieved. Examples of such mitigation include limiting the life of a component (giving it a 'fatigue life') or making the component more tolerant to damage[16].

1.6.14. Bell did not determine the MRGB SC's probability of failure, as it was not required for FAA Type Certification[17]. It would appear that Bell did not conduct any fatigue assessment of the MRGB casing or its SC, to underpin its maintenance philosophy, as it would not have been required if the operating assumptions were correct. As the SC had had relatively few fatigue events during its 36-year history, the Panel considered this approach reasonable. Without a fatigue life, the serviceability of the SC was assured instead through scheduled maintenance inspections. As this approach did not require fatigue significant events[18] against the SC to be recorded, the Panel considered factors, which could have contributed to fatigue damage and the likelihood that fatigue had occurred in ZJ241's SC. These factors included Manoeuvre Limits and the rate of Sloping Ground Landings (SGLs).

1.6.15. In the RFM Bell defined the Griffin's manoeuvre limits[19] by stating that 'Aerobatic Manoeuvres were prohibited'. Between 1997 and 2003, the MOD thought it was operating in accordance with the RFM, but it had unknowingly been exceeding the limits set, as its interpretation of what constituted an Aerobatic Manoeuvre[20] was different. It was not until February 2005, when Bell provided numerical limits, that the Release to Service Authority (RTSA) realised the Griffin had been flown outside its design limits. Bell produced a recovery plan in 2009 in response, which included the replacement of components deemed 'affected'. The plan did not recommend replacement of the MRGB SC. The Panel concluded that flight outside the aircraft's design limits had occurred and caused additional unknown fatigue damage to the SC. This had made a fatigue crack more likely.

1.6.16. Bell regarded SGLs as fatigue significant events as they imparted an increased bending moment on the rotor mast. This was reflected in Bell's fatigue substantiation report for the ESGLK. However, the report did not consider the additional fatigue load SGLs placed on the MRGB SC. The rate of SGLs conducted by the UK MOD Griffin fleet was impossible to determine accurately as SGLs were not routinely recorded. However, data from a study on crewman currency, conducted by one of the three DHFS flying squadrons between September 2015 and August 2016, provided an approximation, which could be extrapolated. From this the Panel found even the minimum average rate of SGLs conducted exceeded Bell's design assumptions, with the average potential maximum doing so to a considerably greater degree. The Panel concluded that over the life of the aircraft, the rate of SGLs exceeded Bell's DUS assumptions and was likely to have caused additional un-quantified fatigue damage to the SC.

---

[16] Making the component damage tolerant requires an accurate prediction of crack growth supported by an appropriate inspection regime. Other mitigations include component design and system design.

[17] When the Bell 412 was being designed, Federal Aviation Administration (FAA) guidance did not require comprehensive fatigue testing of all aircraft drive-train parts. Bell's design and certification work did not reveal any limitations with the MRGB Support Case, which would have resulted it being deemed a 'Critical Component' under FAA Section 29.1309, amendment 29.24.

[18] A fatigue significant event is one that accrues damage at a higher rate than normal use.

[19] Bell's (design) Manoeuvre Limits for the Griffin (50 degrees angle of bank (AOB) and 15/30 degrees in down/up pitch) were the maximum values considered for Certification.

[20] The MOD applied limits of 90 degrees AOB and 90 degrees in pitch.

1.6.17. In summarising its findings regarding fatigue, the Panel found evidence the Griffin fleet had been operated outside its design parameters, outside the DUS and in high stress scenarios within the design limits[21]. Each of these imposed a level of fatigue loading on the MRGB SC, with the combined load spectrum greater than it should have been, but there was insufficient data available to predict when failure could occur. The Panel concluded, the level of fatigue damage in ZJ241's MRGB Support Case was above that assumed by the designer, but the Panel could not determine with certainty whether fatigue alone led to the SC's failure.

1.6.18. In addition, the Panel thought it likely that fatigue load would have been greatest on UK MOD used Bell 412. Canadian Forces also conduct SGLs with an ESGLK equipped Bell 412, however at a lower rate than the UK fleet. The Panel concluded, it was more likely than not, that some UK MOD Griffin had among the highest fatigue loading on their MRGB SC of any other Bell 412s operating worldwide.

1.6.19. As neither the MRGB nor its SC were given a finite fatigue life and to rule out an inherent fault with ZJ241 that had led to a second SC incident[22], the Panel examined main gearbox assembly and airframe history. ZJ241's MRGB and SC were fitted in September 2015. At the time of the accident, 404.40 airframe hours had been flown since its last major (6,000 hour) overhaul. The SC had been inspected 13:10 airframe hours before the accident, as part of a routine 25-hour servicing schedule, in accordance with Bell maintenance manuals. However, the Panel determined that the description of the SC 25-hour inspection was not specific enough to ensure it was carried out with sufficient detail at an appropriate level of component strip. This made detection of a crack in the SC less likely.

1.6.20. The Panel analysed all six of the MRGBs that had been fitted to ZJ241 throughout its life. The 'accident' MRGB had been fitted to five other aircraft. The Panel found that SCs did not necessarily remain with the same MRGB and were not tracked, as they were not deemed an airworthiness traceable item. This meant SCs that had been fitted to UK Griffin and subjected to fatiguing conditions could be interchanged and fitted to other MRGBs, potentially with an unsubstantiated level of inherent fatigue damage. As Bristows, the overhaul agent, had contracts with other overseas customers, the Panel considered it possible for fatigue damaged SCs to have been unknowingly introduced across a global fleet and within the global supply chain. Accordingly, the Panel observed that MRGB SCs should be identified as a Structurally Significant Item (SSI) and controlled appropriately in accordance with the MRP. Furthermore, as MRGB SCs may be sensitive to fatigue damage, a fatigue analysis should be considered, as a matter of urgency, with a view to applying a fatigue life to affected SCs.

Second Causal Factor – Aircraft Fire

1.6.21. The Panel identified an uncontrollable fire as a second and subsequent Causal factor. Fire destroyed most of the aircraft and burned for over 4 hours. It spread rapidly from initiation and despite efforts from the crew to fight the fire, using both hand-held extinguishers and those fixed within the engine bay, the aircraft was completely engulfed within a few minutes. The crew were forced to egress the aircraft before they were able to complete emergency shut-down procedures, leaving both power supply and fuel booster pumps on. The ferocity of the fire suggested that fuel pipelines had been ruptured during the accident sequence. It was calculated that approximately

[21] The conduct of Hoist operations provided an example where the Griffin had been operated in High Stress scenarios within the Design Limits.

[22] ZJ241 had been the victim of a fatigue crack in its MRGB Support Case in 2006, although this was with a different MRGB and associated SC. A Bell lab report detailed the cause of the crack as being due to fatigue, but did not determine a crack initiator. This response confirmed Bell's acceptance that fatigue cracking could occur on MRGB SCs. The Panel concluded there was insufficient evidence to confirm an inherent fault with ZJ241.

1,640lbs of fuel was on the aircraft at the time of the accident. Witness testimony and evidence, including from a previous reported Foreign Military Sales SC failure in 2006 (mentioned above), made it almost certain that the fuel pipelines and throttle control rods located in the void that surrounds the MRGB (known as the 'Hell-Hole'), were damaged early in the accident sequence by the unrestrained movement of the MRGB. The most likely ignition source was deemed to have been from the metal-to-metal contact between the rotor brake and the SC. The location of these fuel pipelines was regarded as a potential single-point of failure as damage in this area would affect the fuel supply to both engines.

What Led to the Accident Happening

1.6.22. Much of this SI has focused on understanding how the MRGB SC failed and identifying the Cause. Although the Panel could not rule out failure in either overload or fatigue, their analysis has emphasised the importance of operating and maintaining aircraft within set design limits and understanding the risk of not doing so. As a reminder, for the Griffin, these were provided in Bell's RFM and MM and subsequently translated into a military format. This military format will have needed to comply with MAA Regulatory Articles (RAs) on Structural Integrity. They would need to describe how Structural Integrity is managed (established, sustained and validated), to demonstrate the aircraft is airworthy to operate under its Release to Service (RTS) and in accordance with the assumptions made within the SOIU.

1.6.23. For the Bell 412, similar military instructions stipulating Structural Integrity existed dating back to 1993. On the formation of the MAA, the TAA within the SPMAP project team (PT) would have been required to ensure compliance with relevant MAA RAs. The Panel could find no evidence the PT established Structural Integrity for the Griffin in line with RAs. Instead the PT relied on a generic airworthiness strategy. This was considered at 2* level within the DE&S as a reasonable holding position, but with a bespoke Airworthiness Strategy for the Griffin not being issued until 2015, the absence of a (bespoke) Structural Integrity strategy resulted in key stakeholders not being aware of their responsibilities and threats not being treated correctly.

1.6.24. The aim of the SOIU is to convey the intended use of the aircraft to the Design Organisation (DO), with the purpose of allowing the DO to assess accurately how the aircraft will suffer from fatigue during its life. An initial SOIU for the Griffin was produced in 1998. This identified SGLs of up to 10 degrees as part of the usage spectrum, but showed no expected flight time within the 5-10 degree range. Furthermore, no early accurate usage data was captured to test assumptions. This is essential for a new aircraft, but for the Griffin was not done until 2005 and even then, did not specify a SGL rate – 7 years after its introduction.

1.6.25. With regards to manoeuvre limits, pertinent to fatigue damage mentioned above, the RFM's lack of detailed quantitative limits was raised in 1997. The RTSA made the assumption that the term used in the RFM – 'aerobatic manoeuvres' – would be compliant with their definition within the FAA code of federal regulations and the FAA operations inspectors' handbook[23]. Therefore, from 1997 to 2003 the RTSA published manoeuvre limits, which grossly exceeded limits subsequently provided by Bell. The Panel judged Bell should have defined numerical manoeuvre limits in the RFM, as this would have prevented ambiguity.[24] An RTS update in 2003 prompted the RTSA to question Bell via FBH (now Cobham) regarding the lack of published limits. This in turn prompted Bell to revise the RFM and the RTSA subsequently to reduce limits in the RTS, as a protective measure. In 2005, FBH (now Cobham), advised that the limits were set at 50 degrees AOB and 30/15 degrees for pitch up/down. This prompted the TAA to conduct an airworthiness

[23] FAA Code of Federal Regulations, Section 14, Order 91.303 and FAA Operations Inspectors' Handbook Order 8700.1, Chapter 49.

[24] FAA regulations mandated that the RFM must contain the operating limitations under which the aircraft was Type Certified. Bell stated manoeuvre limits were considered as part of Certification, but not included in the RFM.

recovery exercise. Bell subsequently further revised the RFM in October 2007[25] and responded with a formal action recovery plan for the MOD Griffin fleet in 2009. The Panel concluded that although the first edition of the MAR correctly translated the information from the RFM, it did not provide the correct design limits because they were not available. The Panel further opined, the time taken for Bell to initiate recovery action for an airworthiness issue was unreasonably long and the overhaul inspections recommended by Bell would not have been sufficient to assess the level of fatigue damage or predict future failure. It is further notable that Bell only communicated to the MOD the potential cause of the 2006 UK Griffin fatigue crack, as flight outside the normal flight regime, during the gathering of evidence for this SI. From this, the Panel concluded that Bell recognised that exceeding manoeuvre limits would have contributed to fatigue damage accrual within the SC and did not offer attendant advice[26].

1.6.26. Having established Structural Integrity, it then must be managed to ensure it is sustained throughout the aircraft's life. In determining how the Griffin fleet's Structural Integrity was sustained, the Panel considered the monitoring of fatigue significant events, ageing aircraft and environmental damage, and corrosion control. From evidence collected, the Panel determined:

- For the monitoring of fatigue significant events - that the lack of monitoring SGLs during the Griffin's service life prevented the TAA from sustaining Structural Integrity, by comparing actual usage with the design assumptions. In addition, the Panel could find no evidence that the TAA received advice from an Independent Structural Airworthiness Advisor (ISAA), who would have offered key stakeholder information and advice. This reduced the likelihood of detecting issues related to sustaining Structural Integrity.

- For ageing aircraft and environmental damage management - that an Ageing Aircraft Audit (AAA) was not conducted as mandated under MAA RA 5723. RA 5723 states that at 15 years, or at 50% of planned life, an aircraft should undergo an AAA[27]. Although the Griffin fell into this category from 2008, no AAA was planned or conducted by the PT and no application for An Alternative Means of Compliance (AAMC), waiver or exemption to RA 5723 sought. Instead, the PT had relied on Bell civil regulatory compliance and a valid civilian Type Certificate as the sole mitigation against compliance with the RAs and to assure longer-term airworthiness[28]. The Panel concluded that the lack of an AAA reduced the likelihood of identifying fatigue damage in the SC.

- Corrosion Control - that no effective corrosion control programme existed for the SC, to take account of specific environmental conditions[29]. This was potentially exacerbated by the Military Continuing Airworthiness Management Exposition (CAME) contradicting the guidance given in the SOIU, in that the CAME fixed specific aircraft to specific environments for extended periods, thereby increasing the likelihood of corrosion.

---

[25] The revision of the RFM included 'Intentional manoeuvring resulting in roll attitudes in excess of 50 degrees AOB, or pitch attitudes lower than15 degrees nose down or higher than 30 degrees nose up are prohibited'.

[26] Further regarding the UK Griffin 2006 incident, FBH (now Cobham) raised a Mandatory Occurrence Report to the CAA, due to the unsafe condition of the aircraft. Cobham, as the Part M (CAMO) made enquiries to Bell regarding follow-up action to the 2006 fatigue crack, but were not given further information by Bell, or access to the full laboratory report. The Panel also found evidence from Bell regarding the reporting of failures, malfunctions and defects, in compliance with FAA requirements (FAR 21.3), in that they are required within 24 hours of determining a reportable event.

[27] RA 5723 states - 'As aircraft age, Environmental Damage (ED) becomes more widespread and is more likely to occur concurrently with other forms of damage, such as fatigue damage. ED degrades Structural Integrity and if uncontrolled will reduce the inherent ability of the structure to sustain loads in the presence of other forms of damage'.

[28] This assumed UK MOD fleet of Griffin were the same as the global fleet. They were not as they had the enhanced sloping landing kit fitted and routinely landed on slopes up to 10 degrees.

[29] ZJ241 was operated by 202(R) Sqn based at RAF Valley. Its use focused on operations in Maritime and Mountain environments.

1.6.27. To assist in the validation of Structural Integrity, MAA's RAs mandate a triennial review of the SOIU by an appointed Competent Organisation, using aircraft usage data, to carry out a quantitative update. This is to ensure aircraft usage remains within design parameters, the DUS and to highlight changes in usage. The Panel found the only triennial review of the SOIU was carried out in 2006 (using data from the Manual Data Recording Exercise (MDRE) in 2005). At the time of the accident a review of the SOIU was approximately 7 years out of date. Furthermore, the SOIU review process should have included a validation of the number of SGLs, but this would not have been possible as the MDRE did not record SGLs as a discrete data set. In evidence to this SI, the TAA stated the PT had no direct contract with Bell to carry out routine SOIU reviews, and was therefore non compliant with MAA RA 5720.

1.6.28. In their summary of Structural Integrity Management, the Panel concluded that the lack of a compliant Structural Integrity Strategy undermined the ability to treat threats to structural integrity effectively and therefore made the accident more likely.

1.6.29. In addition, the way in which the UK 2006 SC incident was managed (CAA Mandatory Occurrence Report raised by FBH and Bell's FAA, FAR 21.3 response) resulted in no Airworthiness Directive, Alert Service Bulletin or amendment to maintenance practices to be promulgated by Bell, the FAA or the CAA following this incident, to alert other users. It was the Panel's opinion that as a consequence Bell might still have been unaware that other operators may also have inadvertently exceeded design limits during the period prior to 2007, owing to the lack of published quantitative manoeuvre limits in the RFM.

1.6.30. In their consideration of Organisational Factors, the Panel considered Air Safety Management (ASM)[30], trend analysis, risk management and Safety oversight. A number of noteworthy factors were found[31]. Whilst most did not contribute directly to the accident, the Panel found that compliance with civilian regulation alone was widely used to justify non-compliance with Military Regulation. This incorrect practice had become normalised (in culture). The Regulator for Griffin also tacitly accepted it. In its conclusions, the Panel found the lack of an MRP compliant risk management system and effective safety oversight, made the accident more likely.

Concluding Comments

1.6.31. I mentioned earlier that the relevance of this SI will reach far beyond specifics relating to the Griffin helicopter. The initial cause of this accident was a result of a Technical failure of a key component. Technical failures as Causal Factors for manned aircraft accidents are uncommon and therefore the opportunity to examine the "Safe to Operate" elements of the overall Safety spectrum has proved particularly valuable. In hindsight, many of the errors and a failure to follow procedures, might appear obvious, yet they still occurred and many went undetected. There is sufficient regulation, both military and civilian, which if complied with correctly would have made this accident less likely. There are stark lessons for both the Regulator and those regulated. The MRCO construct adds complexity and demands a more thorough understanding of roles and responsibilities and of appropriate process. This is especially pertinent, as the UK MOD will continue to use MRCO, for its clear benefits.

[30] ASM in the MOD is managed by the Duty Holder (DH) system, with its Air Safety Information Management System (ASIMS) supporting the reporting, management and analysis of air safety occurrences. The civilian occurrence reporting system is through the European Co-ordination Centre of Accident and Incident Reporting Systems (ECCAIRS) mandated by European regulations. Within the civilian sector, each operating organisation also has an internal occurrence management system. For Cobham, this was their Safety Process - SP-01. The MAA's RAs require MRCO aircraft to use ASIMS. The Panel found some confusion in the reporting of engineering incidents

[31] These included: the potential for confusion with two reporting systems, a lack DASOR reporting, owing to insufficient access to ASIMS, a lack of engineering occurrence managers for technical DASORs and the ineffective closure of DASORs by DHFS.

1.6.32. The SI does not comment much on the ability of respective levels of Duty Holders (DH) to own (understand and manage) the totality of Risk that they would need to in providing a robust Safety Statement for an air platform. I suspect having digested this SI and understood better the potential consequences of the conditions that led to the destruction of ZJ241, the focus of DHs on understanding the relevance of technical detail and challenging advice provided by respective TAAs, will sharpen.

DG DSA