Defence
Safety
Authority

Service Inquiry

Loss of Watchkeeper (WK042) Unmanned Air Vehicle over Cardigan Bay in West Wales

3 Feb 17

Defence Safety
Authority

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PART 1.1 – COVERING NOTE

20 Apr 18

DG DSA

SERVICE INQUIRY INTO AN ACCIDENT INVOLVING A WATCHKEEPER UNMANNED AIRCRAFT (UA) WK042 THAT OCCURRED NORTH OF WEST WALES AIRPORT ON 3 FEB 17

1. The Service Inquiry Panel convened on the 15 Feb 17 by order of the DG DSA for the purpose of investigating the accident involving Watchkeeper UA WK042 on 3 Feb 17 and to make recommendations in order to prevent recurrence. The Panel has concluded its inquiries and submits the Provisional Report for the Convening Authority's consideration.

PRESIDENT

[redacted]
Squadron Leader
President
WK042 SI

MEMBERS

[redacted]
Lieutenant Royal Navy
Engineer Member
WK042 SI

[redacted]
Sergeant
Aircrew Member
WK042 SI

2. The following inquiry papers are enclosed:

Part 1 (The Report)
Part 1.1 Covering Note
Part 1.2 Preliminaries
Part 1.3 Narrative of Events
Part 1.4 Findings
Part 1.5 Recommendations
Part 1.6 Convening Authority Comments

Part 2 (The Record of Proceedings)
Part 2.1 Diary of Events
Part 2.2 List of Witnesses
Part 2.3 Witnesses Statements
Part 2.4 List of Attendees
Part 2.5 List of Exhibits

PART 1.2 – PRELIMINARIES

Defence Safety Authority

Service Inquiry Convening Order

15 Feb 17

SI President
SI Members

Hd Defence AIB
DSA Legad

Copy to:

PS/SofS	DPSO/CDS	MA/Comd JFC
MA/Min(AF)	MA/VCDS	MA/CFA
PS/Min(DP)	NA/CNS	MA/Dir MAA
PS/Min(DVRP)	MA/CGS	MA/JHC Comd
PS/PUS	PSO/CAS	WKF HQ Comd

DSA DG/SI/03/17 – CONVENING ORDER FOR THE SERVICE INQUIRY INTO THE LOSS OF WATCHKEEPER UNMANNED AIR VEHICLE (UAV) (WK 042) THAT OCCURRED NORTH OF WEST WALES AIRPORT ON 3 FEB 17

1. In accordance with Section 343 of Armed Forces Act 2006 and in accordance with JSP 832 – Guide to Service Inquiries (Issue 1.0 Oct 08), the Director General, Defence Safety Authority (DG DSA) has elected to convene a Service Inquiry (SI).

2. The purpose of this SI is to investigate the circumstances surrounding the 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 1430L on Wednesday 15 February 2017.

4. The SI Panel comprises:

President: **Squadron Leader [redacted] RAF**

Members: **Lieutenant [redacted] RN**
Sergeant [redacted] RA

5. The legal advisor to the SI is **Major [redacted]** (DSA LEGAD) and technical investigation/inquiry support 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

8. The SI Panel will work initially from the Defence AIB facilities at Farnborough. 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

Sir R F Garwood
Air Mshl
DG DSA – Convening Authority

Annex:

A. Terms of Reference for the SI into the loss of Watchkeeper UAV (WK042) that occurred North of West Wales Airport on 3 Feb 17.

Annex A to
DSA DG/SI/03/17 Convening Order
Dated 15 Feb 17

TERMS OF REFERENCE FOR THE SI INTO THE LOSS OF WATCHKEEPER UNMANNED AIR VEHICLE (UAV) (WK042) THAT OCCURRED NORTH OF WEST WALES AIRPORT ON 3 FEB 17

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. Establish whether there are any significant similarities to the causes identified in the loss of WK031 and/or WK006, but not to further investigate known issues.

c. Examine what policies, orders and instructions were applicable and whether they were appropriate and complied with, to include:

i. The environmental limitations for the operation of the system.

ii. The Aircraft Document Set to ensure sufficient information is available to crews to deal with emergency/unusual situations.

d. Determine the state of serviceability and protective systems of relevant equipment.

e. Establish the level of training, relevant competencies, qualifications, currency and supervision of the individuals involved in the activity.

f. Identify if the levels of planning and preparation were commensurate with the activities' objectives.

g. Report and make appropriate recommendations to DG DSA.

2. If at any stage the Panel discover something they perceive to be a <u>continuing hazard</u> presenting a risk to the safety of personnel or equipment, the President should alert DG DSA without delay; in order to initiate remedial actions immediately. Consideration should also be given to raising an Urgent Safety Advice note.

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 or International Policy and Plans team should be informed early when dealing with any other foreign state material.

4. During the course of your investigations, should you identify a potential conflict of interest between the Convening Authority and the Service Inquiry, you are to pause work and take advice from your DSA Legal Advisor and DG DSA.

GLOSSARY

AAMC	Alternate Acceptable Means of Compliance
ABU	Airborne Beacon Unit
ADCC	Approved Design Change Certificate
ADRS	Air Data Recording Systems
ADS	Air Data System
ADU	Air Data Unit
AGL	Above Ground Level
ALARP	As Low As Reasonably Practicable
AM(MF)	Accountable Manager (Military Flying)
AMSL	Above Mean Sea Level
AO	Authorising Officer
AOA	Angle of Attack
AOS	Angle of Slip
ASSC	Air System Safety Case
ATC	Air Traffic Control
ATOL	Automatic Take off and Landing
ATOLS	Automatic Take off and Landing System
ATSB	Australian Transport Safety Bureau
AVDC	Air Vehicle Display Computer
AVGAS	Aviation Gasoline
AWC	Air Warfare Centre
BDN	MOD Boscombe Down
CofC	Certificate of Competence
CAS	Calibrated Airspeed
CEH	Complex Electronic Hardware
CFAOS	Contractor Flying Approved Organisation Scheme
CFOE	Contractor Flying Organisation Exposition
CLE	Clearance with Limited Evidence
CMIC	Continuous Maximum Icing Condition
COD	Certificate of Design
CPLD	Complex Programmable Logic Device
CQT	Certificate of Qualification on Type
CRM	Crew Resource Management
CS	Client Server
CSALMO	Chief Salvage and Mooring Officer
CTPH	Crew Training Post Holder
DAE	Defence Air Environment
DAIB	Defence Accident Investigation Branch
DAOS	Design Approved Organisation Scheme
DASOR	Defence Air Safety Occurrence Reports
DCFO	Defence Contractor Flying Organisations
DE&S	Defence Equipment and Support
DH	Duty Holder
DIS	De-Icing System

DME	Defence Modification Engineering
DO	Design Organisation
DofC	Declaration of Compliance
DQAFF	Defence Quality Assurance Field Force
DRTSA	Delegated Release to Service Authority
DSA	Defence Safety Authority
EASA	European Air Safety Agency
EAT	External Air Temperature
ECU	Engine Control Unit
EEDS	Electro-Expulsive De-Icing System
EMAR	European Military Airworthiness Requirements
EOP	Electro-Optic Payload
ER	Emergency Recovery
ERL	Emergency Recovery Location
ES2	Equipment Standard 2
ESL	Elbit Systems Limited
ETPS	Empire Test Pilot School
FCS	Flight Control Software
FDR	Flight Data Recorder
FELA	Flight Execution Log Author
FEP	Flight Envelope Protection
FLAC	Flight Authorisers Course
Flt	Flight
FOB	Flying Order Book
FOO	Flight Operations Organisation
FOPH	Flight Operations Post Holder
FPM	Feet per minute
FRC	Flight Reference Cards
FSC	Flying Supervisors Course
GBU	Ground Beacon Unit
GCS	Ground Control Station
GCSVR	Ground Control Station Voice Recorder
GDT	Ground Data Terminal
GFCC	Ground Flight Control Computer
GMCC	Ground Mission Control Computer
GMTI	Ground Moving Target Indication
GPS	Global Positioning System
GPS/INS	Global Positioning System /Inertial Navigation System
GRU	Ground Radar Unit
GTOL	GPS Take off and Landing
HCI	Human Computer Interface
HF	Human Factors
IETP	Interactive Electronic Technical Publication
IFF	Identification Friend or Foe
INS	Inertial Navigation System

INS/GPS	Inertial Navigation System/Global Positioning System
IPCC	Intergovernmental Panel on Climate Change
IPR	Intellectual Property Rights
IPS	Ice Protection System
IR	Infrared
iRTS	Initial Release to Service
ISTAR	Intelligence, Surveillance, Target acquisition and Reconnaissance
JPA	Joint Personnel Administration
LLR	Lost Link Procedure
LMAR	Lightweight Multimode Air Radio
LRU	Line Replacement Unit
LS-S	Laser Sub-System
LTDRF	Laser Target Designator and Range Finder
LWC	Liquid Water Content
MAA	Military Aviation Authority
MACP	Military Aircraft Certification Process
MAOS	Maintenance Approved Organisation Scheme
MAR	Military Aircraft Register
Met	Meteorology
MFTP	Military Flight Test Permit
MRP	Military Regulatory Publications
MTC	Military Type Certificate
NAS	Naval Air Squadron
NBDL	Narrow Band Data Link
OCU	Operational Conversion Unit
ODH	Operating Duty Holder
Panel	The Service Inquiry Panel convened to investigate the loss of WK042
PATE	Portable Aircraft Test Equipment
PCDU	Power Control Distribution Unit
PCM	Post-Crash Management
PCMIO	Post Crash Management Incident Officer
PCMO	Prime Contractor Management Organisation
Pilot	The Handling Pilot of the Unmanned Aircraft
PO	Payload Operator
RA	Regulatory Article
RAFCAM	RAF Centre of Aviation Medicine
RAFMRS	RAF Mountain Rescue Service
RFC	Redundant Flight Controller
RFT	Request for Test
RH	Relative Humidity
RMTC	Restricted Military Type Certificate
ROV	Remotely Operated Vehicle
RPAS	Remotely Piloted Air System
RPM	Rotations per Minute
RSA	Royal School of Artillery

RTB	Return to Base
RTDP	Real Time Data Processor
RtL	Risk to Life
RTS	Release to Service
RTSA	Release to Service Authority
RTSR	Release to Service Recommendation
RVT	Remote Viewing Terminal
RVTIU	Remote Viewing Terminal Interface Unit
RWTES	Rotary Wing Test and Evaluation Squadron
Rwy	Runway
SAR	Synthetic Aperture Radar
SDH	Senior Duty Holder
SI	Service Inquiry
SIL	Safety Integrity Level
SMA	Safety Management Arrangements
SME	Subject Matter Expert
SQEP	Suitably Qualified and Experienced Personnel
STANAG	Standard NATO Agreement
STDA	Statement of Type Design Assurance
T&E	Test and Evaluation
TAA	Type Airworthiness Authority
TAS	True Air Speed
TCB	Type Certification Basis
TCE	Type Certification Exposition
TCR	Type Certification Report
TES	Test and Evaluation Squadron
TI	Trial Instruction
TMO	Trials Management Officer
TO	Trial Officer
TRF	Training Record Folder
TRHA	Trial Risk and Hazard Assessment
TRR	Trial Readiness Review
TSM	Trials Safety Manager
UA	Unmanned Aircraft (formerly referred to as UAV)
UAS	Unmanned Air System
UAS TEF	Unmanned Air Systems Test and Evaluation Flight
UAST	Unmanned Air Systems Team
UAV	Unmanned Air Vehicle (now referred to as UA)
UAV Cdr	UAV Commander
UTacS	UAV Tactical Systems Ltd
VMS	Vehicle Management System
VMSC	Vehicle Management System Computer
WBDL	Wide Band Data Link
WCA	Warnings, Cautions and Advisories
WK	Watchkeeper

WTF	Watchkeeper Training Facility
WWA	West Wales Airport

WATCHKEEPER OVERVIEW

1.2.1. **Introduction**. This section gives an overview of the Watchkeeper (WK) programme and system. The information provided represents the SI Panel's understanding of the system and is based on available documentation, discussions and interviews with personnel from Defence Equipment and Support (DE&S) Unmanned Air Systems Team (UAST), Thales UK, hereafter referred to as Thales, and the WK Training Facility (WTF).

Programme Description

1.2.2. **Capability.** WK is a system comprised of an Unmanned Aircraft[1] (UA) fitted with sensors and connected via data-links to a Ground Control Station (GCS). WK was designed to deliver a flexible, 24-hour, Intelligence, Surveillance, Target Acquisition and Reconnaissance (ISTAR) capability. WK is employed primarily within the Land environment and contributes to Information Superiority.

1.2.3. **Procurement**. In 2005, Thales was awarded the contract for the development, manufacture and initial support phases of the WK programme. The system was originally due to reach Initial Operating Capability by Jun 10 and Full Operating Capability in 2013. However, the programme was delayed, partly because of software certification requirements and the rectification of a number of deficiencies in the system's technical publications and training courseware.

1.2.4. **Programme Organisation**. Thales are the Prime Contractor Management Organisation (PCMO) and Design Organisation[2] (DO) for the WK system. As PCMO, Thales leads an industry team consisting of Cubic Corporation (data-links), Elbit Systems Limited (ESL) (UA design), Marshall SV (ground station shelters and ground vehicles), Altran (programme safety) and UAV Engines Ltd (engines). UAV Tactical Systems Ltd (UTacS) is a joint venture company that was created by Thales and ESL to enable technology transfer, the manufacture of and support to the WK system in the UK. UTacS also provide crews and maintenance personnel for WK air operations at West Wales Airport (WWA).

1.2.5. **Thales Flight Operations Organisation.** WK air operations have been conducted at WWA since Apr 10 by the Thales Flight Operations Organisation (FOO). UTacS Ltd provide both the Maintenance Organisation and the Design and Production Organisation, ergo providing both the engineering support and the design production support. All flying at WWA is conducted under Military Flight Test Permits (MFTP) that outline what flying is permissible and any special conditions imposed on the flying activity. The FOO is approved under the Military Aviation Authority (MAA) Contractor Flying Approved Organisation Scheme (CFAOS) and as such has a number of named post holders who are legally responsible within the organisation.

1.2.6. **Military Flying**. On 28 Feb 14 the WK platform was issued with its initial Release to Service (iRTS) and the Royal Artillery commenced flying operations at MOD Boscombe Down (BDN). In Aug 14, WK was deployed to Afghanistan in support of Operation HERRICK, whilst Thales continued to conduct Test and Evaluation (T&E) flying at WWA. In Mar 15, on return from Afghanistan the Army re-commenced WK flying operations from BDN and flying continued until 2 Nov 15. A programme was then put in place for the Royal Artillery to fly WK at Ascension

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[1] Also commonly referred to as an Unmanned Air Vehicle (UAV) or Air Vehicle (AV) throughout the Aircraft Document Set and in manufacturers technical documents. The term UA is used throughout this report, in common with the Flight Reference Cards to distinguish the UA from the Unmanned Air System (UAS), which also encompasses the ground elements of the system.

[2] Formerly referred to as the Design Authority. The Design Organisation is defined in the MAA Master Glossary as the organisation appointed by the Project Team Leader to be responsible for the design or design change of an airborne system or its associated equipment, and for certifying the airworthiness of the design by issue of a Certificate of Design.

Island Base, to allow military personnel to convert onto the Operational Conversion Unit (OCU) build standard WK allocated to the Army. T&E flying continued with the development of Equipment Standard 2 (ES2) aircraft under the FOO at WWA.

System Description

1.2.7. **Overview**. The WK Unmanned Air System (UAS) consists of a number of separate system components and support equipment that enable pre-flight preparation, launch, operation and recovery of the UA, controlled from a GCS. There are also associated ground elements to enable transportation, storage and maintenance. The major UAS components can be broken down as follows:

a. UA.

b. GCS.

c. Ground Data Terminal (GDT).

d. Automatic Take-Off and Landing System (ATOLS) comprising of:

(1) Ground Beacon Unit (GBU).

(2) Ground Radar Unit (GRU).

(3) Airborne Beacon Unit (ABU).

e. Arrestor System.

f. Portable Aircraft Test Equipment (PATE).

Unmanned Aircraft

1.2.8. The UA is the airborne element of the WK ISTAR capability. Externally it comprises a cylindrical fuselage, main wing, V-Tails, rear-mounted engine and propeller, a tricycle undercarriage and payloads, as shown in Figure 1.2.1. The UA has a length of 6.50m, a wingspan of 10.95m and an overall height of 2.18m. It has a maximum all up mass of 500kg. The fuselage is a carbon composite monocoque design. The majority of the avionic components are packaged inside the fuselage, with the payloads, undercarriage and antennae protruding outside.

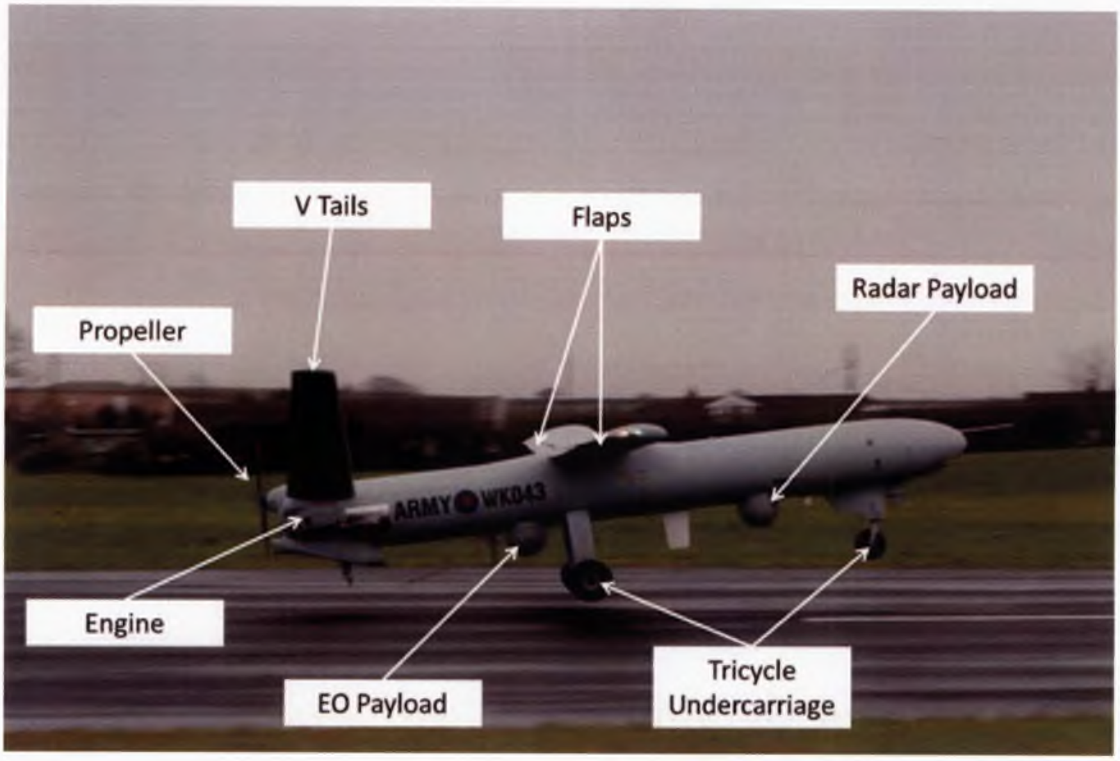

Figure 1.2.1 – Watchkeeper UA

1.2.9. **Undercarriage**. The UA has a non-retractable tricycle undercarriage and is able to take-off and land on paved and semi-prepared airstrips. It has a steerable nose landing gear assembly. There are no wheel brakes; on landing, the UA is halted by a fixed arrestor hook system.

1.2.10. **Propulsion, Fuel, Lubrication and Cooling System**. The UA is powered by a Wankel rotary engine, produced by UAV Engines Ltd in the UK, which runs on aviation gasoline (AVGAS) and drives a pusher type propeller. The fuel system comprises an integral fuel tank and collector tank designed to ensure that the engine will not run dry at low fuel levels or whilst manoeuvring. The engine is water cooled and has a total loss oil system, using Mobil Pegasus 1 oil, which is indirectly heated by the coolant system.

1.2.11. **Payloads.** The UA can carry any combination of two of the following payloads:

a. **I-Master Radar**. Fitted to the forward payload bay, the I-Master Radar payload is an airborne surveillance radar, which can operate as a Synthetic Aperture Radar (SAR) or a Ground Moving Target Indicator (GMTI).

b. **Electro-Optic Payload (EOP)**. One of the following EOPs can be fitted to the aft payload bay:

(1) EOP-P. This system has optical and infrared capabilities including a solid state optical camera, an infrared camera and a laser pointer.

(2) EOP-L. This system has optical and infrared capabilities, plus a Laser Target Designator and Range Finder (LTDRF) and laser pointer.

c. **Dummy Payload**. A dummy payload can be fitted to either the forward or aft position and has the same shape and approximate mass of the above payloads.

1.2.12. **Vehicle Management System (VMS)**. The VMS is an all-encompassing term used to describe the essential electronic installations within the UA and the associated top level tasks it carries out. It is an amalgamation of Line Replacement Units (LRUs) designed to fully prioritise and task the automated UA in providing monitoring and control, automated flight, instrument sensor feedback and navigation throughout all phases of flight. The VMS is controlled directly by software within the Vehicle Management System Computer (VMSC). The VMS has full authoritative control of the UA flying controls, utilising information derived from the UA navigation instrumentation and sensors. The operators in the GCS, therefore, only have indirect control of the flight controls via commands sent to the UA. The VMS monitors and controls the various systems on the UA where real time information is relayed via the data-links to the GCS for display on the client server Human Computer Interface (HCI).

1.2.13. **Vehicle Management System Computer (VMSC)**. The VMSC is a single LRU, which houses dual redundant computers hosting software, which control the VMS. A simplified diagram of VMSC interfaces is shown in Figure 1.2.2. The VMSC responds to the pre-programmed flight mission plan and reacts dynamically to real time commands received from the GCS via the data links. It is designed to automate routine tasks, through all phases of flight. Flight Control Software (FCS) within the VMSC controls all aspects of UA flight dynamics, power and propulsion to keep the UA in a safe and controlled flight envelope. It is a flight critical system with software designated as Safety Integrity Level (SIL) 3[3]. For ES2, the VMSC software intrgrity is being assessed against DO178B Design Assurance Level B requirements[4].

[3] SIL is a quantified level of safety system performance, with SIL 4 being the highest and SIL 1 being the lowest. SIL levels are defined using the International Electrotechnical Commission's Standard IEC 61508, which uses requirements grouped into 2 broad categories : hardware safety integrity and systematic safety integrity.

[4] DO178B is a guideline (often used as the de facto standard) for developing safety critical software, which was developed jointly by the United States Radio Technical Commission for Aeronautics and the European Commission for Civil Aviation Equipment. Design Assurance Levels for software range from A to E, with A being the highest (failure will be catasphophic) and E being the lowest (failure will have no effect). A failure of a Level B item will be hazardous such that it could have a large negative impact on safety or performance.

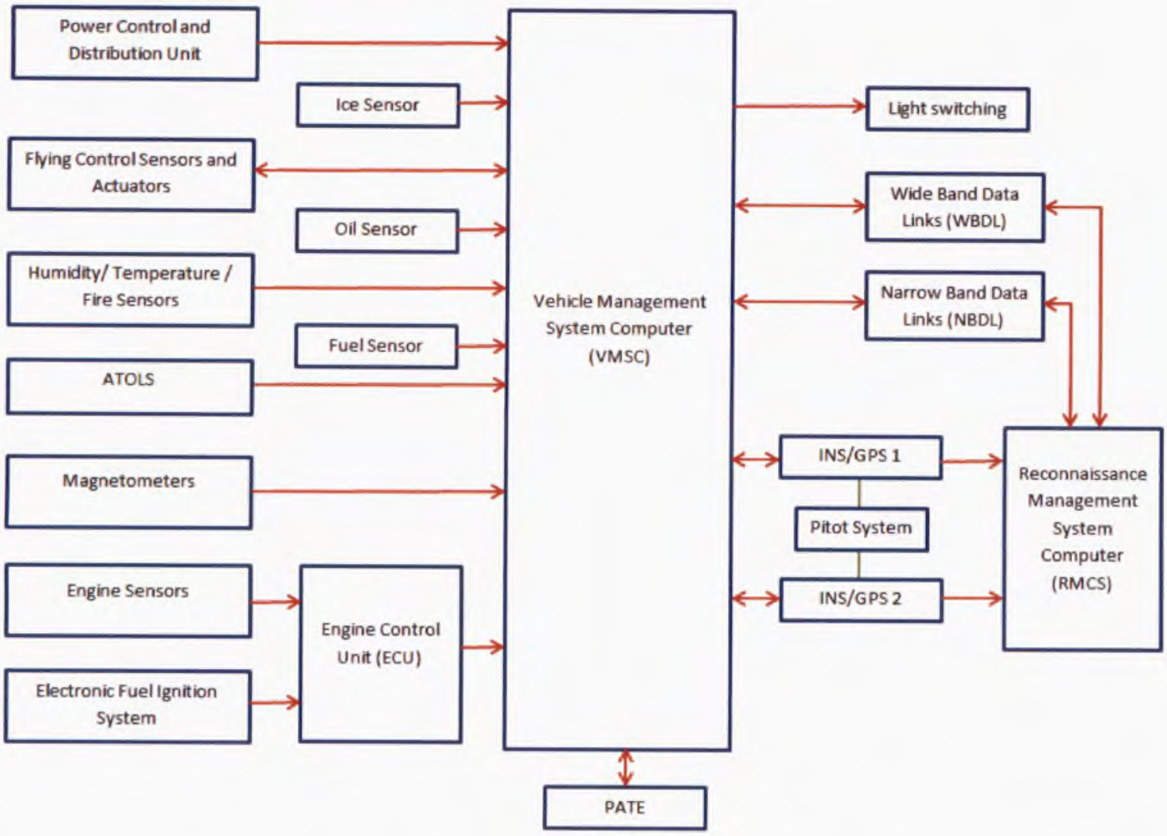

Figure 1.2.2 – A simplified block diagram of the VMSC interfaces

1.2.14. **Flight Control**. The flight control surfaces include ailerons and flaps, installed in the main wing and moving V-Tails that serve as a combined rudder and elevator. All flight control surfaces are moved by dual electrically redundant single linkage electro-mechanical actuators located in the wings and rear fuselage, under the control of the VMSC; this forms a closed loop positional feedback control system. The nose landing gear steering system and engine throttle controls are also electrically dual-redundant. The FCS within the VMSC maintains flight within a pre-designated operating envelope providing a safety margin against structural and flight limitations. The VMSC FCS is programmed to protect against operation outside of the flight envelope design limitations.

1.2.15. **Communications Systems and Data Links**. The UA can utilise the following communication systems and data-links:

a. **Lightweight Multiband Airborne Radio (LMAR**). The LMAR is a VHF/UHF rebroadcast station that allows the UA to communicate with external agencies.

b. **Wide-Band Data Link (WBDL).** The WBDL provides the primary means of communication between the GCS and the UA. It is used to transmit and receive command/control and status data and Full Motion Video. It can also be used to pass voice and data between ground elements of the system and the UA and external systems (via the LMAR). The WBDL is used to provide positional information to the UA during take-off and landing from the ATOLS.

c. **Narrow-Band Data Link (NBDL)**. The NBDL provides a secondary means of command and control of the UA from the GCS. It also provides positional information to the UA during take-off and landing from the ATOLS system.

d. **Remote Viewing Terminal Interface Unit (RVTIU)**. The UA can transmit data directly to a RVTIU, which is a portable device for viewing imagery from the UA designed to give situational awareness to an operational unit.

e. **Identify Friend or Foe (IFF)**. The UA is fitted with a Mk XII Mode 4 IFF transponder. It is controlled and monitored within the GCS.

1.2.16. **Inertial Navigation System and Global Positioning System (INS/GPS)**. The UA is fitted with 2 dual redundant Athena GS-411 integrated INS/GPS and Air Data Units (ADUs). In the event of dual INS/GPS failure (or GPS denial) the UA calculates its position by range and azimuth data from the data-link. In the event of both GPS and data link failure the UA reverts to 'dead reckoning' based on the last known good position using the INS. These modules integrate solid-state gyros and accelerometers, GPS receiver and the air data sensors to provide the VMSC with data such as position, heading, groundspeed, attitude, air data, accelerations, angular rates and rate of climb.

1.2.17. **Air Data System (ADS)**. The Air Data System provides air speed, Angle of Attack (AOA), Angle of Slip (AOS) and static pressure data, which is used for flight control and navigation. The ADS comprises:

a. **Pitot probes**. The UA is equipped with a two independent pitot probes, shown in Figure 1.2.3; a Kollsman pitot probe located on the nose and a Space Age pitot probe located on the left hand side of the fuselage ahead of the mainplane. Both supply static and total pressure to the ADUs. An additional 4 pressure measurements used to determine AOA and AOS are taken from the Kollsman pitot probe.

b. **ADUs.** The ADUs measure the static and total pressure from each pitot. Static and total pressure measurements are then differenced to provide dynamic pressure. The additional pressure measurements used for AOA and AOS calculations are differenced to obtain delta-alpha (used for AOA) and delta-beta (used for AOS) pressure. All static, dynamic, delta-alpha and delta-beta pressure measurement are then passed digitally to the VMSC.

c. **VMSC.** The VMSC monitors, records and calibrates the pressure measurements. The measurements are compared to each other and to estimated values to determine whether any measurements should be disqualified. The VMSC uses an average of the remaining measurements to determine Calibrated Air Speed (CAS), AOA, AOS. If all AOA or AOS measurements are disqualified, the FCS will use estimated values of AOA and AOS, however, dynamic pressure, and therefore CAS, is always based on actual pressure measurements rather than estimated values.

Figure 1.2.3 – Kollsman pitot probe (left) and Space Age pitot probe (right)

1.2.18. **Ice Protection System.** WK ES2 was designed to have an Ice Protection System (IPS) comprising of an:

a. **Ice detection system**. The ice detection system was fitted to the OCU build standard WK and was designed to warn crews of potential of actual ice accretion during flight. The VMSC should be capable of issuing 3 levels of ice warning:

(1) Level 1: Possible icing conditions. This is based on measurements taken from the external air temperature and relative humidity sensors, shown in Figure 1.2.4.

(2) Level 2: A condition in which ice accumulation is detected by an ice detector probe, shown in Figure 1.2.5, up to the Continuous Maximum Icing Condition (CMIC)[5]. The VMSC uses the rate at which ice accretes on the ice detector probe and True Air Speed (TAS) to compute the effective Liquid Water Content (LWC) of the air (cloud) through which the UA is flying. The VMSC holds in its memory a lookup table of air temperature verses the LWC at CMIC. This table is used to determine whether icing conditions are above or below CMIC based on the calculated LWC and outside air temperature measured by the external air temperature and relative humidity sensors.

(3) Level 3: A condition in which ice accumulation is detected by the ice detector at greater than CMIC.

b. **De-icing system (DIS).** The DIS was designed to provide an ice protection capability for ES2 UAs to complement the detection system. The DIS was designed to operate in manual and automatic modes triggered by an Ice Level 2 or 3 warning. To achieve this, an Electro-Expulsive De-icing System (EEDS) was fitted to the main wings and V-tail leading edges. Each EEDS consists of an actuator embedded between layers of carbon fibre. Large pulses of electric current pass through each actuator generating electromagnetic forces repelling the top layers, resulting in the expulsion of accreted ice from the surface.

[5] CMIC is intended to represent icing typical to stratus clouds with amounts of water between 0.2-0.8g/m^3 and droplet sizes of 15-40 microns in diameter over a 17.4 nm encounter.


Figure 1.2.4 – Relative Humidity and Temperature probe, internal (left) and external (right)

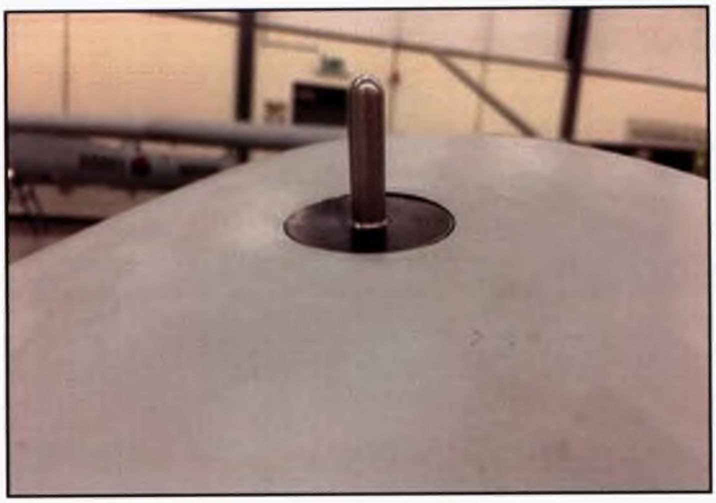

Figure 1.2.5 – Ice detector probe

Ground System Elements

1.2.19. **GCS**. The GCS is a 20ft long, specifically designed, ISO-type container used by the crew for planning missions, command and control of the UA and its sensor payloads during missions (Figure 1.2.6). It is a self-contained unit containing the main computing infrastructure for the WK system. It provides the operators with a safe work environment, which is air-conditioned and temperature controlled at all times during operation. Each GCS can accommodate a Pilot (P1), a Payload Operator (P2), UAV Commander (UAV Cdr), as well as space for 2 other crew. The GCS is fitted for BOWMAN secure military tactical Communications (Comms). It has a V/UHF ground radio for direct Comms with Air Traffic Control (ATC). Ground crew outside the GCS generally use handheld VHF radios to communicate with the ATC tower and the GCS. Further details of the GCS are as follows:

a. **Ground Flight Control Computer (GFCC).** All flight command instructions for the UA are processed by the GFCC, which checks the validity and safety of commands including; terrain clearance, air-space compliance and glide ranges to Emergency Recovery Locations (ERLs). In the absence of an input from the GFCC, the UA is designed to follow an Emergency Lost Link Procedure (LLP); if communication cannot be restored, the UA transits to an appropriate ERL. The UA is protected from erroneous inputs from the GFCC as the UA's higher integrity VMSC will only accept valid commands from the GFCC.

b. **Ground Mission Control Computer (GMCC).** The GMCC provides the monitoring and control function to the UA payloads and the data links. It also acts as a conduit for data flowing from the data-links to the Client Server (CS) and for communication between the CS and the GFCC. The Operators interface directly with the GMCC through a dual set of Hard Keys and Joysticks, and indirectly through a keyboard, mouse and monitors (Figure 1.2.7).

Figure 1.2.6 – Exterior of GCS.

Figure 1.2.7 – Interior of GCS.

c. **Client Server (CS).** The CS provides the interface for operators and is used for mission planning. With the exception of take-off and landing commands and some safety-related functions, the UA is routinely commanded by the CS interface (the GFCC ensures operators commands are valid, prior to uploading to the UA). The mission monitoring function of the CS monitors and displays the UA status and can display the UA position, airspace and route information on a moving map, or imposed on satellite imagery.

1.2.20. **Ground Data Terminal (GDT)**. The GDT is a collection of external ground equipment (Figure 1.2.8) which can be located up to 1 km from the GCS, connected by multi-core optical cable. It comprises antennae, control units and modems for both the WBDL and NBDL. Both data-links receive and transmit encrypted command, control and UA status data and the WBDL has the facility to relay imagery back to the GCS.

Figure 1.2.8 – GDT

1.2.21. **Automatic Take-Off and Landing System (ATOLS).** ATOLS is a system which allows the UA to perform Automatic Take-Offs and Landings (ATOL). It comprises the GRU and the GBU, which are situated next to the runway at accurately surveyed points and the ABU in the UA itself. Based on initial position data passed from the GCS, it tracks the position of the UA and provides 3D position information to the UA via the GCS and data-links using the GBU as a surveyed reference to enable accurate target positioning. In the event of a failure or malfunction of the ATOLS, the UA can still perform an ATOL using the GPS Take-Off and Landing System (GTOLS). The VMSC will select the more accurate of ATOLS or GTOLS during the landing phase. Therefore, the WK can perform a landing using either ATOLS or GTOLS. Figure 1.2.9 shows an example layout and the location of the different systems on the airfield.

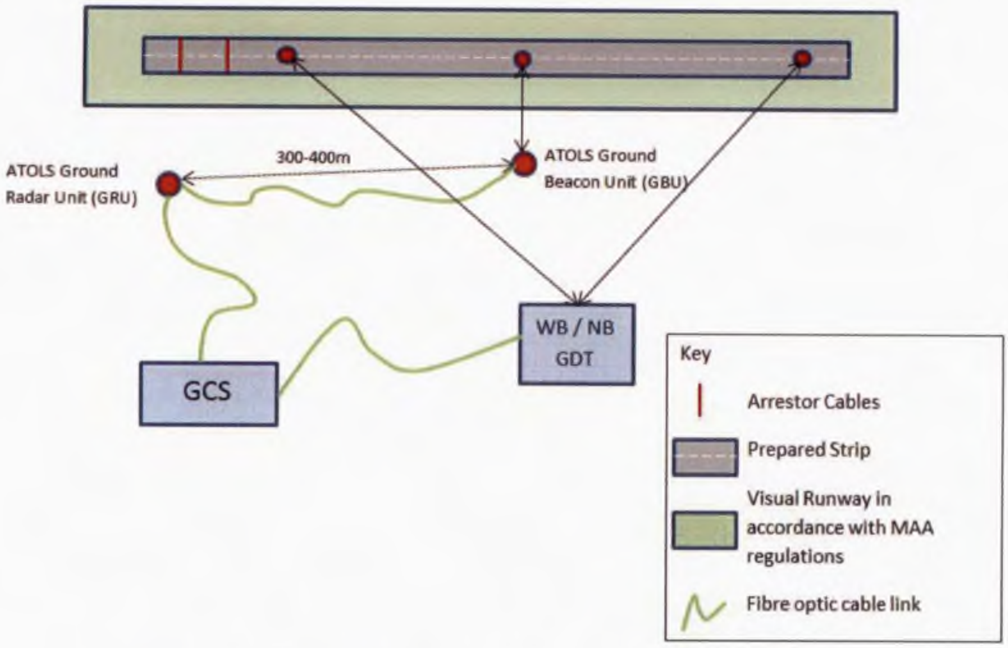

Figure 1.2.9 – Example layout of WK Launch and Recovery site

1.2.22. **Arrestor System**. The arrestor system is used to bring the UA to a smooth stop following a landing or aborted take-off. The arrestor hook on the UA catches the arresting cable laid across the runway. Adjustable braking drums hold the cable taught and provide tension and hence a braking force when the UA 'takes the cable'.

1.2.23. **Portable Aircraft Test Equipment (PATE)**. The PATE Human Computer Interface is provided by Toughbook computer that is normally housed within the Flight Line Section Command Unit, a modified Pinzgauer vehicle (Figure 1.2.10), which is also used to tow the UA during airfield /strip operations. The PATE performs a number of functions including:

a. UA functional system tests.

b. Pre-flight checks.

c. Engine start.

d. Data upload/ download.

e. Support to fault diagnostics to LRU level including payloads.

Figure 1.2.10 – A Pinzgauer vehicle equipped with a PATE towing WK to departure point

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PART 1.3 – NARRATIVE OF EVENTS

PART 1.3 – NARRATIVE OF EVENTS

All times Local (ZULU)

Synopsis

1.3.1. On 3 Feb 17 at approximately 1116hrs, a Thales UK operated Watchkeeper (WK), registration WK042 conducting Flight (Flt) 593, crashed into the sea in Cardigan Bay within the D201 Range Danger Area. Flt 593 was a dedicated icing trial, being flown as part of a series of trials for the Equipment Standard 2 (ES2) build standard aircraft[1]. The intention of the trial was to expose the Watchkeeper to icing conditions for limited periods to test that the system was able to detect and declare icing conditions and the De-Icing System (DIS) would function as designed.

Witness 1
Exhibit 1
Exhibit 2
Exhibit 3
Exhibit 4
Exhibit 5

1.3.2. WK042 departed from West Wales Airport (WWA) at 1007hrs. The Unmanned Aircraft (UA) climbed incrementally above the zero-degree isotherm into cloud but did not declare icing conditions. At 1050hrs and approximately 8800ft Above Mean Sea Level (AMSL), the UA experienced high wind that was momentarily on the allowable limits[2] and the decision was made to descend immediately. Icing conditions were not declared during the descent and the decision was made to continue the descent and return to WWA. From 1102hrs, WK042 displayed numerous warnings and cautions, including Flight Envelope Protection (FEP) manoeuvre warnings and pitching oscillations were observed on the artificial horizon. At 1115hrs the UA Commander (Cdr), believing the UA to be in a spin, declared an emergency before contact with WK042 was lost.

Witness 2
Exhibit 3
Exhibit 4
Exhibit 6
Exhibit 7
Exhibit 8

Narrative

1.3.3. FLT 593 was an attempt to trial the Ice Protection System (IPS) on WK in icing conditions, following a series of ground and flight tests of the equipment. The IPS comprised of an ice detection and warning system and an automatic DIS. Whilst the DIS was a new capability planned for the introduction of WK ES2, the ice detection system was the same as fitted to the Operational Conversion Unit (OCU) build standard, which was operated under a Release to Service by the Royal Artillery. All ES2 flying was being conducted by Thales UK under Military Flight Test Permits (MFTP) approved by the MOD's Type Airworthiness Authority (TAA) for the platform. Sortie planning took place at WWA over the 24hrs proceeding FLT 593, once the forecast Meterological conditions had been deemed favourable for the ES2 De-Icing Trial.

Witness 2
Witness 3

1.3.4. On the 3 Feb 17, WK042 was the designated UA and single WK operating from WWA. The flight crew and engineers started work at around 0630hrs in preparation for a daily flying brief commencing, earlier than normal, at 0715hrs. The flying brief consisted of; a meteorlogical (Met) brief, given by a qualified Met Officer forecaster, the sortie plan and a discussion of the UA's IPS, including icing related warnings and cautions. In addition to the De-Icing trial, additional test points to test geo-tagging capability of the Electro Optic Payload (EOP) were planned as additional activity, known as a Request For Test (RFT).

Witness 4,
Witness 5,
Exhibit 2
Exhibit 4
Exhibit 9

[1] The WK ES2 build standard aircraft had an Ice detection and De-Icing system requiring flight trials to prove it safe and fit for purpose in order to gain a Release to Service clearance for use.

[2] The Flight Reference Cards (FRCs) Iss 2 Jan 2010 AL0, page N10 allows max total wind in flight of 45Kts.

1.3.5. Take-off was planned for 0900hrs to allow for a 2hr sortie to avoid the weather, which had been forecast to deteriorate beyond the allowable limits defined in the MFTP for the recovery of the UA. Following technical difficulties encountered whilst crewing-in, the UA launched from Runway 25 at 1007hrs. Once airborne, the flight crew carried out the EOP RFT. Despite several attempts, the RFT was unsuccessful due to cloud cover obscuring the target on the ground at the test point. The crew aborted the RFT and at 1028hrs WK042 reached Danger Area D201 to commence the De-Icing Trial over the sea. Witness 2 Witness 5

1.3.6. To attempt to find icing conditions, the UA was first commanded to fly at the zero degree isotherm, approximately 3000ft AMSL and then, between 1014 and 1049hrs, incrementally to 8800ft AMSL. However, the, UA did not declare icing conditions at any point. At approximantly 8800ft AMSL high winds were observed by the UA and the crew made a decision to descend to remain within limits, using the descent to continue, albeit unsuccessfully, to find conditions that would make the UA declare icing. Exhibit 3 Exhibit 10

1.3.7. At this point a 20 minute warning was given to the ground crew enabling them to prepare for the recovery. From 1102hrs during the descent to 3000ft AMSL the UA declared multiple Air Data Unit (ADU) faults. Between 1105hrs and 1112hrs WK042 entered into a series of FEP manoeuvres and pitched up and down repeatedly between 3200ft and 3500ft AMSL, with a periodicity for each cycle averaging 27 seconds. WK042 reduced altitude to 2800ft AMSL at 1112hrs and continued to pitch up and down until 1115hrs when it desended rapidly into the sea. Figure 1.3.1 shows a visual representation of the track of FLT 593. Exhibit 3 Exhibit 6

1.3.8. After declaring a PAN the crew advised the Range Controller that the UA had crashed into the sea. The last known position of WK042 was reported to the flight crew from Aberporth Range Control and the Post Crash Management (PCM) sequence was initiated. Witness 6 Exhibit 6 Exhibit 11

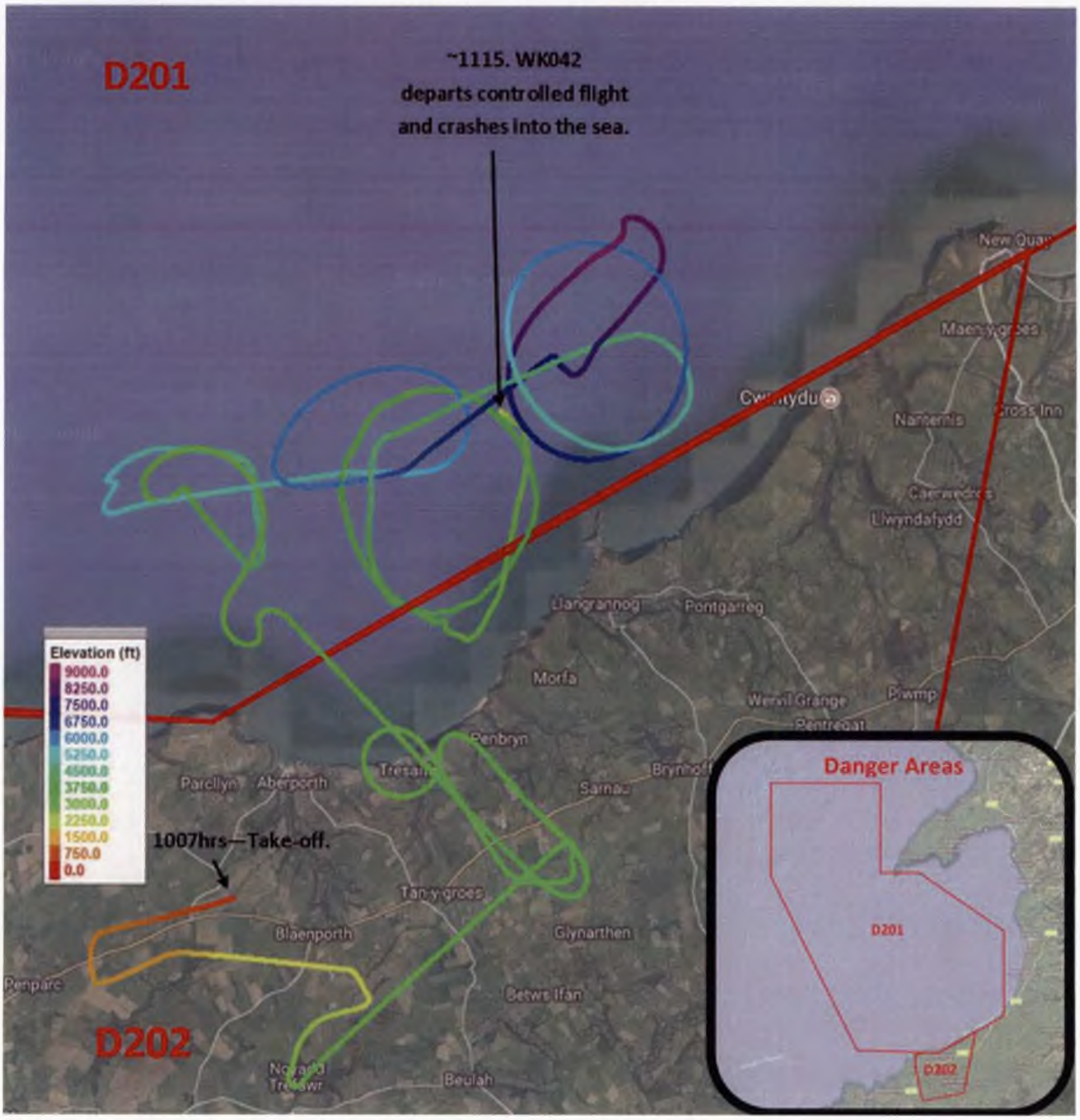

Figure 1.3.1 – WK042 flight profile

Post Crash Management

1.3.9. Initial PCM was co-ordinated by the duty Post Crash Management Incident Officer (PCMIO), a member of the flight line crew. The Ground setup and all associated documentation was impounded and the Coastguard, local police and the RAF Valley PCMIO were informed of the accident. Defence Accident Investigation Branch (DAIB) personnel arrived at WWA in the evening and took initial witness statements and gathered evidence over the following days. Under their supervision, flight data and voice recordings were downloaded from the GCS and impounded.

Witness 6
Exhibit 1
Exhibit 11

Salvage Operations

1.3.10. Using the last reported position of WK042 from MOD Aberporth range radar, Chief Salvage and Mooring Officer (CSALMO), with the assistance of the DAIB conducted a sea search on 4 - 5 Feb 17. The sidescan radar identified 2 potential items of wreckage and a Remotely Operated Vehicle (ROV) was subsequently deployed. The images from the ROV confirmed that the items were not part of WK042 and so the search team then conducted a 200m radius search of the seabed around these items. No wreckage was identified and the decision was made to cease the sea search on 17 Feb 17.

Exhibit 1
Exhibit 12
Exhibit 13
Exhibit 14

1.3.11. On completion of the initial CSALMO search, further work was conducted to extrapolate the UA's last known position to sea level, which increased the accuracy of the UA's entry point into the sea; this enabled CSALMO to conduct a further search for wreckage of WK042 on 7-8 Mar 17. This search attempt highlighted several items of interest on the seabed, but after deployment of the ROV it was again confirmed that they were not WK wreckage. Active sea search was cancelled after the second attempt.

Exhibit 15

1.3.12. On the 4 Feb 17, the RAF Mountain Rescue Service (MRS) based at RAF Valley was informed of the accident. The RAF MRS sought advice from the local Coastguard who was able to use the last known position of WK042, weather and tidal data to determine the most likely areas that any debris would wash up. Using the information gained from the Coastguard, 4 RAF MRS teams were deployed on 8 Mar 17 and conducted a coastal search. The search effort recovered a broken composite panel that was identified as part of the UA's fuselage.

Exhibit 1
Exhibit16
Exhibit 17
Exhibit 18
Exhibit 19
Exhibit 20

Intentionally blank

PART 1.4 – ANALYSIS AND FINDINGS

SECTION 1.4.1 – INTRODUCTION

Background

1.4.1.1. On 3 Feb 17 at 1116hrs a Watchkeeper (WK) Equipment Standard 2 (ES2) build variant Unmanned Aircraft (UA), registered as WK042 and operated by Thales UK, hereafter referred to as Thales, crashed into Cardigan Bay whilst conducting a trial of the De-Icing System (DIS)[1]. The aircraft took off from West Wales Airport (WWA) at 1007hrs and climbed incrementally to 8800ft Above Mean Sea Level (AMSL) seeking icing conditions. During the climb at 1039hrs, the UA reported a "Velocity Sensor Redundancy Lost" caution, which was recorded in the Ground Control Station (GCS). At the top of the climb, wind reported by the UA was at the maximum permitted and the crew decided to descend to ensure that they remained within operating limits. Icing conditions had not been declared by the Ice Protection System (IPS) on the UA and the decision to Return To Base (RTB) was made. During the descent from 1056 – 1115hrs multiple Air Data Unit (ADU) cautions were reported by the UA via the downlink to the GCS. From 1105hrs, the UA entered a series of pitching oscillations, during which the UA declared multiple Flight Envelope Protection (FEP)[2] manoeuvres until 1115hrs, when the UA departed controlled flight and crashed into the sea.

Exhibit 1
Exhibit 3

Definitions

1.4.1.2. **Air Safety.** Air Safety is defined in the Military Aviation Authority (MAA) Master Glossary[3] as *the state of freedom from unacceptable risk of injury to persons, or damage, throughout the life cycle of military air systems. Its purview extends across all Defence Lines of Development and includes Airworthiness, Flight Safety, Policy, Regulation and the apportionment of Resources. It does not address survivability in a hostile environment.* Therefore, this report considers the risk to both the safety of personnel and to equipment.

1.4.1.3. **Accident factors.** The Panel determined the accident factors and assigned them to a category according to the following definitions.

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

b. **Contributory factor.** A factor which made the accident more likely to happen, but did not directly cause it.

c. **Aggravating factor.** A factor, which made the outcome of the accident worse. Aggravating factors did not cause or contribute to the accident.

d. **Other factor.** A factor, which played no part in the accident in question, but is noteworthy in that it could cause or contribute to a future accident.

[1] The Ice Protection System (IPS) consists of a detection and warning system and an automatic De-Icing System (DIS). The detection and warning system was present on the Operational Conversion Unit (OCU) build standard of WK, but the DIS was under trial for the Equipment Standard 2 (ES2) build standard WK.

[2] A Flight Envelope Protection (FEP) manoeuvre is triggered when certain reported parameters exceed pre-programmed limits for stable flight, depending on what limit has been exceeded depends on what FEP has been triggered. The FEP is a manoeuvre the UA does to prevent stalling and to bring the UA back inside of the pre-programmed limits for stable flight. During a FEP manoeuvre, the UA will not accept any commands or inputs from the GCS.

[3] MAA02: MAA Master Glossary.

1.4.1.4. **Observations.** In addition to identifying and categorising the accident factors as described above, the Panel made a number of observations. These are points or issues, identified during the course of the Service Inquiry (SI), worthy of note to improve working practices and have a positive effect on improving overall air safety.

1.4.1.5. **Probabilistic language**. The Defence Accident Investigation Branch (DAIB) Probability Terminology Table (Figure 1.4.1.1) is designed to facilitate standardised communication of uncertainty in Defence Safety Authority (DSA) Accident and Incident reporting. The terminology used in this table is based on terms published by the Intergovernmental Panel on Climate Change (IPCC) in their Guidance Note for Consistent Treatment of Uncertainties, as well as the Australian Transport Safety Bureau (ATSB) in their paper on Analysis, Causality and Proof in Safety Investigations.

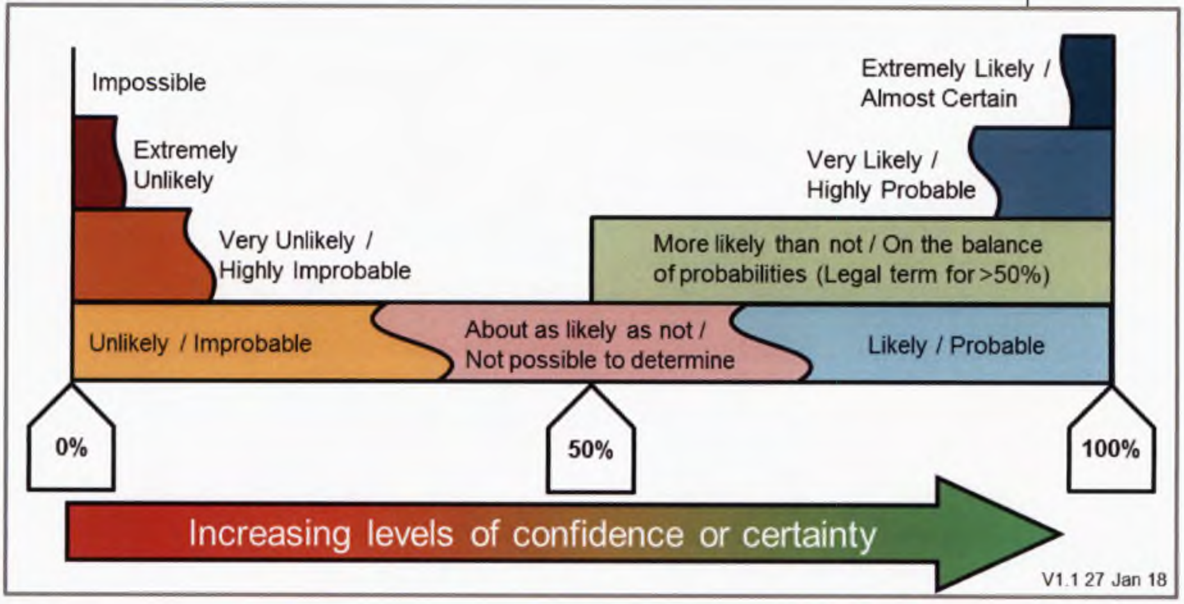

Figure 1.4.1.1 – DAIB Probability Terminology

1.4.1.6. **Human Factors (HF)**. Human Factors are defined[4] *as the interaction between; people and people, people and machine, people and procedures and people and the environment. It encompasses the understanding and application of physical, physiological and behavioural factors in the design, operation, maintenance and management of aerial systems to optimise safety, performance and capacity. It is multidisciplinary and embraces individuals, teams and organisations.* Some accident factors and observations made in this report are also identified as being HF.

Evidence

1.4.1.7. The following paragraphs list the evidence made available to the Panel. The wreckage of the UA was not located. Therefore, UA components including the Vehicle Management System Computer (VMSC) and its recorded data were not available for analysis.

[4] MAA02: MAA Master Glossary.

1.4.1.8. **Witness statements.** The Panel had access to written witness statements and recorded witness interviews. Witnesses included:

Witness 1
Witness 2
Witness 3
Witness 4
Witness 5
Witness 6
Witness 7
Witness 8
Witness 9
Witness 10
Witness 11
Witness 12
Witness 13
Witness 14
Witness 15
Witness 16
Witness 17
Witness 18
Witness 19

a. The crew of WK042, comprising of an Authorising Officer (AO)[5]/P1, P2[6] and Trials Officer (TO).

b. The Post Crash Management Incident Officer (PCMIO).

c. A pilot who was in the Air Traffic Control (ATC) tower at the time of the accident.

d. WWA Operations Officer.

e. Ground crew working on the day of the accident.

f. The Range Controller.

g. The Met forecaster.

h. Thales Accountable Manager Military Flying (AM(MF)).

i. Unmanned Air Systems Team (UAST) personnel.

j. Former Flight Test Engineer and Ice Trials Speciallist.

1.4.1.9. **Ground Control Station Voice Recorder (GCSVR).** The Panel had access to the full GCSVR recording from initial power-up on 3 Feb 17 to power-off after the crash.

Exhibit 6

1.4.1.10. **Flight data recorded in the GCS.** A sub-set of data from the Vehicle Management System (VMS) on the UA was recorded in the GCS, this was downloaded by Thales and UAV Tactical Systems Ltd (UTacS) and passed to the SI Panel. In addition, the GCS also recorded commands sent to the UA and Warnings, Cautions and Advisories displayed to the crew. Some of the flight data was also recorded in the 'Sniffer Room'[7].

Exhibit 21
Exhibit 22
Exhibit 23
Exhibit 24
Exhibit 25
Exhibit 26

1.4.1.11. **Mobile phone footage taken in the 'Sniffer Room'.** On realising that the UA was encountering difficulties, some of the ground crew recorded the final few minutes of the flight from the displays in the Sniffer Room. This footage was made available to the Panel.

Exhibit 27

1.4.1.12. **Video footage from the Electro Optic Payload (EOP).** Thales made video footage from the EOP available to the Panel. This was predominantly taken in the visible spectrum, with short sections of infrared (IR) footage.

Exhibit 28

1.4.1.13. **Wreckage.** Although the UA was not located, a number of pieces of wreckage were washed up and recovered. These included an aileron and composite material from the fuselage.

Exhibit 17
Exhibit 29

[5] The AO was also the first Pilot or P1.

[6] The P2 is the second pilot and payload operator in a Watchkeeper crew.

[7] The 'Sniffer Room' is a room away from the GCS used by system engineers for certain trials activities to monitor flight parameters real time.

1.4.1.14. **Air Safety material.** This included three Defence Air Safety Occurrence Reports (DASORs) submitted in response to the loss of WK042, previous WK DASORs and SI reports.

1.4.1.15. **Orders, procedures and guidance.** Relevant orders procedures and guidance included:

a. MAA Regulatory Articles (RA).

b. Thales Flying Order Book (FOB) Issue 9.

c. Thales Flight Operations Test and Evaluation Process Issue 2, 3 Aug 15.

d. Contractor Flying Organisation Exposition (CFOE) Issue 2, Dec 16.

Exhibit 30
Exhibit 31
Exhibit 32
Exhibit 33
Exhibit 34
Exhibit 35
Exhibit 36
Exhibit 37
Exhibit 38
Exhibit 39
Exhibit 40
Exhibit 41
Exhibit 42
Exhibit 43
Exhibit 44
Exhibit 45

1.4.1.16. **Flying and trials related documents.** Relevant flying and trials related documents included:

a. Thales Flight Operations Organisation (FOO) Authorisation sheets for the previous 3 months.

b. Crew and AO Flying Logbooks and training records.

c. Trial documentation including the Trial Instruction, Trial Readiness Review and Trial Risks and Hazards Assessment.

d. Sortie planning and briefing material including Met forecast and Flight Test Cards.

e. Flight Reference Cards (FRCs), Issue 2.

f. WK Known Problems and Workarounds Issue 3.

g. Military Flight Test Permit Issue 11, 15 Dec 16.

Exhibit 2
Exhibit 4
Exhibit 10
Exhibit 46
Exhibit 47
Exhibit 48
Exhibit 49
Exhibit 50
Exhibit 51
Exhibit 52
Exhibit 53
Exhibit 54
Exhibit 55
Exhibit 56
Exhibit 57
Exhibit 58
Exhibit 59
Exhibit 116

1.4.1.17. **Engineering records and technical documentation.** Engineering records and technical documentation included:

a. UTacS Form 700 for WK042 and Ground Systems Log Books.

b. Records of MOD F760 and F765s.

c. The WK Interactive Electronic Technical Publication (IETP) Version 9.1.

Exhibit 61
Exhibit 62
Exhibit 63
Exhibit 64
Exhibit 65
Exhibit 66

1.4.1.18. **Specialist reports.** The Panel received reports from the following Subject Matter Expert (SME) organisations:

a. No 1710 Naval Air Squadron (NAS).

b. RAF Centre of Aviation Medicine (RAFCAM).

c. The Met Office.

d. RAF Mountain Rescue Service (RAF MRS).

Exhibit 17
Exhibit 67
Exhibit 68
Exhibit 69
Exhibit 70

1.4.1.19. **Technical documentation.** The Panel was provided with, Thales and Elbit Systems Limited (ESL), hereafter known collectively as the Design

Exhibits 71 - 101

Organisation (DO), technical documentation detailing the functioning, operation and test and evaluation (T&E) conducted on various systems. The DO was also able to provide the Panel with manufacturers data for sensors and components fitted to the UA.

Services

1.4.1.20. Personnel and agencies which provided assistance to the Panel included:

a. Defence Accident Investigation Branch (DAIB).

b. Defence Equipment and Support (DE&S) and the UAST.

c. QinetiQ Flight Test Engineers and Air Data Recording Systems (ADRS) analysts.

d. Thales UK.

e. ESL.

f. UTacS.

g. Unmanned Air Systems Test and Evaluation Flight (UAS TEF).

h. MAA.

i. RAFCAM.

j. Rotary Wing Test and Evaluation Squadron (RWTES) MOD Boscombe Down.

k. Air Warfare Centre (AWC).

l. Independent Environmental Trials Specialist.

m. Previous Watchkeeper Service Inquiry Personnel.

n. Chief Salvage and Mooring Officer (CSALMO).

o. The Met Office.

p. RAF MRS.

q. WK Force Headquarters.

r. Royal School of Artillery (RSA) Watchkeeper Training Facility (WTF).

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SECTION 1.4.2 – WATCHKEEPER FLIGHT 593

Briefing cycle

1.4.2.1. **Met brief.** Most personnel involved in the flight arrived at West Wales Airport (WWA) between 0630hrs and 0700hrs. The flight brief started with a Met forecast at 0715 hrs conducted by a qualified Met Office forecaster. At the brief was the UAV Cdr (also the AO), P2, Trials Officer (TO) and the Flight Line Manager. The Met forecaster had arrived at work at 0430hrs and had prepared the brief at the Aberporth Met Office before leaving for WWA at 0700hrs. The cross-section, valid 030640Z FEB 17, is shown at Figure 1.4.2.1 below.

Witness 1
Witness 4
Witness 5
Witness 8
Witness 9
Witness 10
Witness 11
Witness 12
Witness 15
Exhibit 102

1.4.2.2. **Met forecast.** There was a low pressure to the south, with a frontal system moving north towards WWA, which was going to thicken and lower the cloud as the morning progressed. Rain was expected from around 1000hrs, which would continue intermittently for the rest of the day, with some patchy heavy rain at times, with a corresponding reduction in visibility. The cloud base would lower to around 1000ft Above Ground Level (AGL) at times, with the main cloud base staying at 1500-2000ft AGL, but with a continued risk of scattered and broken amounts of stratus beneath. At 2000ft AGL the wind was expected to increase from 25kts to 50kts by the middle of the day. Initially, surface winds were predicted to be a south-easterly flow of approximately 8kts, with gusts of 15-18kts. The gusts would increase steadily throughout the morning, reaching 18kts between 0930-1000hrs from a direction of 140°, which was across the runway. By 1200hrs the surface wind was expected to be 15-18kts with gusts of 25-30kts. Potential for moderate icing conditions in thick frontal cloud was brought to the crew's attention, with the zero degree isotherm (freezing point of water in a free atmosphere) forecast at approximately 3000ft AGL. Mountain wave activity greater than 300 feet per minute (fpm) was **not** expected in the morning, however mountain waves of 500fpm at 10000ft were forecast for the afternoon.

Witness 15
Exhibit 10
Exhibit 57
Exhibit 102
Exhibit 214
Exhibit 215

1.4.2.3. **Weather considerations.** Wind was reported to be the greatest potential issue throughout the day. Witnesses recall 0830-0930hrs being briefed as the best weather window for the flight, after which the wind would steadily increase, making it more likely that the 15kts crosswind limit for take-off and landing would be exceeded. Although not necessarily highlighted in the Met brief, but shown on the cross-section, the wind was forecast to increase beyond WK's 45kts maximum wind limit above 2000ft AGL, later in the day. The Met forecast showed that the UA had a reasonable chance of encountering moderate icing above 3000ft AGL required for the trial of the Ice Protection System (IPS). Although there were no specific limits for mountain wave activity[8], the UAV Cdr assessed that mountain waves of 500fpm would have presented a problem due to WK's rate of climb of 400-500fpm, however no mountain wave activity of more than 300fpm was expected in the morning. As expected, the Thales Flying Order Book (FOB) and the Military Flight Test Permit (MFTP) prohibited flight beyond defined wind limits. Neither the FOB or the MFTP, specifically prohibited flight when the weather was only forecast to be out-of-limits (but was not actually out-of-limits), allowing the Authorising Officer (AO) some degree of latitude to asses local

Witness 3
Witness 2
Witness 15
Exhibit 52

[8] Thales Hot Poop direction regarding Mountain Waves was released 9 Feb 17, acknowledging that there were no formal limits in the MFTP or FRCs, but instructing crews not to be airborne from 90 minutes prior to forecast mountain wave activity of greater than 300fpm to 60 minutes after.

conditions. As WK was only permitted operated from WWA, no diversion airfield was available for Flt 593.

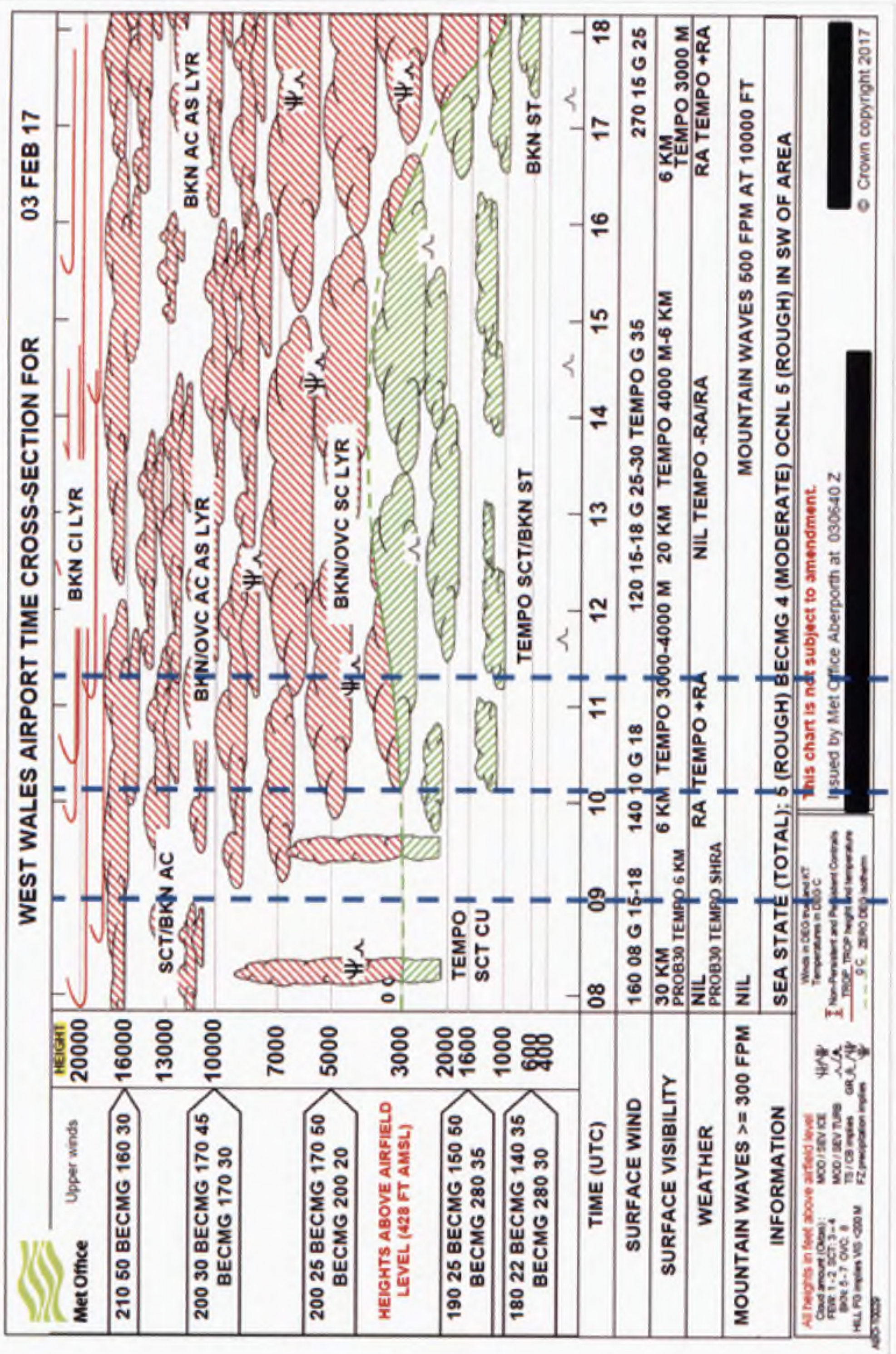

Figure 1.4.2.1 - Met Cross-Section

1.4.2.4. **Flight brief.** Following the Met brief, the crew and one additional pilot, conducted a flight brief led by the P1. The P1 was also the UAV Cdr and AO. The additional pilot was tasked to monitor the surface winds from within the Air Traffic Control (ATC) tower, which is standard practice at WWA when the wind is forecast to be within 20% of take-off and landing limits. The flight brief consisted of going through the pre-prepared Flight Test Cards and the specific test points that they wanted to achieve. Also briefed was an additional Request for Test (RFT), to test a geo-tagging capability associated with the Electro-Optic Payload (EOP). The crew also went through De-Icing System (DIS) failures and a DIS emergency. The brief was reported, during interview by those present, to be normal and unhastened, despite the need to get the sortie completed in the available weather window. Witness 2 Witness 5

1.4.2.5. **Conclusions.** The Panel concluded that the Met brief and pre-flight brief were conducted in an appropriate and timely manner for the planned activity, including the RFT, and the correct personnel were present for both briefs. The Panel noted that the crew were not prohibited from taking-off when the weather was forecast to be out of limits and that no diversion airfield option existed, but concluded that it was appropriate for the flight to be an AO decision, in common with other aircraft types. The Panel concluded that it was good practice to use the additional pilot in the ATC tower to monitor the weather. Overall, the Panel concluded that the briefing cycle was **not a factor**.

Pre-take-off

1.4.2.6. **Delay.** Take-off was planned for 0900hrs. The P2 was the first of the crew to arrive at the GCS, at approximately 0815hrs, having completed the pre-flight briefing process and found that it was not ready for crew-in[9] because the datalinks had not been acquired. The P2 was joined shortly after by the additional pilot, who was going to assist with the data checking before going to the ATC tower. The System Engineer informed the P2 that the Ground Data Terminal (GDT) location was not visible in the Client Server[10] or Air Vehicle Display Computer within the GCS. Updating the mission plan from WK043 (which was the tail number originally assigned for the sortie, but had gone unserviceable) to WK042 rectified the issue; the data links were acquired and the P2 commenced his pre-flight checks. The EOP failed to start up correctly, giving poor imagery. Powering it down and then up again seemed to fix the issue. Part of the P2 sensor checks included a Ground Moving Target Indication (GMTI) check, which was completed but failed; however, as GMTI was not required for the flight, the crew progressed with their checks. EOP imagery was lost completely when switching from the Radar Payload to the EOP. This was fixed by a Real Time Data Processor (RTDP) reset, during which time the engine was started remotely by the Portable Air Test Equipment (PATE) technician. Flight Reference Cards (FRC) checks were completed in full before taking off at 1007hrs. Witness 4 Witness 7 Exhibit 6

1.4.2.7. **Change in wind.** Table 1.4.2.1 shows the surface wind direction and speed recorded by the pilot in the ATC tower at WWA. It shows that the forecast wind strengths were broadly accurate, but the gusts were slightly lighter than expected. This met with the expectation of the crew, who, in interview, explained that surface winds at WWA were usually slightly lighter than forecast. The forecast indicated that Runway (Rwy) 25 would have a crosswind throughout the morning with the wind direction changing to give a tailwind component towards the middle of the day. The wind direction, however, changed more rapidly than expected giving a Witness 2 Witness 4 Exhibit 6 Exhibit 58 Exhibit 103

[9] Defined as crew standard operating procedures conducted in the GCS before a flight.

[10] The Client Server provides the interface for operators and is used for mission planning. It is described further in the System Description given in Part 1.2.

greater tailwind component. WK has a crosswind limit of 15kts and a tailwind limit of 5kts for both take-off and landing. The Table shows that WK042 took-off within wind limits.

Time	Description	Wind Direction (°)	Wind Speed (kts)	Headwind component (kts)*	Crosswind component (kts)
0855-0940	Mean observations	150-160	11-12	-1	11
	3 separate short (<3 mins) gusty periods observed over 45 min period	150-160	14-16	-1	15
0945-0952	Mean observation	130	7-8	- 4	6
0952-0954	Mean observation	150-160	n/r		
	'swinging to'	130	10	- 5	9
0957-0959	Mean observation	150-160	n/r		
	Single gust	130	13	- 7	11
0959	Single gust	130	13	- 7	11
1000-1006	Mean settled	130-140	7-9	- 3	7
1007	WK042 t/o from Rwy 25. Wind observed	130	8	- 4	7
1015-1116	Mean observations	130	6-8	- 4	6
	Occasional gusts	130	10	- 5	9

* Negative value denotes tailwind

Where the observation is quoted as a range, the mid-value is taken in calculating the Head and Crosswind components.

Table 1.4.2.1 – Wind observations from ATC tower and calculated head/crosswind components to Rwy 25

1.4.2.8. **Runway change.** The crew correctly concluded that they were in limits for take-off, and then requested a runway change to Rwy 07 for the UA recovery as soon as they were airborne. They requested that this be complete by 1100hrs. Had they recovered on Rwy 07 over the period 1015-1115hrs, the winds observed in the ATC tower would have given a crosswind component of no more than 9kts and a headwind of no more than 5kts, well within limits. The Met cross-section, however, indicated that the wind would be out of limits for recovery on either runway over the same period. Exhibit 6 Witness 13 Witness 7

1.4.2.9. **Conclusions.** The detail in Table 1.4.2.1 shows that the crew were aware of the conditions and the take-off limitations and actively monitored the wind using an additional pilot in the ATC tower. The Panel concluded that the weather at the time of take-off was in-limits and had no bearing on the eventual accident and therefore was **not a factor** in the loss of WK042. The Panel **observed** that the forecast indicated that the wind would be out of limits for recovery on either runway. An update from the Met Office following the delay may have provided the crew with more information of the likelihood of the weather remaining in limits throughout the flight and for the recovery. The decision to get airborne without a Met update is discussed further in paragraph 1.4.5.19 within supervision and authorisation.

Post-take-off

1.4.2.10. Figure 1.4.2.3 shows the Global Positioning System (GPS) track and height of the UA during the flight and the approximate start time of the activities undertaken. After take-off WK042 climbed north-east to 3000ft AMSL to carry out the EOP geo-tagging RFT points that had been planned. At 3000ft they were in cloud and unable to complete these test points and as time was short decided to Exhibit 3 Exhibit 6 Exhibit 58 climb above the zero degree isotherm in search of icing conditions to satisfy the de-icing test points. From this point, the rest of the flight was over the sea as stipulated in the Trial Risk and Hazard Assessment for the de-icing trial. The UA climbed to 8800ft AMSL without declaring icing or potential icing conditions. During the climb, the UA reported a velocity sensor redundancy loss, indicating a problem with an Air Data Unit or pitot blockage, which cleared after 14s. At 8800ft AMSL the crew noticed that the wind was at its 45kts limit and decided to descend. It was during the descent that an increasing number of Warnings, Cautions and Advisories (WCAs), including Flight Envelope Protection (FEP) manoeuvres, were encountered and the focus of the crew switched away from looking for the test points to dealing with them.

Exhibit 104
Exhibit 105
Exhibit 106

1.4.2.11. The first FEP manoeuvre occurred just after 1100hrs and just above 4000ft. Following the FEP the UA pitched up and climbed nearly 300ft before it then pitched down and continued with the descent. At 3360ft the UA commenced a set of pitching oscillations. Each oscillation lasted on average 27s, during which time the UA gained and lost approximately 200ft of height. During this time the crew were unable to get the UA to descend any further, but they were able to keep it flying over the sea within the D201 and D202 Danger Areas, as shown in Figure 1.4.2.2, by using a series of fly to coordinate commands. Due to the FEP manoeuvres, which take priority over new commands, the number of commands issued and the non-recovery of the UA Vehicle Management System Computer (VMSC), it is unclear which commands were accepted and actioned by the UA, however, lateral control does appear to have been maintained. The Panel concluded that the decision of the crew to remain over the sea in the D201 Danger Area was the safest and most suitable course of action.

Exhibit 3
Exhibit 107

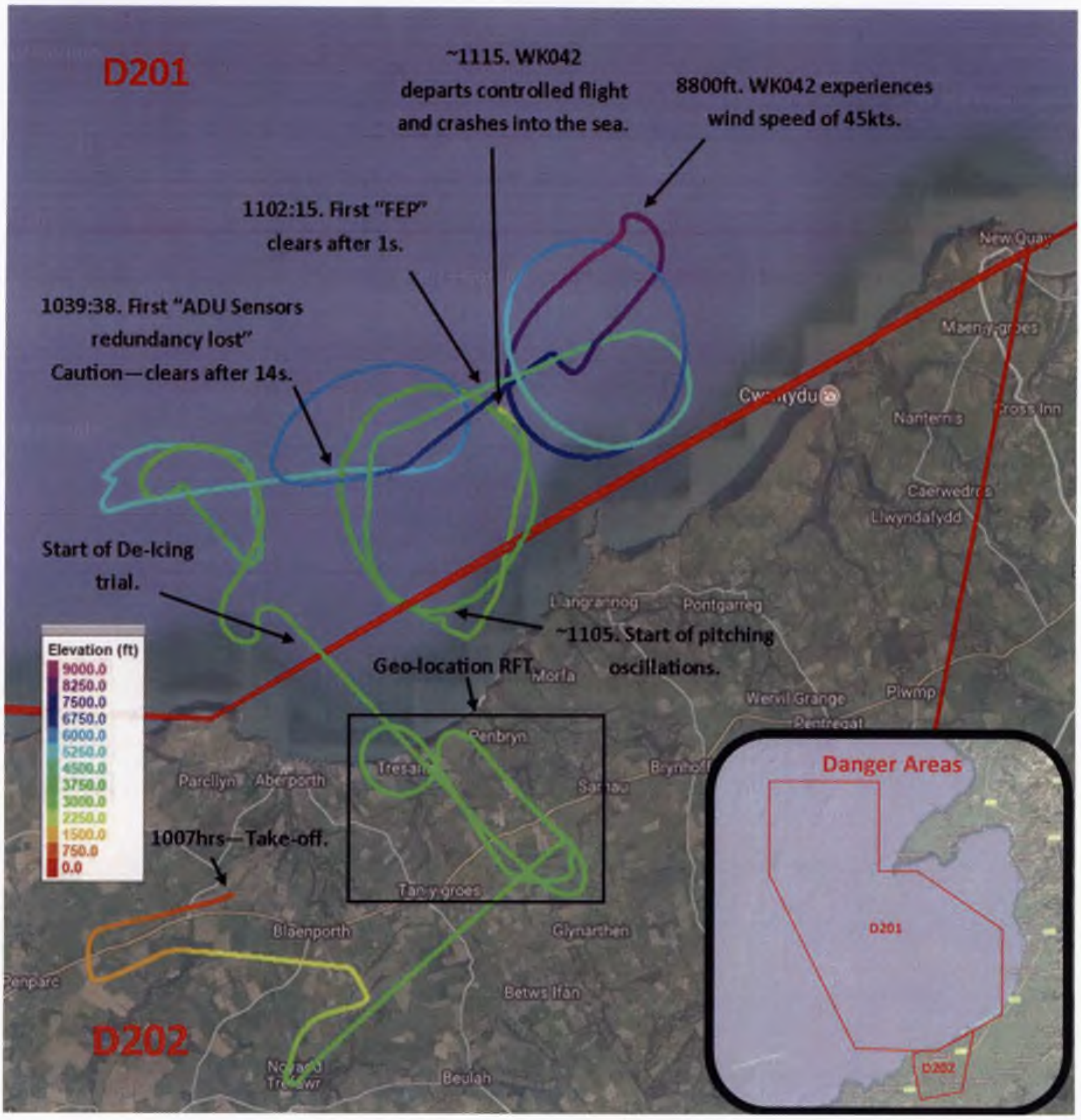

Figure 1.4.2.2 – Flight 593 overview

1.4.2.12. **Warnings, Cautions and Advisories (WCAs).** The flight altitude profile together with the WCAs seen is illustrated at Figure 1.4.2.4. The Panel reviewed and analysed the reason for each WCA and the frequency at which the crew were receiving them. A brief explanation of each WCA registered in the GCS and seen by the crew during the flight and its expected cause is at Table 1.4.2.2. The crew's response to the WCAs is considered in Section 1.4.7 under Human Factors.	Exhibit 3 Exhibit 74 Exhibit 76 Exhibit 108 Exhibit 109 Exhibit 110

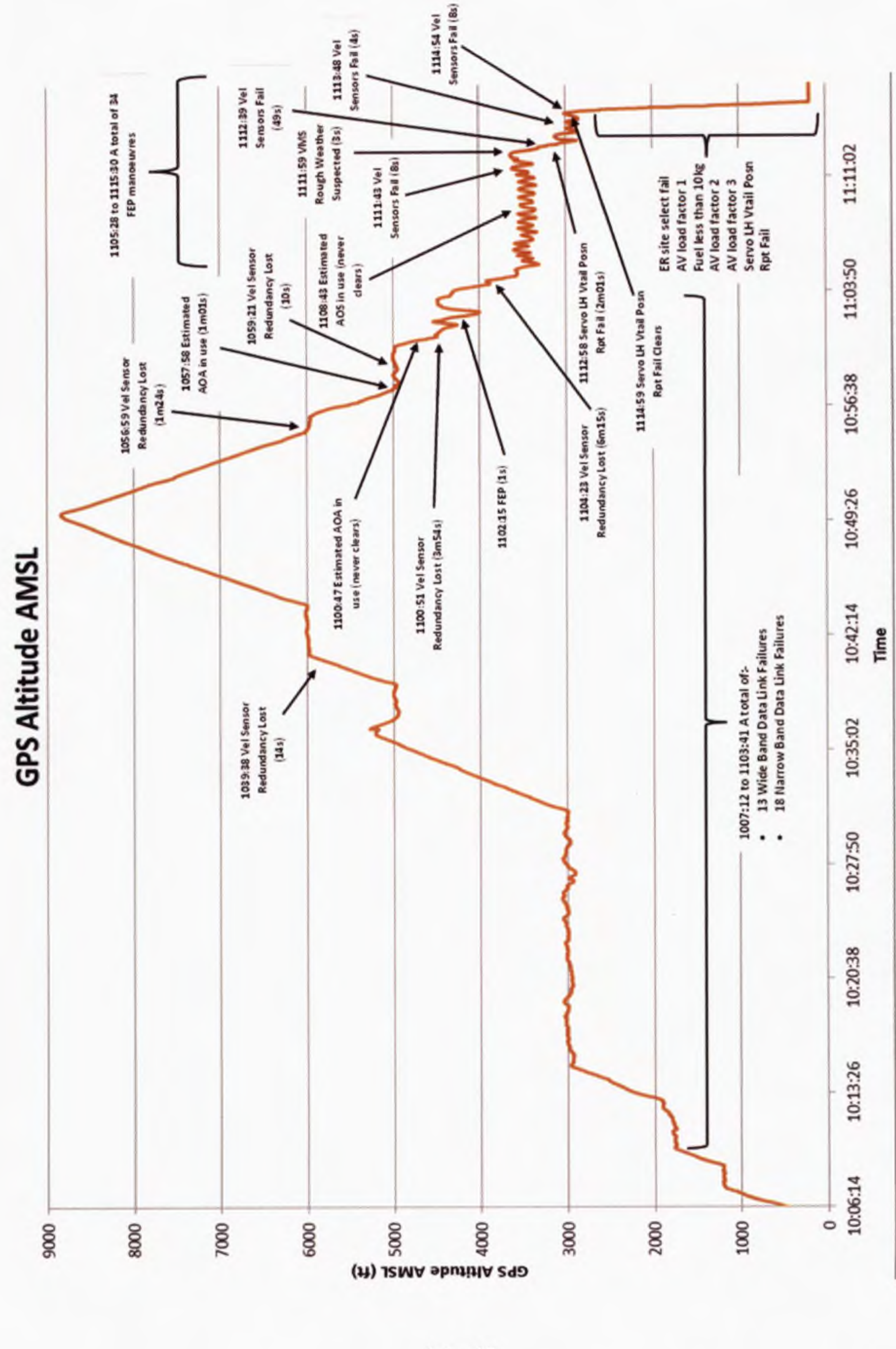

Figure 1.4.2.4 – Flight profile with Warnings, Cautions and Advisories displayed to the crew

Warnings, Cautions & Advisories	Brief description	First declaration
Caution. VMS ER site select Fail	The UA's calculated glide path potential will not enable the UA to reach the nearest programmed Emergency Recovery (ER) Site. Seen as expected during take-off.	1005:56hrs
Caution. VMS comms with WBDL Fail	Either no messages are being received via the Wideband Data Link (WBDL) or the messages are faulty.	1007:12hrs
Caution. VMS comms with NBDL Fail	Either no messages are being received via the Narrowband Data Link (NBDL) or the messages are faulty.	1032:32hrs
Caution. ADU VEL Sensors Redundancy lost	Between 1 and 3 of the 4 total pressure sensors have been disqualified by the VMSC. The UA will continue to fly using an average of the remaining non-disqualified total pressure sensors.	1039:38hrs
Caution. ADU estimated AOA in use	The VMS has switched to using estimated Angle of Attack (AOA).	1057:58hrs
Warning. Flt Envelope Protection active	Either Calibrated Air Speed (CAS) or AOA have gone outside of limits. A FEP will be initiated to attempt to restore the failure condition. During a FEP the UA will not accept commands.	1102:15hrs
Caution. ADU estimated AOS in use	The VMS has switched to using estimated Angle of Sideslip (AOS).	1108:43hrs
Warning. ADU Velocity Sensors Fail	The VMSC has declared all 4 total pressure sensors have been disqualified which may be caused by both pitots being blocked. The UA will fly from an average of all 4 sensors, which may cause the UA to enter uncontrolled pitch fluctuations, may become uncontrollable and/or enter FEP.	1111:43hrs
Caution. VMS Rough Weather suspected	The UA has reported a wind variance that is above pre-determined limits, which indicates that it may be experiencing turbulent conditions.	1111:59hrs
Caution. Servo Left VTail Position rpt Fail	There is a difference between the commanded position and the reported position of the left V-tail servo.	1112:58hrs
Caution. INS/GPS different Position data	The UA is receiving conflicting position data between the 2 INS/GPS units.	1115:10hrs
Advisory. AV Load Factor 1	The UA's measured G-Force could cause structural damage and is to be inspected after landing.	1115:17hrs
Caution. INS/GPS 1/2 No GPS	No positional data is being received from either of the INS/GPS units.	1115:18hrs
Warning. Fuel less than 10Kg	Total remaining fuel is less than 10% of total capacity. If UA is flying outside of its flight envelope then fuel readings may be inaccurate.	1115:18hrs
Caution. INS/GPS 2 less than 3 Satellites	INS/GPS 2 unit is receiving information from less than 3 satellites and therefore the UA's position/location will be degraded.	1115:21hrs
Caution. AV Load Factor 3	The UA's measured G-force could cause structural damage and at the first opportunity should be inspected during flight using the UA's sensors.	1115:22hrs
Caution. INS/GPS 1 Less than 3 Satellites	INS/GPS 1 unit is receiving information from less than 3 satellites and therefore the UA's position/location will be degraded.	1115:23hrs
Advisory. INS/GPS Degraded Position Accuracy	The UA's reported position is inaccurate.	1115:23hrs
Advisory. AV Load Factor 2	The UA's measured G-force could cause structural damage and is to be inspected after landing.	1115:23hrs
Caution. INS/GPS different GPS data	The UA is receiving conflicting GPS data between the 2 INS/GPS units.	1115:28hrs
Caution. INS/GPS Inertial data Compact check Fail	The INS unit has a difference in pitch, roll, heading and acceleration that is greater than allowed. If the failure is detected in a single INS unit the UA will switch to the remaining INS unit.	1115:35hrs
Caution. INS/GPS different Att data	The VMSC has conflicting information of attitude of the UA flight profile.	1115:36hrs

Table 1.4.2.2 – Flt 593 Warning, Cautions, and Advisories

1.4.2.13. **Ice detection.** Despite the forecast for moderate icing conditions and the crew actively seeking the thicker cloud in freezing conditions, the UA did not declare Icing Level 1, Icing Level 2 or Icing Level 3 during the flight. Icing Level 1 indicates a potential icing risk based on relative humidity and temperature measurements of above 95% and less than 2 °C respectively. Icing Level 2 or 3 indicates icing is occurring and also uses the ice detector probe. Subject matter expert analysis of the Electro-Optic Payload footage recorded from the flight, in both normal (visible light) and IR modes, suggests that there was no significant

Witness 1
Witness 2
Witness 5
Witness 19
Exhibit 3
Exhibit 27
Exhibit 111
Exhibit 112

accretion of ice on the observable parts of the airframe. The Panel noted that the view of the airframe from the EOP was limited as no upper surfaces or leading edges of the wings or V-tails could be seen. Despite this, the absence of ice accumulating on other objects in free airflow, such as the arrestor hook, suggest that it was unlikely that ice was accumulating anywhere. The UA's ability to detect Icing Level 1, 2 and 3 is discussed further in Section 1.4.8. Exhibit 113

1.4.2.14. **Conclusion.** The Panel concluded that although the UA was being flown in potential icing conditions, which is likely to have met the definition of Icing Level 1, ice accretion did not occur during the flight. Ice accretion was therefore **not a factor** in the accident.

Post-Crash Management (PCM)

1.4.2.15. The Thales Flight Operations Organisation (FOO) had a pool of qualified Post Crash Management Incident Officers (PCMIO). Immediately following the crash, the duty PCMIO, a UTacS employee and member of the ground crew, initiated PCM actions in accordance with the Thales PCM plan for WWA. These included notifying the relevant authorities, gathering aircraft maintenance documentation and aircrew records. A foot search of the Tresaith beach was conducted by personnel at WWA and the DAIB investigation team arrived on site that evening. The PCMIO kept a comprehensive record of agencies notified, actions taken, contact details of personnel involved and documentation impounded. This proved useful to the investigation. The Panel concluded that PCM actions were carried out effectively.

Witness 6
Witness 7
Exhibit 1
Exhibit 11
Exhibit 114
Exhibit 115

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SECTION 1.4.3 – DETERMINING THE CAUSE OF THE ACCIDENT

Air System maintenance

1.4.3.1. Following the accident, the following equipment and associated documentation was secured for examination:

Exhibit 1
Exhibit 61
Exhibit 62
Exhibit 67
Exhibit 116
Exhibit 117
Exhibit 118
Exhibit 119
Exhibit 120
Exhibit 213
Exhibit 216
Exhibit 217

a. **GCS.** The GCS used to control WK042 on 3 Feb 17 (GCS008) was quarantined and examined by DAIB investigators with the assistance of technicians at the FOO. The Ground Flight Control Computer (GFCC) logs and GCS Voice Recorder (GCSVR) were downloaded onto digital media. No issues with the serviceability of the GCS or other parts of the ground system were identified by the Panel.

b. **Documentation.** All UAS F700s were impounded during the PCM process. A review of the F700s was carried out by the Panel and engineers from the DAIB.

c. **Fuel.** At launch, WK042 had 38kgs of fuel on board. As the UA was not recovered, the DAIB impounded a sample of aviation fuel from WWA that was used on 3 Feb 17. The sample was sent to 1710NAS for analysis. The fuel sample was confirmed as the correct type (Avgas) and the analysis concluded that the density and total water content were satisfactory; the chemical properties did not highlight any evidence of degradation or contamination.

1.4.3.2. **Aircraft history.** WK042 had a certificate issued from the MAA placing it on the Military Aircraft Register on 29 Oct 15. It was first allotted to Thales on 10 Nov 15 and passed its acceptance tests on 8 Jun 16. At launch on 3 Feb 17, the airframe had flown 32:42hrs of its 6000hr life. The engine had used 59:48hrs of its 250 hour life, having had its first service[11] and a ground run before the flight. Both the MOD Flight Authorisation Certificate and Engine Ground Running Certificate signed by Defence Quality Assurance Field Force (DQAFF) were in date.

Exhibit 61

1.4.3.3. **UA maintenance documentation.** The Panel and the DAIB conducted a review of the UA F700 and noted the following:

Exhibit 33
Exhibit 61
Exhibit 121
Exhibit 122
Exhibit 219

a. WK042 was in date for flight servicing and all associated signatures were present.

b. WK042 had no aircraft operating limitations.

c. WK042 had no acceptable deferred faults.

d. All scheduled maintenance had been carried out in accordance with the servicing schedule.

e. Section 9 of the UA F700 was the Weight and Balance (W&B) operating data. The Panel noted that the W&B did not reflect the role state of WK042 on 3 Feb 17. The W&B data stated that the radar dummy payload was fitted rather than the radar. As the weight of the dummy payload and live payload are the same, it was normal practice at WWA not to update the W&B

[11] Engine is due a service every 62:30hrs up to its 250 hour overhaul. The engine was serviced at 59:43hrs.

data in the F700. The Panel questioned this practice and noted that there were no 'instructions for use'[12] for completing W&B in the F700.

f. Section 10 of the UA F700 gave a list of all components and their respective serial numbers that were fitted to WK042. Some of the serial numbers had been crossed out and amended by hand to reflect component changes. This was the only method of tracking what components were fitted to the UA and no electronic records existed.

g. Due to the suggestion that the loss of the UA might have been related to the V-tail, the Panel sought clarification of the maintenance of the V-tail. Flight servicing required the V-tail to be removed and refitted to gain access to the rear avionics bay. Therefore, in accordance with MAP-01 Chapter 6.10 an independent check for correct assembly of a primary flying control would have been required. This had been correctly documented as having been carried out. Additionally the UAV Cdr was required to check it as part of his pre-flight walk-round. In total 3 separate individuals signed for actions including checking the V-tail locking. The Panel were therefore satisfied that the risk of the V-tail being left unlocked and becoming detached during flight had been mitigated as far as possible and concluded that V-tail locking was **not a factor** in the loss of WK042.

1.4.3.4. **Conclusion.** The UAS airworthiness documentation provided an audit trail indicating that WK042 and the associated systems were serviceable immediately prior to launch on 3 Feb 17. The Panel therefore concluded that aircraft serviceability at take-off was **not a factor** in the accident. The Panel **observed** that there were no instructions for completing W&B in the F700 and therefore a risk existed that individuals may have completed the forms differently. The Panel also **observed** that there were no means of electronically recording UA maintenance data and therefore component lifing and tracking could be hindered as a result. At the time of the accident, Thales were however, already planning to migrate to GoldESP to address this observation and to standardise with the Army.

1.4.3.5. **Recommendation.** The Thales Accountable Manager, Continuing Airworthiness should ensure that the Form700 contains instructions for use in order to ensure that all forms are used correctly and in a consistent manner.

Initial analysis

1.4.3.6. **Crews' initial thoughts.** During the PCM triage interviews, conducted by the DAIB, the UAV Cdr reported that he believed that the Air Data Unit (ADU) related warnings and cautions indicated that the UA may have suffered a double pitot blockage. As mountain wave activity had been forecast for later in the day, the UAV Cdr reported that he believed that the pitching oscillations experienced during the flight may have been a result of mountain wave activity, although he could not be certain. As the EOP did not show ice to be accreting on the airframe and the Ice Protection System (IPS) had not declared icing conditions, the crew did not believe, either during or after the flight, that they had encountered icing conditions.

Witness 2
Witness 5
Exhibit 3
Exhibit 10
Exhibit 28

1.4.3.7. **Initial Design Organisation (DO) analysis.** Following the crash, engineers from the DO were able to download and analyse flight data that had been recorded in the GCS. The set of flight parameters recorded in the GCS is at Annex A and includes EW and NS wind speed. Wind speed is a geometrically

Exhibit 97
Exhibit 123
Exhibit 124
Exhibit 125

[12] MOD Form F700 typically contain instructions, titled 'instructions for use' at the start of each section.

derived parameter based on ground velocity (GPS ground speed north and east), true air velocity, Angle of Attack (AOA), Angle of Slip (AOS), magnetic heading, pitch and roll[13]. Analysis of the wind speed throughout the flight, shown in Figure 1.4.3.1, shows a severe wind vector change from 158° 37kts to 085° 53kts over a 27s period just after 1100hrs. This coincided with recorded sideslip angles of just over 10° and a descent of just under 500 ft. A roll to the left followed and then the pitching oscillations began. This led to an initial conclusion, by the DO, that a weather event, possibly a large gust or wind shear, had damaged the left V-tail and that the UA entered a control loop[14], unable to maintain a steady pitch until a component eventually failed, causing a catastrophic loss of control. The DO accepted that this was not a full or complete explanation and warranted further investigation. They believed it provided a good explanation as to why the left V-tail position report fail caution had cleared at the point the UA departed controlled flight.

[13] ESL provided the Panel with details of the input parameters and calculations used to calculate wind speed and the corresponding lines in the Functional Requirements Specification (FRS) for the VMSC.

[14] A control loop is defined as a series of control operations, including measuring an output, establishing what the output should be, and taking corrective action to correct it. If part of the system is damaged a control loop can often result in cyclic behaviour if the system is not able to reach a stable state, but constantly chases a parameter.

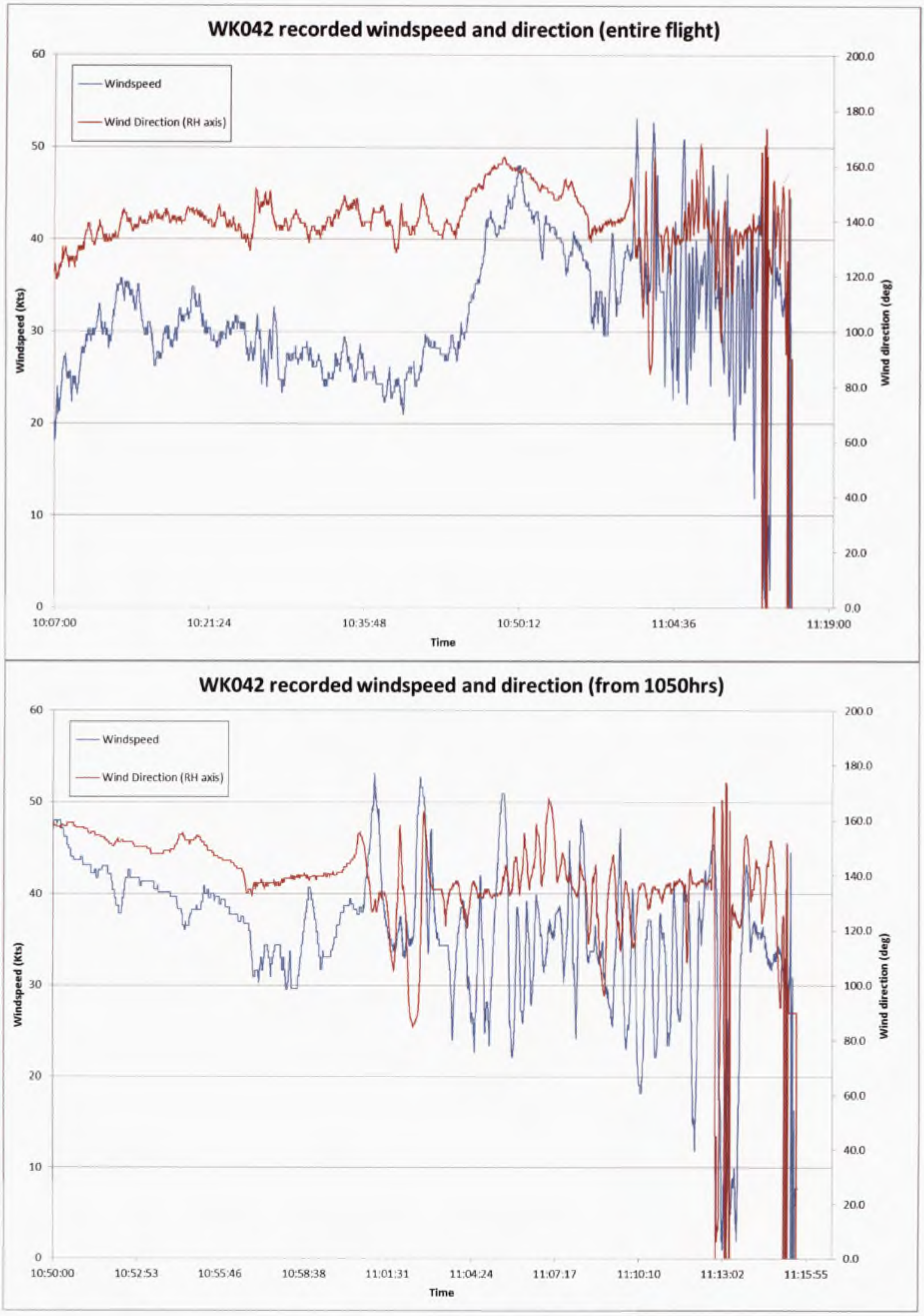

Figure 1.4.3.1 – Wind speed as measured by WK042

1.4.3.8. **Met analysis.** The Met Office produced a detailed aftercast for the 3 Feb 17, focusing on the time that WK042 was airborne and in particular from 1100hrs until it crashed at 1116hrs. The senior Met forecaster covering the MOD Aberporth range complex commented that in his experience, the conditions on the day were unlikely to have resulted in the wind vector change recorded by WK042 at the altitude that it was flying. He explained that such wind vector changes could only have been expected much closer to the surface in heavy showers, where the downdraught may have been deflected horizontally by the ground. He further commented that he believed that moderate turbulence due to mountain waves and the rainfall would have materialised as forecast, but doubted that the UA would have encountered any severe turbulence during its flight. Although no lee-wave aftercast was available, mountain waves of up to 500fpm were forecast for the end of the afternoon, however, there was no evidence that they were any greater than forecast during the flight. The Met forecaster suggested that mountain waves more in the region of 1000fpm vertical motion would have been required for the rapid descent recorded. Additionally, as WK042 was flying in precipitation during the end of its flight, the radial velocity of the precipitation had been captured at various points in time by a local Doppler weather radar. No evidence of such severe wind vector changes could be identified by the Panel when the resulting Doppler weather radar plots were analysed, although turbulence or very local wind vector changes would not be detected by the radar due to cell sizing[15]. Exhibit 69 Exhibit 126

1.4.3.9. **Conclusions.** The Panel noted that there was a mismatch between the Met as recorded by the UA systems and the conditions shown in the Met Office aftercast. Based on the analysis of the Met data, the Panel concluded that the severe wind vector change reported by the UA and recorded in the GCS data (paragraph 1.4.3.7) was highly improbable and therefore, **not a factor.** The Panel further concluded, therefore, that it was extremely likely that the wind data recorded by the GCS was erroneous after approximately 1100hrs.

Flight data analysis

1.4.3.10. The Panel analysed Calibrated Air Speed (CAS), Pitch, GPS height and engine RPM data that was recorded in the GCS. These parameters are shown against time overlaid with the WCAs received for the last 20 minutes of flight in Figure 1.4.3.2. During this time pitch and engine RPM did not have the expected effect on CAS. This was most notable during the pitching oscillations, where positive pitch (pitch-up), accompanied by a reduction in RPM, resulted in an increase in recorded CAS contrary to a logically expected decrease. Additionally, CAS could be seen to correct itself sharply both up and down. This is shown on a large scale during the last 10 minutes of the pitching oscillations in Figure 1.4.3.3. The Panel concluded that this was not physically possible and therefore determined that recorded CAS, pitch or engine RPM must have been erroneous. Exhibit 3 Exhibit 127 Exhibit 128

[15] The radar effectively measures the mean radial velocity of the precipitation in a volume of space, which is governed by its pulse duration and beamwidth (horizontally and vertically). Cell sizing therefore limits this approach to looking for wind vector changes over several hundred metres at the appropriate range from the radar.

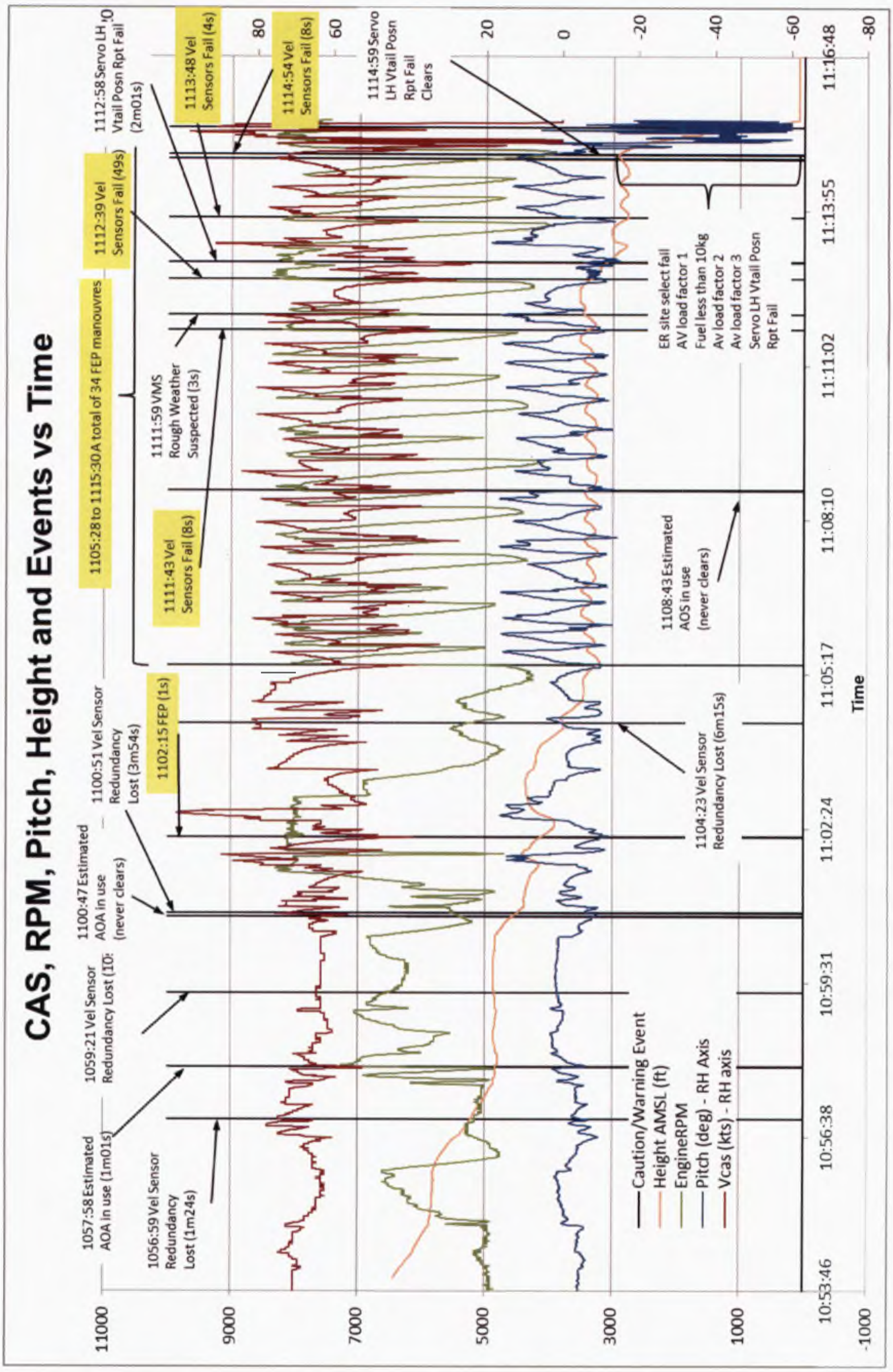

Figure 1.4.3.2– Recorded CAS, Pitch, Engine RPM and Height against time and WCAs

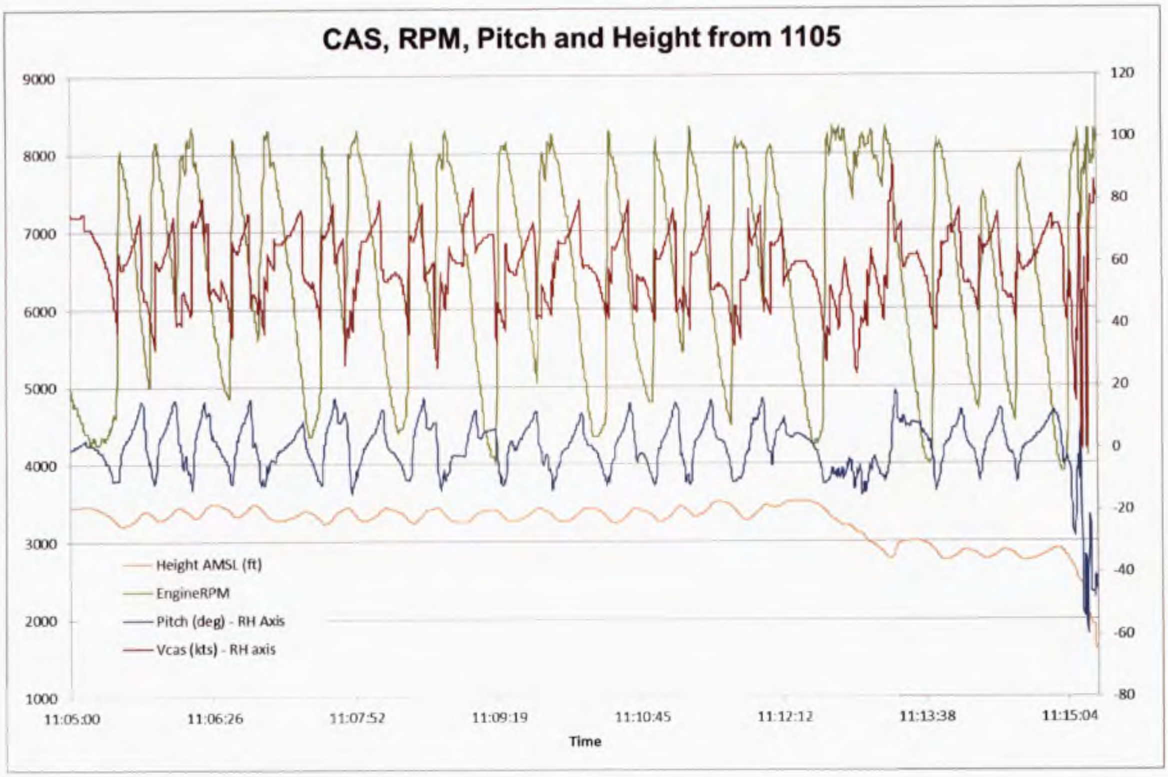

Figure 1.4.3.3 – Recorded CAS, Pitch, Engine RPM and Height against time during pitching oscillations

1.4.3.11. The UA has two Rockwell Collins Athena GS-411 Inertial Navigation System/Global Positioning System (INS/GPS) units fitted, which, along with other parameters, determine pitch. There were no WCAs indicating a mismatch between these units and a clear relationship between pitch and change in height can be seen in Figure 1.4.3.2, therefore, the Panel concluded that pitch was being reported correctly. Engine RPM is controlled by a mechanical throttle operated by a servo controlled by the VMSC. No throttle servo WCAs were recorded and there was no Engine Control Unit (ECU) throttle stuck warning that would indicate a mismatch between engine RPM and commanded power. The Panel therefore concluded that the engine RPM was being reported correctly. CAS is determined from total and static pressure measurements taken from the Kollsman and Space Age pitot probes[16]. The ADU velocity sensor redundancy lost cautions and the ADU velocity sensor fail warnings that were recorded are indicative of total pressure measurements deviating from each other and a reference value by more than defined limits. This can be due to either faulty pressure transducers or blockages in the pitot system. After analysing the data set available, the Panel concluded that the recorded CAS measurements became unreliable after 1056hrs. This supported the Panel's previous findings regarding wind speed and direction not being credible after approximately 1100hrs (paragraph 1.4.3.9) as air speed is an input into the VMSCs wind calculation.

Exhibit 3
Exhibit 78

Air speed analysis

1.4.3.12. Having determined that the recorded values of CAS were unreliable at the end of the flight, the Panel investigated whether it was possible to determine

Exhibit 3
Exhibit 129

[16] This is described in Part 1.2.

reliably True Air Speed (TAS) and CAS in order to learn more about the dynamics of the final part of the flight. To achieve this, the Panel considered the following data available to them: Exhibit 130

a. WK042 GPS position recorded in the GCS as a WGS84[17] latitude, longitude and height. This enabled the panel to determine ground speed, track heading and corrected height above sea level.

b. WK042 Magnetic heading. This allowed the Panel to compare the heading of WK042 with the GPS track heading. Differences are typically a result of aiming into wind to maintain a track heading or a result of sideslip.

c. Doppler Weather radar measurements over the period. These showed the wind radial velocity in relation to the radar as a series of snapshots over time. The Panel were able to analyse the changes in radial velocity[18] in the region in which WK042 was flying in order to estimate the wind speed and heading. This analysis is described further in Annex B.

1.4.3.13. True air velocity, ***V***, the aircraft's velocity in relation to the body of air in which it is flying, can be determined using the velocity triangle, shown in Figure 1.4.3.4, from the GPS velocity, ***S***, and the wind velocity, ***W***. True Air Speed (TAS) is simply the magnitude of the vector ***V***. The Panel were able to determine ***S*** from the GPS position data reported from WK042 and recorded in the GCS, however as previously concluded the reported wind speed was unreliable after ~1100hrs. The Panel, therefore, had to estimate wind speed and direction as a 95% confidence range based on the Doppler weather radar data; for example, between 1111hrs and 1122hrs the mean wind speed was between 16 and 19m/s on a heading between 134 ° and 144 °. This analysis is presented at Annex B.

Figure 1.4.3.4 – Velocity Triangle

1.4.3.14. At low speeds and altitudes, CAS can be calculated from TAS if the air density is known. Air density was found from pressure and temperature measurements in the air data recorded in the GCS. The Panel were able to calculate CAS based on the wind analysis from 1100hrs. The calculated CAS Exhibit 3

[17] WGS84 or World Geodetic System 84 is the earth centred fixed terrestrial reference system around a geodetic datum with constants that model the earth's size and shape. WGS84 is the standard commonly used in GPS navigational systems including the Athena units fitted to WK.

[18] In a uniform wind field the change in radial velocity with heading from the radar will form a sine curve with the zero velocity heading being perpendicular to the wind heading. Over a local region, where the wind field may be assumed to be uniform, it is therefore possible to estimate wind speed and heading by looking at the change in wind radial velocity. Assuming the look-up angle of the radar is relatively small, this is only true of the horizontal wind component.

values are shown in Figure 1.4.3.5. The Panel noted that the UA flew above its maximum speed of 85kts and below its stall speed[19] of 43kts over the period, with the lowest speed at 1115hrs. Flight data shows that this corresponded with a right hand roll to 11.6^0 then the left hand wing dropping to in excess of 70^0, accompanied by a rapid loss of height[20]. This is shown in Figure 1.4.3.6. The Panel concluded that WK042 had experienced an aerodynamic stall from which it did not recover.

[19] Based on the aircraft weight and fuel state from 1100hrs.

[20] Maximum permitted roll for Watchkeeper is 25 °.

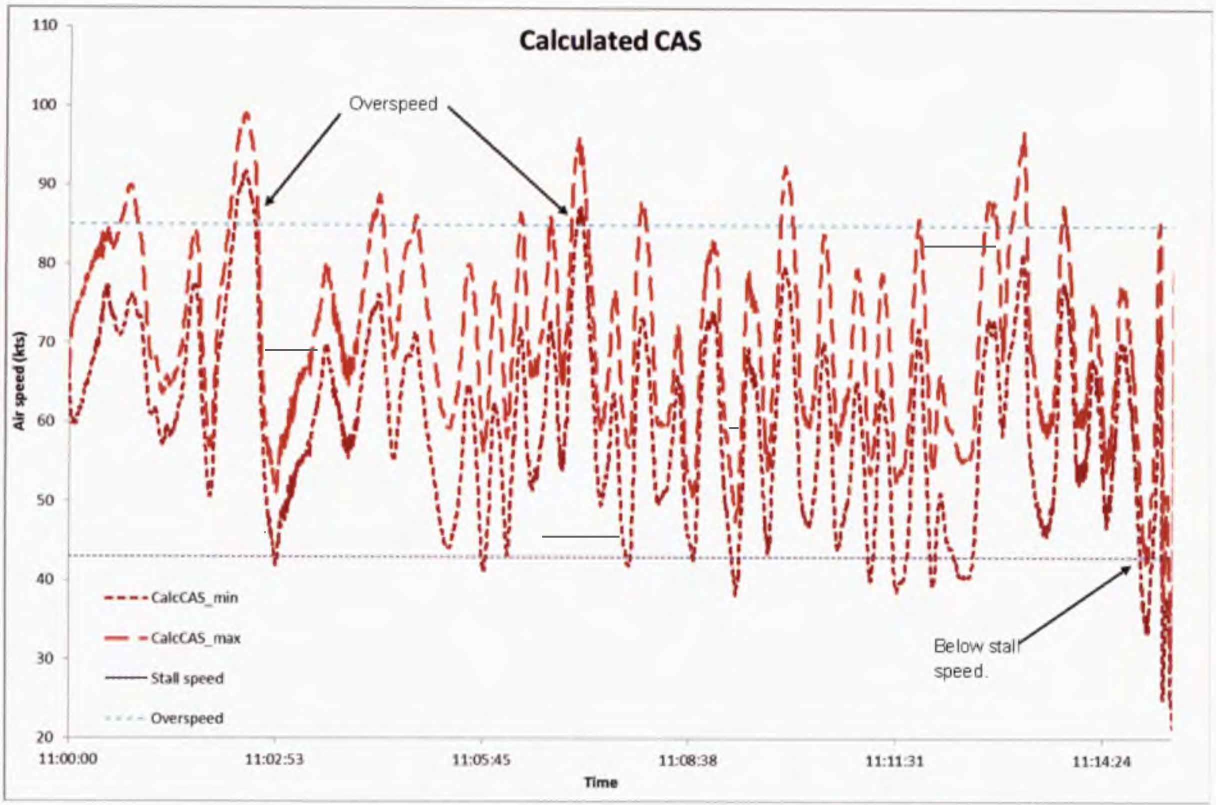

Figure 1.4.3.5 – Calculated CAS range from 1100hrs

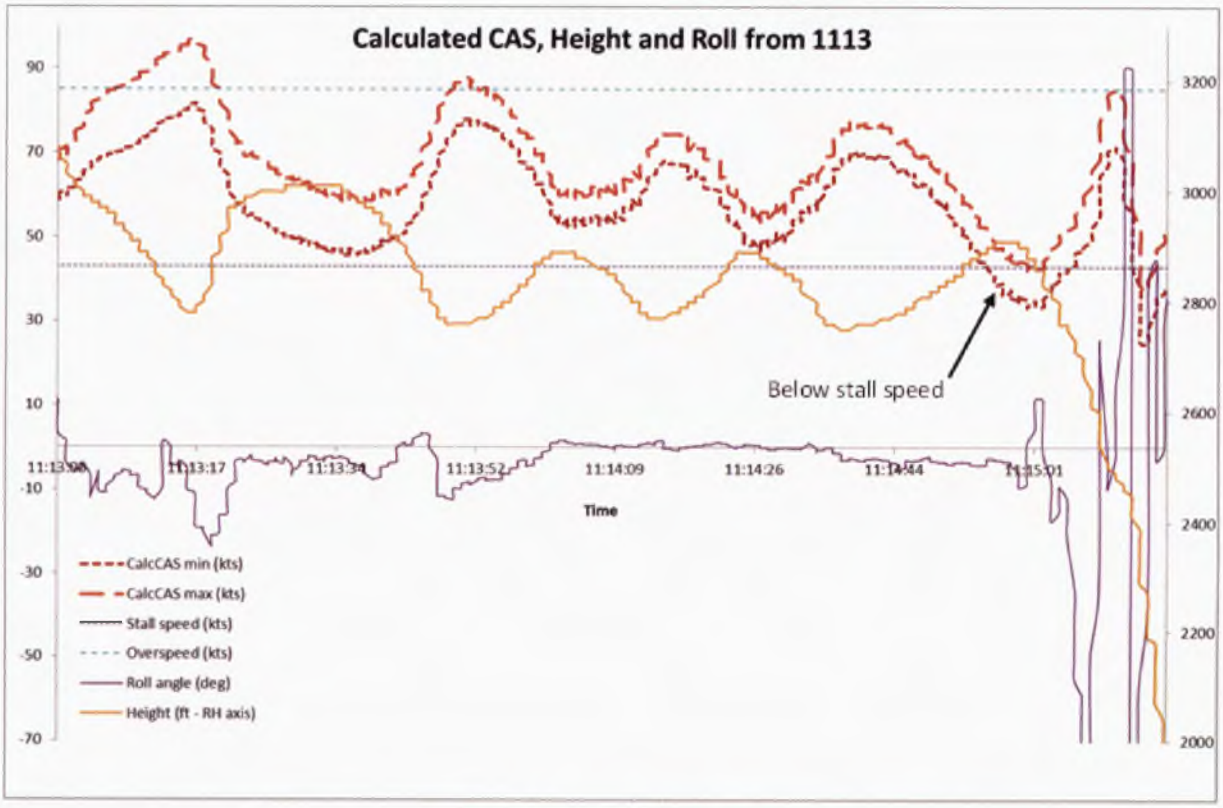

Figure 1.4.3.6 – Calculated CAS range, roll and height from 1113hrs

Air data

1.4.3.15. **Air Data System (ADS) architecture.** To understand the likely cause of erroneous CAS and the sudden fluctuations in CAS seen at the end of Flight 593, it was necessary to understand how a value of CAS is determined from the Kollsman and Space Age pitot probes, for use by the Flight Control Software (FCS), within the VMSC. An overview of the ADS is shown in Figure 1.4.3.7. Both the Kollsman and the Space Age pitot probes are conventional type heated pitot probes that measure static and total pressure external to the aircraft. The Kollsman pitot probe also measures AOA (alpha) as two pressure measurements and AOS (beta) as two pressure measurements. Each air pressure is separated at an air splitter and fed to pressure transducers in the Rockwell Collins Athena GS-411 INS/GPS Air Data Units (ADUs), labelled as INS/ADU1 and INS/ADU2, to be measured digitally. Dynamic pressure (the difference between total and static pressure), static pressure and alpha and beta differential pressures are passed as digital data to the VMSC. The VMSC determines values for CAS, AOA and AOS, which are used by the FCS. Details on the algorithm used to calculate these parameters are at Annex C, however, key points are:

Exhibit 77
Exhibit 78
Exhibit 85
Exhibit 86
Exhibit 99
Exhibit 100
Exhibit 101
Exhibit 131
Exhibit 132
Exhibit 133

a. The VMSC applies calibration factors and compares sensor measurements with each other and with a dynamic pressure reference value and estimated alpha and beta values.

b. The dynamic pressure reference value and estimated values are calculated based on additional inputs to the VMSC from the INS/GPS units and other sensors, as shown in Figure 1.4.3.7.

c. For CAS a set of logic conditions, based on the difference between dynamic pressure measurements and the dynamic pressure reference value, are used to determine which calibrated values will be used and which will be disqualified.

d. For alpha and beta, logic conditions are also used, but estimated values can also be used as the final solution, unlike CAS, which will always be derived from actual air data.

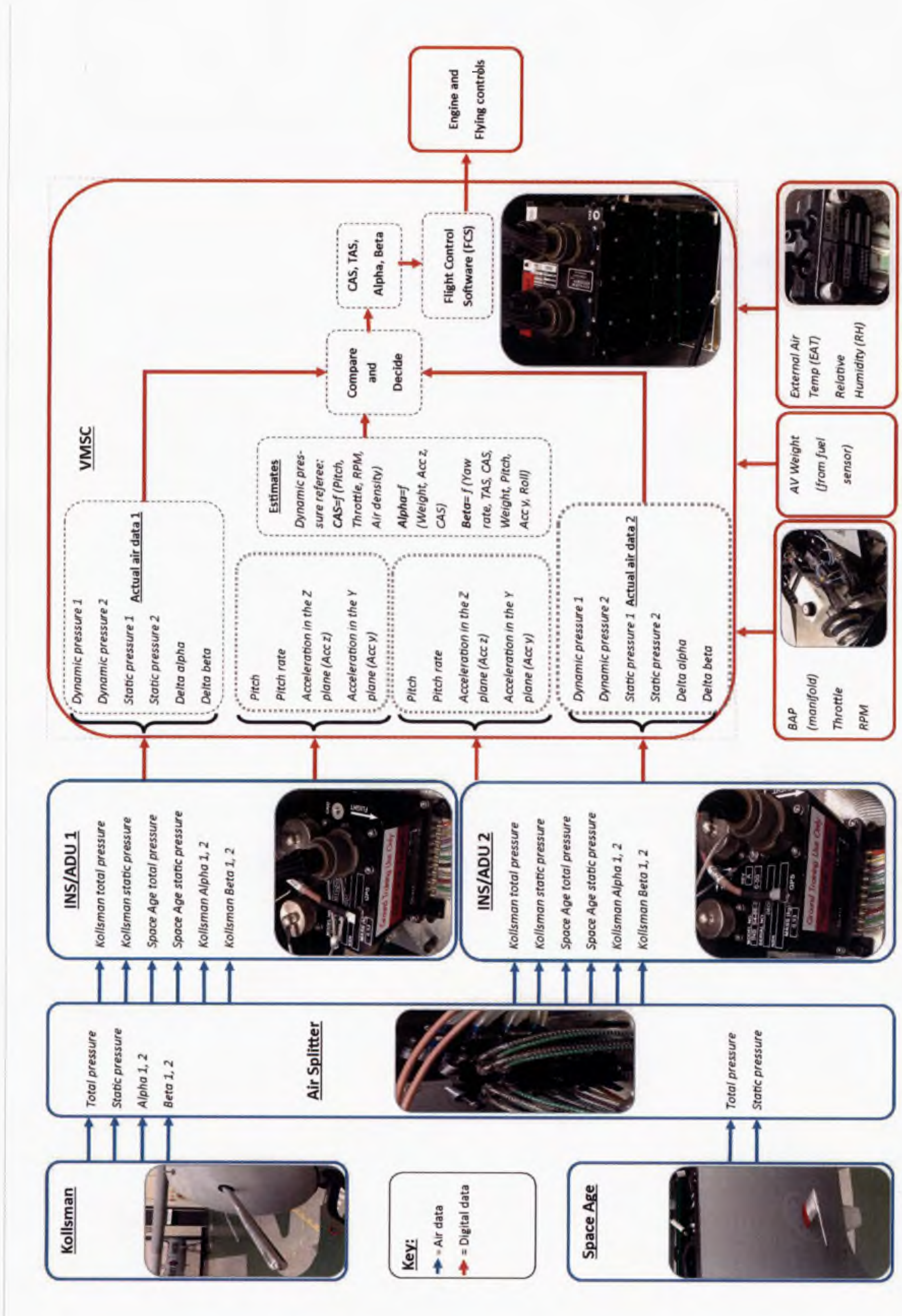

Figure 1.4.3.7 – Air Data System architecture

1.4.3.16. **Cause of erroneous CAS.** Prior to the loss of WK042, the DO had determined that ADU cautions and warnings had previously been caused by moisture in the pitot system, which had accumulated into blockages affecting the total pressure measurements. The DO had taken measures to address this issue through a combination of pitot purges as part of the maintenance schedule and by permanently operating with the pitot heaters on. Erroneous CAS readings can also be caused by incorrect static pressure readings. This was, however, ruled out by the Panel by comparing recorded static pressure and temperature with GPS altitude and observing the expected relationship between temperature and pressure[21]. The Panel, therefore, concluded that the cause of the erroneous CAS was inaccurate total pressure measurements due to blockages in the pitot system. Exhibit 58 Exhibit 134

1.4.3.17. **Cause of pitot blockages.** The Panel confirmed that the correct ground maintenance had been recorded as having been carried out on the pitot system and that the pitot heaters were ON[22] during the flight. This and the absence of any ADU related cautions indicated that it was extremely unlikely that the UA took off with blocked pitots. It is highly probable, therefore, that moisture accumulating in the pitot system during flight was the cause of the pitot blockages. The Panel considered two mechanisms by which water could accumulate in the pitot system: Exhibit 61 Exhibit 135 Exhibit 136

a. **Droplet ingress**. Although both pitot systems fitted to the WK are unvented internally[23], so that no air flows through them, the systems are open in free airflow at the point of measurement. It is, therefore, possible for foreign matter, including water droplets in cloud or rain to enter the pitot tube. Analysis shows that, whilst very small droplets are carried in slipstreams around the stagnation point, as shown in Figure 1.4.3.8, other droplets may leave the slipstream and enter the end of the pitot tube, due to their mass and higher relative momentum[24]. Therefore, in cloud or rain conditions it may be possible for enough water droplets to enter the pitot tube over a period of time to cause a blockage. The rate at which a pitot is likely to block, will be a function of airspeed, pitot design, liquid water content of the cloud or precipitation, the water droplet size, the temperature of the droplets and air and the effectiveness of the pitot heaters. It is, therefore, currently not possible to comment on what would constitute a 'safe' exposure time to cloud or precipitation or rainfall rate, however, for WK the DO have a large repository of relevant flight data, with which to make an assessment.

b. **Condensation**. Neither the Kollsman or Space Age pitot probes are heated uniformly along their lengths. The condensation point of water would, therefore, have varied throughout the probe; the lowest point being at the unheated parts. This is illustrated in Figure 1.4.3.9, where it can be seen that the inner walls of the pitot tube are electrically heated preventing condensation and evaporating any moisture entering the tube, but causing a

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[21] Defined by the hypsometric formula, applicable up to approximately 27,000ft after which the relationship between temperature and pressure becomes linear.

[22] On the ES2 build standard the pitots turn on automatically at take-off, therefore should be recorded as being on throughout the flight. The crew are able to check that they are on.

[23] The Space Age pitot has a small drain hole close to the tip, which improves its resilliance to blocking ahead of the drain hole by building a pressure differential which should move a liquid blockage. Aft of the drainhole the system is unvented. The size of the drain hole is small in relation to the pitot bore, hence pressure bleed is minimal and only a negligible amount of air will flow out of it, which is calibrated for in software.

[24] For reference, cloud droplets typically range in size between 0 and 100 microns in diameter with a mean of 10-15 microns. Early theoretical analysis, carried out for the DO, shows that at 25 m/s, droplets of greater than 3 microns in diameter are likely to be ingested by the Kollsman pitot.

temperature gradient along the tube and a condensation risk in any cold spots. Accumulation of the condensate could then block the tubes further back in the system. It is common on rotary wing platforms for pitot systems to be fitted with moisture traps, which are drained periodically as a maintenance activity.

The Panel believe that whilst the heaters are very likely to have been effective at evaporating any water entering the probe, it is possible that this would have increased the relative humidity inside the tube, with condensation forming at cooler points. WK042 was flying for an extended period in cloud and during its descent in sleet and then rain after having been cold soaked at a higher altitude below freezing point. It is therefore very likely that the blockages in the later part of the flight were caused by a combination of precipitation droplet ingress and condensation. It is also very likely that the velocity sensor redundancy loss caution seen briefly earlier in the flight was a result of precipitation ingress, which was quickly cleared by the heaters.

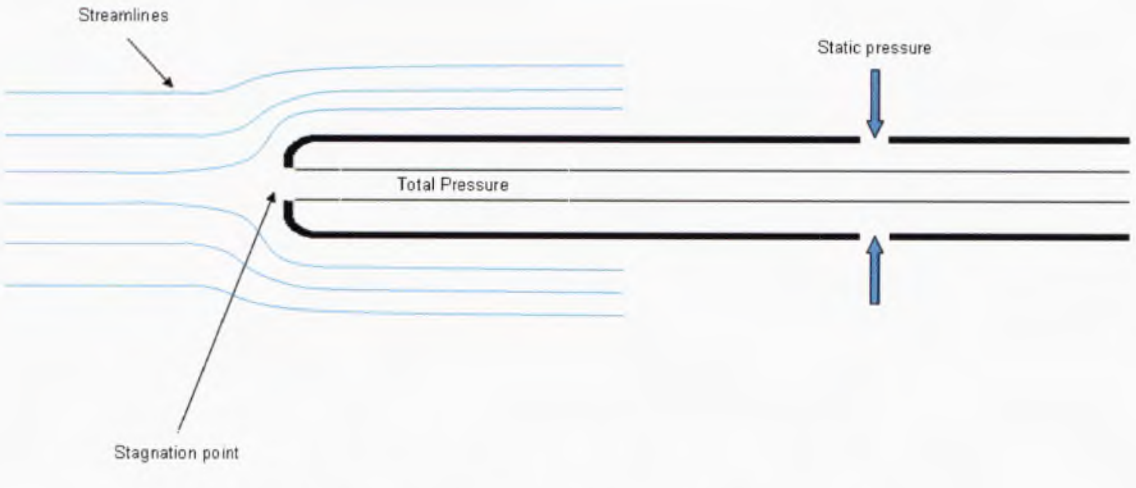


Figure 1.4.3.8 – Air flow around a pitot probe

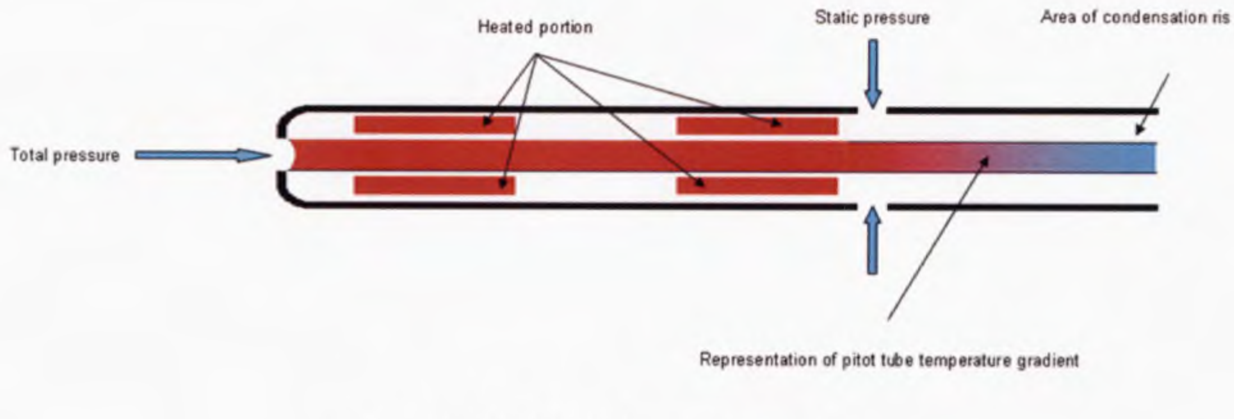


Figure 1.4.3.9 – Typical heated pitot probe

1.4.3.18. **Effect of pitot blockage.** As previously concluded, CAS was erroneous during the pitching oscillations, which the Panel determined is very likely to have been caused by moisture blocking the pitot tube total pressure feed. As CAS is based on the dynamic pressure, which is the total pressure minus the static pressure, relatively modest changes in altitude can have an effect on the CAS reading of a blocked total pressure feed. This is because static pressure reduces as altitude increases, increasing the relative pressure of air trapped behind a blockage on the total pressure side. The opposite is true when altitude decreases. A well-documented symptom[25] of a blocked pitot tube is an observed increase in instrumented airspeed in a climb and a decrease in a descent. This is illustrated in Figure 1.4.3.10. It is also possible that due to changes in AOA changing the total pressure ahead of the blockage, that pitch may also have an effect. Due to the pressure differential changing over the blockage, the weight and viscosity of the water, the blockage may temporarily clear, move and reform as illustrated in Figure 1.4.3.11. Changes in pitch are also often associated with changes in altitude and hence static pressure, will of course also change as illustrated. Exhibit 96 Exhibit 220

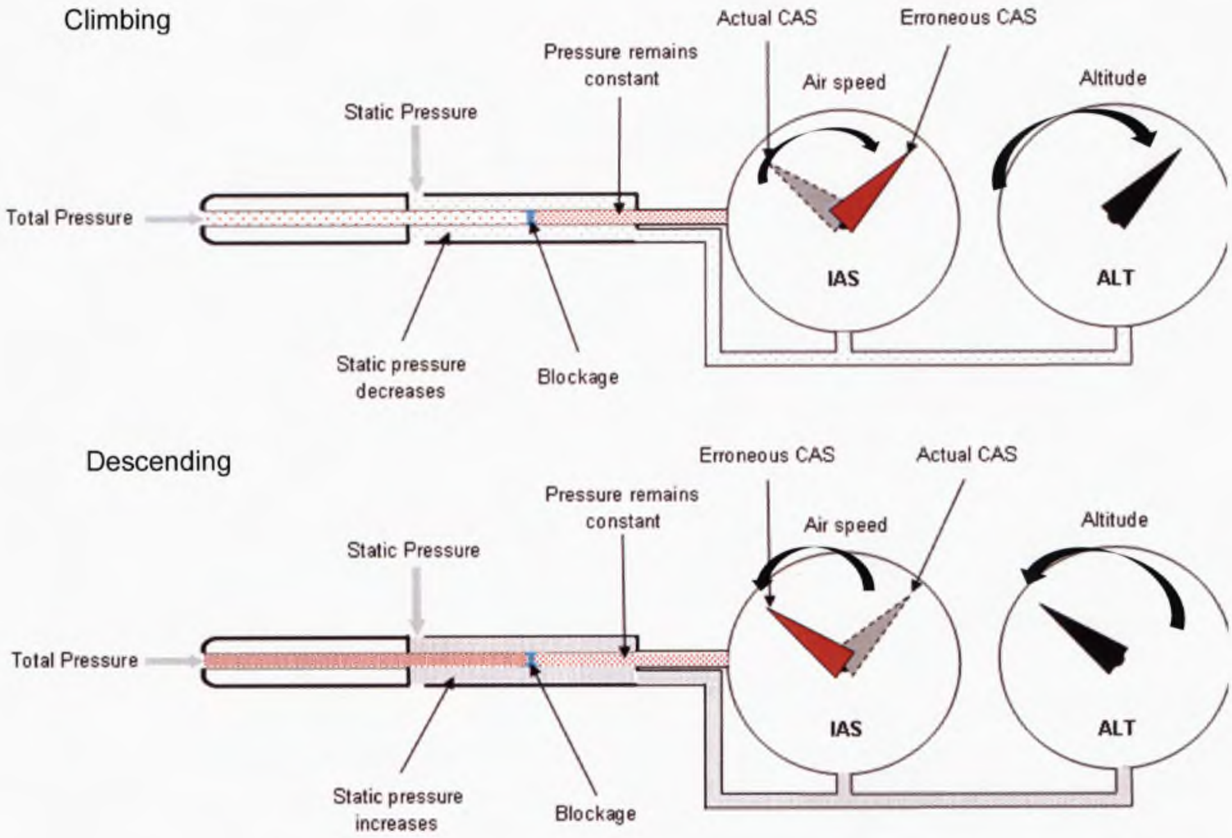


Figure 1.4.3.10 – Effect of pitot blockage on air speed with change in altitude

[25] AP3456 Chapter 5 describes the effect of pitot blockages on air speed indicators.

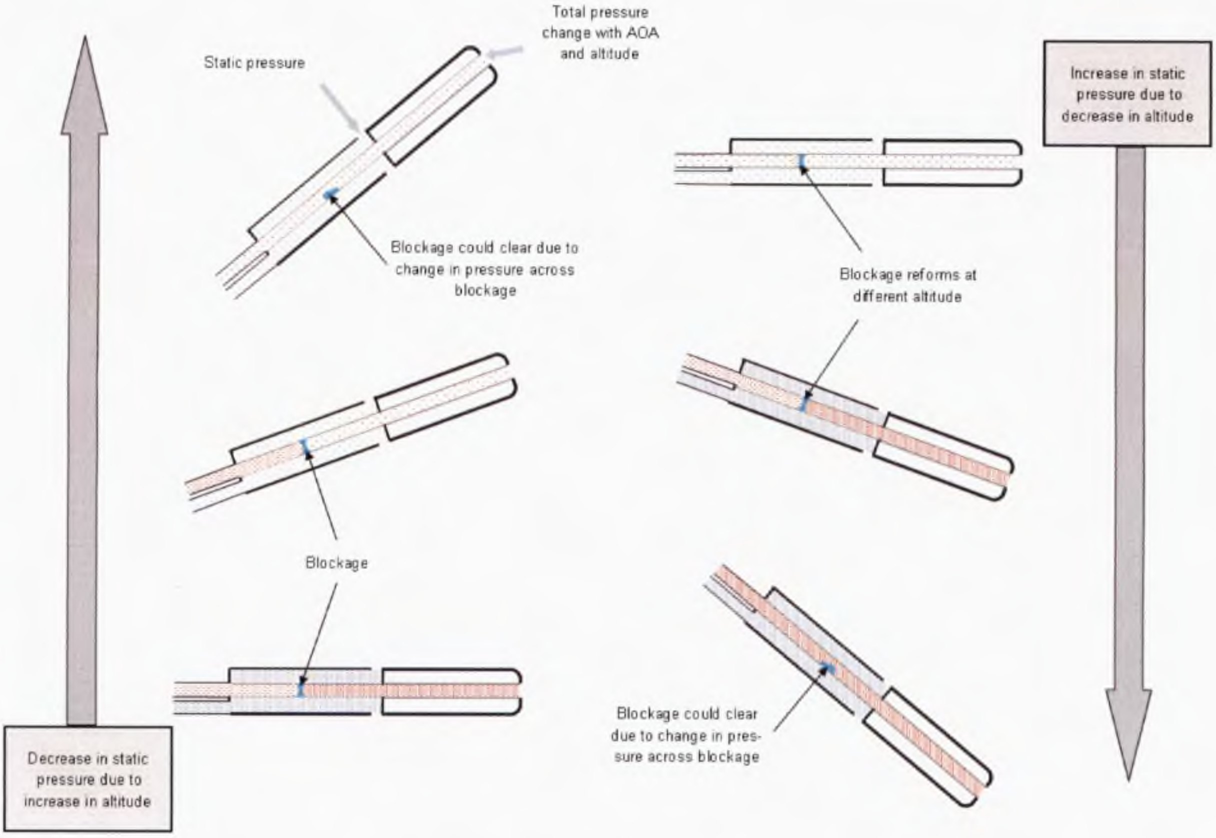
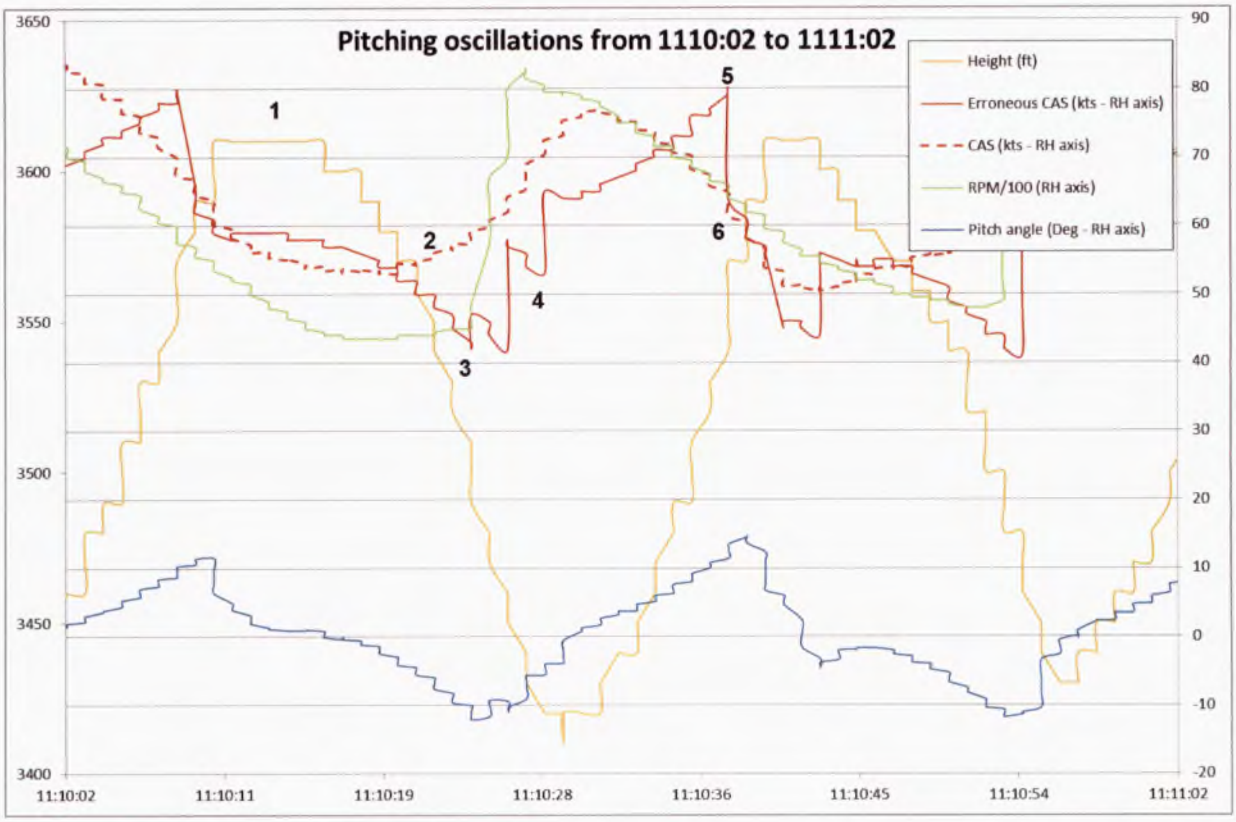


Figure 1.4.3.11 – Effect of pitch on pitot blockage

1.4.3.19. **Cause of pitching oscillations.** With CAS sensitive to pitch and changes in altitude, it is therefore possible that the FCS could respond unexpectedly to an erroneous change in CAS driven by a pitch or altitude change. For example, a high CAS input may trigger the FCS to command a reduced throttle setting or increase AOA. A corresponding increase in height would cause a reduction in static pressure and relative increase in total pressure in a blocked pitot, hence causing the erroneous CAS input to increase further. If the CAS reading then corrected due to the blockage clearing temporarily or the measurement being disqualified by the system, a low CAS input (from the reduced throttle setting and increased angle of attack) would result. This would trigger an increase in throttle and pitch down causing CAS to increase and restarting the cycle. This is illustrated in Figure 1.4.3.12. Further evidence supporting this hypothesis can be found in FRC Card E9, where it stated that *uncontrollable pitch oscillations* might be associated with ADU Velocity Sensor Fail Caution. The Panel were unable to positively determine the origin of this statement in the FRCs, but believe it to be a carry-over from the Quick Reference Handbook, which was based on Hermes 450[26] documentation and used by ESL during WK trials in [redacted] and at WWA before the FRCs had been developed. The Panel concluded that it was highly likely that blocked pitots caused the pitching oscillations seen at the end of the flight.

Exhibit 58
Exhibit 137

[26] Hermes 450 was an ESL Medium Altitude Long Endurance (MALE) UA of similar size to WK, formally operated by the Royal Artillery as an Urgent Operational Requirement.



Period	Description
1 - 2	CAS diverges from the erroneous CAS value being used by FCS. The UA begins to fly slower than FCS believes, so RPM is set lower than required, which induces a slight reduction in height. This causes static pressure to increase slightly. The blocked pitot causes a relative reduction in total pressure in relation to static pressure, hence dynamic pressure decreases and CAS becomes erroneously low.
2 – 3	The UA continues to pitch down in an attempt to maintain CAS.
3 - 4	In response to low erroneous CAS, RPM increases in an attempt to maintain CAS, despite a -10 degrees nose down. This is followed by series of CAS corrections upwards (either due to pitot blockage clearing or pitot disqualification logic). FCS increases pitch in response to higher reported RPM value and CAS. As the UA pulls up the blockage reforms and CAS becomes erroneous again.
4-5	RPM reduces as reported CAS become satisfactory. The UA continues to pitch up in an attempt to reduce CAS, however, a reduction in static pressure with the increase in height, induces a relative increase in total pressure and CAS becomes erroneously high.
6	CAS corrects downwards (either due to pitot blockage clearing or pitot disqualification logic) and the cycle restarts.

Figure 1.4.3.12 – Examples of erroneous air speed driving pitching oscillations

1.4.3.20. **Other effects of erroneous CAS.** The Panel noted that the VMSC used total pressure to calculate a number of other air data parameters. Erroneous CAS would have resulted in erroneous wind calculations, TAS, AOA and AOS measurements and could affect estimated values. Erroneous TAS in turn has an effect on the effective liquid water content used by the VMSC to determine if icing conditions are above the Continuous Maximum Icing Condition (CMIC)[27]. Table 1.4.3.1 shows the main air data parameters, the measurements that are used to calculate the parameters and the sensors on the UA responsible for the measurements. The Panel noted that, whilst as shown in the Table, an erroneous measurement can affect multiple parameters, there is a good level of redundancy in the overall system to mitigate single sensor failure. In the opinion of the Panel, however, the software algorithms used to identify and disqualify single sensor failure were not always well understood by the DO within the UK. Consequently, the effectiveness of the algorithms at maintaining the integrity of the air data required by the FCS for safe flight was in part unknown.

Exhibit 75
Exhibit 78
Exhibit 96
Exhibit 138
Exhibit 139

[27] CMIC is intended to represent icing typical to stratus clouds with amounts of liquid water between 0.2-0.8g/m^3 and droplet sizes 15-40 microns in diameter over a 17.4 nm encounter. The VMS uses the rate at which ice accretes on the ice detector probe and the measured temperature and relative humidity to calculate CMIC. If conditions are below CMIC, an Ice Level 2 warning will be generated; above CMIC, an Ice Level 3 caution will be generated.

 ~~OFFICIAL-SENSITIVE~~

LRU level sensor		Pitot (Kollsman or Space) Age)		Kollsman Pitot				INS1/ADU1 INS2/ADU2							Engine			Temp & RH Sensor		Ice Detector	Fuel Sender	Magnetometer
Measurement		Total Pressure	Static Pressure	Alpha 1	Alpha 2	Beta 1	Beta 2	Pitch	Roll	Yaw Rate	Pitch Rate	Acceleration Y	Acceleration Z	GPS Pson	Throttle Posn	RPM	BAP	External Air Temperature	Relative Humidity	Ice accretion	Aircraft Weight	Aircraft heading
Parameter	Calibrated Air Speed (CAS)	✓	✓					×							×	×	×	×				
	Dynamic Pressure Reference Value (CAS referee)		✓					✓							✓	✓	×	✓				
	True Air Speed (TAS)	✓	✓					×							×	×	×	✓				
	Angle of Attack (AOA)	✓	✓	✓	✓						✓		×				×	✓			×	
	AOA Estimate	✓	✓										✓				×				✓	
	Angle of Slip (AOS)	✓	✓			✓	✓		×	✓	×	×					×	✓			×	
	AOS Estimate	✓	✓						✓	✓	✓	✓					×	✓			✓	
	Wind	✓	✓	✓	✓	✓	✓	✓	✓					✓	×	×	×	×				✓
	Turbulence	✓	✓	✓	✓	✓	✓	✓	✓					✓	×	×	×	×				✓
	Continuous Maximum Icing Condition (for icing Level 2 and 3	✓	✓					×							×	×	×	✓		✓		
	Ice Level 1 – ice risk																	✓	✓			

✓ Measurement used to derive parameter   × Measurement not used but may cause parameter to be penalised or disqualified

Table 1.4.3.1: Air Data Parameters and Sensors

Flight Envelope Protection (FEP) manoeuvres

1.4.3.21. FEP manoeuvres, known as FEPs, are pre-programmed responses to high or low AOA and low air speed conditions, designed to keep the UA within its flight envelope. FEPs take priority over other flight commands and therefore it may appear that the UA is not responding to commands whilst the UA is in FEP. The basic declaration and cancellation conditions are given in Table 1.4.3.2. Exhibit 123

FEP Type	Declaration	Cancellation	Pitch Command (°)	Throttle Command
Low Air Speed	<Vstall + 1 m/s	>Vstall + 3 m/s	0	Wide Open
High AOA	AOA > 10 °	0 ° < AOA < 7 °	+3	
Low AOA	AOA < -8 °		+3	Idle

Table 1.4.3.2 – FEP conditions and responses

1.4.3.22. The Panel analysed the recorded air speed and AOA measurements for each recorded FEP against the criteria in Table 1.4.3.2. Full analysis of each FEP is at Annex D. The Panel noted that all the FEPs were in response to low recorded air speed or high AOA measurements resulting in wide open throttle and 0° or 3° of pitch being commanded. Wide open throttle could be seen to be commanded, when the throttle setting was not already high in response to the low (erroneous) air speed. The commanded 0° or 3° pitch was often not achieved before the air speed or AOA cancellation condition was met. Exhibit 3

1.4.3.23. **Conclusion.** As previously discussed, both air speed and AOA were likely to have been erroneous during the FEPs, therefore, although the FEP response was correct based on the erroneous air data, a FEP was not always required. Equally, where air speed was close to the stall condition, but the UA believed CAS to be higher, no FEP was initiated, unless the AOA (also potentially erroneous) was recorded as being too high. The Panel determined that it was highly likely that the UA flew perilously close to its stall speed on a number of occasions during the pitching oscillations as a result of erroneous CAS, before it stalled at 1115hrs as discussed in paragraph 1.4.3.14. The Panel concluded that the FEPs had little or no effect on the pitching oscillations and therefore were **not a factor**.

Stuck V-tail simulation

1.4.3.24. The DO conducted modelling and simulation to investigate whether a stuck V-tail or physical damage to a V-tail could have been a factor in the loss of WK042. Their analysis considered this possibility in isolation from the air data system issues and for the purpose of the simulation assumed that the air data was correct in order to assess the effect of a stuck V-tail. The simulation showed that a single V-tail stuck in the same position could result in the UA pitching up and down with a constant frequency and amplitude. Due to the limitations of the model used the exact shape of WK042's pitching oscillations could not be recreated. Exhibit 140

1.4.3.25. Of note, the simulation showed that the pitching oscillations would be accompanied by rolling motions, as with one V-tail stuck and the other moving, there would be a secondary effect on roll in response to a pitch command. The Panel looked at WK042's flight data and were able to identify changes to the roll angle, but were not able to positively link it to the pitching oscillations. WK042 was Exhibit 140 in a shallow left turn for the majority of the pitching oscillations. It was wings level for most of the FEPs, with an increased left bank following most FEPs, possibly as a result of returning to the pre-FEP flight track. AOS was erratic during the turn indicating instability, although erroneous CAS and turbulence may have affected this. Finally, torque reaction (from rapid changes in engine RPM) or turbulence may also have affected roll.

1.4.3.26. The DO suggested that the following events indicated that physical damage to a V-tail may have occurred: Exhibit 140

a. The steep descent following the first FEP at 1102hrs accompanied by high air speed, pitch and roll.

b. Abnormal heading changes between 1105 and 1112hrs.

c. VMS rough weather suspected caution recorded at 1111:59hrs.

d. Left V-tail servo position report fail recorded at 1112:58hrs, which cleared immediately before the UA departed controlled flight.

1.4.3.27. The Panel considered (a)-(d) above in the context of the air data system issues and noted the following: Exhibit 3 Exhibit 82 Exhibit 83 Exhibit 84 Exhibit 91 Exhibit 92 Exhibit 93 Exhibit 94 Exhibit 140 Exhibit 141 Exhibit 142 Exhibit 143 Exhibit 144

a. The steep descent followed the first FEP and coincided with a velocity sensor redundancy lost caution. It is highly likely therefore that the CAS, wind speed, AOA and AOS reported by WK042 at this point would have been erroneous. The Panel's analysis of air speed (shown in Figure 1.4.3.5), however, shows that it is likely that the UA exceeded its V_{NE}[28] by between 5 and 15kts. The DO conducted some analysis on the likely hinge moment and current drawn by the servo during this manoeuvre and concluded that they were well within design limits and unlikely to have caused damage to the hinge or servo in isolation.

b. Heading changes were noted at:

(1) 1108:43hrs, which corresponded with the caution '*AOS estimators in use*.'

(2) 1109:18hrs, which could be instability caused by low air speed and turbulence.

(3) 1111:43hrs, which corresponded with a '*velocity sensors fail*' warning.

(4) 1112:29hrs, which corresponded with a '*velocity sensors fail*' warning. The DO analysis showed that at this time the heading change, accompanied by pitch and loss of height, exceeded the design limits for the hinge moment and current draw for the servo, which could have resulted in a damaged V-tail.

The Panel noted that the abnormal heading changes were coincident with erroneous air data parameters, but could not establish a direct causal link to the erroneous air data. It is, therefore, possible that they may have been exacerbated by local turbulence. The DO explained to the Panel that it was

[28] Velocity Never Exceed. AP3456 defines a 'Never Exceed' limits as a limit close to the limit of the tested or design flight envelope, beyond which there is no guarantee or airworthiness; in particular controllability, resistance to flutter and structural integrity.

also possible that the Space Age pitot had experienced blanking if the aircraft was side slipping significantly to the left in an unstable turn, with a corresponding effect on CAS.

c. The VMS rough weather mode caution indicated flight in above severe turbulence conditions, as defined by the Dryden wind turbulence model[29]. The WK calculates the magnitude of the turbulence based on the variance of 300 wind measurements over a 15-second period. As previously discussed, Met analysis suggests that the turbulence was not severe and it is believed that the wind speed measurements were erroneous. The Panel determined, therefore, that is was highly likely that this caution was triggered erroneously.

d. A left V-tail position report fail caution indicated that the left V-tail servo had not achieved its commanded position[30]. It was therefore likely that this caution was caused by a stuck servo. It was not possible to determine whether this would have been as a result of physical damage to the V-tail or hinge assembly or a seizure inside the servo. The absence of other servo cautions, suggested that the servo did not fail electronically and that communications were maintained between the servo and the VMSC. It was not clear what caused the caution to clear immediately before the departure from controlled flight; this could have been the result of something in the restricted control run releasing, allowing the servo to achieve its commanded position, but relinquishing control of the V-tail. Alternatively, it is possible that low air speed aerodynamically unloaded the V-tail allowing the servo to achieve its commanded position.

1.4.3.28. **Conclusion.** The Panel concluded that physical damage leading to a stuck V-tail was a possibility. The damage, however, could not have accounted for the Air Data System issues alone, but there was insufficient evidence to show that the abnormal heading changes were caused solely by the erroneous air data. The Panel determined, from the Meteorological evidence, that it was extremely unlikely that turbulence was sufficiently severe to have caused damage to the UA. As the DO analysis reported that the hinge moment and current draw could have exceeded design limits following the 1112:29hrs manoeuvre, which was followed by the position report fail caution at 1112:58hrs, the Panel concluded that, although the cause could not be determined, it was highly likely that the V-tail stuck or was in some way damaged from this point in the flight. The Panel further concluded, therefore, that it could not be discounted that the departure from controlled flight was in part due to reduced controllability of the UA due to loss of control over the left V-tail, although could not determine how probable this was.

Cause of the crash

1.4.3.29. During the final pitching oscillation, the estimated air speed was below the predicted stall speed, but the erroneous air speed fed to the FCS was significantly higher; this precluded an appropriate throttle or pitch response or a FEP manoeuvre and provided the conditions for an aerodynamic stall. The Panel concluded that the most likely **cause** of the crash was aerodynamic stall due to erroneous air speed used by the FCS within the VMSC.

1.4.3.30. The Panel considered that a combination of the length of time that WK042 spent flying in cloud and precipitation, pitot blockages and the VMSC's

[29] The Dryden wind turbulence model is a mathematical model describing the statistical theory of turbulence, first published in 1952 and accepted for use in certain aircraft design and simulation applications, including the US Department of Defence MIL-STD-1797A.

[30] Deviation between the commanded position and the position achieved on one of the sides of the servo by more than 10 °.

logic for disqualifying sensor readings and computing air speed led to the erroneous air speed input to the FCS. Individually, they were factors that made the crash more likely and therefore were **contributory factors**.

Previous flights with Air Data Unit (ADU) cautions

1.4.3.31. In an attempt to further understand the most likely cause of the erroneous CAS, the Panel analysed previous flights with ADU cautions, where, unlike for WK042 Flight 593, the full VMSC post flight down load was available giving full sensor level detail of the flight at a high sample rate. The following paragraphs summarise the findings from this analysis. Exhibit 95 Exhibit 81

1.4.3.32. **Flight 164.** Flight 164 took place in Jul 12 at WWA. During the climb out the UA repeatedly appeared to level off before resuming its climb. The DO suggested that these might have been similar to the pitching oscillations seen on WK042. The full analysis conducted by the Panel is at Annex E. Analysis showed that the dynamic pressure readings taken from the Space Age pitot deviated from the dynamic pressure reference value and the Kollsman pitot readings, which were similar to each other. The Panel concluded that the Space Age pitot was giving an erroneous total pressure measurement to the ADUs. The Space Age dynamic pressure readings corrected sharply at lower pitch angles inducing a sudden increase in the CAS fed to the FCS and inducing an increase in pitch. The Panel concluded that the Space Age pitot system had a moving blockage, highly likely to have been caused by a build-up of moisture that was forming and clearing in relation to pitch. Although the Kollsman pitot system was functioning correctly the Space Age total pressure readings had sufficient effect on the CAS calculation to induce the pitching oscillations. The Panel could find no evidence of the VMS disqualifying the erroneous pitot pressure measurements as expected, but were informed by the DO that the disqualification parameters were modified at some point after this flight and before Flight 493. Despite the difference in disqualification logic the Panel concluded that the analysis showed that a pitot blockage could induce pitching oscillations. Exhibit 145 Exhibit 146

1.4.3.33. **Flight 493.** Data from Flight 493, flown from WWA in Jan 16, was presented to the Panel to analyse as an example of a flight with multiple ADU cautions and the same Air Data System (including software ADS disqualification parameters) as WK042 Flight 593. The Panel analysed the air data to verify its behaviour against the information detailed in the Thales Technical Note describing the functioning of the Air Data System for the Safety Case. The full analysis is at Annex E. The Panel identified that both the Space Age and the Kollsman pitot total pressure readings deviated from the dynamic pressure reference value at different times during the flight and briefly at the same time. The Panel determined that this was indicative of blockages forming and clearing. There was also evidence of the VMSC disqualifying erroneous resultant dynamic pressure readings from the CAS calculation, hence avoiding wildly inaccurate air speed and other air data readings being used by the FCS. The Panel, however, noted occasions when readings that should have been disqualified, having met the criteria described in the Technical Note, were curiously not. Further internal investigation by the DO revealed additional logic conditions of which Thales were not aware. The Panel **observed** that Thales had an incomplete understanding of the Air Data disqualification logic. The DO provided assurance to the UAST that the ADS was functioning as designed. The implications of the incomplete understanding in the Technical Note are considered under Additional Technical Findings in Section 1.4.8. The Panel concluded that the air data disqualification logic improved the air data fed to the Exhibit 98 Exhibit 147

FCS, but noted that the data from this flight did not fully test the system as the only concurrent pitot blockages were relatively short lived with limited effect on CAS.

Design considerations.

1.4.3.34. As the Air Data system on WK is similar to that found on other aircraft, the Panel considered why pitot blockages posed such a risk to the platform. The Panel considered the following design points:

a. **Manual flight.** WK is a fully automated system, which means that the crew have no way of taking control from the autopilot. On other platforms taking control from the auto pilot and manually flying with a level attitude and a safe power setting would usually be sufficient to protect against stall should CAS become erratic and erroneous. The Panel noted that ESL's Hermes 450 could be flown manually in 'sticks' mode, giving the operator or external pilot full throttle and stick control of the platform as required. The system architecture for WK is, however, quite different and there is currently no way of manually flying the UA.

b. **Air speed**. Pitot blockages due to moisture are most likely to form and have greatest effect at relatively low air speeds. Slower aircraft operating in moisture-laden environments are therefore most at risk.

c. **Moisture traps and drain holes.** It is common for pitot systems to have small drain holes through which moisture and humidity can escape. The disadvantage is that air pressure can also escape and the reduction in total pressure has to be calibrated for. The total pressure error has greatest affect at low speeds. If the pitot blocks before the drain hole, then pressure behind the blockage will bleed away through the hole reducing the total pressure and hence air speed reading to zero, until the total pressure ahead of the blockage is sufficient to clear it. If the blockage is behind the drain hole then the total pressure trapped by the blockage will remain constant making air speed sensitive to altitude variation (as was the case in WK042 and described in paragraph 1.4.3.18). An alternative approach common on Rotary Wing platforms is to fit water traps with drain points that are drained as a maintenance activity on the ground. This approach was not adopted on WK because it was believed that it was highly improbable that both pitots would block at the same time and the VMSC disqualification logic was sufficiently robust to negate the effects of a single pitot blockage.

d. **Multiple pitots.** It is common for platforms to be fitted with multiple pitot tubes and multiple static measurement points or ports. The theory is to provide redundancy, so that a grossly erroneous pressure measurement can be identified and discounted through software. The main drawback of this approach to redundancy is that the sensor design is not diverse and all total pressure measurements will usually be taken in the same environment, making them most prone to blockage at the same time. Different pitot tube designs have different characteristics for blocking and unblocking and using two different designs, as is the case for WK, can partially but not completely mitigate the risk. Static measurements need to be taken from a point not affected by the airflow, which is commonly from multiple points on the side of the pitot tube or aircraft skin. For a completely unpressurised aircraft, static measurements can be taken internally. Adding more pitots tubes adds weight and complexity to the platform.

e. **Heated pitots.** As previously discussed pitot heaters are effective at vaporising moisture that enters the pitot static system, but in an undrained system can raise the relative humidity making condensation a possibility in unheated parts. More powerful heaters that heat uniformly along the length of the pitots are most effective. Larger more powerful aircraft, such as rotary wing platforms are able to overcome the moisture issue by fitting more powerful heaters. The Panel was informed that the emergency power budget from the back-up battery for WK is limited and this has reduced the choice of heated pitots available to the platform.

f. **Air speed estimation.** Another way of adding redundancy to a pitot system, or even dispensing with it altogether, is to estimate CAS using other 'non-air' data. WK uses a CAS estimation algorithm, which estimates CAS as a function of throttle position, pitch, engine speed and air density. Presently its output is not used as a redundancy to the pitots, but to calculate the dynamic pressure reference value, which was used in combination with dynamic pressure readings to identify and disqualify erroneous dynamic pressure readings. Several academic papers on CAS estimation exist and the Panel were able to develop a CAS estimation algorithm and prove the concept using WK flight data[31].

1.4.3.35. **Conclusion.** The Panel concluded the design of the current air data system limited the UA's ability to fly in cloud and precipitation and was therefore a **contributory factor**. However, in the opinion of the Panel the DO are capable of developing a demonstrably robust and therefore certifiable, technical solution within the size, weight and power constraints of WK, to enable the platform to determine air speed in high levels of cloud and precipitation.

1.4.3.36. **Recommendation.** Head Unmanned Air Systems Team should ensure that Watchkeeper has a robust method of determining air speed across its envelope of operation.

Non-recovery of the Unmanned Aircraft

1.4.3.37. The Panel, whilst confident in their conclusions, were unable to determine any further technical details regarding the crash. For example, due to the non-recovery of the VMSC, it was not possible to determine what the individual air data sensor readings were, or even when the individual pitots blocked and unblocked. Likewise, it was not possible to determine with any certainty what, if any, damage had been caused to the V-tail, V-tail hinge or servo, or indeed when and how any damage had been caused. The dataset recorded by the GCS was insufficient alone to determine the cause of the crash. Additionally, and perhaps more significantly, non-recovery of the UA slowed the process of understanding the technical issues and risks associated with the crash, which resulted in a pause in flying, delaying the ES2 programme and Army flying training.

Exhibit 3
Exhibit 148
Exhibit 149

1.4.3.38. WK did not have a crashworthy Flight Data Recorder (FDR) including a means of locating it[32]. The Panel noted that previous justification for not fitting a sonic locator beacon had been articulated in the Technical Certification Exposition for WK dated 19 Dec 2012. The main justification was that it did not affect safety because the crew are located in the GCS, the accident data recorder was considered to be part of the GCS and that wreckage recovery, whilst possible,

Exhibit 150

[31] The estimator used the ground velocity vector from GPS track data and magnetic heading to find wind velocity over a short time period using a Least Mean Squares estimation technique. True air speed is then found as the difference of the ground velocity and wind velocity and converted into CAS by correcting for the air density (based on measured or forecast temperature and air pressure for the altitude of the vehicle).

[32] iaw Def Stan 00-970 Iss 12, Part 13, Section 1.3.

would most likely be cost prohibitive. The Panel consider that this SI has highlighted the following limitations to the current flight data recording solution:

a. **Data rate.** The data recorded in the GCS was at 4 cycles per second. The VMSC operates on data refreshed at up to 20 cycles per second. Data that could have been useful for understanding the VMSC response and the dynamics of the flight was therefore unavailable. Assuming the bandwidth available is limited, improving the data rate may limit further the subset of parameters downloaded.

b. **Lack of physical wreckage to aid accident investigation.** Whilst it was accepted that flight data is often essential to accident investigation, it is only part of the story. SME examination of wreckage is often able to substantiate data analysis or identify mechanical modes of failure, assembly or maintenance errors or contamination.

c. **No-Comm situations.** All No-Comm periods would present as gaps in the data, including the final seconds before a crash when communication is lost when the UA goes over the horizon beyond line of sight for the datalink.

1.4.3.39. **Conclusion.** The Panel **observed** that the data set recorded by the GCS was insufficient alone to determine the cause of the crash. Furthermore, due to the limited data rate, line of sight limitations and a lack of physical wreckage to assess, relying on flight data transmitted to and recorded on the ground is, in the opinion of the Panel, very unlikely to be a satisfactory solution for future accident investigations. The Panel also **observed** that WK did not have a crashworthy and locatable FDR. However, in the opinion of the Panel, the data recorded in the VMSC, had it been recovered, was very likely to have been suitable for determining the cause of the accident and therefore the VMSC could potentially satisfy many of the requirements of a FDR. Finally, the Panel concluded that the impact in terms of understanding the technical issues associated with the crash and the resultant programme and training delays was an **aggravating factor.** Exhibit 151

1.4.3.40. **Recommendations.** Head of the Unmanned Air Systems Team should:

a. Ensure that the Unmanned Aircraft can be located following a crash in order to aid post crash accident analysis.

b. Review the use of the Vehicle Management System Computer to ensure that it can be used as a Flight Data Recorder.

SECTION 1.4.4 – POLICY AND REGULATION

Contracting with competent organisations

1.4.4.1 As WK042 was a pre-Release to Service (RTS) aircraft being flown and maintained by contracted organisations, the Panel first considered the arrangements under which the contracted organisations were operating. RA1005 detailed the approvals schemes, provided by the MAA, which enabled organisations that operated within the Defence Air Environment (DAE) to be contracted to provide specified Design, Maintenance, Contractor Flying and Air Traffic Management activities. The rationale of the regulation was to assure the SofS for Defence that organisations that provide these Air Safety related products and services to the UK MOD were competent to do so and were contracted to the correct MAA Regulatory Publications (MRP) to ensure the latest regulatory standards and practices were adhered to. The schemes applicable to the contracted design, maintenance and operation of WK were: Exhibit 36

a. **Design Approved Organisation Scheme (DAOS).** DAOS is a scheme managed by the MAA, it gives assurance that a company has proven competence to design airworthy materiel within a scope of design. The DAOS award approves an organisation for a defined range of products. RA5850 states, "*One of the four pillars*[33] *of airworthiness is the use of competent organizations. The Design Approved Organization Scheme (DAOS) is a mechanism by which the competence of a Design Organization (DO) can be assessed. Approval under DAOS is subject to adherence with the established procedures and rules governing the responsibilities and privileges for Military Design Approved Organizations.*" The certificate defines the approved scope of work and the persons approved to sign Certificates of Design. The issue of a DAOS approval is recognition that the MOD accepts certification by the organisation and that a specified performance attribute or objective has been achieved. A number of DAOS approvals were held by companies within the DO for various elements of the WK system design. Exhibit 38 Exhibit 152 Exhibit 153 Exhibit 154 Exhibit 218

b. **Maintenance Approved Organisation Scheme (MAOS).** The MAOS is a means by which the MOD can assess the competency of an organisation that wishes to provide continuing airworthiness support services for military registered aircraft. To become MAOS, an organisation needs to demonstrate compliance against RAs 4800-4849 (MRP 145)[34]. UTacS were awarded MAOS accreditation 25 Jun 15 for WK maintenance at WWA. Exhibit 39 Exhibit 155

c. **Contractor Flying Approved Organisation Scheme (CFAOS).** To give the MAA oversight of all defence aviation activity, all contractor flying organisations need to be approved under CFAOS by the MAA. The rationale of RA2501 is "*Defence Contractor Flying Organizations (DCFO) that operate UK military registered Air Systems not in the UK MOD Service Environment are required to operate under an appropriate approval scheme which will ensure such organizations comply with the MAA Regulatory Publications (MRP).*" The MAA requires the organisation to produce a Contractor Flying Organisation Exposition (CFOE), which demonstrates their compliance against the MRPs. Thales was initially approved as a CFAOS organisation Exhibit 40 Exhibit 156 Exhibit 157

[33] The four pillars of airworthiness are a the use of a safety management system, recognised standards, competent persons and organisations and independent assessment. These are described further in RA1220.

[34] RA 4800-4849 is a discrete set of RAs that govern maintenance organisations, named MRP Part 145 due to their derivation from the European Military Airworthiness Requirements (EMAR) 145.

for the operation of WK on 26 Aug 15. This approval was updated on 11 Nov 16 and extant for the flight on 3 Feb 17.

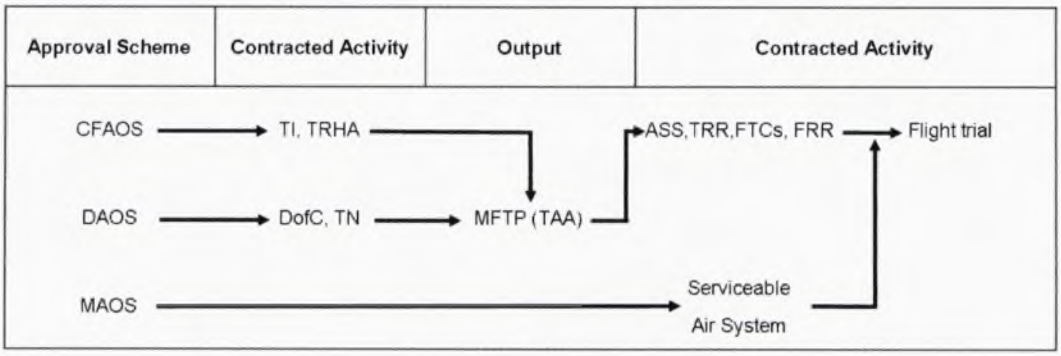
1.4.4.2 **Accountable Manager Military Flying AM(MF).** In the absence of a military Duty Holder (DH), the CFAOS organisation needs an AM(MF) to actively manage Air Safety, ensuring that RtL is at least Tolerable and As Low as Reasonably Practicable (ALARP) within their defined areas of responsibility. The AM(MF) is accountable for the maintenance of standards and safety primarily focused on RtL. RA1024 details the roles and responsibilities and the appointment and qualifications of an AM(MF). In accordance with the regulation, Thales had an approved AM(MF) at an appropriately senior level within the company. He was based at Thales Crawley and therefore was not involved in the day-to-day operations at the FOO. The Panel found that he was aware of his roles and responsibilities, as defined in the RA, and was actively involved in the Trial Planning and Approval process discussed in Section 1.4.6.

Witness 16
Exhibit 37

1.4.4.3 **Contractor flying of WK.** Approved contractor organisations designed, maintained and operated WK on behalf of the MOD. The Design Organisation and CFAOS organisation produced the evidence to support an MFTP application that was approved by the Defence Equipment & Support (DE&S) Type Airworthiness Authority (TAA) for the MOD prior to Test and Evaluation (T&E) flying being conducted by the CFAOS organisation.

Exhibit 158
Exhibit 159
Exhibit 160
Exhibit 161
Exhibit 162

1.4.4.4 **Analysis.** Figure 1.4.4.1 summarises how the MAA approvals schemes were applied to the contracted T&E flying of WK. Whilst it was clear that the TAA had an input into the airworthiness aspects, the Panel noted that there was not any mandated MOD operator input into the contracted T&E activity at WWA. The impact of this is discussed in the Section 1.4.6.



CFAOS—Contractor Flying Approval Organisation Scheme.
DAOS—Design Approval Organisation Scheme.
MAOS—Maintenance Approval Organisation Scheme.
TI—Trials Instruction.
TRHA—Trials Risk and Hazard Assessment.
DofC—Declaration of Compliance.
TN—Technical Notes.
MFTP—Military Test Flight Permit.
TAA—Type Airworthiness Authority.
ASS—Air Safety Statement.
FTC—Flight Test Cards.
TRR—Trials Readiness Review.
FRR—Flight Readiness Review.

Figure 1.4.4.1 – Application approval schemes for WK flying at WWA

1.4.4.5 **Conclusion.** The Panel concluded that, notwithstanding the absence of mandated operator input into the contracted T&E activity at WWA, the flying activity itself was regulated and approved by the MAA. The MAA approvals schemes were being used appropriately and as intended by the MOD and were **not a factor** in the accident.

Certification process

1.4.4.6 **RA5810 – Military Type Certificate**. RA5810 was released in Aug 16 and stated that it was necessary to demonstrate that an Air System's Type Design met appropriate safety requirements. A systematic, independent certification process was required for new types of UK military registered Air Systems. The regulations stated that new military Air Systems that are intended to be operated on the UK Military Aircraft Register in the Service Environment **shall** be certified prior to their RTS. RA5820 dealt with changes to Type Design and stated that during the life of an Air System (including related products, parts and appliances) there would be changes in the Type Design. It was important that any such changes met the appropriate safety requirements to ensure the airworthiness implications of the change were fully recognised. Any such changes were subject to classification and approval prior to the implementation of the change. Exhibit 34 Exhibit 35

1.4.4.7 **RA1500 – Certification of UK Military Air Systems**. Now obsolete, but extant when WK Operational Conversion Unit (OCU) build standard went through the certification process, MAA RA1500 set out the regulation for the certification of both new types of military registered Air Systems and for major changes to existing designs. It placed the responsibility on TAAs for ensuring that new UK Military Air Systems that would be operated in the Service Environment on the Military Aircraft Register (MAR) or Major Changes[35] to Type Designs of in-service Air Systems were certified in accordance with the Military Air Systems Certification Process (MACP). The MACP mirrored the civil approach to obtaining a civil Type Certificate and comprised of the following 6 phases: Exhibit 163

a. **Phase 1** – Identify the requirement for, and obtain organisational approvals.

b. **Phase 2** – Establish and agreed the Type Certification Basis (TCB).

c. **Phase 3** – Agree the Certification Programme.

d. **Phase 4** – Demonstrate compliance with the TCB.

e. **Phase 5** – Produce Final Report and issue Certificate.

f. **Phase 6** – Undertake post-Certification actions.

Detail on each of the 6 phases was included in Annex A to RA1500. Successful completion of the full MACP for a new platform would result in the issue of a Military Type Certificate (MTC) by the MAA. An MTC would be underpinned by a Type Certification Report (TCR). Similarly, successful completion of the MACP for a Major Change would result in an Approved Design Change Certificate (ADCC), also underpinned by a TCR, issued by the MAA.

[35] Details of what constituted a Major Change were given in the Annexes to RA1500.

1.4.4.8 **Legacy platforms**. RA1500 stated that there was no intent to retrospectively apply the MACP to in-service platforms, but that future Major Changes to Type design would be subject to the MACP. Platforms that were post-RTS prior to RA1500 are commonly referred to as 'legacy platforms'. Exhibit 163

1.4.4.9 **Special cases**. RA1500 also made provision for more recent legacy platforms that were pre-RTS but post Main Gate[36] on the 1 Sep 11, by allowing for an individually tailored version of the MACP to be applied. The same provision existed for Major Changes to type design that were post-Main Gate but pre-RTS on 1 Apr 12. Tailored application of the MACP would normally[37] result in the issue of a Statement of Type Design Assurance (STDA) from the MAA to the TAA, which like an MTC or ADCC, would be underpinned by a TCR. The STDA identified to what extent the MAA had been able to assure the certification evidence provided and detailed any areas where the evidence was not available, incomplete or not understood. An STDA could offer one of four possible categories of assurance: Exhibit 163

a. *No Assurance*.

b. *Limited Assurance*, meaning that significant non-compliances had been identified or MAA involvement with or oversight of the design compliance programme was limited because of a late stage of engagement.

c. *Substantial Assurance*, meaning that there were limited areas where minor non-compliances were identified.

d. *Full Assurance*.

The range in assurance levels, defined fully in Annex A to RA1500, were aimed at informing the Release to Service Authority (RTSA) and DH to what extent the certification process had been complied with and thus what level of technical risk existed based on the certification evidence.

1.4.4.10 **Regulation change**. In 2016 the Design Modification Engineering (DME) RA5000 Series underwent a major review, part of which was to develop the RA5800 series based on the European Military Airworthiness Requirements (EMAR) 21 – *Certification of Military Aircraft and Related Products, Parts and Appliances and Design and Production Organisations*. This saw the introduction of RA5810 and RA5820 titled *Military Type Certificate (MRP 21 Subpart B)* and *Changes in Type Design (MRP21 Subpart D)* respectively. RA5810 and RA 5820 incorporated RA1500 making it obsolete, but took the same fundamental approach to Certification (mirroring the civil approach). The MAA did however incorporate several changes that it considered necessary as a result of experience gained, since the inception of the MAA, through certification programmes and as a result of feedback from the Regulated community. Provision was made for existing programmes undergoing certification to either adopt the new regulation or remain on RA1500. Exhibit 34 Exhibit 35 Exhibit 163 Exhibit 164 Exhibit 165

1.4.4.11 **Analysis of changes**. The change from RA1500 to RA5810 and RA5820, in the opinion of the Panel, did not represent a fundamental change in

[36] MOD Architecture Framework 12 Dec 12 - Main Gate occurs after the assessment work has been undertaken and is the major decision point at which the solution and 'not to exceed figures' are approved. No manufacture or service contracts can be signed prior to approval.

[37] If the MAA's certification assurance activities concluded that the requirements of the MACP had been met in full, a MTC or ADCC (as appropriate) could be issued rather than an STDA.

approach to certification. The Panel considered the following points to be particularly worthy of note:

a. As part of the RA5810 MACP Regulation development, the MAA changed their terminology for areas that required corrective action by the TAA in their TCR and Release to Service Recommendation (RTSR) Audit Reports. The previous terminology used the terms 'Recommendations' and 'Observations' to capture areas that required further evidence to demonstrate compliance with a requirement, or areas that would improve the TAA's argument respectively. Both the terminology and the way in which the Recommendations were worded allowed, in some cases, for the TAA (or RTSA) to merely consider the Recommendation made by the MAA. The MAA's current wording uses the much less ambiguous term, **'Actions'**, to identify where evidence is not deemed sufficient to satisfy the certification requirements and action needs to be taken to address this either prior to an MTC being issued or by a specified date after an MTC is issued. Where observations are made that are not deficiencies in the Certification evidence or Regulatory Non-Compliances, but nonetheless warrant consideration by the TAA, these are identified as **'Recommendations'**; resolution is not mandatory but they are included to provide visibility of the issues to the RTS Stakeholders. Exhibit 34 Exhibit 164

b. RA5810 allows for the issue of a Military Type Certificate (MTC) or Restricted MTC (RMTC), where the requirements of RA5810 have not been fully satisfied, but certification evidence has been assessed to the satisfaction of the MAA. An RMTC would be issued for a provisional period when an Air System was approaching RTS, but did not have a complete Type Design or Aircraft Document Set, until the Type Design or Aircraft Document Set could be demonstrated to be complete and accurate. Similarly, shortcomings in the Certification evidence provided in the Type Certification Exposition (TCE) or RTSR, may result in the issue of an RMTC until any actions are closed or progressed to a level deemed acceptable by the MAA. The regulation states that any restriction identified in the RMTC should be copied into the RTS verbatim by the RTSA. Therefore, for new platforms, if there are any aspects of the TCB that cannot be fully complied with, and an equivalent level of safety cannot be demonstrated then a RMTC will normally be issued. The Restriction will be placed on the RMTC notes page detailing the shortfall and any operating restrictions if applicable and copied verbatim into the RTS. Exhibit 34 Exhibit 164

c. For existing platforms, if full Certification evidence is provided for a Major Change in accordance with RA5820, then an ADCC would be issued for the Major Change element only. If there were aspects of the TCB that could not be fully complied with, but an equivalent level of safety can be demonstrated then an ADCC may still be issued by the MAA. Exhibit 35 Exhibit 164

1.4.4.12 **Certified platforms to date**. For context, at the time of writing, a total of 4 Air Systems (AW109, Juno, Jupiter and Prefect) had received an MTC or RMTC and 6 more platforms were due to receive an MTC over the following 3 years. Reaper and Air Seeker are examples of platforms, which have not achieved Certification. Their RTS are restricted accordingly (as per the regulation) and the risks associated with their operation when uncertified have been articulated to the Secretary of State and actively managed by the Senior Duty Holder (SDH). Exhibit 164

1.4.4.13 **Conclusion**. On the face of it, it may appear that Certification regulation is complex and ever changing, however, the Panel concluded that despite the change from RA1500 to RA5810 and RA5820, the MAA had been consistent in its approach and provided transitional arrangements for programmes undergoing Certification activity during the change. The current regulation is clearer and more robust in articulating and communicating Certification action required and any shortfalls to the RTS community including the DH. The regulation also allows greater flexibility for the TAA and MAA working together. The process has been tested and can be seen working on a number of platforms that have achieved Certification and some that have not. The Panel therefore concluded that the changes in the Certification process were **not a factor.**

Certification of Watchkeeper

1.4.4.14 WK is a legacy platform that was post Main Gate, but pre-RTS on 1 Sep 11, and as such, it is first important to note that it was not intended to achieve full certification leading to a Military Type Certificate in accordance with RA1500, instead a Tailored MACP was agreed. Whilst recognising that the majority of the WK OCU design and test programme work had already been completed prior to the release of RA1500, a tailored certification programme was established as a retrospective exercise to match existing design and test reports to the requirements of a TCB. As described in paragraph 1.4.4.9, this approach was recognised within RA1500 for legacy programmes and was agreed by the MAA formally on 26 Apr 12.

Exhibit 164
Exhibit 166

1.4.4.15 One of the main challenges with WK being a legacy platform was that a standard to certify WK against was not agreed between the MAA and TAA from the outset. For new platforms seeking an RTS, the standard to be implemented (the Airworthiness Code or Codes) is agreed at the second phase of the MACP in establishing the TCB. The Code usually used for UK military registered aircraft is Defence Standard (Def Stan) 00-970 and specifically 00-970 Part 9 for Remotely Piloted Air Systems (RPAS). WK was reportedly designed by ESL, in part, against STANAG 4671 – Edition 1, a NATO standard written specifically for the design and production of UAVs[38]. Edition 2 of Standard NATO Agreement (STANAG) 4671 was adopted by the MAA for the Part 9 of Def Stan 00-970, with the addition of MAA specific caveats. In addition to meeting the Part 9 requirements, the TCB also required WK to meet requirements from Part 1, Part 11 and Part 13 of the Def Stan. Several other Alternate Acceptable Means of Compliance (AAMC) were also used, which demonstrated that WK did in fact meet more comprehensive compliance criteria. For example, the European Aviation Safety Agency (EASA) Certification Specification for Engines provided more comprehensive compliance criteria than the Def Stan 00-970 Part 11, which covers the MAA certification requirement for engines. In other instances compliance could be demonstrated against other internationally recognised standards, such as Federal Aviation Regulations as AAMC. Table 1.4.4.1 and the following paragraphs describe some of the main Certification and related events from the WK OCU TCE to agreeing the certification process for WK ES2.

Exhibit 164
Exhibit 150

[38] Structural Integrity Requirements were taken from this standard and used in the WK design.

Event	Brief description
UAST - TCE	• Dated 19 Dec 12. • Contained the certification plan/proposal for WK OCU. • Acknowledgment that OCU would follow a **tailored MACP.**
MAA - STDA	• Dated 20 Sep 13. • MAA's output to the review of the TCE. • Gave **Limited Assurance** based on the evidence presented and the level of MAA engagement. • Gave recommendations that **should** be addressed prior to OCU RTS. • Recommendation stated that the TAA **should** ensure that the risk associated with the lack of rigorous independent evaluation and MAA assurance of the VMSC monitor, PCDU, CLPD, RFC software and CEH items is understood, mitigated and articulated to the DH and include suitable recommendations to support iRTS.
UAST - RTSR	• Dated 19 Dec 13. • Initial RTSR that was submitted to the MAA for review. • Aimed to demonstrate that the WK OCU was sufficiently safe to gain an iRTS.
MAA – RTSR audit report	• Dated 10 Feb 14. • Reviewed the RTSR. • The audit report **should** be read in conjunction with the TCR and STDA. • Para 8 stated that there were a number of recommendations that required action before iRTS (Annex A, serial 1 – remains open concerning the lack of rigorous independent evaluation and MAA assurance of the VMSC monitor).
WK OCU RTS	• Dated 24 Feb 14.
UAST – STDA Ext request	• Formal request to the MAA asking for an extension to the STDA (expired 31 Aug 14). • Provided evidence/justification for an extension request.
MAA – STDA (2)	• Dated 4 Nov 14. • STDA extended to 31 Dec 15. • Noted concerns with SIL3 software, specifically – independence, assurance levels and reliance on process evidence.
MAA – uplift to STDA	• Dated 12 May 15. • Review of SIL3 and CEH items of the WK OCU. • Uplifted original assurance to **Limited Assurance** for the CEH items. • Stated that recommendations **should** be addressed prior to RTS of the ES2, but no later than 31 Dec 15.
UAST – approach to ES2 cert and RTS	• Dated 1 Sep 16. • Set out the UAST's strategy to achieve full ES2 certification and RTS. • Acknowledged that ES2 specific upgrades were classified as **major modifications** and would undergo full MACP. • Annex B – WK OCU TCR/RTSR route to closure, serial 1, expected that the lack of rigorous testing and independent evaluation of the VMSC would be complete by Nov 16.
MAA response to UAST approach to ES2 cert and RTS	• Dated 16 Sep 16. • Acknowledged the UAST's approach to ES2 certification and RTS.

Table 1.4.4.1 - Certification events

1.4.4.16 **Type Certification Exposition (TCE).** The TCE was released on 19 Dec 12. This document was written by the UAST and aimed to demonstrate compliance against the agreed tailored MACP. The aim of the TCE was to: Exhibit 150

a. Demonstrate that, although WK was designed and procured before the existence of the MAA, the design and test process could be shown to meet current MAA regulation and was therefore worthy of MAA certification.

b. Summarise the work undertaken to ensure that independent scrutiny of design compliance evidence has been applied throughout the programme.

c. Formally apply for MAA certification for the WK UAS through the issue of a Statement of Type Design Assurance (STDA).

1.4.4.17 **Statement of Type Design Assurance (STDA).** The WK STDA awarded on 20 Sep 13 for the OCU variant acknowledged the tailored MACP owing to the legacy status of the WK UAS. The outcome of this STDA was *Limited Assurance*; this was awarded based on the evidence presented and the level of MAA engagement throughout the project at that point in time. *No Assurance* was initially granted to the Complex Electronic Hardware (CEH) elements of the system. The STDA gave the TAA recommendations that were given a to be completed date of 31 Aug 14. Of note, the first recommendation was "*The TAA **should** ensure that the risk associated with the lack of rigorous independent evaluation and MAA assurance of the VMSC Monitor, Power Control Distribution Unit (PCDU), Complex Programmable Logic Device (CPLD), and the Redundant Flight Controller (RFC) software and Complex Electronic Hardware (CEH) items is understood, mitigated and articulated to the DH and included in suitable recommendations to support Initial Release to Service (iRTS)*". Exhibit 167 Exhibit 164

1.4.4.18 **OCU Release to Service Recommendation (RTSR).** The iRTS process started with Watchkeeper UAS RTSR submission, which was produced on 19 Dec 13 and presented to the MAA for audit. The RTSR submission included the proposed iRTS that had been drafted by Thales. The document was prepared in accordance with RA 1300 and aimed to demonstrate that WK OCU was sufficiently safe to gain an iRTS by stating the organisational structure, airworthiness arrangements, safety management system, compliance with design standards and evidence against the recommendations from the STDA. Exhibit 168

1.4.4.19 **OCU RTSR audit report.** This report was produced by the MAA on 10 Feb 14 in response to the RTSR submission. The report commented positively on the comprehensive RTSR submission that was produced by the TAA. The report advised the TAA on minor amendments that were required to the proposed wording to some areas of the iRTS. It also commented on the claims from the submission against the STDA recommendations. Exhibit 169

1.4.4.20 **WK OCU RTS.** The WK OCU RTS was authorised on 28 Feb 14. It described the operating envelope, conditions, limitations, design standard, standard of operational software and safety related engineering maintenance requirements. Exhibit 170

1.4.4.21 **STDA extension.** The UAST wrote to the MAA requesting an extension to the STDA. On 4 Nov 14, the MAA authorised an extension with a new to be completed date of 31 Dec 15. The letter acknowledged the work that the UAST had done on the recommendations outstanding and the continued engagement with the MAA. The STDA extension highlighted "Independence, Assurance levels and Reliance on process evidence" as areas of concern and as Exhibit 171 such would require additional work to increase the level of assurance that would be offered by the MAA.

1.4.4.22 **STDA CEH uplift.** On 12 May 15 the MAA wrote to the TAA stating that due to the continued work, the MAA were able to uplift the level of assurance on the CEH items of WK to 'Limited'. The letter noted that there was no evidence provided that recognised good practice had been applied in either the implementation or the verification and validation activities. Exhibit 172

1.4.4.23 **UAST approach to ES2 certification and RTS.** On 1 Sep 16 the UAST wrote a letter to the MAA, detailing the proposed approach to ES2 certification and RTS. Certain elements of the ES2 were classed as 'major modifications' over the OCU build standard and as such were subject to full MACP. The letter also acknowledged the requirement to close open TCR and RTSR recommendations and stated an intent to do so prior to seeking an RTS for ES2. The MAA response acknowledged the approach and re-iterated that a regulatory waiver would be required for aspects of ES2 introduced under a Clearance with Limited Evidence (CLE) without certification and without having closed down the original WK OCU STDA recommendations. Exhibit 173 Exhibit 174

1.4.4.24 **WK042.** WK042 was an ES2 build standard and pre-RTS and was flying under a Military Flight Test Permit (MFTP) when it was lost. It therefore, had no certification, although aspects were the same as the OCU build standard, some of which had limited assurance. The MFTP process is covered in Section 1.4.6. Exhibit 164

1.4.4.25 **Conclusion.** The Panel recognised that in terms of certification, the WK UAS was classed as a 'legacy' platform and as such was inherently challenging to certify. Whilst a lack of Certification does not necessarily present an inherent flight safety hazard, it leaves a question mark as to how safe the platform was. By meeting an approved standard or demonstrating an equivalent level of safety, confidence in the platform is increased. For WK, providing the required technical certification evidence has clearly been complex. Moving forward to certifying ES2, rigorous application of the TCB will ensure that the platform can operate with an increased level of confidence where certification is given. If certification cannot be given in any areas, the shortfall and required action, together with any associated risk or operating limitation will be communicated more effectively to the RTS community including the DH. The panel concluded that the application of the certification process was **not a factor** in the loss of WK042.

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SECTION 1.4.5 – TRAINING, COMPETENCIES, QUALIFICATIONS, CURRENCY AND SUPERVISION

Introduction

1.4.5.1 The MAA Regulatory Articles 2000 Series sets out the regulation for the responsibility and authority required to conduct flying operations. Specifically the 2100 series RAs cover aircrew training, qualification, competency and currency. The 2300 series RAs cover the operation of aircraft including the authorisation and supervision of flying. The Thales Flying Order Book, Issue 9, extant at the time of the accident, detailed the specific training, qualification, competency, currency, authorisation and supervision requirements applicable to the Thales FOO and was Thales' approved means of complying with the regulation. This section of the SI report aims to establish the level of training, relevant competencies, qualifications, currency and supervision of those involved in the activity by comparing recorded activity against these approved requirements.

Requirements

1.4.5.2 The Panel reviewed the qualification, competency and currency requirements detailed in the Thales FOB for the pilots (P1 and P2), the UAV Cdr, the AO, the Flight Execution Log Author (FELA) and Trials Officer (TO). The requirements for these different roles are summarised in Table 1.4.5.1.

Exhibit 43

Requirements	**Role**					
	FELA	**TO**	**P1**	**P2**	**UAV Cdr**	**AO**
Qualification						
Entitlement to conduct flying duties, as approved by AM(MF)			x	x	x	x
Certificate of Qualification on Type (CQT)			x	x	x	x
Two years of previous flight trials experience		x				
Flying Authorisers Course (FLAC) & Flying Supervisor Course (FSC)						x
Segregated Instrument Rating exam			x	x	x	x
Non-segregated Instrument Rating exam and simulator skills test			x			
Competency						
CQT in Training Record Folder (TRF)			x	x	x	x
Certificate of Competency (CofC) to current build standard being operated in TRF		x	x	x	x	x
Signed as having read and understood FOB & extant Hot Poop	x	x	x	x	x	x
Two yearly independent competence check			x	x	x	
Currency						
One flight within 31 days			x			
One flight within 60 days				x	x	
One simulator flight within 45 days to include, practice in flight and ground emergencies			x	x		
Instrument Rating procedures for flight in non-segregated airspace within 3 months			x			
6 monthly GCS evacuation drill		x	x	x	x	
Valid medical certificate			x	x	x	
Signed as having read and understood any new Hot Poop and changes to the FOB.	x	x	x	x	x	x
Signed as having read and understood the FOB and Hot Poop within the last 6 months.	x	x	x	x	x	x
FSC (and FLAC)[39] refresher training course (5Yr Validity)						x

Table 1.4.5.1 – Thales FOB qualification, competency and currency requirements

[39] The FSC re-qualifies individuals who have previously completed the FLAC to Authorise flights.

1.4.5.3 **Authorisation.** RA 2306 describes the roles and responsibilities of an AO and the different types of authorisation. The FOB described the authorisation arrangements for flying within FOO. It stated that the AM(MF) had issued a letter of delegation empowering the Flight Operations Post Holder (FOPH) to appoint AOs within the FOO. To be eligible to conduct the duties of a AO, an individual must have met the following criteria: Exhibit 43 Exhibit 41

a. Be a qualified pilot on type.

b. Have held Certificate of Qualification on Type (CQT) for a minimum of one year.

c. Demonstrated systems limitation and performance knowledge.

d. Demonstrated general airmanship and awareness of MAA regulations to the satisfaction of the FOPH.

e. Once the above had been achieved, the individual would be considered for attendance on the Flying Authorisers Course (FLAC).

All individuals meeting the criteria to become a AO would then be formally appointed by the FOPH, who would maintain a record of all AOs within the FOO.

1.4.5.4 **Flying Supervisor.** The Thales FOB stated that the AM(MF) had appointed the AO to supervise WK flying operations. To aid flight planning, the Crew Training Post Holder (CTPH) was responsible for producing and maintaining a 'whereabouts plan' in which he directed which supervisor was to be available and immediately contactable during the weekly flying programme. Exhibit 43 Exhibit 175 Exhibit 176

1.4.5.5 **Discussion.** During their investigation, the Panel noted the following: Exhibit 43

a. Qualification, competency and currency requirements were set out logically referencing the RAs and explaining how Thales sought to comply with the regulation.

b. A live flying currency requirement was stated for UAV Cdrs, but there was no simulator currency requirement specified. In the opinion of the Panel it would be advisable for UAV Cdrs to maintain a level of currency in the simulator, as this is where the majority of emergency drills are practiced. The Panel considered that UAV Cdrs were in practice also P1 and P2s, and therefore, would maintain appropriate simulator currency, however, the FOB did not expressly state that all UAV Cdrs would always be a P1 or P2.

c. The minimum criteria for maintaining live and simulator currency was not included in the FOB currency table, but was included in a note at the bottom of the table. In the opinion of the Panel, this flight currency requirement was not satisfactorily clear.

d. The requirements to become an AO described in the FOB, were clear, sufficiently rigorous and compliant with regulation.

e. The AO was always required to undertake the role of flying supervisor and be immediately contactable during the weekly flying programme. However, should the AO be flying, there would be no direct supervision of flying operations outside of the GCS. In such an event, the opportunity, should the need arise, for a UAV Cdr to seek an authoritative 'second opinion' or guidance from outside of the GCS would be unavailable.

1.4.5.6 **Conclusions.** The Panel concluded that the requirements to become an AO were reasonable, but the supervision of flying operations requirement warranted further analysis alongside the issue of self-authorisation. This is covered in Para 1.4.5.15. The crew qualification, competency and currency requirements stated in the FOB were compliant with the RAs. However, the Panel **observed** that qualification, competency and currency requirements were not clearly defined against each specific role within the GCS. Specifically, there was no clear simulator currency requirement for UAV Cdrs and the minimum requirement for maintaining live and simulator flight currency was not satisfactorily clear.

1.4.5.7 **Recommendation.** The Thales Accountable Manager (Military Flying) should ensure that qualifications, currency and competency requirements for all Ground Control Station crew roles are clearly defined within the Thales Flying Order Book.

Establishing qualification, currency and competency

1.4.5.8 The Panel reviewed the Training Record Folders (TRFs) and Logbooks of the UAV Cdr (also AO and P1), P2 and TO, to establish the qualification, currency and competency of the crew. The Panel's findings are shown in Table 1.4.5.2. The following paragraphs discuss these findings in further detail.

Exhibit 46
Exhibit 47
Exhibit 48
Exhibit 49
Exhibit 175
Exhibit 177
Exhibit 178
Exhibit 179
Exhibit 180
Exhibit 181
Exhibit 182
Exhibit 183

Requirements	Role				
	TO	P1	P2	UAV Cdr	AO
Qualification					
Entitlement to conduct flying duties, as approved by AM(MF)		x	x	x	x
Certificate of Qualification on Type (CQT)		x	x	x	x
Two years of previous flight trials experience	x				
Flying Authorisers Course (FLAC) & Flying Supervisor Course (FSC)					x
Segregated Instrument Rating exam		x	x	x	x
Non-segregated Instrument Rating exam and simulator skills test		x (note 4)			
Competency					
CQT in Training Record Folder (TRF)		x	x	x	x
Certificate of Competency (CofC) to current build standard being operated in TRF	x	x	x	x	x
Signed as having read and understood FOB & extant Hot Poop	x	x	x	x	x
Two yearly independent competence check		x	x (note 3)	x	
Currency					
One flight within 31 days		x			
One flight within 60 days			x	x	
One simulator flight within 45 days to include, practice in flight and ground emergencies		x	x		
Instrument Rating procedures for flight in non-segregated airspace within 3 months		x			
6 monthly GCS evacuation drill	x	x	x (note 2)	x	
Valid medical certificate		x	x	x	
Signed as having read and understood any new Hot Poop and changes to the FOB.	X (note 1)	x	x	x	x
Signed as having read and understood the FOB and Hot Poop within the last 6 months.	x	x	x	x	x
FSC (and FLAC)[40] refresher training course (5Yr Validity)					x

Notes:
1. Had not signed for reading Hot Poop 19 Jan 17 Take-off and landing brief for ES2.
2. Expired 16 Nov 16 (according to Thales Whereabouts Plan).
3. Individual had not yet completed 2 years on type, therefore was not due.
4. Currently all WK flying is conducted in segregated airspace.

Table 1.4.5.2 – Qualification, competency and currency of the crew of WK042

[40] The FSC re-qualifies individuals who have previously completed the FLAC to Authorise flights.

1.4.5.9 **AO.** In accordance with the Thales FOB, the AO was also responsible for the supervision of flying operations. In order to comply with the Thales FOB and RA 2306, the AO should have completed the MAA FLAC[41] and the MAA Flying Supervisors Course (FSC), both within the last 5 years. The AO's TRF showed that the individual had completed the FSC within the required timeframe, however did not record attendance on a FLAC within the last 5 years. The Panel established with the MAA Centre of Air Safety Training (CoAST), that the individual's attendance on the FSC re-qualified him as an AO, hence he was not required to complete a dedicated FLAC. The Panel concluded that the AO was current and competent to supervise and authorise flights. The Panel however, **observed** that for individuals who do not have their competencies recorded on Joint Personnel Administration (JPA), there was no means of recording the FLAC competency when it was maintained as refresher training as part of the FSC. The Panel discussed this with CoAST, who informed the Panel that they were now annotating Flying Supervisor Course Training certificates with 'Refresher Flying Authoriser Course training' when proof of attendance at a previous qualifying Flying Authorisers Course is provided.

Exhibit 41
Exhibit 43
Exhibit 47
Exhibit 177
Exhibit 184
Exhibit 185

1.4.5.10 **UAV Cdr & P1.** On the 3 Feb 17, the AO was also the UAV Cdr and the P1. His TRF, flying logbook showed that he was qualified, competent and current in all respects to undertake these duties. His currency was further verified by the Thales Whereabouts Plan and FOO Currency Tracker, showing that his currency was being managed by the Thales CTPH. The Panel **observed** that on some occasions the individual had signed simulator record sheets as having acted as both the student and the assessor.

Exhibit 46
Exhibit 47
Exhibit 176
Exhibit 175
Exhibit 186
Exhibit 187

1.4.5.11 **Recommendation.** The Thales Crew Training Post Holder should review procedures to ensure that all assessed simulator sessions are run by a qualified instructor, who is not participating as crew in the simulator session.

1.4.5.12 **P2.** The Panel found the P2 to be qualified, current and competent in accordance with the Thales FOB, with one exception; he was recorded as being out of date for the GCS evacuation drill.

Exhibit 49
Exhibit 48
Exhibit 175
Exhibit 176
Exhibit 186
Exhibit 187

1.4.5.13 **TO.** The Panel found that the TO was qualified and competent as defined by the Thales FOB in all respects. However, he had not signed as having read the latest Hot Poop[42].

Exhibit 176
Exhibit 175
Exhibit 186
Exhibit 187

1.4.5.14 **Conclusion.** The Panel conclude that all members of the GCS were qualified and competent. The minor discrepancies with currency, in the opinion of the Panel, would not have affected the individuals' ability to be able to conduct their roles effectively. The Panel concluded that the qualification, competency and currency of the crew was **not a factor.**

[41] This course is aimed at unit executives and Flight Commanders who will be supervising aircrew in flying roles. Applications from senior engineering and air traffic control officers are also appropriate. FSC currency counts as both FSC and FLAC currencies provided the FLAC has been completed at least once (ie there is no requirement to maintain both FSC and FLAC currencies). It also counts as HF continuation training competency.

[42] Hot Poop is Thales' notices to WK operators (or 'pilots to see') that includes information that is deemed beneficial to operators, they must read and sign for having read as part of their currency.

Supervision

1.4.5.15 The Thales FOB allowed for the situation that occurred on 3 Feb 17, where a single individual was responsible for supervising flying, self-authorising a flight trial and acting as UAV Cdr and P1. The Panel considered to what extent supervisory roles could be combined without detriment to safety. Exhibit 43

1.4.5.16 **UAV Cdr and P1.** The Panel first deliberated whether it was safe for the UAV Cdr to act as P1 also. The Panel considered:

a. **Crew workload.** The Panel questioned whether the crew workload was likely to be such that an additional crew member was required. The Panel noted the FOB requirement for a qualified TO to form part of the crew for trial flights and the common practice to employ a FELA for other flights. The FOO also made use of additional aircrew to act as observers outside the GCS when required. The Panel also noted that the difficulties that seemed to be commonly encountered crewing-in and the number of WCAs (discussed further in Section 1.4.7) significantly added to the crew workload. Witness 2 Exhibit 43

b. **Mission type.** On occasion it makes sense to have a UAV Cdr who is not P1 or P2, for example if the crew are under training. The Panel considered whether any mission types would necessitate a separate UAV Cdr. The Panel concluded that trial flights would not usually warrant a separate UAV Cdr.

c. **Common practice on other fleets.** On Reaper UAS it is common practice for the P1 to also be the UAV Cdr and with manned fleets the same is true. On trials, it is also common practice for crew to be kept to a minimum, although this is primarily aimed at ensuring risk to life is kept ALARP on manned fleets, it can also serve to minimise distractions.

d. **Crew Resource Management (CRM)**. With RAFCAM the Panel analysed the CRM on Flt 593 to determine if there was any obvious reason why the UAV Cdr should have been separate. The Panel noted that the CRM was assessed to be effective throughout the flight. Exhibit 6

The Panel concluded that there was no obvious reason why the UAV Cdr should have been separate from the P1 on Flt 593 as the crew workload was not excessive and the mission type did not require a separate UAV Cdr.

1.4.5.17 **Crew and AO.** The Panel considered the scenario when the AO was also part of the augmented crew, known as 'self-authorisation'. The Panel noted:

a. **RA 2306.** RA 2306 covers authorisation inclusive of self-authorisation. It states, "*Suitably qualified aircrew may be granted powers of Self-Authorization by an Approving Officer with any limitations detailed on an appropriate certificate. Independent authorization, rather than self-authorization, is encouraged.*" In most military aviation units, there is an independent supervisor separate from the AO, who oversees all flying activities and provides independent assurance when the AO is part of an aircraft crew. Exhibit 41

b. **Thales FOB.** Thales FOB stated, "*Where the Flight Authorizer is also part of the GCS Crew he may self-authorize (if permitted in his letter of delegation) for UAV flights. However, this is not to be the normal procedure and it is highly desirable to have the Flight Authorizer separate from the GCS Crew.*" The Panel noted therefore, that self-authorisation was permitted, but Exhibit 43 not desirable. The Panel further noted that the Thales FOB also stated that the AO would also act as Flying Supervisor. Therefore, the situation could legitimately have arisen whereby there would have been no supervision of flying outside of the immediate crew members.

c. **Common practice on other fleets.** On other military UAS, the AO is independent from the crew. One of the key advantages of UAS is the ability to conduct a crew change without having to land the UA. In such cases, a member of the current crew can authorise the sortie for the successor crew continuing on the same flight with the same UA. In manned aviation, some Squadrons routinely self-authorise, however, they usually have a duty authoriser, who is qualified aircrew, able to provide a level of independent assurance to the flight planning process. In accordance with RA 2305 a flying supervisor would be immediately available and contactable to supervise flying conducted at the unit. Exhibit 42

1.4.5.18 **Level of self-authorisation.** The Panel analysed the amount of self-authorisation over the 4-month period prior to the accident. The results are shown in Figure 1.4.5.1. The FOO stated that on some self-authorised flights the AO was only acting as the UAV Cdr or a crew member for a small amount of the flight. Exhibit 4 Exhibit 188

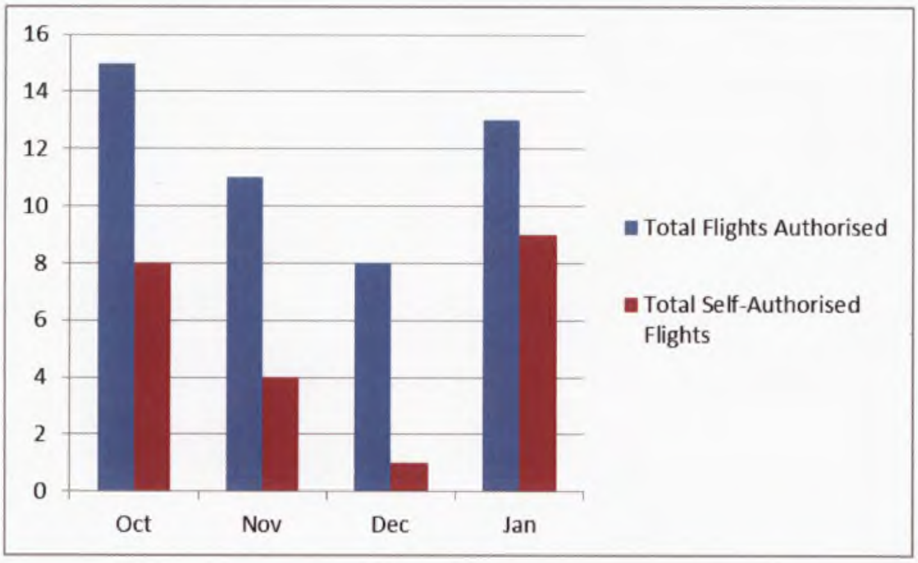

Figure 1.4.5.1– Self-authorisation over preceding 4 months

1.4.5.19 **Analysis of self-authorisation.** Although Thales FOB had stated self-authorisation should not be the "*norm*", Figure 1.4.5.1 shows that it had become regular practice, although the level of self-authorisation varied significantly from month to month. The RAFCAM HF report, discussed further in Section 1.4.7, noted that the process of self-authorisation has no form of independent assurance, which leaves room for error from the planning/preparation process, allowing undetected transfer into the sortie/flight. The Panel noted that no Met update was requested following the delayed take-off time (paragraph 1.4.2.9) and considered whether this was due to the crew being close to capacity with the task of crewing-in. Exhibit 43

1.4.5.20 **Conclusions regarding self-authorisation.** The Panel concluded that the AO, UAV Cdr and P1 were working close to capacity in an important trials flight. The presence of an independent authoriser/supervisor would have been able to consider and advise the UAV Cdr on the weather, and the consequences of the delay in take-off and landing due to the impending weather conditions being out of forecast limits. An independent authoriser/supervisor would have had more awareness of the overall flight operations at WWA and should be regarded as an asset that frees up the capacity of the UAV Cdr to be able to focus on flying.

1.4.5.21 **Authoriser and flying supervisor.** The Panel considered whether the tasks of AO and Flying Supervisor should be conducted by separate individuals. In military organisations, the roles are separated, allowing individuals to provide sufficient overwatch to flying activities. The Thales FOB had no Terms of Reference (ToRs) specific to Flying Supervisor as the role had been appointed to the Flight Authoriser by the AM(MF). This appeared to be sufficient, provided the AO remained independent of the flying activity taking place. When the authoriser/supervisor is also part of the augmented crew, there is no independent assurance over the flying activities. Exhibit 43

1.4.5.22 **Conclusion.** The Panel concluded that the FOO complied with the regulation regarding authorisation and supervision of flying on 3 Feb 17. The Panel **observed** that there was no supervision outside the immediate GCS crew. In the opinion of the Panel 2 key risks existed. Firstly, there was a risk of errors made in the flight planning process being carried through to the flight, and secondly there was a risk of time pressure and task focus reducing wider situation awareness. The case for independent authorisation was further considered by the RAFCAM HF report, which is covered in Section 1.4.7.

1.4.5.23 **Recommendation**. The Thales Accountable Manager (Military Flying) should amend the Flying Order Book to ensure that a flying supervisor, who is not part of an augmented flying crew, remains available to supervise flying activity.

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SECTION 1.4.6 – TRIAL PLANNING

1.4.6.1 Trial planning was conducted in accordance with the Thales Flight Operations Test and Evaluation Process document authorised by the AM(MF). Testing was broken down into 7 stages, comprising of 5 previously completed stages and 2 remaining flight trial stages: Exhibit 44 Exhibit 52 Exhibit 71 Exhibit 72 Exhibit 73 Exhibit 75 Exhibit 88 Exhibit 89 Exhibit 90 Exhibit 189

a. Modelling and testing in wind and icing chambers completed between 2007 and 2009.

b. Flight in non-icing conditions with foam strips on the wing and V-tail leading edges to simulate accreted ice, completed in [redacted] in 2013.

c. Endurance testing of the wings and connectors.

d. Flight in non-icing conditions with the de-icing wings installed, but not electrically connected on all tail numbers from WK031.

e. De-icing mutual compatibility testing on the ground.

f. Flight in non-icing conditions to confirm safe flight with the De-icing System (DIS) connected and operating, planned as the first part of the icing trial.

g. Flight in icing conditions, planned as the final part of the icing trial.

The following paragraphs consider the documentation produced in support of the icing trial flights, within the context of the overall icing capability development.

Trial Instruction (TI)

1.4.6.2 **Introduction.** The Thales de-icing TI, described the anticipated flight trial requirements for WK ES2 to achieve a RTS with provision for flight in icing conditions using the DIS. The aims stated in the TI were initially to demonstrate that the DIS could operate in flight with no impact on the operation of the UAV or other systems. The subsequent aim was to fly in icing conditions, and demonstrate that the DIS was effective in removing accreted ice, enabling safe flight for up to 15 minutes in icing conditions. Following on from the aim the TI stated two objectives as follows: 076

a. Confirmation that the UAV operation in the air was unaffected by activation of the DIS.

b. Confirmation that the UAV operation maintained safe flight in icing conditions, by the VMS recognising that the UAV was flying in icing conditions and the DIS clearing ice in the air, in the same manner as demonstrated during ground testing at NASA Glenn in 2009[43].

1.4.6.3 **Principle of operation.** The TI described in some detail the operation of the DIS. This included: 076

a. Operator settings.

[43] The TI contained a list of completed ground testing including wind and icing chamber testing at NASA Glenn.

b. The detection of icing conditions by the VMSC based on external temperature and relative humidity sensor readings and the ice detector probe.

c. Definitions of Icing Levels 1 to 3 and the anticipated system and appropriate crew response to each.

1.4.6.4 **Trial resources.** Under the heading *Trial Resources*, the system build standard was specified to be the latest ES2 build standard, as defined in the Trials Master Record Index, with updated VMS, Power Control and Distribution Unit (PCDU) and Distributors and De-Icing wings fitted and electronically connected. It stated that the build standard could potentially include cameras, which were not currently part of the Master Record Index, mounted on the front access panel or in the position of the front payload to monitor in real-time ice accretion on the wings. It stated that a Systems Engineer was required to monitor the 'Sniffer Room' during flight and that, post flight, ESL would need to analyse the VMS logs to confirm that the DIS had no effect on flight operation. Essential trials personnel were not named, but listed to be: Exhibit 52

a. Trials Officer (TO).

b. Project Aircrew.

c. Systems Engineer

1.4.6.5 **Test area.** The TI listed the range danger areas where the trial flights would be conducted. The trial would initially take place over the sea and then later over land for a noise assessment. Exhibit 52

1.4.6.6 **Flight test profiles and amount of flying.** The TI stated that at least 3 successful flights in non-icing conditions would be required before flight in icing conditions could be considered. Only a single flight in icing conditions was contractually required, however the TI suggested that the MOD might wish to consider additional flights in order to expand the scope of the RTS. During the flights in non-icing conditions, the DIS would be connected and fully functional although generally set to 'Off' except during specific DIS sections of the flights. It was anticipated that a total of 5 flights in non-icing conditions would be required in order to: Exhibit 52

a. Confirm that there were no abnormal responses from the UA and its systems (including the GPS, Datalinks and Identification Friend of Foe (IFF)) during operation of the DIS for 5 minutes.

b. Exercise the Lightweight Multimode Air Radio (LMAR) whilst operating the DIS for 15 minutes.

c. Exercise the Radar Payload (Synthetic Aperture Radar (SAR) and GMTI) while operating the DIS for a total of 60 minutes.

d. Operate the laser, if permitted[44], whilst the DIS was operating.

e. Measure the received signal strength of both datalinks out to a specified nominal range whilst operating the DIS.

[44] The Trial Instruction stated that Laser operation was not possible if the EOP was in de-icing mode and was not allowed if there was obscuration of the target due to ice on the camera lens.

f. Conduct a subjective assessment of DIS acoustic noise over land.

Details of test points and pass/fail criteria for flights in non-icing and icing conditions were stated in an Annex to the TI.

1.4.6.7 **Test setup.** Under the heading *Test setup* the TI repeated the possible use of cameras with a feed to the GCS to monitor the leading edges real time. Under the same heading, in the following paragraph, it stated, *"the current proposal is to monitor the engine parameters to determine if the UAV is starting to accrete ice and require more power to maintain level flight"*. Exhibit 52

1.4.6.8 **Data collection, analysis and reporting.** The fourth section of the TI listed the essential data collection requirements, post flight analysis requirements and stated that the results would be presented in a De-Icing Flight Trials Report. The requirements for the 'Sniffer Room' to be manned by a System Engineer during the first 3 flights in non-icing conditions and initial flights in icing conditions and the use of the DO to carry out post flight analysis of the VMS data, were re-stated. Exhibit 52

1.4.6.9 **Trial Risk and Hazard Assessment (TRHA), Air Safety Statement and Flight Test Type.** The fifth section of the TI stated the requirement for a Design Safety Review Board for the trial followed by a separate FOO Operating Safety Assessment for the connection of the DIS and initial operation in non-icing conditions and then for flight in icing conditions. It stated that an Air Safety Statement had already been issued for the connection of the DIS and that a further one would be required for deliberate flight into icing conditions. The flight test category for flights in icing conditions would be *Development Test Flights* as defined in MAA02, whereas flights in non-icing conditions would be *Clearance* flights. Section 5 also listed the main risks described in the TRHA and stated the following limitation was to be observed in addition to limitations defined in the MFTP, TRHA, Certificates of Design and FRCs: Exhibit 52 Exhibit 190 Exhibit 191

> *The DIS shall only be enabled in a safe area over the sea during the first three flights.*

1.4.6.10 **Trials Readiness Reviews (TRR) and approval.** The final section of the TI described the need for a TRR and programme approval. It also stated that individual Flight Readiness Reviews (FRRs) were to be held prior to each flight in accordance with established Thales procedure. Exhibit 52

1.4.6.11 **TI review.** The Panel reviewed the TI with an Empire Test Pilot School (ETPS) qualified project test pilot currently serving on a Test and Evaluation Squadron (TES) and separately with an Air Warfare Centre Trials Management Officer (TMO). The Panel noted the following: Exhibit 52 Exhibit 192 Exhibit 193

a. The layout was logical and the document contained all the expected headings and references to other documents. The document had evidently gone through an approvals procedure and was signed-off by the Test and Evaluation Post Holder and Technical Authority.

b. There was evidence of progressive testing to minimise risk, for example testing the interoperability and functioning of the system in non-icing conditions, prior to testing it in icing conditions. That said, the stated aim of the TI did not lead on to a set of discrete and progressive objectives, required to satisfy the aim. It was important to understand which objectives depend on the satisfactory completion of earlier objectives to underpin a safe and progressive trial. This is known in the T&E community as the 'Crawl-Walk-Run' approach.

c. In the description of Level 1 icing, the TI stated, "*during level 1, icing accumulation may occur but will not be detected by the ice detector*". The Panel interpreted this to be a warning that there was a risk that the ice detector might not declare icing level 2 as soon as ice started to accrete[45]. The risk of icing level 2 not declaring was not discussed or mitigated further in the TI or explicitly considered in the TRHA[46]. The TRHA is considered further from paragraph 1.4.6.13.

d. Under the heading of 'Principle of Operation', it was stated that the firings from the two distributers are not synchronised and could vary by up to 6s. There was no explanation of what the implications of this might have been, other than a statement that ESL had confirmed that this would have no effect on the stability of the UA. The sentence implied that this statement from the UA designer had been taken at face value, rather than considered and proven correct. The Panel concluded that additional information about this should have been presented or ESL's analysis of the effect on stability of the UA should have been included as a reference.

e. The possible use of additional cameras to allow the crew in the GCS to monitor ice on the wings was described, and seemingly considered, in the TI but there was no indication as to whether they were essential or desirable, or whether they would indeed be fitted. The purpose of a TI is to describe how a trial will be conducted and to instruct personnel and organisations of their actions required in support of the trial. The Panel, therefore, considered that stating that additional equipment 'might be fitted' to an aircraft, without requesting an appropriate clearance or describing how such a modification could be embodied safely, was meaningless. In the Panel's opinion, it would have been preferable to include the requirement and then up-issue the TI if it was subsequently determined that the equipment was no longer required for the trial.

f. It was not clear whether the potential use of cameras to monitor the ice accretion on the wings was to assess the efficacy of the DIS, or to reduce the risk of loss of the UA, or both. Recordings from the trials fit camera were listed as an essential data collection requirement, although only if fitted, leading the Panel to infer that they were not deemed to be essential for data collection. The DO explained to the Panel that they had decided that the cameras were not required because the crew should be able to observe:

(1) Ice accreting on other parts of the airframe viewable with the EOP.

(2) An increase in engine RPM to produce more thrust, indicating any significant loss of lift or increase in weight due to ice accretion on the upper surfaces, which could not be seen with the EOP.

g. The list of essential trials personnel for the activity did not include a Trials Safety Manager (TSM). It is common practice for trials organisations to

[45] The ice detector probe is used by the VMSC to turn on the De-Icing System.

[46] The TRHA describes 'THT003c-1 Environmental Conditions (Ice)' as 'encountering severe icing conditions for longer than expected or anticipated'. Ice detector alerts are described as a barrier to this risk.

identify a dedicated TSM within a TI for a flight trial. The TSM is often an engineer with an approved trials competency level.

h. Essential trials personnel were not identified by name within the TI. Even though it was stated in the TI, the 'Sniffer Room' was not manned by a systems engineer for the first flight in icing conditions. The Panel considered that it would have been best practice to name individuals with key roles to ensure that they had time to understand their responsibilities, to prepare for the trial and to ensure that they would be kept informed of any changes to the TI or TRHA. A further sentence stating that any amendments to the essentials trials personnel list must be approved by the Head of Flying would have allowed scope for substitutions to be made, whilst maintaining appropriate oversight.

i. The TI clearly stated the process that the trial would be conducted in accordance with and what type of air release it would be flown under (a signed MFTP) as well as the authorisation requirements for the trial flights.

j. The Flight Test Overview was well described, first laying out the 7 stages of testing required and providing references to what had already been completed.

k. The plan was to fly in to icing conditions with the DIS set to AUTO from the outset, hence relying on the system under test to detect and declare icing conditions. In the opinion of the Panel sufficient confidence in the ability of the system to declare all icing levels, with the DIS SET to ON[47] to protect against ice accretion, should have been gained, prior to the system being tested in AUTO.

l. The TI stated that the time in icing conditions would be built up progressively, with the goal of achieving up to 15 minutes in icing, with an assured exit route available should any abnormal behaviour be exhibited by the UA. The TI noted that in reality this would be difficult to achieve, as cloud structure and extent are uncontrolled and unknown. There was no further detail on how limited exposure would be achieved or the risk of longer than intended exposure would be mitigated. Escape route criteria could for example have included the requirement to reach clear air within a specified time and detail whether the plan was to descend out of icing cloud into warmer air or climb into clear air and sunlight.

m. There were no 'knock-it-off' or 'stop-stop-stop'[48] criteria specified in the TI. The Panel considered that stop-stop-stop or knock-it-off criteria should have been included to cover eventualities such as flight in potential icing conditions without the system declaring icing conditions or any specified abnormal behaviour with the system under test or related systems.

n. There was no mention of the requirement for an enhanced Met brief or live Met updates other than Met observations by the crew. The Panel considered whether given the anticipated difficulty of finding icing conditions

[47] It is understood that with the DIS selected to ON, the icing levels will still be declared and displayed to the crew and the outside air temperature and relative humidity sensor readings used to declare Icing Level 1 remain available to the crew.

[48] 'knock-it-off' criteria are pre-arranged criteria set for a trial flight, which if met, mean that the trial activity should cease for the remainder of the flight. 'Stop-stop-stop' criteria are pre-arranged criteria for a trial flight, which if met, will result in a pause to the trial activity, until it is considered safe to resume the activity.

and the hazards associated with finding them, it may in fact have been prudent to request a dedicated forecaster on hand throughout the trial.

o. Where the TRHA is referred to and the risks listed, it was not clear if the risks are listed in order of assessed severity (a combination of likelihood and consequence).

1.4.6.12 **Conclusion.** The Panel concluded that the TI had a logical structure, however, **observed** that:

a. The TI did not contain discrete and progressive objectives in support of a single clear aim to underpin a 'crawl-walk-run' approach.

b. Equipment essential for the trial was not clearly defined in the TI.

c. Personnel with specific trials responsibilities were not identified by name in the TI.

d. There was insufficient detail on how the trial test points would be achieved in practice and no 'knock-it-off' or 'stop-stop-stop' criteria were identified in the TI.

Trials Risk and Hazard Assessment (TRHA)

1.4.6.13 The TRHA was a separate document to the TI designed to consider the specific risks associated with conducting the trial, above those associated with normal flying and considered in the Air System Safety Case (ASSC) assessment. The TRHA included a spread sheet of specific risks and mitigations, which considered the resultant change to both Risk to Life and the risk of losing a UA. The TRHA concluded with a list of specific mitigations and instructions for inclusion in the Flight Test Cards (FTCs).

Exhibit 51
Exhibit 188

1.4.6.14 In consultation with an EPTS qualified project test pilot and AWC TMO, the Panel considered the specific risks and mitigations covered in the TRHA and noted the following:

Exhibit 51
Exhibit 192
Exhibit 193

a. One of the mitigations to ice accretion was to conduct flight tests where the conditions permitted flight in temperatures greater than 0^0C to allow the ice to melt. Due to aerodynamic affects, there may have been parts of the airframe where the temperature could remain below 0^0C even if the surrounding airflow was above 0^0C. Additionally, particularly with a cold soaked airframe the rate of thawing could be particularly slow in air temperatures of just above 0^0C.

b. On two occasions the 'Barrier' column was used to continue to describe the threat (risk) rather than a particular barrier to the risk materialising.

c. Alerts from the ice detector were described as a barrier to the risk of encountering severe icing conditions for longer than expected. As the UA had not been flown into icing conditions under test conditions previously, the Panel considered the icing detector to be part of the system under test and therefore not a suitable barrier to a risk.

d. Debris (specifically ice) falling from the aircraft in flight was considered from a point of view of damage to the UA and mitigated by conducting the tests over the sea and within glide range of the Emergency Recovery Location (ERL). This would have mitigated the risk to 3rd parties, but not the stated issue or effect. The increase in risk to loss of the UA was given as 'Not quantified'.

e. None of the risks identified were quantified in terms of a likelihood verses severity matrix. Although increase in RtL and loss of the UA were stated, there was no detail on how the assessment had been made. In several cases, the increase in risk to UA loss was 'Not quantified' despite the threat of UA loss associated with the risk.

f. Mitigations were understandably aimed at reducing the chances of losing the UA and by extension minimising RtL. Should the UA be lost, the resultant RtL was to be minimised by flying over the sea for the DIS trials. Minimising the risk to equipment in the event of UA loss was not considered.

g. Failure of the ice detection system was not specifically considered, although accumulation of ice not detected by the ice detector was identified in the TI as discussed in Paragraph1.4.6.11.c.

1.4.6.15 **Conclusion**. The Panel **observed** that:

a. The TRHA had insufficient detail to quantify the risks identified in terms of likelihood verses severity and could have provided more detail to assess the effectiveness of barriers and mitigations and therefore the likelihood of a risk materialising and the resultant severity.

b. No consideration was given to minimising role equipment carried to mitigate the consequences of losing the UA.

c. Not all risks identified in the TI were explicitly considered in the TRHA.

Military Flight Test Permit (MFTP)

1.4.6.16 Applicable to WK ES2 flying at the time was RA5202 – MFTP[49]. RA5202 stated that the authorisation of specified flights of a Military Air System without a valid Certificate of Usage or where the design build standard was not reflected in an extant RTS would be conducted using an MFTP. The MFTP detailed the authorised flight envelope of the UA and documentation that the system was to be operated in accordance with. As a DAOS organisation, the DO were authorised to apply to the DE&S UAST TAA for an MFTP by providing a Certificate of Design (CoD) to satisfy the Declaration of Compliance (DofC) requirements[50]. The CoD certified the extent to which the design satisfied the requirement of the specification issued by, or on behalf of the MOD, including any exceptions or limitations. As part of the MFTP application process the TAA also received the TI and TRHA as supporting evidence. Subject to the TAA issuing a MFTP, an authorised pilot would be permitted to fly listed tail numbers, at specified build standards, from an approved location in strict accordance with the limitations attached to the permit.

Witness 18
Exhibit 59
Exhibit 194
Exhibit 195

1.4.6.17 The Panel considered the environmental limitations for the operation of the system in the MFTP applicable to WK042. The Panel noted that:

Exhibit 59

a. There was no absolute rainfall rate limit for operation of the UA. The MFTP stated, 'When flying in heavy rain of 8mm/hr or more, caution should

[49] RA5202 has now been incorporated into RA5880 – Military Permit to Fly (MPTF).

[50] DofC requirements were listed in an Appendix to RA5202 and the provision of a CoD to satisfy a DofC was subject to the MFTP Applicant demonstrating that all the requirements of the Appendix had been satisfied.

be exercised and if persistent anomalous behaviour of the pitot systems is experienced, it is recommended to vacate the heavy rain conditions'. There was no way for the crew to determine the rainfall rate in which the UA was flying. The crew would therefore have to rely on their experience of what heavy rain looks like on the EOP or request Met information.

b. Flight in potential icing conditions was permitted and flight in icing conditions up to the continuous maximum, indicated as ice detector level 2, was permitted for up to 15 minutes with the DIS mode set to ON or AUTO.

c. Flight in hail conditions was prohibited due to the risk of structural damage to the aircraft.

d. Flight in snow conditions was *to be avoided* and if snow was encountered during flight, the UA was to vacate immediately.

e. Wind speed was limited to 45kts. The Panel understand this limit was put in place to allow the UA to make sufficient progress into headwinds and to give a sufficient margin to ensure that it can always remain in its allocated airspace.

f. Flight in turbulence greater than MODERATE was prohibited.

g. Limitations for take-off and landing were: Maximum headwind, 25kts; Maximum crosswind 15kts; Maximum tailwind 5kts.

h. There were no specific cloud limitations other than a minimum cloud base for landing and horizontal visibility limitation for take-off and landing.

1.4.6.18 Less than 5mm of rain per hour was recorded in the local area during the flight. The UA was likely to have encountered moderate, but not severe turbulence during the flight (paragraph 1.4.3.8) and there was no evidence of ice accretion (paragraph 1.4.2.13). Therefore, at the time of the accident the UA was flying within all the MFTP environmental limitations, including those for cloud and precipitation. As flight for a prolonged period in cloud and precipitation was identified as a contributory factor (paragraph 1.4.3.30), the Panel concluded that a further **contributory factor** was that the DO may have over-estimated the UA's ability to fly in cloud and precipitation, which led to inaccurate limits being set for the MFTP.

Exhibit 196

Readiness reviews and approvals

1.4.6.19 In addition to obtaining a signed MFTP, the Thales FOO were, in accordance with their Flight Operations Test and Evaluation Process, required to conduct a TRR, any trials training identified in the TI and generate FTCs. Once these actions had been completed, a Thales Programme Flight Authorisation would be provided, allowing the FOO to hold a final FRR immediately before the flight. The FOO were able to demonstrate that they had carried out the necessary reviews and approvals process ahead of Flight 593, although they had not retained a written record of the FRR.

Witness 17
Exhibit 44
Exhibit 53
Exhibit 197
Exhibit 198
Exhibit 199

Flight Test Cards (FTCs)

1.4.6.20 The FTCs were prepared for use by the flight test crew during live trial flights. The front page contained details of other Trials documentation, including the TI and the applicable MFTP, weight and balance data and system configuration information. Inside, was detailed a synopsis of the TRHA, minimum weather

Exhibit 2
Exhibit 188

conditions, lost link route details and a minimum equipment list. The Mission Objectives list on the FTCs were listed to be:

a. Crew Currency.

b. De-icing.

c. Landing logic.

d. EO Area Coverage RFT.

1.4.6.21 Specific test points in the FTCs were listed under the following headings: Exhibit 2

a. Landing logic.

b. Flight in non-icing.

c. Flight in icing.

d. Targeting test points.

1.4.6.22 In consultation with an ETPS qualified project test pilot and AWC TMO, the Panel analysed the FTCs and noted the following: Exhibit 192 Exhibit 193

a. The front page stated that the DIS was electronically disconnected iaw with a Thales concession. This is understood to be a typographical error originating from when the icing system was fitted but not electrically connected. A further typographical error was noted on the system limitation page, which stated that the minimum temperature for the operation of the UA was +34^{0}C; it should have stated -34^{0}C.

b. Although the flight test cards were annotated to be for Flt 593, they appear to contain test points covered by previous flights in the same trial, such as flight in non-icing conditions.

c. It was not clear from the FTCs what the start point for the icing level 1 and 2 test points were. The assumption was that the test point would be considered to have started only when the UA declared the icing level, although this was not documented.

d. In the incremental build up to flying for 15 minutes in icing, no time period to fly out of icing conditions, before returning was defined.

1.4.6.23 The Panel noted that crew currency was stated as the first mission objective and given the time available that the Landing Logic and EO area coverage/targeting test points featured at all in the FTCs. That said the Panel noted the argument for the FTCs to contain more test points than were expected to be achieved to allow for a degree of flexibility and to make the most of the flight should the icing testing not be able to be carried out for any reason. Of significant note was the lack of detail surrounding the icing test points, including actions to be taken if icing was considered likely, but the system did not declare it. The Panel considered that the typographical errors on the FTCs were not misleading, because the crew knew that the icing system was in fact electrically connected and that they could operate the system below +34^{0}C. However, it did appear that the FTCs had not been thoroughly checked over. Finally, whilst an incremental build up to the desired 15 minutes in icing was appropriate, the FTCs did not explain how this would be achieved.

Previous de-icing system flight trials

1.4.6.24 Prior to the loss of WK042, the FOO had conducted 3 flights in non-icing conditions with the DIS operating and had made one previous attempt to test the DIS in icing conditions, although no icing conditions had been declared by the UA. The 3 flights in non-icing conditions are summarised in Table 1.4.6.1 below.

Exhibit 200
Exhibit 201
Exhibit 202
Exhibit 203
Exhibit 204
Exhibit 205
Exhibit 206
Exhibit 207
Exhibit 208

Flight UK560 WK043 13 Oct 16 - NON icing conditions		
DIS time on	**DIS time off**	**Notes during DIS period**
11:39:48	11:45:07	The flap position was noted to have changed as expected with selection of the icing flight mode.
Notes on sortie. Counts of the DIS firing were not available in the GCS. The PATE was reconnected prior to shut down to enable de-icing count to be viewed as the trials crew were unsure if this data would be available post shut down. It was noted by the crew that there was no indication inside the GCS that the DIS was working. The radar payload was fitted, and tested for interoperability with the DIS.		

Flight UK565 WK043 26-Oct-16 - NON icing conditions		
DIS time on	**DIS time off**	**Notes during DIS period**
14:03:46	14:17:46	De-icing runs were carried out with mode ON and OFF
16:50:44	16:58:37	Landing commanded with de-icing mode set to ON. Manual abort of landing before ice mode selected to OFF.
Notes on sortie. The radar payload was fitted, although the sortie notes do not record it being used.		

Flight UK 566 WK043 28-Oct-16 - NON icing conditions		
DIS time on	**DIS time off**	**Notes during DIS period**
11:37:45	11:39:14	
11:50:51	11:52:44	
11:54:45	11:55:46	At 11:55:24 the DIS failed transiently. The crew made a note to check the firing count and to check which part of the system had failed.
11:57:09	11:59:12	At 11:58:56 the DIS failed.
11:59:20	12:03:36	At 11:59:20 the Radar payload was exercised with the DIS. At 12:00:05 the DIS failed transiently. At 12:00:57 a SAR strip was recorded to have been seen – a GS 68Kts and a good SAR image was noted. The LMAR was also tested at the same time as the DIS with the radar and a good receive and transmit was noted with no effect from having the DIS turned on. At 12:02:42 the EOP was exercised with the DIS on and the crew recorded that the DIS has no effect on the EOP.
12:03:52	12:05:24	At 12:04:36 the DIS failed.
12:05:35	12:06:05	
12:09:25	12:11:24	

12:17:41	12:20:11	At 12:17:41 good GMTI returns were noted with no effect from having the DIS on. At 12:18:45 GMTI spot was used, with the DIS still on - good returns were recorded. At the same time the crew recorded transmitting on LMAR TX3 RX4 with the DIS having no effect.
Notes on sortie. At 12:28:43 the DIS was set to ON, it initially reported being ON in the CS tab, but then showed itself to be OFF. ON was reselected on the CS and again reported being ON for approximately 5s before reporting OFF. The AVDC reported icing mode as ON but de-icing OFF.		

Table 1.4.6.1 – Summary of previous DIS flight trials

1.4.6.25 The Panel considered whether the trial programme was ready to conduct a flight in icing conditions by 3 Feb 17. The Panel considered the following: Exhibit 52

a. Three of a total of 5 flights in non-icing conditions that were anticipated in the TI had been completed prior to attempting a flight in icing conditions. The trials documentation did not state that all the flight test points in non-icing conditions had to have been attempted and met the pass criteria prior to a flight in icing conditions.

b. In addition to the ground testing, the DIS had been used on 12 occasions over the 3 flights in non-icing conditions. No issues had been reported on 7 occasions, transient failures had been reported on 2 occasions and other failures or issues on 3 occasions.

c. Opportunities to fly in icing conditions were limited by meteorological conditions and therefore likely to be extremely limited.

d. The crew were able to see if the DIS had failed.

e. Evidence had been obtained of the DIS operating with no effect on the LMAR, the EOP, the radar payload or other flight systems operating simultaneously.

1.4.6.26 The Panel concluded that the totality of the ground and flight-testing conducted in non-icing conditions, prior to 3 Feb 17, demonstrated that the DIS, although yet to prove its reliability, could function without adverse effect to other systems. The Panel determined that provided the risks associated with flying in icing conditions were otherwise mitigated (so as not to have to rely on the DIS or other part of the system under test) then it was not unreasonable to fly the trial in icing conditions.

Conclusions

1.4.6.27 The Panel **observed** that Thales did not maintain a progressive approach to testing throughout the icing trial. Whilst Thales initially adopted a progressive 'crawl-walk-run' approach, turning the system on for increasing amounts of time with other systems in non-icing conditions, this approach was not maintained in the planning for the flight test in icing conditions. The plan was to prove that the UA could detect, declare and automatically turn on the DIS on the first deliberate flight into icing conditions. A more progressive approach would have been to put the UA into icing level 1 conditions for a defined short, safe, period of time with the DIS set to ON (to further guard against possible ice accretion). Regardless of whether icing level 1 was declared, the UA would then leave the potential icing conditions for a defined period of time and the data fully analysed before the next flight. All being well over several flights the test crew could work up to the desired icing conditions to gain confidence in the system's detection and protection capabilities before repeating in AUTO mode. Had this approach been adopted, the issues found by the panel of getting the system to reliably declare icing level 1 (described in Section 1.4.8) would have been discovered through analysis. The Panel consider it highly likely that over several analysed flights that ADU cautions would have been noted during the limited time flying in cloud. Had these been analysed the risk of flying in cloud for prolonged periods may have been better understood.

1.4.6.28 The Panel further concluded that the observations made on the TI, TRHA and FTCs represented areas where the trials paperwork could be improved to better consider risks, adopt best trial practice and enhance overall trials safety and efficiency. The interoperability of the DIS with the radar payload and other systems had been tested in non-icing conditions and in the opinion of the Panel, there was no justification associated with the icing trial for carrying it on the first flight in icing conditions. The loss of the radar payload made the outcome of the accident worse in terms of financial cost and loss of capability. Therefore, the Panel concluded that the carriage of the radar payload was an **aggravating factor** to the accident.

1.4.6.29 **Recommendations.** The Thales Accountable Manager (Military Flying) should:

a. Review the Thales Flight Operations Test & Evaluation Process to ensure that it contains sufficient detail for compiling Trial Instructions and Trial Risk and Hazard Assessments in order to improve trials safety and efficiency.

b. Update the Thales Flight Operations Test & Evaluation Process to ensure that when a Trial Risk and Hazard Assessment identifies an increased risk of losing an Unmanned Aircraft, role equipment is minimised to only that essential to satisfying the specific test point associated with that risk.

1.4.6.30 Finally, the Panel acknowledged that whilst the CFAOS organisation had a legally Accountable Manager owning RtL (discussed in Section 1.4.4), ultimately the MOD held the risk to equipment where the CFAOS organisation had operated within the MFTP. Under the DAOS and MAOS approvals, contracted organisations were also maintaining and setting design limitations for the system with limited MOD oversight. Whilst the UAST conducted technical reviews of the MFTP evidence, the MOD's participation in the T&E activity itself by Suitably Qualified and Experienced Personnel (SQEP) T&E Operators, such as an Air Warfare Centre Test and Evaluation Squadron (AWC TES)[51], was not mandated. The Panel **observed** that there was no MOD T&E oversight for the trial. Overall, the Panel concluded that the conduct and supervision of this trial made the accident more likely, and was therefore a **contributory factor.**

Witness 17
Exhibit 209

1.4.6.31 **Recommendation.** Head Unmanned Air Systems Team should task a Test & Evaluation organisation with flight trial Suitably Qualified and Experienced Personnel, independent from the contractor, to participate in the trials process and review and report on trials documentation used to support a Military Flight Test Permit or Military Permit To Fly application.

[51] It is understood that in previous WK trials the AWC's UAS TES (now part of 56(R) Sqn AWC) had provided SME support to Combined Test Teams.

SECTION 1.4.7 – HUMAN FACTORS

Introduction

1.4.7.1. The Royal Air Force Centre of Aviation Medicine (RAFCAM) were tasked with conducting an investigation into the Human Factors (HF) aspects of the WK042 accident. RAFCAMs involvement in the Inquiry included participation in the SI Panel interviews with those involved in the accident, attendance at the DO's initial analysis of flight data presentation and analysis of the interview transcripts and GCS Voice Recorder (GCSVR). RAFCAM also produced a report and supported the Panel in their deliberations of HF aspects. The HF investigation focussed on 5 key areas: Exhibit 70

a. Authorisation.

b. Pressure.

c. Use of Met information.

d. Communications.

e. Response to Warnings, Cautions and Advisories (WCAs).

This section considers the RAFCAM HF report and recommendations made and draws out HF identified elsewhere in this report as required.

Authorisation

1.4.7.2. Supervision of flying and specifically the self-authorisation is covered in Section 1.4.5 under the heading Supervision. The HF report noted that there was a strong case for the principle of having an independent authorisation process. This is because there was a high degree of coupling between planning a task and checking a task, if both actions are carried out by the same person. This increased the likelihood of an error made in the planning stage, being missed in the checking stage. When the authoriser is closely involved in the sortie planning or execution there are a number of psychological mechanisms that could lead to coupling between tasks planned by the crew and checked by the Authoriser. These include: Exhibit 70

a. The level of confidence the checker has in the person performing the task.

b. Attentional focus, which can mean that the same parts of the task may be missed in both stages.

c. Confirmation bias, which means that individuals tend to seek out information that matches their initial beliefs rather than seeking information to assess whether their initial beliefs are correct.

d. Complacency.

1.4.7.3. The HF report noted that there are various practical methods of improving the level of independence between conducting and checking a task (decoupling the tasks), the most common being to use a different person, and recommended that steps were implemented to increase the independence of the authorisation process for Watchkeeper sorties. The Panel believe that an AO, who was not part of the augmented crew (as previous recommended in paragraph Exhibit 70

1.4.5.22) would have been the most effective way to reliably increase the level of independence of the authorisation process.

Pressure

1.4.7.4. The HF report stated that the majority of interviewees perceived there to be task pressure, but noted mixed perceptions as to whether it was suitable or excessive and whether it increased the level or risk taken. The Panel believe that on the day in question, there was pressure to fly whilst the weather was suitable. Take-off time had originally been planned for 0900hrs and a 1hr earlier start and Met brief was planned to accommodate that. The Met forecaster had stated that there was a window to fly between 0830 and 0930hrs after which the wind would increase steadily such that it would risk being out of limits. The Panel interpreted this to mean that wind was likely to go out of limits after 0930hrs, but not necessarily immediately. A technical issue delayed the take-off by just over an hour, by which time the wind direction had changed, giving a slight tailwind component for take-off. The crew took several minutes to confirm that the small tailwind component was in-limits and took-off at 1007hrs. The HF report noted that expectation regarding the landing time, which was originally to be back before 1100hrs, had gradually drifted to later without any discussion of the implications of this or of modifying the plan to account for the delayed take-off. Witness 3 Witness 15 Exhibit 6 Exhibit 10 Exhibit 70

1.4.7.5. Noting that no Met forecast update was requested (as discussed in paragraph 1.4.2.9), the Panel **observed** that there was an unconscious loss of situational awareness regarding the time required to conduct the task and the time available to conduct it safely ahead of the forecasted out of limits weather. In the opinion of the Panel, an AO outside of the GCS may have provided greater situational awareness and may have had a positive effect on reducing the level of task pressure felt directly by the crew. 098, 099, 100, 101, 102

1.4.7.6. The Panel considered whether some of the practices employed, such as observing wind speed and direction directly from the ATC tower, enabling flight up to the weather limits, may have increased the level of risk taken by the FOO. The Panel concluded that whilst intending to fly close to a limit may increase the risk of exceeding it, to do so was not necessarily bad practice if sound airmanship principles were employed to minimise the risk of exceeding limits. Furthermore, to use a capability to its limits, was in fact desirable to maximise the opportunities to fly and progress the trials programme. For example, the use of an additional pilot to act as a weather observer in the ATC tower to report on the strength and direction of wind gusts would help the UAV Cdr make an informed decision on whether it was safe to take-off. Nevertheless, other practices, if employed, such as planning to land close to the end of a weather window increase the level of risk as they do not account for changing Met predictions, emergency landings or problems encountered delaying the landing time. In conclusion, the Panel **observed** that the FOO had a number of practices, which enabled flights close to operating limitations to be undertaken, but could increase the operating risk in some circumstances.

1.4.7.7. **Recommendation.** The Thales Accountable Manager (Military Flying) should review practices, used by the Flight Operations Organisation to enable flights that are close to operating limitations to be undertaken, to ensure that the risk remains tolerable and As Low As Reasonably Practicable and authorised at an appropriate level to accept additional risks identified.

Use of Met information

1.4.7.8. Use of the Met information that informed the take-off is covered in Section 1.4.2. The HF Report, whilst acknowledging that the take-off was 178 conducted within limits, concluded that the way in which the Met information was used as part of the decision making process increased the risk of decision error and the crew entering a hazardous situation as a result. The principle HF concern was that time and task pressure made it more difficult for the crew to assess contradictory information effectively, leading to risks associated with confirmation bias. The HF report noted that independent authorisation may reduce this risk and also recommended that HF training provided to crews should include training on the factors that influence decision making and the role of decision making biases. This recommendation in the HF Report is considered by the Panel in paragraph 1.4.7.15.

Communications

1.4.7.9. The GCSVR was analysed by RAFCAM and by the Panel; communications within the GCS and to the ground crew outside were clear, accurate and professional. The HF report identified some tensions between ground and aircrews. The source of these tensions appeared to be the way in which concerns about weather limitations by the ground crew on occasions prior to the accident had been received by the aircrew. One pilot noted a preference for using telephone communications rather than radio to reduce the risk of comments about the weather being misinterpreted by others on the radio network. The Panel considered that whilst working level frustrations between different teams often occurs, there was an increased risk that, unchecked, such tensions may inhibit potential flight safety information from being passed openly between teams. The Panel **observed** that the flow of information between ground crew and GCS crew could be improved. The HF report made 4 recommendations to improve communication between ground and aircrews. These are considered in paragraph 1.4.7.15.

Witness 4
Witness 6
Exhibit 6

Response to Warnings Cautions and Advisories (WCAs)

1.4.7.10. The HF Report noted a high rate of WCAs arising, with the rate increasing once the FEPs and pitching oscillations began. It also noted that RAFCAM HF analysis undertaken of the WK006 and WK031 GCSVR had shown a high rate of WCAs, stating that a high rate of WCAs could act as a distraction increasing crew workload and increasing the likelihood of an error being made. Whilst the HF report did not consider the suitability of the response to the WCAs, it noted that in all 3 SI cases[52] analysed, a response had typically been to wait and see if the WCA cleared in a short space of time before deciding to take action. This response was based on experience of many WCAs clearing without any negative impact for the remainder of the flight. The report noted that this approach increased the risk of a WCA being ignored, or acknowledged but assumed spurious, or the response delayed, thus increasing the likelihood of an ineffective response to a hazardous scenario.

Exhibit 6
Exhibit 70

1.4.7.11. The Panel considered the above in response to the WCAs reported by WK042 and noted that the crew of WK042 continued to acknowledge each WCA throughout the sortie until the frequency of the WCAs was such that it was not possible to acknowledge each WCA before the next occurred. Although the Panel concluded, by that stage, there was nothing that the crew could have done to save the UA, the Panel **observed** that the crew were overloaded by WCAs in the final minutes of the flight. The Panel also **observed** that it was not always clear in the FRCs, what actions the crew were expected to take in response to WCAs. For example, the FRC for the 'ADU velocity sensors fail' warning (indicating the loss of

Exhibit 3
Exhibit 6
Exhibit 58

[52] The loss of WK031, WK006 and WK042.

all 4 sensors) advised crews to use minimal manoeuvring and also to carry out controllability checks. In contrast the FRC for the 'ADU velocity sensors redundancy loss' caution (indicating between 1 and 3 of the 4 total pressure sensors have been disqualified by the VMSC), stated 'Land ASAP'. The Panel also **observed** that the FRCs comprised of 265 pages[53], which analysis of the CVR showed that it was difficult for the P2 to find the appropriate card quickly. The Panel also noted that at 1039hrs the crew acknowledged the caution 'ADU velocity sensors redundancy loss', which cleared within 14s. The P2 correctly verbalised that FRC Card E-39 stated that they should 'land ASAP' in response to the caution even though it had cleared. The UAV Cdr did not consider it to be 'latched' and elected to continue with the trial. Given that blocked pitots are a contributory factor to the accident and this was the first sign that a pitot may have become blocked, the Panel concluded that in this case deviating from FRC guidance for a caution not considered to be 'latched' was a **contributory factor**.

1.4.7.12. **Recommendation.** Head Unmanned Air Systems Team should:

a. Oversee a review of the design of the Warnings, Cautions and Advisories to ensure that they are only presented to the crew when they need to be aware of a hazard or take action.

b. Oversee a review of the Flight Reference Cards in order to improve their usability and ensure that that advice to crews on Warning Cautions and Advisories is unambiguous.

RAF Centre of Aviation Medicine Human Factors recommendations

1.4.7.13. In total the RAFCAM HF Report made 10 recommendations to the Panel to consider within context of the Service Inquiry: Exhibit 70

a. That steps are implemented to increase the independence of the authorisation process for Watchkeeper sorties.

b. That the steps implemented to increase the independence of authorisation process include an independent check of sortie changes, including delays to take-off times.

c. That a process is put in place to monitor the level of task pressure being experienced by the Watchkeeper team to ensure that excessive pressure is not influencing flying operations.

d. That a safety review is undertaken of the practices used by crews to enable sorties to be undertaken in the widest range of weather conditions, to ensure that suitable mitigations are in place for increased risk of being unable to land in an emergency.

e. That the HF training provided to Watchkeeper crews includes training on the factors that influence decision making and the role of decision making biases.

f. That the training for Watchkeeper ground crews includes weather limitations, including how these are used and communicated by the GCS crew during take-off and landing.

[53] For context, the Wildcat AH1 helicopter FRCs contain 80-pages.

g. That the frequency of contact between the aircrew and engineering teams at WWA is increased to improve understanding and familiarity with each other's roles.

h. That a system is put in place to review regularly the actions taken to improve communications with further actions being implemented if the issues identified in this report are not resolved.

i. That a review of the design of the Watchkeeper WCAs in terms of the HF issues identified by this and the previous two Watchkeeper SIs. The review should consider:

(1) The frequency with which WCAs are presented.

(2) The transitory nature of many WCAs.

(3) The impact of normalisation, which has developed in the operator responses to WCAs.

(4) The potential for the high number of alarms to overload operators during an emergency.

1.4.7.14. The Panel consider that the intent of RAFCAM recommendation:

a. (a), (b) and (c) is met by the recommendation for the AM(MF) amend the FOB to ensure that a flying supervisor, who is not part of an augmented flying crew, remains available to supervise flying activity, as set out in paragraph 1.4.5.22.

b. (d) is met by the recommendation that the AM(MF) should review practices, used by the FOO to enable flights that are close to operating limitations to be undertaken, to ensure that risk remains tolerable and ALARP and authorised at an appropriate level set out in paragraph 1.4.7.6.

c. (i) is met by the recommendation concerning the design of WCAs set out in Paragraph 1.4.7.12.

1.4.7.15. In the opinion of the Panel, the RAFCAM recommendations concerning training and communication (Paragraph 1.4.7.13 (e) to (h) above) warrant further investigation.

1.4.7.16. **Recommendation.** The Thales Accountable Manager (Military Flying) should commission an independent evaluation of Human Factors at the Flight Operations Organisation.

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SECTION 1.4.8 – ADDITIONAL TECHNICAL FINDINGS

Ice detection

Accuracy of temperature and relative humidity sensors

1.4.8.1. During the course of the Service Inquiry the Panel received manufacturer's data on the temperature and Relative Humidity (RH) sensors used to detect Ice Level 1 and calculate Continuous Maximum Icing Conditions (CMIC)[54] when ice is detected on the ice detector probe. The data gave the accuracy specification of both sensors, including the effect of temperature on the accuracy of the RH sensor. The specification indicated that the accuracy of the temperature sensor was better than +/- 0.5 ^{0}C at 0 ^{0}C and better than +/- 1 ^{0}C at -15 ^{0}C. The RH sensor was most accurate at 25 ^{0}C and between 20-80 %RH, but least accurate at low temperature and extremes of humidity. To illustrate this Figure 1.4.8.1 shows the accuracy of the RH sensor at different RH values against temperature. At 0 ^{0}C and 95% RH the accuracy of the sensor is estimated to be +/- 4.7 % RH.

Exhibit 75
Exhibit 79
Exhibit 80
Exhibit 87

1.4.8.2. The Panel noted that the VMS should declare Icing Level 1 when the temperature falls below 2 ^{0}C and the RH reaches 95% for 20s. A UA flying in clear air at 0 ^{0}C, then entering a cloud should, therefore, declare Icing Level 1 (assuming the ice detector probe does not detect any actual ice accretion). However, due to the accuracy of the RH sensor being +/- 4.7% RH at this temperature, it is possible that it will not declare icing level 1 even if the RH of the cloud is close to 100 % RH. The Panel could not find any evidence of individual sensors being calibrated or of the VMS having any logic to account for low sensor accuracy and the DO agreed that this potential issue warranted further investigation. The Panel concluded that the UA may not reliably be able to detect Icing Level 1 and may not be able to accurately calculate CMIC due to the accuracy of the relative humidity sensor at low temperatures. Given the requirement to operate in icing conditions the Panel consider this issue to be an **other factor**, which if not resolved may contribute to a future accident in icing conditions regardless of the operators intent to fly in icing.

Exhibit 75
Exhibit 87

[54] CMIC is intended to represent icing typical to stratus clouds with amounts of liquid water between 0.2-0.8g/m^3 and droplet sizes 15-40 microns in diameter over a 17.4 nm encounter. The VMS uses the rate at which ice accretes on the ice detector probe and the measured temperature and relative humidity to calculate CMIC. If conditions are below CMIC an Ice Level 2 warning will be generated; above CMIC an Ice Level 3 caution will be generated.

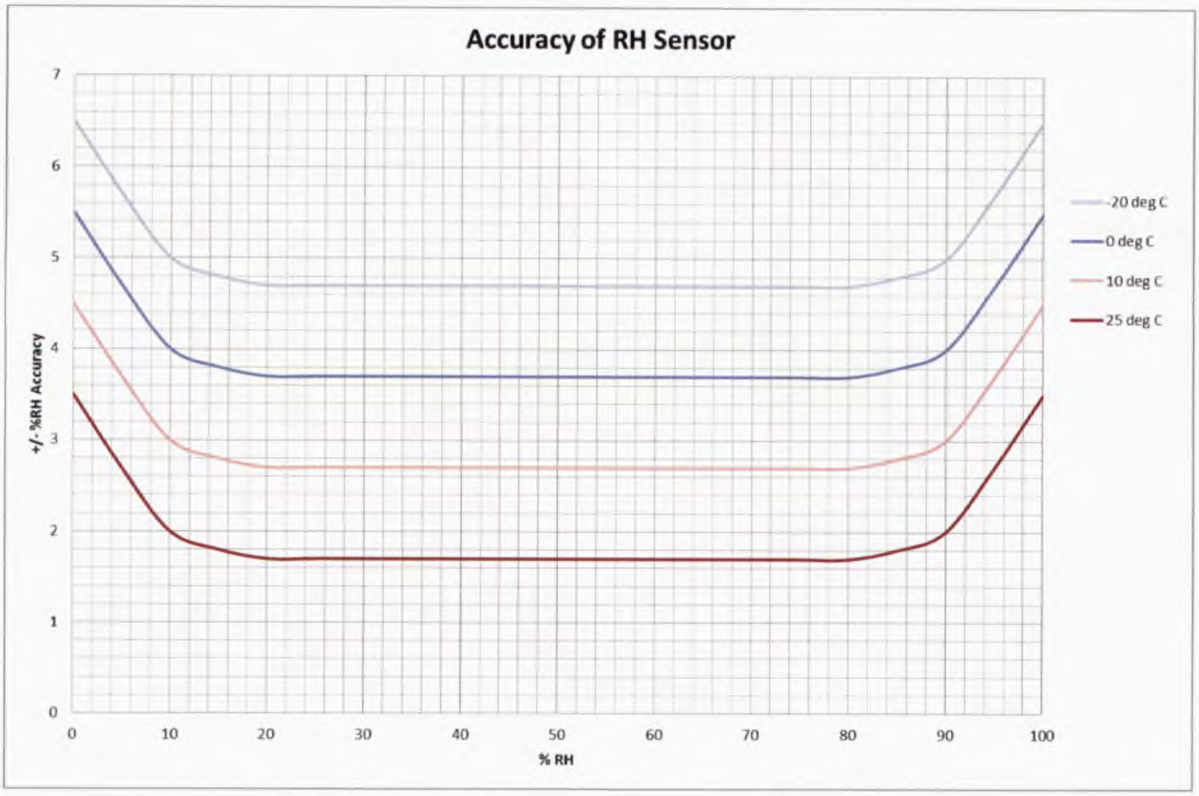

Figure 1.4.8.1 – Accuracy of RH Sensor

Position of ice detector probe

1.4.8.3. The Panel were given access by the DO to all the ground and flight testing reports conducted on the Ice Protection System and related components (the main stages of which are noted in paragraph 1.4.6.1). This included a report analysing the performance of the Ice Detector on WK in an Icing Tunnel. The report considered 2 potential locations for the ice detector; at 11 and 12 o'clock positions when looking at the UA from the nose, as shown in figure 1.4.8.2. The 12 o'clock position was the position taken forward into production. The analysis showed that the ice detector at the 12 o'clock position was in the flow of heated air from the heated Kollsman pitot. This delayed the onset of ice detection by the sensor and required the sensor reading to be calibrated to allow for the VMS to estimate the Liquid Water Content accurately, which is important in the calculation of CMIC. Performance at the 11 o'clock position was better and it is not clear from the report why the 12 o'clock position was selected. The Panel accepted that after calibration the chosen solution could estimate the liquid water content accurately for CMIC and therefore, (notwithstanding the RH sensor limitations described above) declare Icing Level 3 at the correct point. However, the Panel were concerned that the shielding affect may delay the declaration of Icing Level 2, which in marginal conditions could lead to the undetected accretion of ice on other parts of the airframe. Exhibit 73

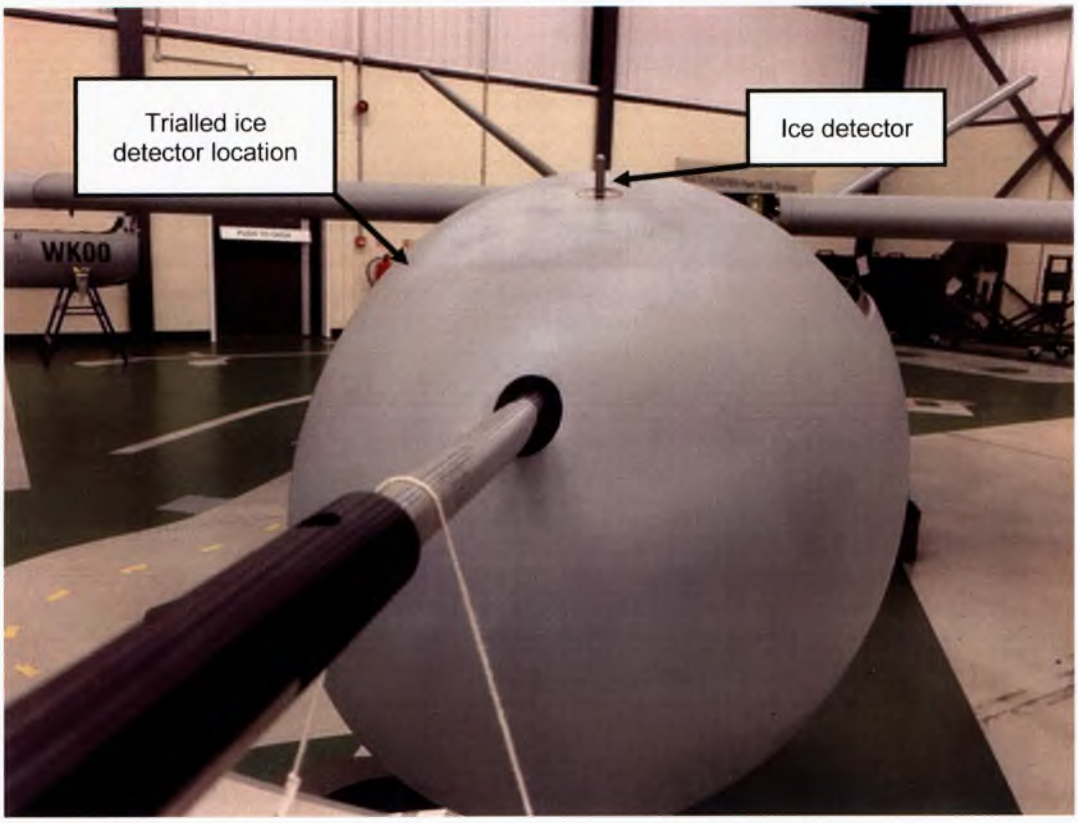

Figure 1.4.8.2 – Ice detector position

1.4.8.4. In the opinion of the Panel, the fact that response of the ice detector probe as fitted to WK is affected by residual heat from the Kollsman pitot heater is a **other factor** worthy of further investigation. This should be carried out in conjunction with any investigation concerning the suitability of the temperature and RH detectors and their integration with the VMS to consider the performance and reliability of the Ice Detection/Ice Protection system as a whole.

1.4.8.5. **Recommendation.** Head Unmanned Air Systems Team should investigate with the Design Organisation that Watchkeeper can reliably detect the defined icing conditions and accurately calculate Continuous Maximum Icing Condition.

Level of system understanding

1.4.8.6. During the course of the Service Inquiry, it emerged that Thales' understanding of the functioning of the ADS was incomplete (paragraph 1.4.3.33). This led to a Technical Note, presented as safety case evidence that incompletely described the disqualification logic for suspected erroneous air data. Whilst it should be stressed that there is no evidence that the incomplete understanding in anyway contributed to the accident, the VMSC's logic for disqualifying sensor readings and computing CAS did (paragraph 1.4.3.30). Clearly any incorrect or incomplete information used to build a safety case is extremely serious as it undermines certification activity and in extremis risks misinforming Duty Holders of the risks associated with operating the equipment. Exhibit 210 Exhibit 211

1.4.8.7. The DO is made up of a number of companies, based in the UK and overseas, with responsibility for different aspects of the WK system. The supervising DO is Thales Defence Missions Systems ISR based in the UK with Exhibit 147 Exhibit 212 which the MOD contracts directly. Thales therefore have the responsibility for total system integration and to provide UAST with evidence that the system meets the MODs requirements and is safe to operate. In practice this will often involve Thales describing the function of a system which they did not design and do not have Intellectual Property Rights (IPR) over. In the case of the ADS this is part of the UA design and is owned by ESL in [redacted] Thales have full access to ESL design data and relevant test reports, however, cannot remove or reproduce certain documents. Thales are therefore faced with the challenge of understanding and presenting to the MOD customer the pertinent safety case information, whilst protecting ESL's IPR. In the opinion of the Panel, this can lead to incomplete understanding and some working level frustrations between the companies and the UAST.

1.4.8.8. During the investigation into the loss of WK042, the Panel also examined the reports into the accidents involving WK031 and WK006. One theme runs through all 3 accidents is the incomplete technical understanding of the WK system by the MOD and elements of the DO and how that translates into a safe envelope of operation for the capability. In the opinion of the Panel, this has highlighted the need for robust T&E effort by the MOD and the DO to ensure that all the capabilities and limitations of the system are fully understood. The loss of WK042 has further highlighted that every reasonable precaution should be taken to make testing as low a risk to the capability as possible – such that any risk is both tolerable and ALARP to the MOD.

1.4.8.9. The Panel considered whether, with the benefit of hindsight, the issues associated with blocked pitots and the incomplete understanding of the Air Data System could have been found before the loss of WK042. The DO have long been aware of issues with the Kollsman pitot blocking with moisture in cloud and precipitation. To provide redundancy they incorporated the Space Age pitot into the design and used an algorithm within the VMSC to compare air data sensor measurements with a reference value and each other, to determine which readings to use to compute air data for use by the FCS. Appropriate maintenance actions such as covering pitot tubes on the ground and purging the system were developed alongside to further reduce the risk of blockages in flight. Nevertheless, velocity sensor redundancy loss cautions had still been encountered during T&E flights. The use of the pitot heaters was found to reduce the level of occurrence of the caution and the software was modified for ES2 to automatically turn on the pitot heaters at take-off.

1.4.8.10. The VMSC records a large amount of sensor level data during every flight, which can be downloaded for analysis. The DO was able to analyse the data produced during pitot blockages to consider; which pitot had blocked, for how long and the system response to it. The Panel considered the analysis that the DO had done on Flights 164 and 493 in response to the pitot blockages. Whilst analysis had been conducted and had correctly identified the cause of the warnings received in flight, the Panel considered that it was never intended to be in-depth analysis and only looked for evidence of the VMSC disqualifying erroneous sensor readings, rather than looking for instances when it did not disqualify readings as expected. Had this analysis looked critically at the system behaviour, it would have highlighted the incomplete understanding. Instead this approach only brought false confidence in the level of understanding of the system. Furthermore, the Panel were unable to find any evidence of the DO considering the statistical likelihood of both pitots blocking concurrently, how long such a situation could persist, or the likely symptoms and consequences. Following the crash, the UAV Cdr correctly identified that he believed a pitot blockage was to blame for the symptoms encountered (paragraph 1.4.3.6). In the opinion of the Panel, multiple pitot

Witness 2
Exhibit 98

blockages were a foreseeable issue and the effects of pitot blockages on the system could have been studied further from existing flight data. The Panel considered that a lack of rigorous post flight data analysis was a **contributory factor** to the accident.

1.4.8.11. **Recommendation.** The Accountable Manager (Military Flying) should ensure that sufficient post flight data analysis on all Test & Evaluation flights is conducted to ensure that all Warnings, Cautions and Advisories or unusual system behaviour are comprehensively understood and any anomalies are properly investigated.

1.4.8.12. Whilst the analysis of real flight data is the best way to learn about a capability under test or to analyse a problem encountered during flight, live flight trials have several limitations. Firstly, there is an element of risk to the capability, especially where the bounds of the flight envelope is being tested. Secondly, due to time constraints and real life environmental conditions, it is often not possible to test in all conditions. It is, however, possible to test a great deal more in the synthetic environment, through a combination of simulation and emulation[55]. For example, during the investigation of a previous WK accident, the DAIB, with the DO, were able to simulate the conditions in which WK031 was flying and then, with a simulation rig containing a VMSC and the actual software used, re-create the accident sequence, thus demonstrating the flawed VMSC landing logic. Had the logic been suitably robustness tested for different sensor inputs and different failures or abort condition and with different overrides applied, it is possible that the hazard present in the logic would have been identified. It is also possible that the different hazard entry conditions to the same hazard that led to the loss of WK006 would have been identified. Whilst the Panel accept that to emulate a dynamic blockage in a pitot may be difficult, the functioning of the air data system with different pitot inputs could have been studied to test the disqualification logic and the dynamic effect on the system, had a suitable simulation rig been available and used.

1.4.8.13. The Panel **observed** that there was a lack of robustness testing of the WK system with the VMSC logic in the synthetic environment. Overall, the Panel concluded that the level of detailed technical understanding of the system in the UK is an **other factor**. Whilst making greater use of new and existing flight data would go some way to addressing this, the Panel believe that only by doing more T&E in the synthetic environment would the envelope be fully tested and understood and any remaining technical risks identified.

1.4.8.14. **Recommendation.** Head Unmanned Air System Team should investigate with the Design Organisation the use of a simulation and emulation to perform robustness testing of the whole Watchkeeper system in the synthetic environment in order to fully test and evaluate the capability with a greater number of conceivable environmental conditions and sensor inputs.

[55] Simulation is the imitation of a real-world process, system or environment. Emulation is the recreation of the real-world process, system or environment. Therefore, a Simulator tries to duplicate the behaviour of the device and an emulator tries to duplicate the inner workings of a device.

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SECTION 1.4.9 – SUMMARY OF FINDINGS

1.4.9.1. The Panel concluded that the cause of the crash was aerodynamic stall due to inaccurate air speed being used by the FCS within the VMSC. This air speed was calculated by the VMSC, which was reacting to inaccurate pitot total pressure measurements caused by pitot blockages from flying in cloud and precipitation over a prolonged period. The FCS response to the erroneous air speed included pitching oscillations and FEP manoeuvres, over speeding and unstable flight near-stall speed, which may have caused physical damage to the left V-tail. Using the Reason's Swiss Cheese Analysis[56], the causal, contributory and aggravating factors are shown in figure 1.4.9.1.

[56] The Reason's Swiss Cheese Analysis model is used for risk management, based on the principle of layered defences. The layers of Swiss Cheese represent the controls, mitigations and defences employed at various levels of an organisation that are in place to prevent accidents. The holes represent the weaknesses in each layer, when the holes line up there is an opportunity for an accident to occur.

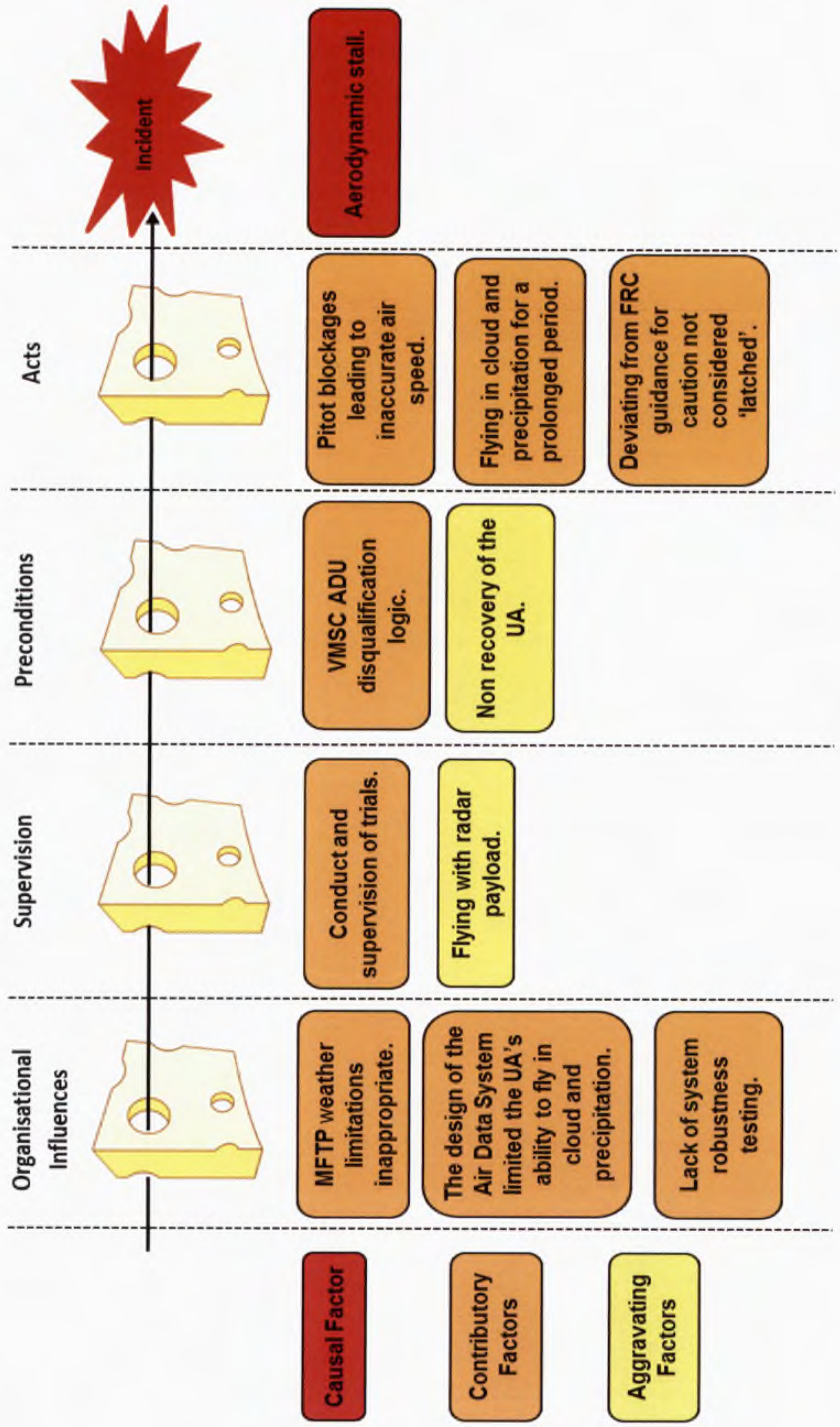

Figure 1.4.9.1 – Reason's Swiss Cheese analysis of the accident

1.4.9.2. **Causal factors**. A causal factor is a factor, which, in isolation or combination with other causal or contributory factors and contextual details, led directly to the accident. The Panel identified the following causal factor:

a. Aerodynamic stall due to inaccurate airspeed being used by the Flight Control Software within the Vehicle Management System Computer. 1.4.3.29

1.4.9.3. **Contributory factors**. A contributory factor is a factor which made the accident more likely to happen, but did not directly cause it. Therefore, a contributory factor in isolation would not have caused the accident. Equally, if a contributory factor was removed, the accident **may** still have happened. The Panel identified the following contributory factors:

a. Flight in cloud and precipitation over a prolonged period of time. 1.4.3.30

b. Pitot blockages, resulting in inaccurate total pressure measurements. 1.4.3.30

c. Vehicle Management System Computer logic for disqualifying sensor readings and computing air speed. 1.4.3.30

d. The design of the Air Data System limited the UA's ability to fly in cloud and precipitation. 1.4.3.35

e. The conduct and supervision of the trial. 1.4.6.30

f. The DO may have over-estimated the UA's ability to fly in cloud and precipitation, which led to inaccurate limits being set for the MFTP. 1.4.6.18

g. Deviating from Flight Reference Card guidance for a caution not considered to be 'latched'. 1.4.7.11

h. Lack of rigorous post flight data analysis. 1.4.8.10

1.4.9.4. **Aggravating factors.** An aggravating factor is a factor, which made the outcome of the accident worse. Aggravating factors did not cause or contribute to the accident, therefore, if an aggravating factor was removed, the accident **would** still have happened. The Panel identified the following aggravating factors:

a. The non-recovery of the UA. 1.4.3.39

b. The carriage of the radar payload. 1.4.6.28

1.4.9.5. **Other factors.** An other factor is a factor, which played no part in the accident in question, but is noteworthy in that it could cause or contribute to a future accident. The Panel identified the following other factors:

a. The UA may not reliably be able to detect Icing Level 1 and may not be able to accurately calculate Continuous Maximum Icing Condition due to the accuracy of the relative humidity sensor at low temperatures. 1.4.8.2

b. Response of the ice detector probe as fitted to Watchkeeper is affected by residual heat from the Kollsman pitot heater. 1.4.8.4

c. The level of detailed technical understanding of the Watchkeeper system in the UK. 1.4.8.13

1.4.9.6. **Observations.** In addition to identifying and categorising the accident factors as described above, the Panel made a number of observations. These are points or issues, identified during the course of the SI, worthy of note to improve working practices and have a positive effect on improving overall air safety. The Panel made the following observations:

a. The Met forecast indicated that the wind would be out of limits for recovery on either runway at West Wales Airport.	1.4.2.9
b. There were no instructions for use for completing Weight and Balance in the F700.	1.4.3.4
c. There were no means of electronically recording UA maintenance data.	1.4.3.4
d. Thales had an incomplete understanding of the Air Data disqualification logic.	1.4.3.33
e. The dataset recorded by the Ground Control Station was insufficient alone to determine the cause of the crash.	1.4.3.39
f. Watchkeeper did not have a crashworthy and locatable Flight Data Recorder.	1.4.3.39
g. Qualification, competency and currency requirements were not clearly defined against each specific role within the Ground Control Station.	1.4.5.6
h. For individuals who do not have their competencies recorded on Joint Personnel Administration, there was no means of recording the Flying Authorisers Course competency when it was maintained as refresher training as part of the Flying Supervisors Course.	1.4.5.9
i. On some occasions an individual had signed simulator record sheets as having acted as both the student and the assessor.	1.4.5.10
j. There was no supervision outside the immediate Ground Control Station crew.	1.4.5.22
k. The Trial Instruction did not contain discrete and progressive objectives in support of a single clear aim to underpin a 'crawl-walk-run' approach.	1.4.6.12
l. Equipment essential for the trial was not clearly defined in the Trial Instruction.	1.4.6.12
m. Personnel with specific trials responsibilities were not identified by name in the Trial Instruction.	1.4.6.12
n. There was insufficient detail on how the trial test points would be achieved in practice and no 'knock-it-off' or 'stop-stop-stop' criteria were identified in the Trial Instruction.	1.4.6.12
o. The Trial Risk and Hazard Assessment did not adequately quantify the risks identified in terms of likelihood verses severity and did not contain sufficient detail to assess the effectiveness of barriers and mitigations and therefore the likelihood of a risk materialising and the resultant severity.	1.4.6.15
p. No consideration was given to minimising role equipment carried to mitigate the effect of losing the UA.	1.4.6.15

q. Not all risks identified in the Trial Instruction were explicitly considered in the Trial Risk and Hazard Assessment.	1.4.6.15
r. Thales did not maintain a progressive approach to testing throughout the icing trial.	1.4.6.27
s. There was no MOD Test and Evaluation oversight for the trial.	1.4.6.30
t. There was an unconscious loss of situational awareness regarding the time required to conduct the task and the time available to conduct it safely ahead of the forecasted out of limits weather.	1.4.7.5
u. The Flight Operations Organisation had a number of practices, which enabled flights close to operating limitations to be undertaken, but could increase the operating risk in some circumstances.	1.4.7.6
v. The flow of information between ground crew and Ground Control Station crew could be improved.	1.4.7.9
w. The crew were overloaded by Warnings, Cautions and Advisories in the final minutes of the flight.	1.4.7.11
x. It was not always clear in the Flight Reference Cards, what actions the crew were expected to take in response to Warnings, Cautions and Advisories.	1.4.7.11
y. The Flight Reference Card comprised of 265 pages, which made it difficult to find the appropriate card quickly.	1.4.7.11
z. Lack of robustness testing of the air data system with Vehicle Management System Computer logic.	1.4.8.13

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PART 1.5 – RECOMMENDATIONS

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

Recommendation	**Analysis Reference**
1.5.2. **Recommendations for Thales UK**	
1.5.2.1. The Thales Accountable Manager (Military Flying) should ensure that qualifications, currency and competency requirements for all Ground Control Station crew roles are clearly defined within the Thales Flying Order Book.	1.4.5.7
1.5.2.2. The Thales Accountable Manager (Military Flying) should amend the Flying Order Book to ensure that a flying supervisor, who is not part of an augmented flying crew, remains available to supervise flying activity.	1.4.5.23
1.5.2.3. The Thales Accountable Manager (Military Flying) should review the Thales Flight Operations Test & Evaluation Process to ensure that it contains sufficient detail for compiling Trial Instructions and Trial Risk and Hazard Assessments in order to improve trials safety and efficiency.	1.4.6.29
1.5.2.4. The Thales Accountable Manager (Military Flying) should update the Thales Flight Operations Test & Evaluation Process to ensure that when a Trial Risk and Hazard Assessment identifies an increased risk of losing an Unmanned Aircraft, role equipment is minimised to only that essential to satisfying the specific test point associated with that risk.	1.4.6.29
1.5.2.5. The Thales Accountable Manager (Military Flying) should review practices, used by the Flight Operations Organisation to enable flights that are close to operating limitations to be undertaken, to ensure that the risk remains tolerable and As Low As Reasonably Practicable and authorised at an appropriate level to accept additional risks identified.	1.4.7.7
1.5.2.6. The Thales Accountable Manager (Military Flying) should commission an independent evaluation of Human Factors at the Flight Operations Organisation.	1.4.7.16
1.5.2.7. The Accountable Manager (Military Flying) should ensure that sufficient post flight data analysis on all Test & Evaluation flights is conducted to ensure that all Warnings, Cautions and Advisories or unusual system behaviour are comprehensively understood and any anomalies are properly investigated.	1.4.8.11
1.5.2.8. The Thales Crew Training Post Holder should review procedures to ensure that all assessed simulator sessions are run by a qualified instructor, who is not participating as crew in the simulator session.	1.4.5.11
1.5.2.9. The Thales Accountable Manager, Continuing Airworthiness should ensure that the Form 700 contains instructions for use in order to ensure that all forms are used correctly and consistently.	1.4.3.5

1.5.3. **Recommendations for Head Unmanned Air Systems Team**	
1.5.3.1. Head Unmanned Air Systems Team should ensure that Watchkeeper has a robust method of determining air speed across its envelope of operation.	1.4.3.36
1.5.3.2. Head of the Unmanned Air Systems Team should ensure that the Unmanned Aircraft can be located following a crash in order to aid post crash accident analysis.	1.4.3.40
1.5.3.3. Head of the Unmanned Air Systems Team should review the use of the Vehicle Management System Computer to ensure that it can be used as a Flight Data Recorder.	1.4.3.40
1.5.3.4. Head Unmanned Air Systems Team should task a Test & Evaluation organisation with flight trial Suitably Qualified and Experienced Personnel, independent from the contractor, to participate in the trials process and review and report on trials documentation used to support a Military Flight Test Permit or Military Permit To Fly application.	1.4.6.31
1.5.3.5. Head Unmanned Air Systems Team should oversee a review of the design of the Warnings, Cautions and Advisories to ensure that they are only presented to the crew when they need to be aware of a hazard or take action.	1.4.7.12
1.5.3.6. Head Unmanned Air Systems Team should oversee a review of the Flight Reference Cards in order to improve their usability and ensure that that advice to crews on Warning Cautions and Advisories is unambiguous.	1.4.7.12
1.5.3.7. Head Unmanned Air Systems Team should investigate further with the Design Organisation to ensure that Watchkeeper can reliably detect the defined icing conditions and accurately calculate Continuous Maximum Icing Condition.	1.4.8.5
1.5.3.8. Head Unmanned Air System Team should investigate with the Design Organisation the use of a simulation and emulation to perform robustness testing of the whole Watchkeeper system in the synthetic environment in order to fully test and evaluate the capability with a greater number of conceivable environmental conditions and sensor inputs.	1.4.8.14

PART 1.6 – CONVENING AUTHORITY COMMENTS

1.6.1. Watchkeeper (WK) registration WK042 crashed into the sea in Cardigan Bay off the coast of Wales at approximately 1116hrs on 3 Feb 17. Despite a sea search, only a small amount of wreckage, mainly composite material, was found washed up on the coast. The Unmanned Air System (UAS) was under Thales operation[1]. It was conducting an icing trial (FLT 593)[2] operating from West Wales Airport (WWA) as part of a series of trials for the Equipment Standard 2 (ES2) build aircraft[3].

1.6.2. WK042 was placed on the Military Aircraft Register on 29 Oct 15. It was first allocated to Thales on 10 Nov 15 and passed acceptance tests on 8 Jun 16. At launch the airframe had only flown 32:42 hours of its 6,000 hour life. It was in-date for flight servicing and scheduled maintenance and had no recorded operating limitations or deferred faults.

1.6.3. I am grateful to the Service Inquiry (SI) President and his Panel for this Report. Determining the causal and other accident factors was particularly challenging, owing to the almost complete loss of the Unmanned Aircraft (UA) in Cardigan Bay and with it much of the evidence needed. Despite these constraints, the methodology used by the Panel proved robust and thorough in its logic and intellectual analysis in meeting fully the Terms of Reference (TORs) set. I agree with the findings of the Report and with the recommendations it makes. If implemented fully, the recommendations will not only help prevent a recurrence of a similar accident, but will assist in the successful delivery to the Army of the WK UAS capability. I hope findings of this SI will also be useful to the wider development of automated flight systems.

1.6.4. The SI Panel concluded the cause of the crash was aerodynamic stall. WK042 stalled because the Flight Control Software (FCS), within the Vehicle Management System Computer (VMSC), was using incorrect air speed values. These values were calculated by the VMSC from pitot total pressure measurements. They were wrong because measurements were taken from pitots that had become blocked following prolonged periods of flying in cloud and precipitation. The FCS's response to these erroneous air speed inputs caused pitching oscillations and Flight Envelope Protection (FEP) manoeuvres, over-speeding and unstable flight near the aircraft's stall speed. These manoeuvres may have also caused physical damage to the left 'V-Tail'. Having stalled aerodynamically, WK042 spun from some 2,500 feet and crashed into the sea.

1.6.5. The Thales Flight Operations Organisation (FOO) had been conducting WK air operations at WWA since Apr 10, with UAV Tactical Systems Ltd (UTacS)[4] providing both engineering and design production support. Flying at WWA was conducted under a Military Flight Test Permit (MFTP[5]), which listed what flying was permissible along with any constraints. The FOO is approved under the Military Aviation Authority (MAA) Contractor Flying Approved Organisation Scheme (CFAOS). The scheme includes a number of named post holders who are legally responsible within the organisation. The Service Inquiry (SI)

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[1] Thales are the Prime Contractor Management Organisation (PCMO) and the Design Organisation (DO) for the WK system.

[2] The WK ES2 build standard required flight trials of its Ice-Detection and De-Icing systems to prove it safe and fit for purpose, as part of it attaining a Release to Service clearance. The accident occurred during the sortie annotated as Flight (FLT) 593.

[3] Equipment Standard 2 (ES2) upgrades the current WK which is at an Operational Conversion Unit (OCU) standard.

[4] UTacS is a joint venture company that was created by Thales and Elbit Systems Ltd. One of its roles is to provide crews and maintenance to air operations at West Wales Airport.

[5] This was in accordance with MAA RA 5202, now incorporated into RA 5880. An MFTP is required for specified flights of a military air system without a valid Certificate of Usage or where the design build standard was not reflected in an extant RTS.

found that the MAA approval schemes were being used appropriately and as intended by the MOD.

1.6.6. As WK042's controlled and safe flight depended on the FCS receiving accurate airspeed values, the SI focused on identifying those factors that affected accuracy. These Contributory Factors (which made the accident more likely), included the length of time WK042 spent flying in cloud and precipitation, the blocking of both its Kollsman and Space Age pitot tubes and the VMSC's logic for disqualifying sensor readings and computing airspeed. I will consider these first, before commenting on how the trial was conducted and on other issues raised by the SI Panel, prior to concluding.

Determining Airspeed

1.6.7. At the time of the accident WK042 was flying within all environmental limitations detailed within the MFTP, including those for cloud and precipitation[6]. Both the Kollsman and Space Age pitot tubes[7] were serviceable and had their heating switched ON for the flight. With no Air Data Unit (ADU) related cautions, it was extremely unlikely WK042 took off with blocked pitots. It was highly probable that the pitots were blocked owing to moisture accumulating during flight, caused by a combination of precipitation droplet ingress and condensation. As a consequence, the Calibrated Airspeed (CAS), itself based on the dynamic pressure[8] became erroneous with even modest altitude changes. Without the ability to disqualify incorrect data, erroneous CAS was fed into the FCS, causing it to respond by varying throttle settings and/or changing the Angle of Attack (AOA) in an attempt to correct and maintain the flight profile commanded. The cumulative effect of these cyclic events manifested as pitching oscillations. These increased in amplitude, with pre-programmed Flight Envelope Protection (FEP) manoeuvres, proving ineffective – the FEP response being correct, but the effect wrong as based on erroneous data. It was highly likely WK042 flew close to its stall speed on a number of occasions during these pitching oscillations before it finally stalled.

1.6.8. From its detailed analysis, the SI concluded that the design of WK's air data system limited its ability to fly safely in cloud and precipitation. Furthermore, the blockage of both pitots whilst flying within MFTP environmental limitations, suggested the Design Organisation (DO) had over-estimated WK's ability to fly in cloud and precipitation.

1.6.9. Given that both pitots blocked simultaneously, it is fair to say that WK did not have a robust means for determining airspeed across its operating envelope. Whilst the VMSC contains 'disqualification logic' to prevent erroneous data being fed to the FCS (as a consequence of a single pitot blockage/sensor failure) it was found the software algorithms, used to identify and disqualify single sensor failure, were not fully understood by the DO within the UK and therefore the effectiveness of the algorithms at maintaining the integrity of the air data required by the FCS for safe flight, was similarly not fully understood. The SI Panel identified potential opportunities for the DO to consider developing WK's use of non-air data for CAS estimation[9].

[6] The MFTP did not state an absolute rainfall limit for flight. It cautioned against flight in rainfall of 8mm/hr recommending vacating should persistent anomalous behaviour of the pitot systems be experienced. Recorded rainfall during FLT 593 did not exceed 5mm/hr.

[7] Pitot tubes form part of a pitot-static system used to measure aircraft airspeed. WK has two pitots; a Kollsman and a Space Age.

[8] The dynamic pressure is the Total Pressure minus the Static Pressure.

[9] There are other methods by which CAS can be estimated using non-air data. WK uses a CAS estimator, but the output from this is not currently used as a means of redundancy vice the pitots. There is an opportunity here for the DO to consider this output in developing a robust, certifiable technical solution.

Trial Planning

1.6.10. The qualification, competency and currency of those involved in the conduct of FLT 593 were not identified as accident factors. The FOO was found to be compliant with regulation concerning authorisation and supervision[10].

1.6.11. The aim of FLT 593 was to trial the Ice Protection System (IPS) on WK in icing conditions and followed a series of ground and flight tests of the equipment. The IPS comprised an Ice Detection and Warning System and an automatic De-Icing System (DIS)[11]. Trial planning for the flight was conducted in accordance with the Thales Flight Operations Test and Evaluation Process document authorised by the Accountable Manager (Military Flying) (AM(MF))[12]. Thales produced a Trial Instruction (TI)[13], which had gone through an approvals process and had been signed off by the Test and Evaluation Post Holder and Technical Authority. Whilst the TI's layout was logical and comprehensive in covering expected headings and references, with evidence of some progressive testing (to minimise risk), it did not contain discrete and progressive objectives in support of a single clear aim; it did not clearly define equipment essential to the trial; it did not name personnel with specific trial responsibilities and there was insufficient detail on how the trial test points would be achieved in practice, without suitable 'knock-it-off' criteria to terminate the trial being defined.

1.6.12. The Trials Risk and Hazard Assessment (TRHA) is designed to consider those risks specific to the trial in addition to those identified for normal flying activities and covered in the Air System Safety Case (ASSC). For FLT 593 the TRHA did not consider all risks identified in the TI; it contained insufficient detail to quantify the risks it did identify in terms of likelihood vs severity and it gave no consideration to minimising role equipment carried to mitigate the consequences of losing the aircraft. This latter point is significant as WK042 was carrying a complete ISR payload, with minimal benefit to the trial[14].

Supervision and Risk Ownership

1.6.13. Under the MAA Approvals process, Thales FOO was a CFAOS organisation and had a legally accountable manager who owned Risk to Life. As long as the CFAOS organisation operated within the MFTP, the MOD ultimately held any risk to equipment. The MOD maintained 'supervisory' oversight through the Unmanned Air Systems Team (UAST) in Defence Equipment and Support (DE&S)[15]. Whilst the UAST conducted technical reviews of the MFTP evidence, the MOD's participation in the Test and Evaluation (T&E) activity itself, by Suitably Qualified and Experienced Personnel (SQEP) in T&E activity, was not mandated[16]. As UAST staff were not T&E SQEP aircrew, it is unsurprising shortfalls in both the TI and TRHA were not identified. More broadly, the SQEP of the UAST WK TAA, in providing supervisory oversight of flying activities conducted within the CFAOS construct, is

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[10] Although, the Panel observed the absence of supervision outside the Ground Control Station.
[11] The DIS was a new capability being introduced as part of the Equipment Standard 2 (ES2) upgrade. The ice detection system was also fitted to the Operational Conversion Unit (OCU) build standard aircraft, which had an extant Release to Service (RTS).
[12] The AM(MF) fulfils the role of a Duty Holder (DH), in absence of a military DH, within the CFAOS organisation. The AM(MF)'s role is to actively manage Air Safety, ensuring Risk to Life is both As Low As Reasonably Practicable (ALARP) and Tolerable. In accordance with regulation, Thales had an approved AM(MF).
[13] This described the anticipated flight trial requirement for WK ES2 to achieve a RTS with provision for flight in icing conditions using the DIS.
[14] This was identified as an Aggravating Factor as the outcome of the accident was made worse by the carriage and loss of the radar payload.
[15] Within the UAST, a Type Airworthiness Authority (TAA) would have been assigned to WK and would be responsible for any CFAOS supervision.
[16] Under the MAOS and DAOS MAA Approvals, contracted organisations were also maintaining and setting design limitations for the system, with limited MOD oversight.

at odds with that required of Duty Holders for WK in the Field Army[17].

Other Issues

1.6.14. The wide ranging nature of the 26 x Observations[18] made by the Panel provides a sense of the challenge faced in delivering a successful and safe WK capability to the Field Army. Some warrant highlighting.

- Simulation and use of Synthetic Environments for T&E and Generic Training. An incomplete level of detailed technical understanding of the WK system, by the MOD and the DO in the UK, is a theme that runs through this SI and those following previous WK losses (WK006 and WK031)[19]. Not only does this emphasise the need for robustness in how T&E is planned and conducted, but questions why the Synthetic Environment (through a combination of simulation and emulation), is not being maximised for the generation of data? The advantages must now be compelling in minimising risk to the capability, saving time and generating greater volumes of data for subsequent analysis[20]. Perhaps more important is the requirement for a fully representative simulator for pilot and crew training. This is long overdue.

- Collection and Analysis of Data. The VMSC records significant amounts of data during every flight, which can be downloaded post-flight. Detailed analysis improves system understanding and how the aircraft behaves and responds to sensor inputs. Whilst the DO did conduct a level of analysis of VMSC data, the SI found opportunities had been missed through the incomplete analysis of data from previous flights[21]. Specifically, it could have improved the DO's understanding of the effectiveness of the Air Data System and on the accuracy of airspeed fed into the FCS. Data is also collected within the Ground Control Station, but this is insufficient, for example, to determine the cause of a crash. As WK does not have a crashworthy and locatable Flight Data Recorder, the VMSC could serve as an alternate. The case for WK to have a means of enabling its post-crash location should now be compelling.

- Crew Workload. WK is largely crewed by NCOs from the Royal Artillery, who are selected and provided assured training to earn a flying brevet. Their training and competence requirements reflect the risks associated with flying unmanned aircraft and are considerably different to those undertaken by Army Pilots. However, a theme running through this and previous SIs, concerns the high workload and detailed system understanding required by WK crews. The high rate of Warnings, Cautions and Advisory (WCA) notifications increased workload and served to

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[17] Risk to Life for routine WK flying in the Field Army is owned by senior officers in Duty Holder (DH) appointments. For WK, these are within the Joint Helicopter Command (JHC), with Commander JHC the 2* Operating Duty Holder (ODH) and the WK Force Commander as the OF5 Delivery Duty Holder (DDH). Both officers are specifically selected for their operator, command and supervisory abilities. It is unlikely a DE&S Project Team TAA, owing to their required engineering career profile, would have these abilities at the required levels.

[18] Observations are points or issues, identified during the course of the SI, worthy of note to improve working practices. They are given with the intent of improving overall air safety.

[19] DSA DG/SI/06/15 and MAA DG/SI/04/14.

[20] For WK042, whilst a dynamic blockage in a pitot might have been difficult to emulate, it could have identified limitations in the disqualification logic.

[21] The SI Panel examined VMSC downloaded data from previous flights (FLTs 164 and 493) conducted from WWA which had experienced ADU Cautions. It was the detailed analysis of this VMSC data that highlighted the DO's incomplete understanding of the Air Data disqualification logic.

distract, increasing the likelihood of error[22]. Combined with Flight Reference Cards (FRC) comprising 265 pages (Wildcat AH1's FRCs contain 80 pages), it would be reasonable to conclude that the complexity of flying WK is disproportionate and adds unnecessary risk to the conduct of safe flight.

Conclusion

1.6.15. The crash of WK042 on 3 Feb 17 was the 3rd occasion a WK had been lost in an accident[23]. It was to be followed some 6 weeks later by WK043, which crashed over Cardigan Bay on 24 Mar 17[24]. At the time of writing a 5th WK had been lost, with WK050 crashing at West Wales Airfield on 13 Jun 18. Details on WK050 are still under investigation, but themes are now apparent. I highlight – the DO (and the MOD) not fully understanding how WK works, not making the most of simulation or from the exploitation of data and providing a disproportionate level of complexity to those who fly WK.

1.6.16. WK was designed to deliver a flexible, 24 hour Intelligence, Surveillance, Target Acquisition and Reconnaissance (ISTAR) system for primary use in the Land environment. Having the ability routinely to operate in cloud and precipitation throughout the year is therefore an important pre-requisite. The necessity to conduct icing trials is a given, but so should be confidence in the basic requirements to do so, such as the correct operation of the pitot system, prior to flight. There are other areas that demand attention – for the DO in improving its safe conduct of trials and for the MOD in providing effective 'Operator' supervision within the CFAOS construct.

1.6.17. Finally, it's appropriate to provide some context for this SI and others concerning WK. There is much that is still novel in complex automated unmanned systems, especially those with advanced technology, designed to operate towards the boundaries defined by extant regulatory regimes. Innovation driven by the opportunities offered by automated systems will require flexibility in defining what a reasonable and appropriate regulatory regime looks like, set against a clearly defined and realistic requirement. For WK, I have confidence in the commitment of the DO's most senior leadership in delivering a useful WK capability to the Field Army and their broader contribution to this important debate.

DG DSA

[22] As per RAFCAM Human Factors contributions to SIs following the loss of WK031, WK006 and WK042.
[23] Previous WK accidents, both of which were subject to DSA SIs, were WK031 at West Wales Airfield on 16 Oct 14 and WK006 at Boscombe Down Airfield on 2 Nov 15.
[24] The loss of WK043 is subject to an ongoing DSA SI.