MAA DG/SI/01/11 SI ZG792

28 Jul 11

DG MAA

SERVICE INQUIRY INVESTIGATING THE ACCIDENT TO TORNADO GR4 ZG792 ON 27 JAN 11

1. The Service Inquiry Panel assembled at RAF Wittering on 28 Jan 11 by order of DG MAA for the purpose of investigating the loss of Tornado GR4 ZG792, as detailed in the convening order MAA DG/SI/01/11 dated 28 Jan 11. The Panel has concluded its inquires and submits the provisional report (including the record of events and supporting paper work). The convening authority is invited to note that, to date, the Panel have been unable to positively determine the initial cause of the fault that led to the accident.

PRESIDENT

Signed........................

MEMBERS

Signed........................

Signed.......................

2. The following inquiry papers are enclosed:

Part 1 (The Report)

1.1 This Covering Note and Panel Details
1.2 Convening Orders and TORs
1.3 Narrative of Events
1.4 Findings
1.5 Recommendations
1.6 Convening Authority Comments

Part 2 (The Record of Proceedings)

2.1 Diary of Events
2.2 List of Witnesses
2.3 Witness Statements
2.4 List of Attendees
2.5 List of Exhibits
2.6 Exhibits
2.7 List of Annexes
2.8 Annexes
2.9 Schedule of Matters not Germane to the Inquiry
2.10 Master Schedule

MILITARY AVIATION AUTHORITY
PROCEEDINGS OF A SERVICE INQUIRY
INTO AN AIRCRAFT ACCIDENT

PART 1.1

DETAILS OF THE PANEL

Convened on 28 Jan 11 at Royal Air Force Wittering

By order of DG MAA

To inquire into an accident involving Tornado GR4 ZG792

1. Composition of the Panel

Duty	Rank, Name, Service No	Branch	Unit
President	Lt Cdr **(S40)**	X(P)	**IV(R) Sqn**
Members	Flt Lt **(S40)** (Replaced on Posting OOA)	GD(P)	**II(AC) Sqn**
	Flt Lt **(S40)**	Eng	**TPF Marham**
	Flt Lt **(S40)** (Replaced Flt Lt **(S40)**)	GD(P)	**XIII Sqn**
In attendance	Sqn Ldr **(S40)**	Eng	**MAAIB**
	Ms **(S40)**	HF	**RAFCAM**
	Ms **(S40)**	HF	**RAFCAM**

MAA SI Convening Order

28 Jan 11

SI President
SI Panel Members

AIR Cmd – Inspector Flight Safety
CO RAF Lossiemouth

Copy to:

AOC 1 Gp
AIR COS Health
OC RNFSAIC

MAA DG/SI/01/11 – CONVENING ORDER FOR SERVICE INQUIRY INTO ACCIDENT INVOLVING TORNADO GR4 ZG792 THAT OCCURRED ON 27 JAN 11

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

2. The purpose of this SI is to investigate the circumstances surrounding the accident involving **Tornado GR4 ZG792 in Scotland on 27 Jan 11** and to make recommendations in order to prevent recurrence.

3. The SI Panel is to assemble at **RAF Wittering on 28 Jan 11 at 1230Z hrs**.

4. The SI Panel comprises:

President:	**(S40)**	**– 4(R) Sqn**
Members:	**(S40)**	**– 2(AC) Sqn**
	(S40)	**– 13 Sqn**

5. The legal advisor to the SI is **Wg Cdr (S40) – MAA** and technical investigation/assistance is being provided by the Royal Navy Flight Safety and Accident Investigation Centre (RNFSAIC).

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 A). It is to record all evidence and express opinions as directed in the TOR. Throughout the Inquiry, the President is to: review the evidence for gaps and the conclusions for objectivity; and, if and when necessary, conduct additional enquiries.

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

Wg Cdr (S40), Medical Advisor – Unrestricted Attendance.

Sqn Ldr (S40), SI Advisor – Unrestricted Attendance.

Ms (S40), RAFCAM HF Accident Investigator – Unrestricted Attendance.

Ms (S40), RAFCAM HF Accident Investigator – Unrestricted Attendance.

8. The RAF Flight Safety Inspector and CO RAF Lossiemouth respectively are requested to provide facilities, equipment and assistance suitable for the nature and duration of the SI as requested by the SI President.

9. Reasonable costs will be borne by DG MAA under UIN D0455A.

Original Signed

T M ANDERSON
AM
DG MAA

Annex:

A. Terms of Reference for SI into Tornado GR4 ZG792– 27 Jan 11.

ANNEX A TO
MAA DG/SI/01/11
DATED 28 JAN 11

TERMS OF REFERENCE FOR SI INTO TORNADO GR4 ZG792 ACCIDENT – 27 JAN 11

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

   a. *Investigate and, if possible, determine the cause of the accident and examine contributory factors.*

   b. *Ascertain whether Service personnel involved were acting in the course of their duties.*

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

   d. *Determine the state of serviceability of the aircraft and relevant equipment.*

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

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

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

   h. *Investigate and comment on relevant fatigue implications of individuals' activities prior to the matter under investigation.*

   i. *Ascertain if aircrew escape and survival facilities were fully utilized and functioned correctly.*

   j. *Investigate the level of any injury sustained and whether such injury (including stress related conditions) will be the exciting cause of later disability, as established from expert testimony.*

   k. *Determine any relevant equipment deficiencies.*

   l. *Confirm that the Aircraft Post-Crash Management procedures were carried out correctly and that they were adequate.*

   m. *Determine and comment on any broader contributory organisational and/or resource factors or causes.*

   n. *Assess whether the security of personnel, equipment or information was compromised and if so to what degree.*

   o. *Ascertain value of loss/damage to the Service and/or extent (and, if readily available, the value) of loss/damage to civilian property.*

   p. *Assess any Health and Safety at Work and Environmental Protection implications in line with JSP 375 and JSP 418.*

   q. *Report and make appropriate recommendations to DG MAA.*

2. You are to ensure that any material provided to the Inquiry by the United States, or any other 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, authorisation 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[2]. You are not to make a judgement on the origin of the classified material[3]. In addition, the relevant PDR directorate should be informed early when dealing with the US or other foreign state material, and should be engaged in the process where doubt exists.

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[2] For intellectual intelligence material this should be done through DIS (DICSD-SEC).

[3] If you are unable to identify the origin of the material, you must contact INFO-ACCESS DPAD or, for intelligence material, DIS (DI CSD-SEC).

PART 1.3 NARRATIVE OF EVENTS

All times Zulu.
Glossary of abbreviations provided at the end of Part 1.3.

BACKGROUND

1. On Thur 27 Jan 11, CACTUS 2 was part of a pairs Operational Conversion Unit (OCU) Long Course Simulated Attack Profile (SAP) sortie. The staff pilot and aircraft (ac) captain occupied the front seat and the student Weapon Systems Officer (WSO) occupied the rear seat. After departing RAF Lossiemouth at 1348, the aircraft (ac) proceeded to Tain Air Weapons Range (AWR) where it dropped a single 14Kg practice bomb, after which it continued at medium level to simulate a Paveway IV TIALD attack. On completion of this attack, the ac descended to low level for the remainder of the sortie. At 1435:46 the crew reported hearing a loud machine-gun-like noise emanating from the right-hand side of the ac. The pilot of ZG792 diagnosed this as an engine surge. He immediately brought both throttles back to idle whilst maintaining less than 10 units alpha. The NH appeared to be decreasing, in response to the throttles being brought back to idle, but the right NH continued to decrease below a level usually expected when selecting idle. At this time the pilot noticed that he had REHEAT and R OIL P captions and informed his WSO that he was shutting down the right engine. Just as he completed this action the crew received a L FIRE caption, with confirmatory signs of fire. The crew attempted to divert to Stornoway, but with the left engine losing thrust and ac control becoming increasingly difficult, the pilot initiated command ejection at 1443:14. Both crew were rescued by Coastguard helicopter and transferred to hospital, where their injuries were assessed as minor.

Witness 1, Part 1, Pg 1
Witness 1, Part 2, Pg 1
Witness 1, Part 3, Pg 3
Witness 2, Part 1, Pg 1,2
Witness 2, Part 2, Pg 1
Witness 2, Part 3, Pg 3,4

Exhibit 1

2. **Ac History**. ZG792 is a Tornado GR4 under the Aircraft Operating Authority (AOA) of AOC 1 Group. At the time of the accident, it was based at RAF Lossiemouth on XV(R) Sqn, the Tornado OCU. At the initial sortie launch time, the aircraft had flown 5240:10 flying hours (fg hrs) and was 124:45 fg hrs away from its next scheduled 'depth' maintenance (due to be a Minor servicing, conducted every 825 flying hours). The left engine had been fitted to ZG792 for 43:50 fg hrs. The right engine had been fitted to ZG792 for 392:15 fg hrs.

Exhibit 2

Exhibit 4

Exhibit 3

3. **Crew Background**

a. A review of the pilot's RAF Form 5200 and logbook found that he had completed flying training to an overall average standard in 1999. He was role disposed to the GR4 OCU where he was assessed as 'satis in most respects'. Following a front-line tour he was posted as a Qualified Flying Instructor (QFI) to RAF Valley, where he was assessed as above average, gaining his A2 instructor category. Returning to the GR4 in 2006 he conducted a further front-line tour, being assessed as above average, before being posted to XV(R) Sqn. His last 5200 and logbook assessments reported him as above average, including laudatory comments from his OC over his performance as a role demo pilot during 2010. At the time of the accident he had accumulated 2936 hours which included 1512 hours

Exhibit 5

Witness 20, Pg 1

on the GR4. He had flown 7 hours in the past 30 days and 100 hours in the past 6 months.

b. The WSO was a student on the GR4 OCU Long Course. He had flown 346 hours total, of which 64 had been on the GR4. A review of his RAF Form 5200 and logbook found that he had finished flying training in 2010 to an overall above average standard, and was posted to the GR4 OCU where he had been for 6 months prior to the accident. He had 9 course syllabus sorties remaining. Although he commented that he had found the course demanding he was, according to his Sqn Cdr, on track to finish.

Exhibit 5
Witness 20, Pg 2

4. **Preceding Events**.

a. The pilot had recently returned to the Sqn following **(S40)**

. On his first sortie back, on the Tuesday, the pilot made an error whilst selecting a new time-on-target (TOT). This resulted in a potential conflict over the target. On Wednesday the pilot was programmed to fly twice, but after the first sortie he vomited by the side of the ac and so went home. He did not consume any alcohol in the 24hrs prior to the accident. He returned to work on the day of the accident well rested and feeling fit to fly. He was programmed to give a PCON (Pilot Conversion) phase brief in the morning, which meant that he missed the start of the sortie plan. Just after leaving the PCON brief and entering the sortie plan, the pilot was informed by a Sqn Qualified Weapons Instructor (QWI) that he would be required to recount the previous day's TOT incident in front of the Sqn that Friday. In his HF interview the pilot stated that he was frustrated by this as he felt that his Flt Cdr, a personal friend, should have told him in person.

Witness 1, Part 1, Pg 6
Witness 1, Part 3, Pg 2
Witness 20, Pg 5
Witness 1, Part 3, Pg 3
Annex A

b. The WSO had been on the Sqn for approximately 6 months and had 9 sorties to complete before finishing the OCU Long Course. Although he commented that he had found the course challenging, he was progressing well and was on track to finish. On the day before the accident the WSO was formally interviewed by his Sqn Cdr over a non-related incident. Although this was expected, in his HF interview the WSO commented on his frustrations at the time the RAF had taken to action the disciplinary findings. On the evening before the accident he had eaten dinner in the Officers' Mess where he lived, before watching a film. He was in bed by 2230 and asleep by 2300. He did not consume any alcohol in the 24hrs leading up to the accident. On the day of the accident he reported for duty at 0900.

Witness 2, Part 3, Pg 1
Witness 2, Part 3, Pg 2,3.
Annex A
Witness 2, Part 3, Pg 2

6. **Sortie Plan, Brief and Outbrief**. The accident pilot was unable to attend the start of the plan due to a previous programming commitment, but joined it shortly afterwards. The plan was supervised primarily by the senior authoriser in the formation (the staff WSO of CACTUS 1). In his informal interview with the Panel the student WSO stated that he was being worked hard, but he didn't go into the brief feeling anymore stressed then he would usually have felt; however, in his HF interview the WSO stated that he had

Witness 1, Part 1, Pg 6
Annex A

felt rushed during the plan and had forgotten most of it by the time the formation took off. The plan was briefed by the student pilot of CACTUS 1, and the student WSO of CACTUS 2. The crew were out-briefed as a formation by the XV(R) Duty Auth, with another formation in attendance as well, prior to changing into their Aircrew Equipment Assembly (AEA). | Witness 2, Part 3, Pg 3; Witness 21, Pg 1

7. **Sortie Pre-Accident Events**. The crew walked for the ac with adequate time to prepare for an on time departure. During his initial checks on the ac, the pilot noticed that the left pitch feel gauge was indicating approximately 100 bar, as opposed to the 60 bar he would normally expect. He called for assistance from a trade specialist, who then advised him that the abnormal indication was not a cause for concern and was residual pressure from the previous sortie. The rest of the start-up and taxy was uneventful. The sortie commenced with a 20-second stream takeoff at 1348. The max dry engine performance check figures were within acceptable limits compared to the placard figures from the F701A. The 2 aircraft remaining in trail for the subsequent Tain departure and entry into Tain AWR. A 30° dive attack was carried out using a single 14Kg practice bomb followed by a medium-level transit to the south-west. A medium-level Paveway IV SAP was carried out prior to entering low level in the Firth of Lorn. The formation then routed north towards another target to the south of Skye. This was a split Op 5° profile, simulating 1000lb retard weapons. The pilot reported that he had a number of ECST captions throughout the sortie, but that he had been able to reset these by selecting the alternate range on the cabin heat control. Other than this, he had no concerns about the serviceability of the ac. He had to transmit a call of '*Give me one*' (a request for the lead ac to reduce power) during one formation rejoin, but thought that this was probably down to throttle mishandling by the lead pilot rather than a lack of thrust in his own ac. The student pilot in the lead ac was unable to successfully prosecute the SAP and, after a discussion with his instructor WSO, elected to manoeuvre the formation for a re-attack. The lead called a 90° battle turn to the left as the formation coasted out near the airfield at Plockton. Shortly after rolling out from the turn on a westerly heading, with CACTUS 2 on the northern side of the formation, the crew of ZG792 heard the machine-gun sound that marked the start of the accident sequence. | Witness 1, Part 1, Pg 3; Witness 11, Pg 1-3; Exhibit 1; Exhibit 3; Witness 1, Part 1, Pg 6; Witness 3, Pg 2

ACCIDENT SEQUENCE

8. **Time References**. T0:00 is defined as the start of the incident, marked by the pilot retarding the throttles in response to the machine-gun-like surge. All other times are expressed in minutes and seconds with respect to this datum, which occurred at 1435:46. This time was calculated by comparing a reference radio transmission from ZG792 with the GPS-derived system time shown on the VRS tape of another GR4 operating in the vicinity of the crash. A break down of the timings is provided at the end of section 1.3.

9. **Accident Reconstruction Validity**. The Replacement-Accident Data Recorder (R-ADR) has 75 channels of recorded data. This does not provide space to capture every possible desired parameter. Only certain CWP captions are recorded (or, in some cases, can be inferred from the recorded data) and there are numerous cockpit switch selections, such as the LP cock position and fire button activation, which are not captured. The CVR does capture the 'lyre bird' audio alarm, indicating a red CWP caption, thus | Exhibit 1

enabling red captions mentioned by the crew but not directly captured by the R-ADR to be linked to a specific time. The sample rate for each channel varies, but is as low as 1Hz in many cases, meaning that a fire caption, for example, could flicker on and off but not register on the R-ADR. This means that any recreation of the accident events, in particular the CWP captions, may contain errors.

10. **ECS Faults.** On several occasions prior to the accident sequence, the pilot had observed ECST captions, indicating a temperature error in the Environmental Control System (ECS). He had been able to rectify the fault on every occasion by selecting the alternate range on the temperature control. At the start of the accident sequence, the pilot reported that an ECST caption was present, a situation he was again trying to remedy, although the cockpit air flow was adequate and the system gave him no cause for concern. Witness 1, Part 1, Pg 6

11. **Initial Symptoms**. The first symptom of an engine fault was a loud machine-gun noise from the right side of the ac. The WSO described this as being exactly like that he had experienced during hot strafe passes. The pilot, suspecting a surge, instinctively brought both throttles to idle and looked in at his engine instruments and CWP. As well as the previous ECST caption, he also saw a REHEAT caption on the CWP and that the right nozzle area indicator indicated Emergency Nozzle Close (ENC). Witness 2, Part 3, Pg 6; Witness 1, Part 1, Pg 1

12. **Mechanical Failure Diagnosis.** At T0:13, the pilot concluded that he had a right engine fault and advanced the left throttle to max dry. He turned north, remaining over the sea, and entered a gentle climb, eventually reaching approximately 6000ft and 290KCAS by T5:00. At T0:16, with the right NH at 36.7%, the 'lyre bird' alarm went off and the pilot commented that he had a R OIL P caption. After a brief discussion of the various symptoms, he confirmed that he had a right mechanical failure and, at T0:38 selected the right throttle to HP Shut. Exhibit 1; Exhibit 6

13. **L FIRE Caption.** Whilst dealing with the right mechanical failure, the pilot was interrupted by the appearance of a L FIRE caption. This prompted him to diagnose a rear fuselage fire, in response to which he selected the Air System Master to Emergency Ram Air (ERA). He also closed the right LP cock and discharged the fire extinguisher bottle into both engine bays by pressing both fire buttons simultaneously. The exact order of this sequence could not be positively determined. Exhibit 1; Exhibit 6

14. **Visual Inspection From CACTUS 1.** The crew of CACTUS 1 elected to follow CACTUS 2 throughout the emergency, remaining on the right-hand side at a distance of around 1-2nm. Both crew members reported seeing a smoke trail from the aircraft, along with a bright orange glow from the left engine nozzle area. The presence of the glow prompted the instructor WSO of CACTUS 1 to ask, at T0:51, if CACTUS 2 was using reheat. At T1:00, the pilot of CACTUS 2 asked if there were any signs of fire, to which the WSO of CACTUS 1 replied *"Affirm…you have smoke and flames from the rear of the aircraft".* The WSO of CACTUS 2 was able to observe the rear of the aircraft using his mirrors and saw smoke emanating from the right side of the rear of the aircraft. The pilot concluded that the right side of the rear fuselage and possibly engine was on fire. Witness 3; Witness 4; Exhibit 6; Witness 2, Part 2, Pg 1; Witness 1, Part 2, Pg 1

15. **Emergency Radio Transmissions.** After hearing of the initial problem, the instructor WSO in CACTUS 1 conducted all of the formation's radio transmissions to Scottish Centre on Guard UHF. After declaring a 'Mayday', he discussed the possible use of Stornoway as a diversion with Scottish Centre, and also requested that the Stornoway Coastguard SAR helicopter be ready to rescue the crew in the event of an ejection. Throughout the emergency sequence the WSO of CACTUS 1 divided his time between talking to his student pilot on intercom, the pilot of CACTUS 2 on the formation chat frequency and Scottish Centre on UHF Guard.	Exhibit 6 Witness 4, Pg 9
16. **Other Fault Indications.** As the emergency progressed, the crew were subjected to multiple 'lyre bird' audio warnings and witnessed numerous CWP captions, both intermittent and constant. These included CABIN, FUEL, L and R THROT, L and R OIL T, L and R FUEL T, GEN, R FIRE, and both L and R VIB captions.	Witness 1, Part 3, Appendix I.
17. **Ejection Preparation**. Believing the situation to be critical, the pilot ensured his navigator was suitably prepared and informed CACTUS 1 to standby for a premeditated ejection at T2:10. CACTUS 1 relayed this information to Scottish Centre.	Exhibit 6
18. **Control Failures.** At T2:50 the Command and Stability Augmentation System (CSAS) incurred several failures and the tailerons entered mechanical mode. The pilot did not directly observe which specific failures had occurred, but observed CSAS (both red and amber captions) and PFCS captions and felt the control quality degrade.	Exhibit 1 Witness 1, Part 2, Pg 2
19. **Relight Attempt.** The pilot then discussed his symptoms with the crew of CACTUS 1 as well as his WSO. He asked to be guided towards Stornoway, although he acknowledged that it was unlikely that he would be able to make it that far. He ensured once again that his WSO was ready for ejection and warned him this would be via the pilot's ejection handle. At T3:38 the pilot decided to attempt to relight the right engine. He moved the right throttle to idle and selected the engine start switch to RIGHT. There was no response from the engine, apart from the appearance of a R TBT caption, and the green START light did not illuminate. At no stage during the sequence did the pilot indicate that he had re-opened the right LP cock.	Exhibit 6 Witness 1, Part 3, Pg 10-11
20. **Left Engine Control.** After further discussion with his WSO and the crew of CACTUS 1 about the nature of the external symptoms, the pilot briefly exercised the left throttle and observed that he had no control over the left engine.	Witness 1, Part 1, Pg 2
21. **CACTUS 1 Observations of Left Engine**. At T4:54 the pilot of CACTUS 1 noticed that the glowing from the left engine appeared to have ceased. This was relayed to CACTUS 2 by his WSO. On hearing this, the pilot decided to remain with the aircraft to see if a recovery to Stornoway would be possible.	Exhibit 6
22. **Loss of Left Engine Thrust**. At T6:01 the pilot noticed his left NH gauge fluctuate, although the thrust output felt constant. This was followed at T6:20 by a perceived loss of thrust and deceleration.	Witness 1, Part 1, Pg 2 Exhibit 6

23. **Ejection Decision.** In the latter stages of the emergency, the pilot became aware that he had to apply more and more right control column input to correct a tendency for the aircraft to roll to the left. Believing that a total loss of control was imminent, he warned the WSO and initiated command ejection at T7:28 at 6250'AMSL and 238KCAS. The ejection process was entirely normal. During the descent the crew carried out their post-ejection drills, including the inflation of their LSJs and were well placed for their water entry. During the descent both crew descended through a layer of cloud, which they described as unsettling, but otherwise unremarkable. During the descent both pilot and WSO reported that the PSP, which had automatically lowered after ejection, caused a significant pendulous motion upon the parachute descent. Upon landing in the water, both PSPs automatically deployed their respective life rafts and the crew boarded with relative ease in calm seas. Once in their life rafts both crew commented that they initially experienced difficulty in untangling themselves and their equipment from the parachute canopy lines, but were eventually able to carry out their post life raft entry drills. Both crew activated their Fastfind PLBs and prepared their pyrotechnic flares for use. The pilot removed his helmet and placed the aircrew survival hood on before using his helmet to bail out the water from the life raft. Due to the advanced notice that the formation had had with regards to a potential ejection, CACTUS 1 had already requested the SAR helicopter for Stornoway be launched prior to the ejection and as such it was on task very quickly. The crew spent approximately 20 minutes in their life rafts before being winched into a Coastguard helicopter. Although a double strop was not available, the Coastguard winchman used the lifting beckets on the crews LSJ, combined with a strop placed around the knees to achieve the same result and minimize the possible impacts of thermal shock which may have been experienced if a vertical lift had been attempted.

Exhibit 1
Exhibit 6
Annex B
Witness 1, Part 3, Pg 15-16
Witness 2, Part 3, Pg 14
Exhibit 6

24. **Post-ejection Care.** The crew were initially transferred to Raigmore hospital, Inverness. Unsure of how to deal with ejectees, the Raigmore registrar discussed the necessary arrangements and precautions that needed to be considered with the RAF Lossiemouth SMO. Both crew were supine and in stiff neck collars with head blocks taped to the trolley at two points. The RAF Lossiemouth SMO arrived at the hospital shortly after the crew were admitted and was able to speak to them first hand. A detailed account of the SMO's findings is contained at Annex C. The SMO was able to examine both the pilot and the WSO and had no reason to believe that they were under the influence of drugs or alcohol, and as such PIDAT was not initiated. The crew were transferred to the Aeromed team at 2210 and placed on a C130 for the flight down to Queen Elizabeth Hospital (QEH), Birmingham, for specialist treatment. Of note, prior to being discharged from QEH there was significant confusion as to how the crew would be transferred back to RAF Lossiemouth. The WSO was collected from the hospital by family members; however the pilot seemed unsure of his return plans. As such, the Panel made arrangements for him to spend the night with them at the RAF Cottesmore Officers' Mess, prior to sharing a ride back to RAF Lossiemouth on the HS125 that had been tasked to transport the Panel.

Annex C

AIRCREW ESCAPE AND SURVIVAL FACILITIES AND AIRCREW EQUIPMENT ASSEMBLIES (AEA)

25. **Personal AEA**. Both aircrew were wearing standard Mk10c helmets and wearing Mk20 immersion suits. The pilot was wearing a non issue blue 'Polar Bears' bunny suit under his immersion suit, and the WSO wore a standard issue flying suit. Both aircrew wore standard green flying roll necks, although both were wearing non standard 'long johns'. All pieces of AEA appeared to have withstood the ejection process

Annex B, Pg A-1

26. **Mk 41 Life Jacket.** Both aircrew were wearing the standard Mk41 lifejacket. After ejecting the crew inflated their LSJs in accordance with post ejection drills. Both crew reported that the inflated lifejacket significantly impeded their ability to look around and down, and that as such an assessment of the exact landing location was difficult. Under the LSJ both crew wore a standard green Combat Survival Waistcoat (CSW) which housed the Fastfind Beacons.

Annex B

27. **ZQ Mk1 Personal Survival Packs and SS Mk15 Single man life rafts.** After ejection both PSPs auto detached from the seat and were hanging on the PSP lowering lines as expected. Upon contact with the water, both MK15 life rafts automatically inflated and remained so throughout the recovery procedure.

Annex B

28. **Fast find locator beacons**. Both pilot and WSO manually operated their Fastfind Location Beacons housed in their respective CSWs. The operation and performance of the Fastfind was thoroughly investigated by the Panel, and its detailed findings can be found at Annex G.

Annex B, G

DEGREE OF INJURY

29. The panel found that:

a. **(S40)**

Annex B, Pg 8

b. **(S40)**

Annex B, Pg 8

c. **Civilian Personnel**. There were no injuries to civilians.

DAMAGE TO AC, PUBLIC AND CIVILIAN PROPERTY

30. Damage to ac, public and civilian property was assessed as follows:

a. **Ac**. An initial damage assessment report was carried out by MAAIB. ZG792 has been classed as Cat 5 (SCRAP) by the Panel.

Annex D

b. **Environmental**. The Panel received a number of requests for information as to any environmental impact caused by the crash. Air Cmd sent a MinSub draft for the Panel to comment. MAAIB have staffed these requests having taken advice from the Institute of Medicine, MOD Abbey Wood and The Maritime and Coastguard Agency. All assess the environmental impacts as low. Prior to the wreckage recovery procedure, a full site survey was carried out to map the extent of the debris field. On completion of the recovery, a second survey was conducted and no further obvious signs of wreckage could be identified. Annex D, Pg 5

c. **Civilian**. There was no recorded damage to civilian property.

d. **Costs**. The Net Book Value for ZG792 is £13,094,000. Exhibit 7

LOSS OF, OR DAMAGE TO, CLASSIFIED MATERIAL

31. **(S26)**

a. **(S26)**

b. **(S26)** .

AC RECOVERY

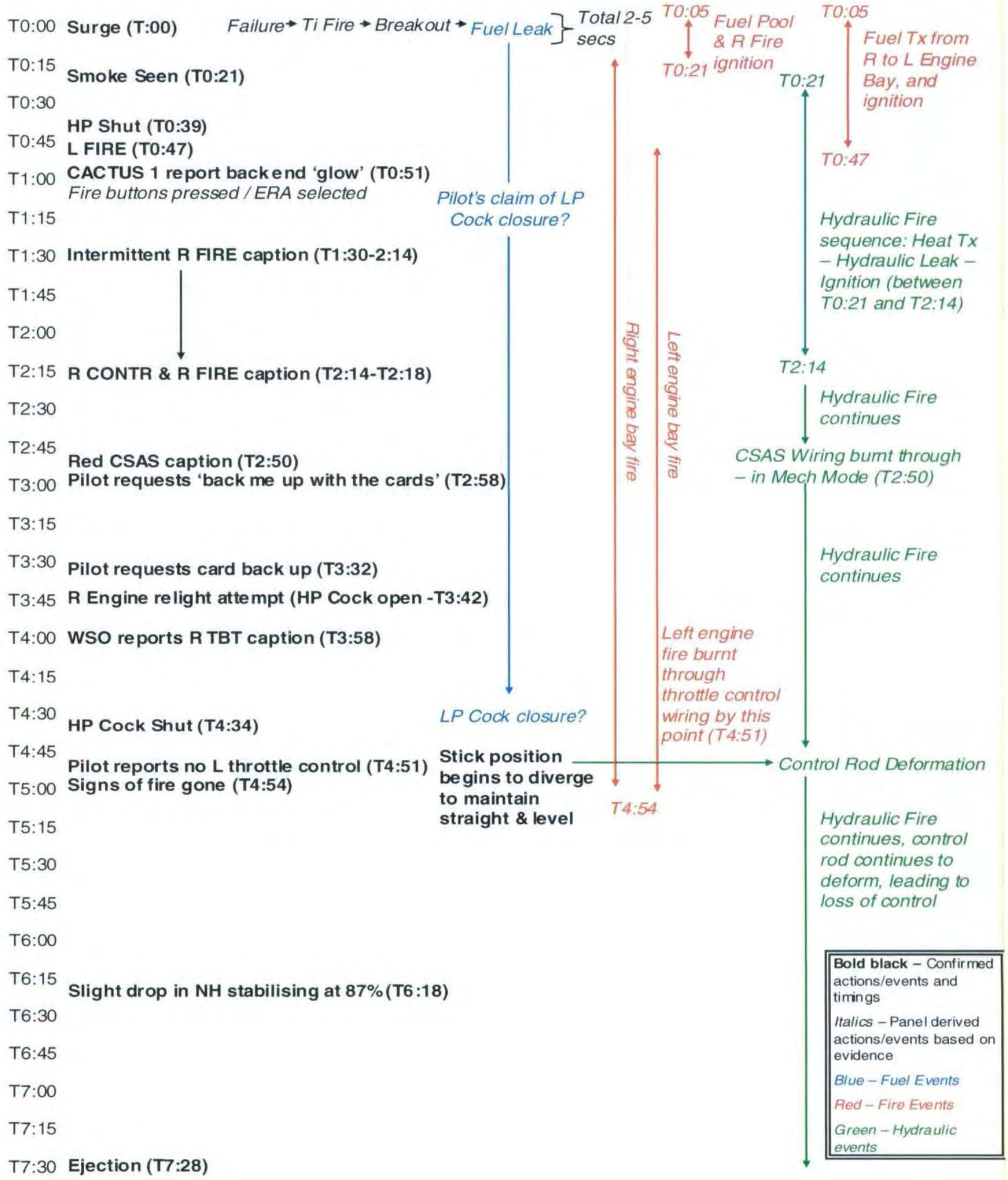
32. **Recovery from the crash site**. Following ejection the ac entered a nose down descent and rolled to the right. It impacted the sea at 384KCAS in a diving attitude of 27 degrees with 11 degrees of right bank at **(S26)** . Investigations into the accident were initially delayed by the significant difficulties encountered in salvaging ZG792. HMS Blythe, a RN Sandown class minesweeper exercising in the area, was able to provide assistance in pinpointing the aircraft wreckage. Initially, the rocky sea bed made it difficult for a clear sonar picture to pinpoint the wreckage. Once this was achieved, poor weather off the west coast delayed salvage operations. Salvage was finally commenced by CSALMO on 15 Feb and lasted for four days. The ac suffered considerable break-up during impact (see Figure 1), and eventually came to rest at a depth of **(S26)**. Notwithstanding, the salvage vessel docked in Invergordon with approximately 70% of the ac on 19 Feb. Exhibit 1; Annex D, Pg 4

Figure 1 - One of two ISO containers housing the recovered parts of ZG792.

33. **Recovery to RNFSAIC**. The remaining wreckage was transported in ISO containers, by road, from Invergordon to RNFSAIC at RNAS Yeovilton. The wreckage has remained in the RNFSAIC hanger.

Annex D, Pg 4

ZG792 Timeline of Events



GLOSSARY

ac	Aircraft
AEA	Aircrew Equipment Assembly
AOA	Aircraft Operating Authority
AWR	Air Weapons Range
CSALMO	Chief of Salvage and Mooring Office
CSAS	Command and Stability Augmentation System
CSW	Combat Survival Waistcoat
CVR	Cockpit Voice Recorder
CWP	Centralised Warning Panel
ENC	Emergency Nozzle Close
ERA	Emergency Ram Air
fg hrs	Flying Hours
Flt Cdr	Flight Commander
HF	Human Factors
HP	High Pressure
KCAS	Knots Calibrated Air Speed
LP	Low Pressure
LSJ	Life Support Jacket
MAAIB	Military Air Accident Investigation Branch
MOD	Ministry of Defence
NH	High Pressure Compressor Speed
OCU	Operational Conversion Unit
PCON	Pilot Conversion
PIDAT	Post Incident Drug and Alcohol Testing
PLB	Personal Locator Beacon
R-ADR	Replacement Accident Data Recorder
RAF	Royal Air Force
SAP	Simulated Attack Profile
SMO	Senior Medical Officer
TDM	Transportable Data Module
TIALD	Thermal Imaging Airborne Laser Designator
Tor PT	Tornado Project Team
TOT	Time on Target
UHF	Ultra High Frequency
WSO	Weapon Systems Officer

PART 1.4 - FINDINGS

Introduction

1. Given the technical nature of the accident involving ZG792, the Panel elected to present a chronological description of its findings. A modified version of the James Reason model is then subsequently used to categorise the various factors identified by the Panel.

Evidence

2. **Available Evidence.** The Panel had access to a significant amount of evidence. However a major limiting factor was that only approximately 70% of the airframe wreckage was recovered from the crash site. All recovered wreckage had been severely damaged as a result of the sequence of events leading up to the impact with the sea, or the high speed impact with the water itself. The evidence available included: Annex D Para 1.4.1

a. Interviews with the Crew of ZG792.

b. Cockpit Voice Recorder (CVR) and Replacement Accident Data Recorder (R-ADR) coverage of the sortie and accident sequence from both CACTUS 1 and 2.

c. The Video Recording System (VRS) video from ZG792 although badly damaged, was copied onto a new tape by QinetiQ (QQ) and showed a series of interrupted still images from the various cockpit displays.

d. The VRS in CACTUS 1 did not record, however several other Lossiemouth-based ac were within radio-earshot of the accident, and their VRS videos were available to the Panel.

e. Witness statements, including eye witness accounts from the ground and the recollections from the crew of CACTUS 1.

f. Associated documentation including flying logbooks, all aircraft (ac) engineering documentation and sortie planning and briefing materials.

g. The partially recovered airframe, engines and role equipment of ZG792.

h. The ac recovery report from Joint Aircraft Recovery and Transportation Squadron (JARTS).

i. Interim report produced by Military Air Accident Investigation Branch (MilAAIB) containing input from Rolls-Royce (RR), Materials Integrity Group (MIG) and BAE Systems.

j. The review of the ac's documentation conducted by Engineering Publications and Records (EP&R) at RAF Marham.

k. Analysis reports provided by the Royal Air Force Centre of Aviation Medicine (RAFCAM).

3. **Unavailable evidence**. The Panel did not have access to the following:

a. Approximately 30% of the ac was unrecoverable from the crash site.

b. The VRS from CACTUS 1 did not record.

4. **Services**. To assist the Panel, the services of the following personnel and agencies were available:

a. Specialist technical support from MilAAIB, Air Accidents Investigation Branch (AAIB), RR, MIG, QQ and BAE Systems.

b. RAFCAM.

c. MilAAIB Advisors.

5. **Ac recovery.** The recovery of the ac was complicated due to the initial difficulty in locating the wreckage and delays caused by severe weather. The damage sustained to the ac during the accident and/or the impact with the sea complicated an already demanding and time consuming technical investigation. The following components were distributed for specialist investigation: Annex E

a. **R-ADR**. The recovered R-ADR was sent to QQ on 21 Feb 11. The Panel received a full recording from the accident sortie and exploited the data in order to enable full analysis of the accident sequence of events. From this data, QQ were able to create a flight simulation GDAS model, which was made available to the Panel for analysis. Annex D Para 1.3 Exhibit 1

b. **CVR**. The CVR was recovered by QQ along with the R-ADR data, providing the Panel with a full recording of the accident sortie. Annex D Para 1.3 Exhibit 1

c. **Engines**. Recovered elements of both engines and gearboxes were transported to RR Filton and detailed examination commenced on 22 Feb 11. Both engines sustained significant impact damage; hence this protracted an already complex technical investigation. Support to RR and oversight throughout the investigation was provided by MilAAIB and MIG. Annex D Para 1.5

d. **Airframe wreckage.** Very little of the front fuselage was recovered, the Mauser cannon, nose undercarriage leg and the front pitot probe were the only major recognisable components. The majority of components recovered in the centre fuselage were Line Replaceable Units (LRUs) and wiring looms. Both main undercarriage legs were recovered, along with the left and right accessory gearboxes' hydraulic pumps and generators, sections of the wing box and the right engine Annex D Para 1.4 Annex D Para 1.4

LP fuel cock. No evidence of a fire or smoke damage could be found on the front or centre areas of the fuselage, indicating that a fire had not originated nor penetrated in this area. The largest number of recognisable components and ac panels were recovered from the rear section of the ac. Recovered components included both left and right engines, forward engine bay doors, the centre keel wall, both taileron Primary Flying Control Units (PFCU), the fire bottle and hydraulic components including both reservoirs and powerpacks. A large section of the tail fin was also recovered. The wreckage was transported to RNAS Yeovilton for examination. Following the initial interviews with the crew and evidence of smoke or fire on a number of rear components, the MilAAIB focussed its investigation on the reconstruction of the rear fuselage. Support to assist with this complex task was provided by the Tornado Maintenance School, RAF Marham.

Annex D Para 1.4
Annex D, Para 1.4

e. **Main Engine Control Unit (MECU).** The left MECU was Engine Health and Usage Monitoring System (EHUMS) modified, and the EHUMS card was recovered in the wreckage. Although this card was significantly damaged, Goodrich, under the supervision of MilAAIB, attempted to extract the data. Although some data was recovered, unfortunately no data was available from the accident sortie.

Annex D Para 1.5.4

f. **VRS.** The VRS video was recovered from the wreckage and despatched to QQ at Boscombe Down. Despite using enhancing techniques, the full video could not be recovered and the images were distorted. However by using still images, the Panel were able to obtain figures for the total fuel contents for the majority of the flight.

Annex D Para 1.10

6. **Ac details and maintenance.** The ac flying hours (fg hrs) prior to the accident were 5240:10. The last scheduled maintenance carried out was a Primary Servicing at 5174:15 and the subsequent scheduled maintenance was Minor Servicing due at 5364:55. The ac was not carrying any significant limitations. At 0815 on 27 Jan 11, ZG792 completed a 1:30hrs sortie, returning with no faults reported by the crew. A turn-around servicing was completed by XV(R) Squadron engineers with no faults documented. The flight servicing was coordinated at 1200, and the ac was signed out by the pilot at 1310. The ac last completed air to air refuelling (AAR) 2 days preceding the accident and confirmation was given by the VC10 tanker Sqn that no faults were found to the refuelling pod that carried out this AAR operation.

Exhibit 2
Exhibit 4
Exhibit 8
Exhibit 2
Exhibit 29

a. **Ac fit. (S26)**

Exhibit 9

At the time of the accident, 1 x 14kg practice bomb had been released during the sortie.

Witness 4 Pg 2

b. **Engines.**

(1) The left engine had been fitted to ZG792 for 43:50 fg hrs. The previous removal of this engine was following a birdstrike, and engine modules were replaced at RR Filton.

Exhibit 3

Magnetic chip analysis was carried out 15:30 fg hrs prior to the accident, with no damage recorded. Boroscopes of the combustion chamber were carried out 4:25 fg hrs prior to the accident, during which no damage was reported. High Pressure Compressor (HPC) boroscopes had not been carried out since the installation of this engine to ZG792, and was not due until 5316:20 fg hrs. Exhibit 11 Exhibit 10 Exhibit 12

(2) The right engine had been fitted to ZG792 for 392:15 fg hrs. The previous removal of this engine was following REHEAT, VIB and THROT captions and engine modules were replaced by Tornado Propulsion Flight (TPF), RAF Marham. Magnetic chip analysis was carried out 6:25 fg hrs prior to the accident and no concerns were raised. HP Turbine boroscopes were carried out 4:25 fg hrs prior to the accident, again with no damage reported. Boroscopes of the combustion chamber were carried out 4:50 fg hrs prior to the accident with no damage reported. HPC boroscopes were carried out 73:50 fg hrs prior to the accident as part of the GOOP 150 grouped maintenance. During this maintenance period, 6 Low Pressure Compressor (LPC) blades were found to be 'nicked' and examination considered these were within limits for blending. Blending was carried out in accordance with the required maintenance procedure. Exhibit 3 Exhibit 11 Exhibit 10 Exhibit 12 Exhibit 13

(3) The performance of both engines are tracked and trended by the propulsion support team at RAF Lossiemouth in accordance with their Placard figures. No abnormalities had been highlighted in the build up to the accident and hence the engines were not subject to additional monitoring. Exhibit 3

c. **Petroleum, Oils and Lubricants (POL).** Samples of POL were taken and analysed, and all fluids were considered to be within specification and without deterioration.

Annex D Para 1.11

WRECKAGE EXAMINATION

Initial failure

7. **Right engine examination**. Following initial interviews with the crew of ZG792, the Panel focussed its initial investigation on the right engine. On recovery, it was found to be approximately 1 meter shorter than its original design length and debris from the ac intake was found in the LPC stage; both of which were attributable to impact damage with the sea. Evidence of burnt wiring looms were evident and clear evidence of breakout was found in the HPC casing, as shown in Figure 1. Annex D Para 1.5.1

Figure 1 - HPC Casing Damage

8. The right engine was subsequently stripped down to its individual modules for further inspection. Examination of the LPC and Intermediate Pressure Compressor (IPC) was carried out, however the main focus was on the HPC. The force of the impact had severely damaged the LPC stage 1 and LPC stage 2 fan blades. Debris had also been forced by the impact into the IPC and HPC stages of the engine. During investigation, small traces of tungsten and silver were found on one of the HPC stage 1 rotor blades. This mix of metal is similar to that found in a blade blending kit, however these elements are also found in other sources within the engine. A full and extensive investigation was carried out, including 100% physical check of all blade blending kits at RAF Lossiemouth. The Panel could not find any link between the traces found on the HPC blade and the blade blending carried out, and therefore concluded that these traces had originated from other parts of the engine during impact with the sea. Table 1 details the distribution of the damage sustained to the HPC in a table format. The categorisation of the damage found is divided to either missing; more than 70% of the aerofoil lost; less than 30% of the aerofoil lost and minor or no damage. The figures of each category of damage are detailed from left (front of compressor) to right (rear of compressor) in order of rotors and stators stages 1 through to 6.

Annex D Para 1.5.1

Annex I

Annex D Para 1.5.1

	Rotor 1 (52)	Stator 1 (90)	Rotor 2 (87)	Stator 2 (85)	Rotor 3 (113)	Stator 3 (105)	Rotor 4 (135)	Stator 4 (153)	Rotor 5	Stator 5	Rotor 6	Stator 6
Missing	0	**9**	0	**27**	0	**18**	0	0	0	0	0	0
More than 70% aerofoil loss	0	0	**1**	0	**17**	**2**	**12**	0	0	0	0	0
Less than 30% aerofoil loss	0	**81**	**86**	**58**	**96**	**85**	**123**	**153**	**139**	0	0	0
Minor/No Damage	**52**	0	0	0	0	0	0	0	0	159	141	117

Annex I

Table 1 - HPC Damage Table

9. Damage within the HPC was found to be concentrated between the stage 1 and stage 4 stator vanes. Very minor damage was discovered on both the leading and trailing edges of the HPC stage 1 rotor blades. The damage to the trailing edge was in varying locations and levels on the blades, thus indicating that it is unlikely that the initial failure was a stage 1 stator vane fatigue failure. The tip of a failed stage 2 rotor blade was found lodged in the stage 4 area, and damage was discovered on both the leading and trailing edges of the blades and vanes within stages 2 to 4. This indicated that debris from an initial failure was probably transferred forward and back between these stages. The reason for the rotor blade failure has not been positively determined, however it is possible that it resulted as a consequence of a neighbouring vane failure. The majority of stage 3 rotor blade tips were found to be deformed or missing. A number of blades showed evidence of overheating. Fracture surfaces of the damaged blades were found to be covered in the abradable coating that lines the engine inner casing. This would suggest that some of the stage 3 rotor blades were damaged/missing prior to the loss of abradable coating and hence, the subsequent fire event. The Panel determined that the most likely cause of the initial failure was either FOD, ingested into the right engine, or the fatigue failure of a rotor blade or stator vane. Debris forced by the impact of the sea into the IPC and HPC stages has made the identification of pre-impact FOD damage difficult and identification of fatigue failure has yet to be discovered. At present there is no evidence to fully support either theory and investigation continues at RR Filton.

Annex I

Annex I

10. **Ti fire.** The Panel observed evidence of a 'hot-spot' on the HPC inner casing at the HPC stage 2 stator vanes and HPC stage 3 rotor blades area, indicating the origin of a Ti fire. A number of trailing edges of the stage 2 stator vanes in this area were found to have burned. The edges of the

Annex I

breach of the HPC casing as shown in Figure 1 were found to be molten in appearance. This type of breach with molten edges is typical of a Ti fire. The Panel are of the opinion that debris, which had originated as a consequence of the initial failure, became lodged in the stage 2 stator vanes, overlapping into the stage 3 rotor blades path and was caught on each blade as it rotated. Titanium ignites at a lower temperature than it melts and has a low conductivity of heat. Hence, heat will not have been readily conducted away from the initial source and the titanium components will have rapidly risen in temperature to the ignition point. Ti fires are fast burning with a high heat intensity and contain molten particles. In-service experience shows that the time taken between the start of a Ti fire and breakout of the engine casing on Tornado can be in the region of 2 to 3 seconds. Given the damage observed, it is highly probable that molten particles found in the Ti fire burned through the compressor casing resulting in a radical expulsion of molten or incandescent metal which originated from the HPC. Annex I; Annex D Para 1.5.5; Annex D, Para 1.5.5

11. **Breakout.** Analysis of the engine examination indicated that there was a breach in the HPC casing, the Combustion Chamber Outer Casing (CCOC) and the by-pass duct. The Panel concluded that the Ti fire containing molten particles which originated in the HPC, burned through the CCOC and then the by-pass duct. The breakout location was in the region of the engine main and reheat fuel lines, highlighted in Figure 2. Optical pyrometer lines which run through the breakout area were recovered with fire damage to the outer braiding, supporting the conclusion that the fire broke out of the engine outer casing. The Panel were unable to locate the main fuel supply line, however 2 segments of the reheat fuel supply line were recovered originating from the breakout area; the material in the centre of this area, the direct path of the Ti fire, was not recovered. On examination of these segments, perforations in the pipeline wall and evidence of fire damage on both internal and external surfaces were found. Deposited titanium was also discovered on the pipeline outer surface. Hot spots were identified on both pipe sections; further sectioning revealed cracks emanating from the hot spots. Given the available evidence, the Panel considered a number of possible scenarios that may have caused the fuel line rupture: Annex D Para 1.5.1; Annex D Para 1.5.1; Annex I

a. The Ti engine fire may have penetrated outboard to the reheat fuel line causing it to rupture at a hot spot. Annex D Para 1.5.1

b. Violently ejected heated material impacted the fuel line causing failure at a hot spot.

c. Violently ejected material impacted the fuel line causing overload failure.

The Panel could not positively determine the exact cause of the fuel line failure.

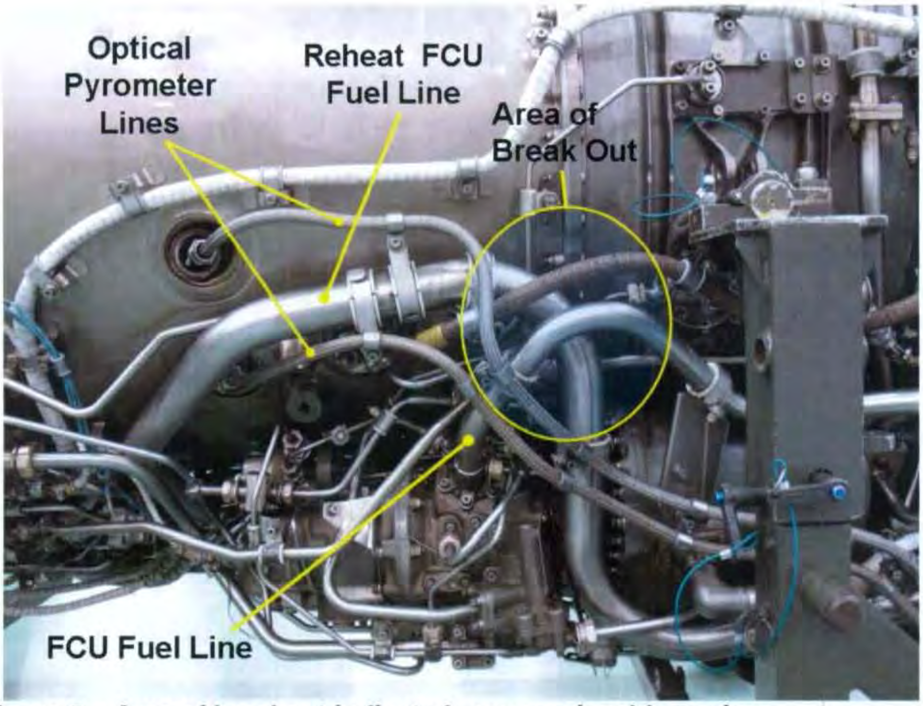


Figure 2 – Area of breakout indicated on a serviceable engine

Following the rupture/fracturing of the reheat fuel line, fuel under pressure would have leaked into the right engine bay. The LP cocks are mounted on the firewalls within the Secondary Power System (SPS) bay, hence they are external to the engine bays. They are used to shut off the engine fuel supply lines and reheat return flow lines to prevent fuel from entering and exiting the engine bays. The HP cock is a component within the Fuel Control Unit (FCU) mounted onto the engine. When open, the HP cock admits the main flow to the vaporisers within the engine. The fuel line rupture/fracture was in a location between the LP and HP cocks, hence the HP cock position had no affect on the fuel leak. It was however, imperative that the right LP cock was closed, to prevent fuel from entering the engine bay fuel lines and leaking through the rupture/fracture. The pilot stated that the LP cock was not closed instantly when the right engine was shut down, due to his distraction by the L FIRE caption. The LP cock was discovered in the wreckage and found in the closed position. The Panel therefore looked to ascertain the approximate volume of fuel lost through this leak and hence confirm the timing of the LP cock closure.

Witness 1, Part 2, Pg 1
Annex D Figure 6b

Fuel leak investigation

12. **WSO TV/TAB fuel total**. The R-ADR does not record any fuel data. However, the VRS video does record the rear cockpit TV/Tab displays, one of which is usually set to display the WSO's NAV display, showing an ac total fuel figure. The VRS video from ZG792, whilst damaged, still contained usable images, albeit as a series of frozen frames rather than a continuous video feed. By using Operating Data Manual (ODM) fuel burn data and the throttle settings from the R-ADR, the predicted fuel total was compared with the actual fuel displayed on the TV/Tab. It is possible that a discrepancy identified between the two figures could be attributed to a fuel leak.

Exhibit 1

Annex D, Para 1.10

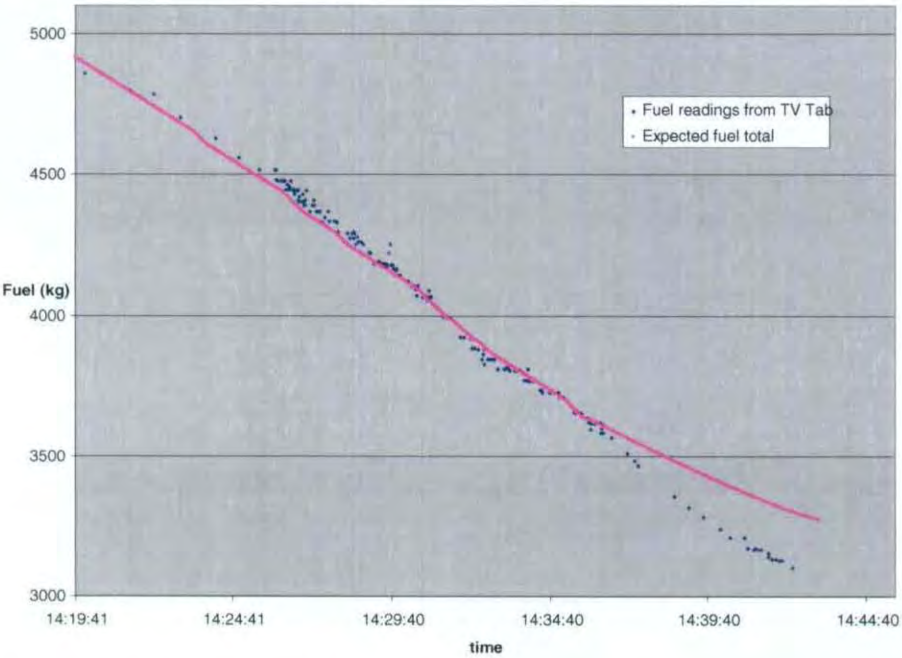


Figure 3 - Predicted and actual fuel use

Figure 3 shows the predicted and actual fuel usage from 1420:00 (T-15:46) onwards, covering the low-level portion of the sortie, through the initial point of the Mech fail at 1435:46 (T0:00) through to 1442:23 (T6:37) of the accident sequence, which is the last usable fuel figure available from the VRS. Exhibit 1

13. Figure 3 clearly shows that the fuel usage rate is as would be expected in normal flight up until the initial point of the Mech fail. From T0:00 onwards, however, the predicted and actual fuel usage rates diverge, with approximately 200kg more fuel being used than would have been expected. This can be more clearly represented in Figure 4, which shows the time from T0:00 onwards. This graph shows 2 predicted fuel lines, one calculated from the previous figures, and the other showing the calculation worked backwards from the last known fuel totals. The delta between the lines represents the fuel discrepancy of approximately 200-250kg.

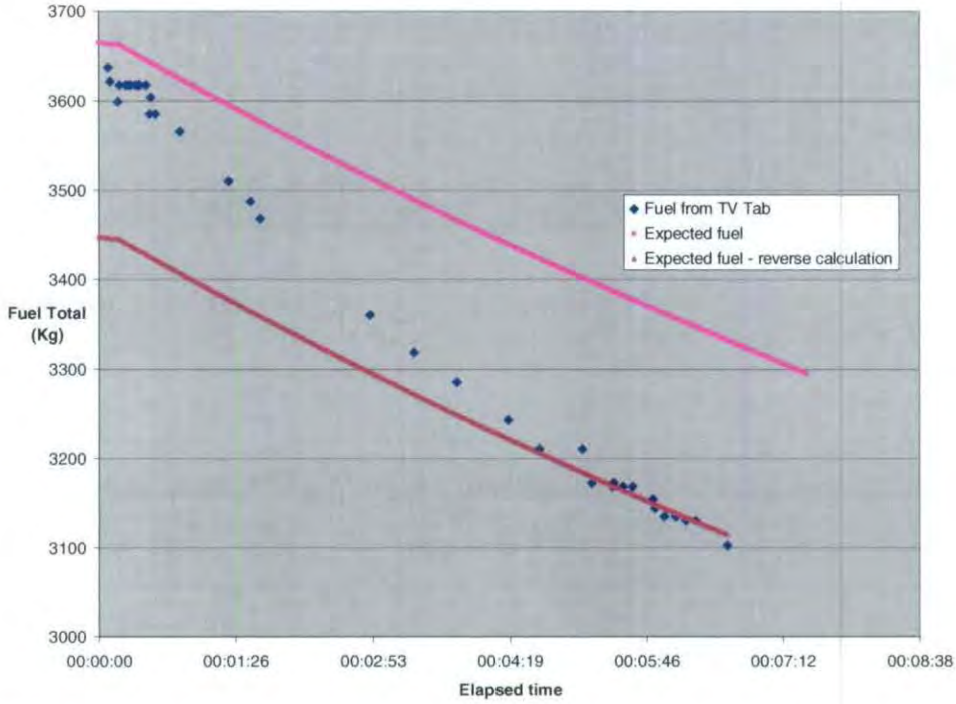


Figure 4 - Predicted and actual fuel use during accident sequence

14. **LP cock closure timing.** The LP cock was recovered in the wreckage and found to be in the closed position. However, LP cock closure is not a recorded parameter on the R-ADR. As such the Panel had to rely upon the formal evidence given by the crew of ZG792, specifically the pilot, and the evidence of fuel consumption from the WSO TV/Tab. During formal interviews the pilot could not recall the exact order that he actioned the Immediate Action (IA) drills for the Mech fail and suspect rear fuselage fire. He commented that his IA drills for the Mech fail were interrupted by the L FIRE caption, and this caused a delay in closing the LP cock. Throughout the course of the investigation the Panel have sought to explain how the left engine fire kept burning for approximately 4 minutes. Analysis of the fuel loss during the incident provided the Panel with conflicting evidence as to the exact point the LP fuel cock was closed. Evidence from the pilot suggested the LP cock was closed as part of the right engine shutdown at approximately T1:00. Fuel flow data could suggest that it was not shut until T4:30. The Panel considered both possibilities to determine the point of the LP fuel cock closure in the sequence of events.

Annex D Para 1.4.3
Annex D Fig 6b

Witness 1, Part 3, Pg 8

Witness 1, Part 1, Pg 1

15. **LP Cock closed during initial shut down.** Through both his informal interview with the Panel immediately after the accident, his formal statement to the Panel and his formal interview with the Panel one month after the crash, the pilot continually stated that he closed the LP cock during the initial shut down of the right engine. The Panel conducted a 2nd formal interview with the pilot in an attempt to clarify the exact timing of the LP cock closure. Throughout the interview the pilot remained adamant that he had closed the LP cock during the right engine shut down drill. He stated that he remembered doing it, and he could visualise the position of the switches after he shut down the right engine. The pilot is an experienced operator and instructor. He commented that he was aware that his drills for actioning

Witness 1, Part 1, Pg 1
Witness 1, Part 2, Pg 8
Witness 1, Part 3, Pg 3

Witness 1, Part 4, Pg 3

the Mech fail had been interrupted and so, after the initial drama of the accident sequence, he took time to look around the cockpit and confirmed that the LP cock was in the closed position. Witness 1, Part 4, Pg 7

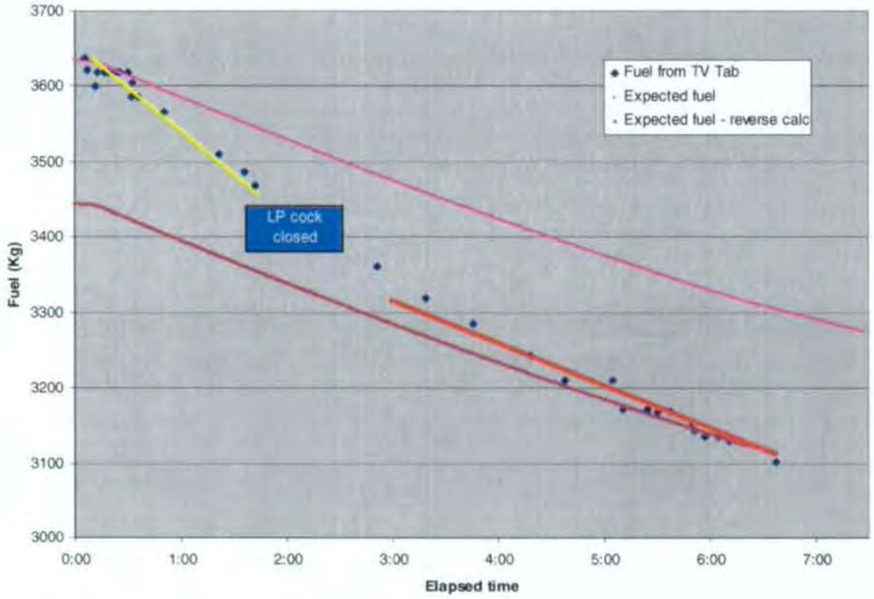


Figure 5 - Fuel Flow graph - LP Cock closure at T1:00 theory

The rate of fuel flow can be drawn at the rate shown in Figure 5. The actual fuel usage shown in this figure indicates that the majority of the abnormal fuel usage occurred in the early stages of the accident sequence. This theory is supported by the evidence of fuel pooling found in the right engine bay door, which suggests fuel pooling fed the left engine fire. In this presentation, by approximately T3:00 the fuel usage rate had returned to that expected of an ac running with one engine at max dry in the same flight conditions as CACTUS 2 prior to the ejection. Allowing some time for the fuel figure to catch up with the correct fuel total and for the fuel already in the pipe downstream of the LP cock to leak, the Panel concluded that if this theory is correct, the pilot closed the LP cock at some point around T1:00 just before he pressed the fire buttons. Annex D Para 1.4.5

16. **LP Cock not closed until T4:30.** Using the same fuel burn and fuel total figures from Figure 5, the Panel considered a theory that, contrary to the pilots assertion, the LP cock was not closed until after the aborted right engine relight attempt. Using the estimated fuel leak data (approx 250kg) the Panel were able to use the BAE Systems fuel drainage report in Annex F and ascertain that this fuel would have resulted in a pool of fuel of approx 0.18m deep within the engine bay. Using the BAE Systems model, the Panel were able to ascertain that, at a depth of 0.18m, this fuel should have drained away from the ac in approx 15-25s. Had the LP cock been closed at T1:00 then, in theory, this fuel should have drained away by approx T1:25. In reality the visual signs of fire were not seen to extinguish until T4:53. The Panel were unable to explain why the fire had continued, unless there was an additional source of fuel.

Annex D Para 1.10
Exhibit 30

Exhibit 30

Exhibit 6

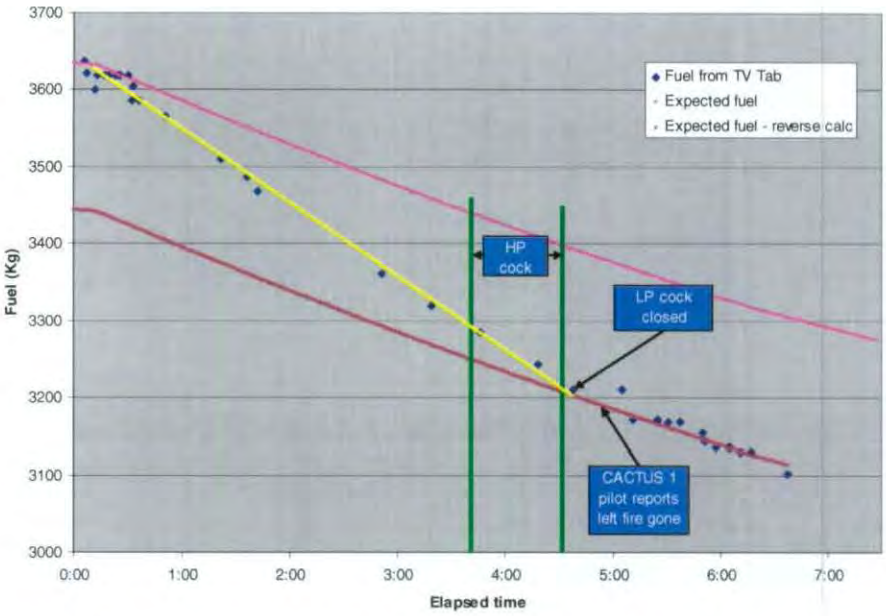


Figure 6 - Fuel flow graph - LP Cock closure at T4:30 theory

The average rate of fuel flow can also be drawn as in Figure 6. This shows that the actual fuel consumption is relatively constant up until the point the re-light is aborted, implying a steady and continuous leak. Had the LP cock been left open, it is possible that any damage sustained by the main and reheat fuel lines could have been the continuous source of fuel into the right engine bay. It is possible that, in the confusion that the pilot felt during the initial stages of the accident sequence, he omitted to shut the LP cock as his natural flow would have been interrupted by the emergence of the L FIRE caption. During interviews with the Panel, the pilot stated that the onset of the L FIRE caption happened just as he closed the HP cock on the right engine. He used this to explain how his drills had become delayed. However the Panel was able to ascertain from R-ADR data that there were 8s between closing the HP cock and the onset of the L FIRE caption. Whilst it may be reasonable to expect the pilot to have spent some of this time observing the right engine instruments (to ensure the engine was correctly winding down) it could not explain this process taking 8s. The Panel opined that there was sufficient time in the 8s gap, between HP cock shut and L FIRE, to have made the selection of LP cock shut. Although the pilot commented that he completed most of his drills silently, he actually verbalizes more then he recalled. During the initial onset of the emergency he verbalizes all his diagnosis and his actions (such as selecting 25° wing sweep). He also verbalizes the action of closing the HP cock (T0:38), and confirms this action when it is complete (T0:43). Later on during the emergency, at T2:25, he further runs through his actions with the crew of CACTUS 1. He states that he has shut down the right engine, the cross drive has closed and then, at T2:40, that he had pressed both fire buttons. At various stages throughout the emergency he verbalises every one of his actions, apart from the shutting of the LP cock. This action is not mentioned at any stage in the emergency. When the pilot attempts to relight the engine at T3:40, a few seconds after opening the HP cock (T3:44) the Panel believe

Witness 1, Part 1, Pg 1

Exhibit 1

Witness 1, Part 4, Pg 3

Exhibit 6

Exhibit 1

Exhibit 1

the crew received a R TBT caption, audible on the CVR and reported by the WSO at T3:58. The Panel could not rule out the possibility that this caption was spurious; however, we determined it was also possible that the R TBT caption may have been an indication of fuel flowing back into the engine and igniting. This action would have required the LP cock to have been open, yet in his formal interview the pilot stated that he did not re-open the LP cock at this stage. The pilot abandons his relight attempt at approx T4:34. At this stage it is possible that after closing the HP cock the pilot now shut the LP cock, as per the Mech fail IA drills. 20s later, at T4:53, CACTUS 1 reported that there were no more visual indications of fire, indicating that there was no longer fuel feeding the fire. Exhibit 6 Exhibit 6

17. **GR4 cockpit ergonomics.** In his formal interview the pilot stated that he had pushed both fire buttons with his left hand. Given the position of the fire buttons (see Figure 7) this would have been an unnatural hand to have used. The LP cocks are positioned on the left side coaming of the cockpit, just below eye-level but both easily accessible and obvious (Figure 8). Had the pilot only operated the fire buttons the Panel believed it would have been more natural to have used his right hand (Figure 10). However, if his left hand was already available from having just closed the LP cock, the Panel reasoned that it would be understandable to use the same left hand to reach across and push the fire buttons (Figure 11, Figure 12). This would speed the process up and avoid the pilot having to swap hands on the control column. The fact that the pilot used his left hand to activate the fire buttons suggested that he may have previously used it to close the LP cock. Just prior to receiving the L FIRE caption, the pilot initiates a right hand turn. This action would have required a positive control input from him. Given that the Panel believe the pilot actioned the fire button press during the turn, it is also possible that he failed to close the LP cock but used his left hand as his right hand was occupied flying the ac. The HF report also alludes to the fact that this unnatural use of his left hand could have made the omission of the LP cock more likely, as his use of the left hand may have convinced him that the action was done. The Panel was unable to determine which of these sequences was correct. Witness 1, Part 4, Pg 4 Annex A, Part 2, Pg 6

Figure 7 - Fire buttons on right side of cockpit

(S26)

Figure 8 - Open LP cocks from pilots view

(S26)

Figure 9 - right LP cock closed

Figure 10 - Using right hand to push fire buttons

~~RESTRICTED – SERVICE INQUIRY~~

Figure 11 - using left hand to push fire buttons with right hand on control column

Figure 12 – using left hand to push fire buttons

18. **Post accident recollection**. It is not uncommon for crews who have been through the trauma of an ac crash can have errors in their recollection. The Panel sought to determine if this might be the case with the accident pilot. In order for the T4:30 theory to be correct the pilot would have had to have made not just one, but at least two errors in his recollection. Firstly his assumption that he closed the LP cock before actioning the fire button push

Annex A, Part 2, Pg 7

would have to be incorrect. Then his recollection of the re-light attempt would also have to be incorrect. The pilot repeatedly stated that, during the re-light attempt, at no stage did he consider or action the LP cock. As the Panel found the right LP cock in the closed position, it is known that it was closed at some point in the accident sequence. Whilst there is some confusion in the pilot's recollection of events (he could not remember whether he selected ERA before or after pushing the fire buttons, and his second formal statement to the Panel contradicted his first in this sense) the Panel noted that his recollection of events was generally detailed and consistent.

Witness 1, Part 3, Pg 10
Annex D Para 1.4.3

19. **LP Cock guard made but not switch.** The Panel considered whether the pilot could have started the process of closing the LP cock by opening the guard, but then not made the 'down' switch selection (Figure 13). Had the pilot been distracted by the L FIRE during the 2 stage process of closing the LP cock, it is possible that his natural pairing may have been interrupted but he could have been left with an impression that he closed the LP cock through the action of opening the guard. During his subsequent scan of the cockpit the open guard would have provided a powerful visual indication that the LP cock was closed. Only a more detailed inspection would have shown that the actual switch was still 'up' and hence the LP cock still open. Having abandoned the re-light attempt, with the guard already open, the process of closing the LP cock would have been simpler. It is possible that the pilot closed the LP cock at this stage, but again because his natural pairing may have been broken, he may not have had a recollection of this action.

Annex A, Part 2, Pg 12

(S26)

Figure 13 - LP cock switch un-guarded, but switch at open position

20. **3rd Party Analysis of data.** Given the two contradictory theories, the Panel requested analysis from an additional 3rd party. BAE Systems propulsion department were asked by the MilAAIB to review the fuel flow

data, and provide their opinion as to the most likely sequence of events in order to determine when the LP cock was closed. Initially all the JPEG photos from the WSO's TV/Tab were re-checked by personnel not involved with the original collection of data. Again, data was only used if both a time and fuel figure could be derived from the snap shot; no interpolation was used. This check confirmed that the original figures used were correct. This information was provided to BAE Systems propulsion who spent 2 weeks independently reviewing the data. The department were provided with the fuel level figures and asked to plot them against BAE Systems predicted fuel flow rates. BAE Systems used their own models to calculate the predicted burn rates which are detailed in Annex J. These models allow for a greater degree of accuracy then the ODM as the models allow more specifics to be entered in calculating the exact fuel burn rate (of note the BAE Systems fuel flow rates closely matched the Panel's ODM rates). Figure 14 shows the BAE Systems plotted fuel flow rates. The Pink lines show the BAE Systems modelling of the fuel level and the blue line shows the actual fuel quantity as displayed on the WSOs TV/Tab. What can clearly be seen is a consistent divergence from the predicted fuel quantity set against the actual fuel quantity implying a leak. The lines become more parallel at approx T4:37, implying that at this stage the leak had reduced (and/or stopped) and as such the fuel to the engine had been isolated. This graph supports the theory that the fuel was not isolated until much later on in the emergency. After the graph had been produced BAE Systems were asked to comment on the likely cause of this leak and the conclusions from MilAAIB. BAE Systems concurred with the analysis from MilAAIB and stated that they believed that the LP cock was left open until T4:37.

Annex J

Annex J

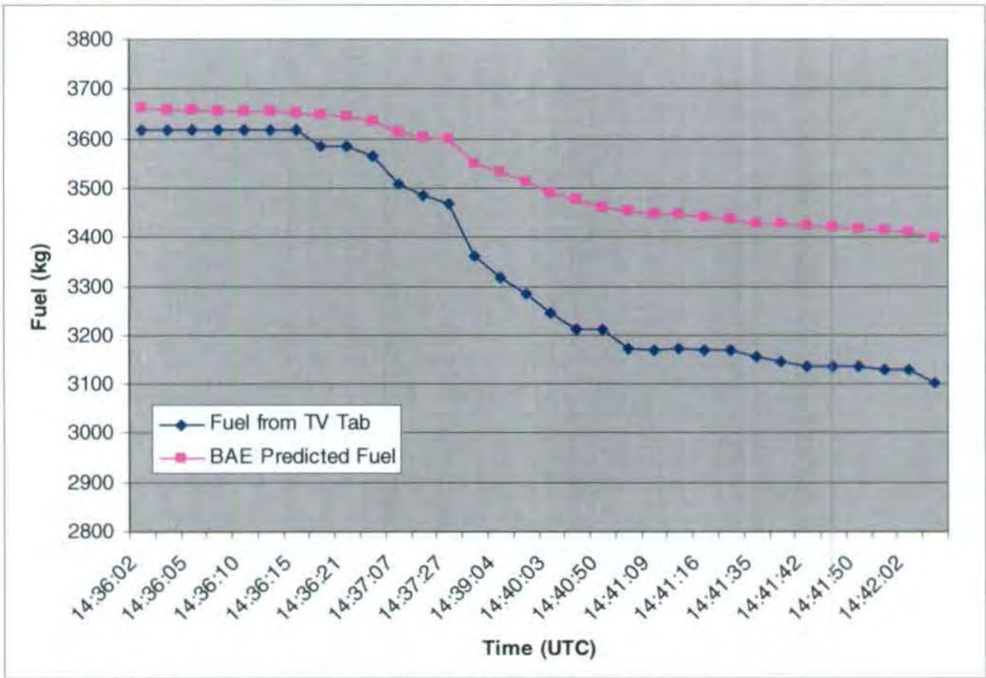


Exhibit 31

Figure 14 - BAE Systems Fuel Flow Rates

21 **Conclusion.** The Panel had difficulty in determining which theory was correct. The pilot repeatedly stated that he closed the LP cock, and remembered seeing it closed. Given the position of the LP cock switches in the cockpit the Panel reasoned that it should have been obvious if they were

not closed. They also reasoned that there was ample time in the emergency to pick this up, and the pilot's statement that he scanned the cockpit and confirmed the position of the LP cock is convincing. There remained the possibility that he had made the guard, but not the switch, although the HF report felt that this was unlikely due to his natural pairing. We could not, however, discount the alternative theory. The Panel could not explain why the pilot had been unable to close the LP cock in the 8s between HP cock shut and L FIRE. Likewise it noted that at no time in the emergency sequence did the pilot talk about the LP cock, although he did talk about every other action and at no stage did the crew confirm the full FCC actions verbally. It also reasoned that the presence of a suspected R TBT caption 7s after the HP cock was selected back on, and the fire extinguishing approximately 20s after the HP cock was closed (and by assumption the LP cock at this stage) was equally convincing. Given that the HF additional report stated that both options were a possibility, the Panel had to base its conclusions on the weight of the technical evidence presented to it. Given the MilAAIB interpretation of the fuel flow rates, and the fact that this evidence was independently confirmed by BAE Systems, the Panel reasoned that the technical evidence supporting the LP cock closure time was the most likely. **Ultimately the Panel were unable to positively determine when the LP cock was closed, but given the weight of technical evidence, we reasoned that this was most likely to have been at T4:30**

Witness 1, Part 4, Pg 3
Witness 1, Part 4, Pg 7
Annex A, Part 2, Pg 14
Exhibit 6
Annex J

22. **Right engine bay fuel fire.** The forward right engine bay door was badly damaged and showed visual evidence of sooting and heat damage. The distribution of the sooting showed evidence of 'tide marks' suggesting that fuel had pooled in the door and burnt away leaving these marks. Both the left and right rear engine bay doors were not recovered and hence it is not known whether these were lost during impact or were significantly damaged by fire during the accident sequence. Scottish Military Air Traffic Control reported a small radar return falling behind the ac at this time. The Panel concluded that this was most likely to be a rear engine door. The right engine bay titanium firewall was recovered and showed visual evidence of 'blueing'. This highlighted that there has been excessive heat applied to the titanium firewall. Following the rupture in the fuel line, a combination of fuel, fuel vapour and fuel spray would have filled the right engine bay. The following sources of ignition were considered:

Annex D Para 2.2.1
Exhibit 27
Annex D Fig 9c
Annex D Para 1.4.4

a. Electrical arching (Annex D Para 2.2.1)

b. Hotplate ignition

The Panel discounted the possibility of electrical ignition as wiring harnesses are protected by protective sheathing, and no indications of failed engine systems were recorded by the R-ADR prior to the accident sequence. Previous analysis carried out by RR and BAE Systems describe that a likely source of ignition within an engine bay can occur when fuel vapour contacts a hot-surface – known as hot plate ignition. The nozzle control unit and reheat control unit are known to reach surface temperatures of above 300°C during normal flight and the flashpoint of Avtur is approximately 240°C. The Panel concluded that the most likely source of ignition was hot plate ignition on the nozzle control unit surface. With fuel pooled in the base of the engine

Annex D Para 2.2.1
Annex D Para 2.2.1
Exhibit 17
Annex D Para 2.2.1

bay, a static fuel source would have been able to feed the fire. In addition, fuel leaking from the ruptured fuel line would have leaked in random directions, whilst under pressure. Both sources would have resulted in the right engine bay fire being omni-directional. Evidence confirmed that this fire reached a temperature of at least 635°C and analysis by BAE Systems suggests that the temperature range was 700-1667°C. Annex D Para 2.2 Annex K

23. **Right fire indications.** The Pilot did not receive a R FIRE caption until T1:33. This was then followed with a number of intermittent indications, and a 5-second indication from T2:14. The intermittent captions were co-incident with a loss of nozzle signal, which would indicate an electrical power failure. The final indication was coincident with a R CONTR caption, which the Panel consider could be attributable to electrical fire damage in the hydraulic equipment bay. ACM Book 2 Part 3 emergencies, states that a rear fuselage fire can cause damage to wiring looms and cause short circuits. Another theory for the intermittent R FIRE caption may be a result of the fire wire controller, which is mounted on the engine bay fire shield, breaking down due to heat transfer from the engine bay. Although the reasoning behind the intermittent R FIRE captions in the accident sequence is undetermined, the Panel aimed to ascertain why the pilot did not receive a R FIRE caption at the onset of the accident, during the initial moments of the fire. The following reasons were discussed; Exhibit 1 Exhibit 15 Annex D Para 1.6 Annex D Para 1.6

a. There was a latent fault in the fire detection system

b. The fire wire was damaged by the Ti fire.

c. The fire wire was affected by the fuel pool from the right engine bay fuel leak.

d. The fire wire was affected by the fuel pool from the right engine bay fuel leak and subsequently damaged by the engine bay fire.

The Panel concluded that option (a) is unlikely as the fire detection system passed the pre-flight built in test check. The Panel assumed that unless there was a latent undetected system failure, the fire wire system remained serviceable. The Panel also concluded that option (b) was unlikely, as the fire wire route was not in the area where the Ti fire broke out of the engine. The Panel therefore concluded that it was unlikely the fire wire was breached by the Ti fire. The Panel is of the opinion that option (c) was possible. The fuel leak pooled in the base of the right engine bay and submerged the fire wire sensing element, effectively cooling it. The right engine bay door shows clear evidence of fuel pooling, and the rubber grommets holding the fire wire in this area were found unburnt but contaminated with fuel. A R FIRE caption is triggered when the capacitance of the fire wire system rises. This cooling may have been sufficient to prevent the overall system capacitance from changing, even though other areas of the fire wire were directly exposed to heat and flames. The report of the accident of ZE830, dated Apr 00, also supports this theory for a delayed R FIRE caption. Annex D Para 1.6 Annex D Para 1.6 Annex D Para 1.6 Exhibit 16

The Panel concluded that option (d) was most likely. We are of the opinion that the fuel initially cooled the fire wire sensing element, but the fire wire was subsequently damaged by the intense fire in the right engine bay. This Annex D Para 1.6

intense fire reached in excess of 635°C and destroyed much of the aluminium structure on the engine bay doors, on which a large section of the fire wire is mounted. It is therefore highly likely that the fire wire was damaged, resulting in intermittent warnings, and then final failure. Ongoing investigation by MilAAIB aims to engage with the fire detection system manufacturers in order to assess the effects of fuel cooling on the fire wire and the effects of radiated heat on the controller. Annex D Para 1.6

24. **Firewall integrity and heat transfer**. Figure 15 details the area of right engine bay firewall that was recovered in the wreckage. The shaded red area indicates the area of the firewall that was not recovered. This is in the location of the Ti fire breakout path and the area where the heat intensity of the engine bay fire was highest. It is highly likely that the fire was funnelled up the bay around the engine. Due to the curvature of the wall, this fire would have heated the titanium firewall concentrating the heat intensity in the upper area of the red shaded area. This is in line with the lower area of the right hydraulic reservoir on the other side of the titanium wall. Although the Panel could not positively determine whether the Ti fire broke through the firewall into the hydraulic equipment bay, analysis of the edges around the missing section of firewall show no signs of heat distress, with all edges being clean sheared; this would indicate that the damage was sustained on impact. In addition, analysis of the hydraulic power pack and hydraulic accumulator, only show evidence of heat and smoke damage. The lack of fire damage in this area suggests that the fire did not penetrate the wall. The Panel conclude that the firewall was most likely intact prior to impact with the sea.

Annex D Para 1.6

Annex D Para 2.2.1

Annex D Para 2.2.3.1

Figure 15 - Representative area of right firewall recovered

Right rear fuselage hydraulic fire

25. **Fire damage**. Examination of the wreckage suggests that a localised fire took place in the upper part of the right hydraulic equipment bay

(airbrake bay) in the region of the hydraulic reservoir. This did not spread into any other zones; the 'V' Bay and tail fin showed no evidence of fire damage. Components in the lower area of the hydraulic equipment bay showed very little evidence of heat damage. Sooting was found on the power pack, fire bottle and hydraulic accumulator, but there was no exposure to significant heat or direct fire. The right taileron PFCU lower side showed only smoke damage, however the upper edge, which is located in the same area as the hydraulic reservoir, shows signs of heat distress and fire damage. The CSAS wiring had been destroyed by fire, along with the left and right hydraulic input pipes at the connection point. A small section of right taileron was found still attached to the PFCU and the skin showed no signs of fire damage. Analysis of the hydraulic reservoir found that it had been severely heated and had deformed on impact. The right hydraulic reservoir power piston was found completely retracted inside the low pressure chamber, suggesting that at the time of impact, the right hydraulic reservoir had been empty. The Panel also looked in the left hydraulic equipment bay and found that the left hydraulic power piston was at the mid position, indicating that this reservoir was approximately half full at the time of impact; no signs of smoke or fire damage were discovered in this area. The right hydraulic reservoir HP tailstock was badly damaged, showing signs of fire damage. The low level microswitch was missing; however a R CONTR was recorded at T2:14. This therefore may be attributable to electrical fire damage. This warning indication is the first to highlight a fire in the hydraulic equipment bay area. The Panel could not confirm whether this caption was a result of electrical damage, or highlighting that the protected hydraulic system had lost pressure. The Panel concluded that if it was the latter, then this would be the point to consider the ac unrecoverable, as there was no means of extinguishing this fire.

Annex D Para 1.4.4

Annex D, Fig 11

Annex D, Fig 12

Exhibit 1

26. **Fuel source.** Evidence showed that the intense heat within the right engine bay reached at least 635°C and analysis by BAE Systems suggests that the intense heat within the right engine bay, reached between 700 and 1667°C. This heat transferred through the Titanium firewall of 0.9mm thickness increasing the ambient temperature in the hydraulic equipment bay. The temperature within the bay reached at least 635°C, confirmed by the discovery of aluminium splattering on the hydraulic reservoir, originating from the airbrake weather shield, which was also found to be destroyed by fire. As the hydraulic pipelines in this area are manufactured from steel with aluminium couplings, the intense heat would lead to different coefficients of expansion, potentially leading to a hydraulic fluid leak under pressure from the right hydraulic reservoir. Mottling discovered on the surface of the mechanical control rods in this area suggests that hydraulic fluid had been spraying onto hot surfaces in the bay.

Annex D Para 2.2.2

Annex K

Annex K

27. **Hydraulic leak analysis.** Total hydraulic line failure is expected at 600-650°C; however a hydraulic leak will occur before the lines reach this temperature. The flexible hydraulic pipelines which feed into the PFCU from both the left and right hydraulic systems, were found to be destroyed at the point of connection, however other sections of this piping from the hydraulic bay were recovered. On closer inspection, signs of heat distress were observed, with the inner Teflon layer extruding through the outer armour. This suggests that hydraulic fluid was also escaping through the heat-softened pipeline. The Teflon hoses are only designed to sustain a

Annex K

Annex D Para 1.4.8

temperature of 134°C for up to 120 seconds and the ambient temperature in this bay is already at 100°C. Assessment of in service ac shows the clearances between hydraulic pipes and the firewall in this area is minimal, thus supporting the probability of heat transfer. Annex K details a mathematical model used to work out the time required for heat transfer from a fire within the engine bay to reach the closest hydraulic line (in this case the No1 system taileron actuator return hose) and heat it up to a temperature of 600°C – i.e. to cause a leak. As the maximum temperature of the fuel fire is unknown, a number of temperatures were imputed into the model; Annex K Annex D Para 2.2.2 Annex K

Temperature of Engine Bay Fire (°C)	Time taken for hydraulic line to reach 600°C (secs)
700 (approx fuel burn temp)	**428.2**
1100 ('typical' temp defined in Def Stan 00-970)	**77.45**
1300 (a 2nd 'typical' temp defined in Def Stan 00-970)	**49.45**
1667 (melting point of Ti)	**4.33**

Table 2 - Heat Transfer

Annex K

The Panel therefore opine that the time taken from the initial failure to the hydraulic leak is most likely between 49 and 77 seconds.

28. **Ignition source.** The Panel considered the most likely cause of ignition of hydraulic fluid in the bay. The following options were considered;

a. Hot plate ignition as a result of hydraulic fluid spray hitting the heated engine bay firewall Annex D Para 2.2.2

b. Ignition as a result of an electrical arc caused by the breakdown of electrical cabling

c. A combination of option a or b.

After discussion with subject matter experts, the Panel concluded that neither option (a) nor (b) could not be discounted, hence the most likely cause of ignition was option (c); given Hydraulic fluid has an auto ignition temperature of only 230°C, the Panel concluded that it is highly probable that fluid from the hydraulic leak will have ignited when it came into contact with the hot titanium firewall. As the leak is most likely to have been an atomised spray, this will have increased the probability of hot-plate ignition. Due to the number of spurious warnings received by the pilot, there is evidence that the cables in this area were failing. The wiring looms in this area provide power to services including CSAS, and assessments on in-service ac show that these looms run with clearances of less than 5mm to the firewall; some were found to be touching the firewall. The Panel concluded that following heat transfer, it is highly probable that the wiring loom insulation degraded, exposing the inner core wiring, leading to short circuits and electrical arching, providing a 'spark' required for ignition. Annex K Annex D Para 2.2.2

Flying control failures

29. **CSAS failures**. At T2:50, the R-ADR shows that the tailerons reverted to Mech mode. The CSAS wiring into the right taileron PFCU was found completely destroyed by the fire, hence the Panel concluded that T2:50 was the point at which the hydraulic fire damaged the CSAS wiring looms, preventing its operation. This would have generated red CSAS and amber CSAS and PFCS captions, along with associated P/R LNK, ROLL MD and PITCH MD warnings on the CSAS control Panel. The pilot transmitted that he was "*...losing CSAS as well...*" at T2:58. He did not recall exactly what CSAS captions and warnings he observed, nor did he make an attempt to reset any of the faults, as he had satisfactory control in Mech mode and prioritised dealing with the rear fuselage fire.

Exhibit 1

Annex D Para 1.4.8

Exhibit 6

Witness 1, Part 3, Pg 8

30. **Control degradation**. Sections of right taileron control rods were discovered in the wreckage. Examination of these showed that they had failed whilst the material was soft and under load, suggesting that they had been damaged by a fire in the equipment bay. As discussed previously, the Panel can confirm that the temperature within the hydraulic bay areas reached at least 635°C. All mechanical control rods in this area are manufactured from an aluminium alloy, which has a melting point of approximately 650 °C. This alloy would begin to start losing its material properties at approximately 530°C, suggesting that the rods in this area gradually deformed as the fire and heat intensity increased.
In his interview, the pilot described how, in the later stages of the emergency, he felt the ac develop a tendency to roll to the left. This was controllable initially, but he feared a total loss of control was imminent and thus decided to eject. The R-ADR lateral control parameters show clear evidence of the increasing right control column inputs. Figure 16 shows the stick position and roll angle throughout the accident sequence on a normalised scale. At T5:00 the stick position moves progressively further to the right, despite the ac remaining roughly wings-level.

Annex D Para 1.8

Witness 1, Part 1, Pg 2

Exhibit 1

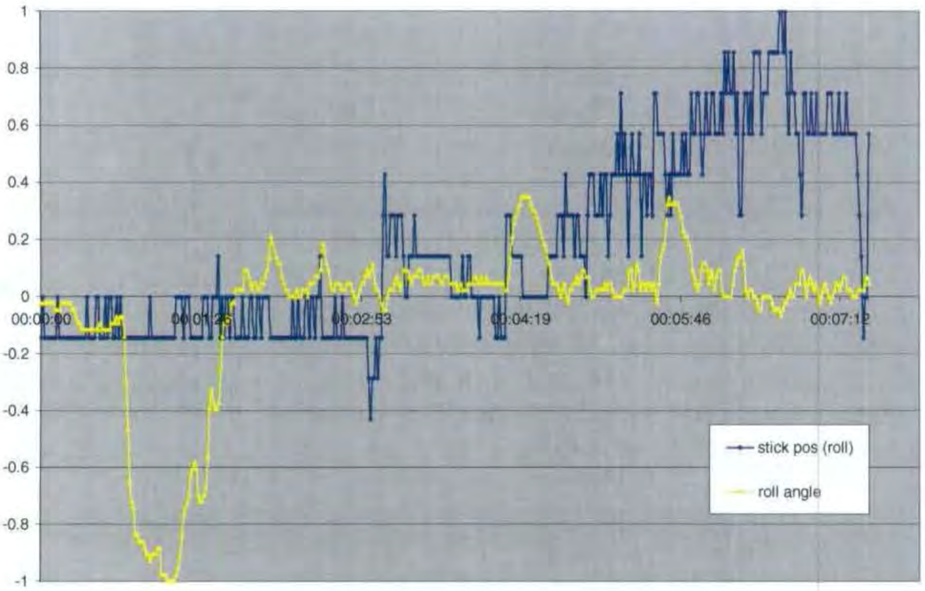


Figure 16 - Normalised lateral control data (+ve = right)

Given the pilot's recollection of events shortly before ejection and the data displayed in Figure 16, the Panel conclude that there was a gradual loss of control of the right taileron, as the mechanical control rods deformed due to heat damage. This gradual loss of control ultimately led to the decision by the pilot to eject.

Left engine bay fire

31. **Left engine.** The left engine was recovered in 2 parts; the engine core and the exhaust. Visual inspection showed no evidence of internal fire damage or mechanical failure. Sooting and visual evidence of fire damage was found on the engine outer casing, nozzle, thrust reverser buckets and external wiring. Visual inspection showed that the LPC stage 1 fan blades had all detached from the roots of the blades. A number of blades were recovered from the sea bed and showed signs that they had failed in overload, supporting the R-ADR data that the left engine was rotating at the point of impact with the sea. Annex D Para 1.5.2

32. **Left engine bay.** The rear left engine bay door was not recovered. The forward engine bay door showed clear evidence of fire and heat damage, however it was not as badly affected as the right engine bay door. Additional fire damage was discovered on the engine wiring, but not all looms were destroyed. The recovered arrestor hook torque tube showed signs of sooting on the right-hand side with no visual evidence of fire or sooting on the left. This indicated that the fire in the left engine bay did not spread as far forward as the fire in the right engine bay. Very little of the left engine bay titanium firewall was recovered intact, however those areas that were recovered showed less evidence of heat distress than in the right. No evidence of a secondary fire was discovered in the left hydraulic equipment bay. There was no evidence to suggest a fuel leak from the left engine or fuel pipes in the left engine bay. The entire inner keel wall (the firewall that segregates the left and right engine bays) was recovered and showed visual evidence of heat damage on both sides. However, there were no signs of pre-impact penetration nor were there any visible leak paths for fluids to transfer between engine bays from right to left engine bays. Annex D Para 1.4.5 Annex D Para 1.4.5

33. **Fuel transfer.** As the inner keel wall did not show any evidence of a breakthrough enabling the transfer of fuel/fire from the right engine bay to the left, nor was there any evidence of a fuel leak in the left engine bay, the Panel considered what other scenarios could have caused the left engine bay fire. Evidence from previously conducted BAE Systems flight trials has shown that in certain flight conditions it is possible for leaked fuel to transfer from one engine bay to the other via re-ingestion through engine bay door apertures. Given all of the evidence presented, the Panel consider that as the right engine bay filled with fuel, fuel leaked from the forward overboard drain, and the engine bay door latched panel, hinges, seals and fasteners. Most of the leaked fuel would drain via the forward over-board drain at the centre keel, tracking back. The aerodynamic effects around the airframe and differential pressures inside and outside the ac will have resulted in fuel re-entering the left engine bay via door seals and the thrust reverse motor exhaust outlet. Annex G Annex D Para 1.9

34. **Hot points and ignition.** Analysis of previous Tornado airborne fires in engine bays shows that ignition can result as the re-ingested fuel comes into contact with hot surfaces around the rear of the engine bay, for example the nozzle air motor and supply pipe which can reach surface temperatures of above 300°C during flight. With an auto-ignition point of 240°C, fuel ingested through an exhaust outlet may give rise to an atomised spray, thus increasing the probability of ignition. The Panel dismissed the likelihood of ignition from electrical arching as the engine harnesses are protected by sheathing and there were no indications of a failed engine system recorded on the R-ADR. Exhibit 17 Annex D Para 2.2.1

35. **Left engine bay fire**. Following ingestion into the left engine, It is likely that the fuel would have leaked past the fire seal and around the left exhaust which, when ignited, would have given the impression that the left engine was in reheat, which was reported by the crew of CACTUS 1. Given the electrical loom damage, it is reasonable to consider that the wiring insulation was melted in the fire resulting in the shorting of un-insulated wires. The Panel concluded that this may have been the cause of false/unreliable cockpit indications. Exhibit 6 Annex D Para 2.2.1

36. **Engine performance data.** In the absence of EHUMS data, the Panel needed to utilise the limited engine data on the R-ADR to reconstruct the engine response and performance throughout the accident sequence. Exhibit 1

a. The REHEAT caption is not captured by the R-ADR. However, the nozzle area is a recorded parameter and shows that the right nozzle failed to the Emergency Nozzle Close (ENC) position at T0:03, consistent with a REHEAT caption. The right nozzle remained at ENC until T1:03, when it started to oscillate. It eventually stabilised at 50%, thus indicating a loss of signal to the gauge, at T2:09. The left nozzle failed to ENC at T1:26, changing to a 50% reading at T1:57. Annex D Para 1.4.4 Exhibit 1

b. When both throttles were moved to idle at the start of the accident sequence, the NH of both engines wound down accordingly. The R-ADR identified that the NH decay of both engines was initially similar, however the left NH stabilised at a normal idle reading of approximately 69% at T0:06, whereas the right NH continued to decay, eventually reaching 11.5%, the minimum threshold that the R-ADR can record, at T1:20. Exhibit 1

c. The R OIL P caption is a recorded R-ADR parameter, and was reported by both crew and is coincident with a 'lyre-bird' alarm on the CVR at T0:16. The low oil pressure could have been caused by a failure within the oil system or simply because the sub-idle NH was not sufficient to generate enough oil pressure. Exhibit 1

d. The left throttle was left in the max dry position for most of the emergency sequence. The R-ADR initially shows the left NH as being approximately 95%, which is similar to the max dry figure that both engines achieved throughout the flight. The NH responded to a brief movement of the throttle at T2:42, but when the pilot attempted another movement at T4:51 there was no response at all. At T4:40 Exhibit 1 the R-ADR data shows the left NH rising to approximately 99%. From T4:42 to T6:16 the NH very gradually increased from 99% to 101%NH. At this point, it rapidly decayed to approximately 83% at T6:19, and settled at 87% by T6:22, where it remained until impact with the sea. At T6:20 the pilot reported a loss of thrust, coincident with the reduction in NH and his speed from around 290KCAS to 238KCAS by the time of the ejection. At T6:01 the pilot had reported that his left NH indications were fluctuating, although the rapidly changing indications did not appear to bear any relation to the engine thrust output. RR transient modelling has suggested that the sudden drop of NH could be caused by either an uncommanded opening of the left nozzle, or the NH emergency over-speed governor operating. This would explain the reported loss of thrust by the pilot. Exhibit 1

e. R-ADR data indicates that the left engine was operating with an NH of 87±1% from T6:22 up until the point of impact. It is the opinion of the Panel that the engine electrical harness cabling failed as a direct result of the left engine bay fire and resulted in the selected engine power output at the time of electrical burn-through being maintained by the engine until impact. Exhibit 1

ANALYSIS AND FINDINGS

37. **Model of Detailing Factors**. The Panel used a modified version of the James Reason accident model to categorise the factors identified. It derived its initial model from the ICAO Safety Management Manual, but also used inputs from the Australian Transportation Safety Bureau's interpretation of this model.

a. **Organisational influences**. The latent factors that were in place at the commencement of the sortie of the crew of ZG792. These include management decisions and organizational processes, as well as preventative risk controls.

b. **Supervision**. Details of the supervision of the crew of ZG792.

c. **Preconditions**. The latent factors in place highlighted by the accident sequence.

d. **Acts**. The physical Acts that took place during the accident sequence, both technical and crew related.

38. **Accident Factors**. The factors identified in this accident are defined in JSP832 and JSP551 as follows;

a. **Causal Factor**. A factor which led directly to the accident.

b. **Contributory Factors**. Factors that did not directly cause the accident but made it more likely.

c. **Aggravating Factors**. Those factors which did not cause the accident but aggravated the final outcome – i.e. made it worse.

d. **Other Factors.** Noteworthy features including deficiencies discovered by the Panel that were not causes, aggravating or contributory factors of this accident, but which if actioned may prevent future accidents.

e. **Observations.** Other points that are not considered a factor in the accident but are worthy of comment and may have recommendations.

ORGANISATIONAL INFLUENCES

Emergency handling training

39. The Panel considered the standard of emergency handling by the accident crew, and how this may have compared to other TGRF aircrew. In order to assess this, a trial was devised by the Panel to be conducted in the Tornado GR4 simulator. In addition, and as directed by DG MAA, the Panel also conducted a broader investigation into emergency training over the entire TGRF. The trials aspect would examine the handling of similar emergencies amongst a variety of current TGRF crews, to provide a comparison with the crew of ZG792. The trial was split into 2 different phases:

a. **Trial phase 1 - mechanical failure diagnosis and shut-down time.** It was agreed with the GR4 Simulator Training Manager (STM) that, without direct supervision by the Panel, the simulator staff would give a variety of different crews engine mechanical failures and record how long they took to diagnose the fault and shut down the affected engine. The simulator instructors were briefed not to discuss the reasons for the trial or to give the crews any advanced warning. Furthermore, they were asked to try to initiate the emergency at a point in the simulator exercise where the crew would not necessarily expect to have to deal with an engine failure. Records were made of crew experience levels, the times to diagnosis and shut-down as well as any other comments on crew performance. The trial was conducted on 13 crews in total. Exhibit 18

b. **Trial phase 2 - full reproduction of ZG792 accident symptoms.** The Panel also subjected 2 crews, with pilots at different ends of the experience spectrum, to as close a reproduction as possible of the emergency faced by the crew of ZG792. This was observed and supervised directly a Panel member. Exhibit 18

40. **Simulator limitations.** There are 2 main limitations in using the simulator to assess typical crew performance:

a. The GR4 simulator is not able to completely recreate the exact symptoms experienced by the crew of ZG792. It is not possible, for example, to give crews a nozzle failure to ENC and a REHEAT caption Exhibit 18

1 The Panel was made aware of 12 Ti fire events since 1990, but these figures require further verification.

at the same time as an engine mechanical failure. Indeed, the only way to cause a REHEAT caption (without having a THROT caption as well) is to pre-arm a reheat failure which the crew will only experience if the pilot attempts to use reheat. Furthermore, with high power settings, it is difficult to generate mechanical failure-related surges in the simulator that do not cause an associated TBT warning – a caption not initially experienced by the crew of ZG792 (possibly due to the pilot retarding the throttles quickly on hearing the machine-gun noise). Bearing these limitations in mind, the Panel asked the simulator staff to present the Trial 1 crews with surges outside of normal surge parameters with at least one additional engine-related caption. Exhibit 18

b. It is inevitable that crews operating in the simulator environment, despite attempts to occupy them with other tasks, will be more alert to the possibility of emergencies occurring. Furthermore, when presented with emergencies, crews are likely to take actions (such as shutting down an engine or ejecting) with less regard for their consequences than would normally be the case. The Panel judged that this would probably shorten the typical response times seen in the simulator when compared with those seen in real emergency situations. Exhibit 18

41. **Trial phase 1 timing results.** The results table at Exhibit 18 show the experience level of each crew along with the time to diagnosis, time to selecting HP SHUT and any comments on the crew's performance. Unless specifically commented on, the crews shut the LP cock immediately after the HP cock was shut. There was a large spread of reaction times seen across the 13 different crews, with the quickest initiating the correct IA drill after just 3 seconds. The slowest of the crews that correctly dealt with the emergency initiated the IA drill after 30 seconds. There did not appear to be an obvious correlation between experience level and response time. Allowing for the fact that the crew of ZG792 were dealing with a real emergency situation and that shutting down the engine was a serious decision with major consequences, the Panel judged that the crew's response time (of 38 seconds) was not outside the bounds of normality. This view was supported by STANEVAL (F), RAF Marham, who commented that the crew's handling of the emergency in the initial stages was calm and methodical. Exhibit 18

42. **Trial phase 1 errors.** 2 of the 13 crews, both of which had pilots with considerable Tornado experience, made critical mistakes in handling the emergency:

a. One crew reacted to the TBT caption but ignored the other symptoms and therefore carried out the TBT drill initially. They only started to deal with the engine mechanical failure after 1 minute.

b. The other crew incorrectly diagnosed the mechanical failure as a locked-in surge. The pilot selected HP SHUT after 9 seconds but, as he was not carrying out the correct drill, never closed the LP cock or used the fire extinguisher. Exhibit 18

43. **Trial phase 2, crew 1.** This crew undertaking this full emergency recreation were of similar experience level to that of the crew of ZG792.

The pilot was very experienced on both GR4 and other types and the WSO was in the early stages of his first tour. The timeline of significant events is shown at Annex A. The Panel made the following observations: Exhibit 18

a. The crew diagnosed the fault reasonably quickly, taking only 9 seconds to commence the IA.

b. The L FIRE caption was brought on immediately after the right HP cock was closed. As with the crew of ZG792, this delayed the carrying out of the rest of the drill. The GR4 ACM states that Ti fires may cause 'a confusing contradictory fire indication on the good engine'. The pilot in this case, unlike that of ZG792, decided to press only the left fire button as he believed that only the left engine had a fire. Exhibit 14

c. Notwithstanding the confusion caused by the L FIRE caption, the LP cock was closed after just 21 seconds. However, just as the pilot of ZG792 had done, the pilot in this case decided to attempt a relight of the right engine. In so doing, he opened the right LP cock again, causing an additional period of possible fuel leakage of some 14 seconds. Exhibit 18

d. The GR4 FCC emergency drills clearly state that if signs of fire remain after the fire extinguisher has been used then the crew should eject. As with ZG792, the trial crew opted to try to recover the ac to a nearby diversion airfield, despite worsening symptoms of a rear fuselage fire. The trial crew only initiated ejection when the simulator staff failed the taileron controls. Exhibit 14

44. **Trial phase 2, crew 2.** The pilot of this crew was somewhat less experienced than that of ZG792, being 2 years into his first tour. The WSO was also a first tourist of similar experience to the pilot. The Panel made the following observations in this trial run: Exhibit 18

a. As with crew 1, this crew were reasonably quick to initiate the required IA drill, taking 10 seconds from the initial symptoms to close both the HP and LP cocks.

b. Again, the appearance of the contradictory opposite engine fire warning caused considerable confusion. The crew took a further 30 seconds to decide on an appropriate course of action, opting to fire the extinguisher into the left engine (the engine with a fire warning) only, contrary to the IA drill. Exhibit 18

c. This crew also opted to remain with ac right up to the point of loss of control, rather than ejecting earlier due to the confirmatory signs of fire.

45. Given the wide variety of actions carried out by different GR4 aircrew in the sim trial, and the actions of other crews who had faced this actual emergency, the Panel consider that greater training in dealing with this situation is necessary. Specifically, more focussed training was required to equip crews to deal with complex, multiple emergencies with potentially

conflicting information.

46. **TGRF Emergency handling and training within the TGRF.** The Panel reviewed over 700 Sim reports chosen at random from current members of the TGRF (all Sqns and OCU staff). However, OCU student reports were not reviewed. Sortie content, allowing for RAF Lossiemouth's OCU training, was broadly similar across the two bases (RAF Marham and RAF Lossiemouth). However, this sortie content is "customer driven" and misgivings concerning the balance between operational training and emergency handling/pure flying were expressed at both Sims. The Panel noted that sim instructor experience and background was considered to be good, with the majority having Tornado experience and a considerable number of instructors had recent GR4 experience. Of the sorties reviewed, a small but significant number contained errors in emergency handling resulting from poor system knowledge and a lack of airmanship in line with the results of the trials at Para's 42 and 43. In addition, informal and anecdotal evidence suggested that crews lacked system knowledge and airmanship in fundamental aircraft handling and specifically in emergency procedures and ac emergency handling. Major errors, including misidentification of specific emergencies and carrying out subsequent actions, appear concentrated in the multiple failures or the series of failure emergencies that can occur on the Tornado GR4 ac. These types of emergencies tend to require deeper system knowledge and invariably higher levels of airmanship. Examples of this type of emergency are: engine mechanical failure leading to a Ti fire, engine failure with additional speed switch failures, TBT captions (a dual CWP caption requiring diagnosis of what has failed), massive fuel leaks and gearbox failures. All of these emergencies have and do occur on the Tornado GR4 ac. Further emergency training is given across the TGRF at daily emergency briefings at Sqn Met briefs and in structured ground training in association with the TTS (Tornado Training Syllabus) 8, as well as in preparation for the TGRF standardization visits. These visits now include pre and post Op deployment visits by wing Stds personnel as well as the formal TGRF standardization visit from the OCU Stds flight. A review of these Stds visits reports confirms the evidence from the Sim sortie review that emergency handling and fundamental flying skills appear to be declining across the TGRF. It would appear that, coupled with low flying hours, the decline has come about as the TGRF has focused on operational knowledge and procedures to the detriment of pure flying skills. **As such, the Panel concluded that TGRF emergency handling training was a CONTRIBUTORY factor in the accident.**

Annex L

Annex L

Engine Mod State and FCC advice

47. **HPC modification.** RR Modifications 41237 and 41278 introduced a 0.35-0.55mm thick layer of zirconium dioxide within the engine HPC inner casing to reduce the probability of a Ti fire breakout. This is due to the low thermal conductivity of zirconium dioxide. Mod 41278 encompassed this within a re-design of the front stages of the HPC stator vanes to avoid critical resonance and hence improve their tolerance to aerodynamic disturbance. Both engines had Mod 41278 embodied. At the RB199 Risk Assessment Meeting dated Nov 10, Turbo-Union stated that Mod 41278 has successfully addressed the blade/vane fatigue failures, but the fire protection aspects

Exhibit 19

Exhibit 19

have not made a significant change to the likelihood of Ti fire breakout. Turbo-Union are currently focussing on a new modification to reduce the risks of Ti fire breakout in the RB199 and the Tor PT are aware of this. **The Panel concluded that the HP Compressor modification state was a CONTRIBUTORY factor in the accident.**

48. **GR4 mechanical failure/Ti fire drill.** The Panel observed some variation in the understanding of the reason for the 15-second pause in the IA drill amongst TGRF aircrew and simulator instructors. The Panel reviewed 2 BAE Systems reports that state that the delay is to allow, in the event of a breakout causing a fuel leak, the majority of any fuel pooled in the engine bay to drain away. The extinguisher would then be capable of suppressing any residual fires in the bay. Mathematical modelling in the reports suggests a 200kg fuel leak would have almost completely drained from the ac after 15 seconds. However, the fire observed in the left nozzle area of ZG792 did not appear to extinguish until approximately 5 minutes into the accident sequence. This could indicate incorrect assumptions about the drainage rate, thereby explaining the presence of the glow until T5:00. However, if the LP cock was not closed until later in the emergency, then clearly this would provide a constant flow of fuel. Notwithstanding, the Panel determined that, having diagnosed a Mech fail/Ti fire, it was important to ensure that fuel was isolated asap. **As such, the Panel concluded that the content of the mechanical failure/Ti fire drill remained valid and the FCC advice was NOT a factor in the accident.**

Exhibit 26
Exhibit 30

Exhibit 6

Survival Equipment (SE)

49. **Initial use of SE.** Both the pilot and WSO of ZG792 reported a number of difficulties they had encountered accessing their SE. The Fastfind Personnel Locator Beacons (PLB) were housed in a Combat Survival Waistcoat (CSW). On initially boarding their life rafts, both crewmembers had difficulty opening the zips on the CSW to gain access to the beacons. The Panel concluded that had the crew sustained injuries that affected their arms or hands, this process would have been even harder. Likewise, had cold affected the dexterity in their hands, the Panel concluded there was a very real risk they may not have been able to access their beacons. Once in the liferaft, the pilot commented that the length of the lanyard attaching the beacons to the CSW was not sufficiently long enough to allow it to be placed level on his lap. In the case of the WSO, this led to the beacon resting on its side against the side of the liferaft.

Witness 1, Part 1, Pg 3
Witness 1, Part 1, Pg 4
Witness 2, Part 1, Pg 4

Witness 1, Part 3, Pg 16

Witness 2, Part 1, Pg 4

50. **Fastfind Performance.** One week after the accident, the Panel was contacted by the UK Maritime Coordination Centre (UKMCC) at RAF Kinloss over concerns about the performance of the Fastfind Personnel Locator Beacons. Following the decision not to monitor the 243 MHz PLBs traditionally carried by fast jet aircrew, Air Command purchased Fastfind PLBs to give crews an up to date COTS solution to bridge the gap prior to the introduction of PELS. The system is manually operated by the survivor and crews should have been briefed at a local level by squadron survival instructors on its use. Once activated, the Fastfind should transmit its position 2 mins after activation, giving an alert (containing position) and beacon ID every 50s. The position is updated every 20 mins. UKMCC reported that they only received one coarse position data burst from the

Annex G

pilot's beacon, and only one data burst from the WSO's beacon which did not contain any position.

51. **Air Platform Systems (APS) Project Team Functional Trials.** Following on from the concerns about Fastfind performance, the APS PT were requested by the SI President to conduct trials into the Beacons' performance. They had access to both beacons used by the crew of ZG792, but also the un-used beacons carried by the crew of ZD741. This ac was involved in an accident 2 weeks later in which the crew ejected at RAF Lossiemouth. As such the beacons had been subject to ejection conditions, but had not been activated. All 4 beacons were functionally tested at the RAF Centre of Aviation Medicine (RAFCAM) where 3 passed the functional checks. Since these checks were carried out in an adhoc test facility, they were passed back to McMurdo and factory tested whereupon all 4 passed functional checks. Annex G

52. **APS PT Field Trials.** Given that the functional testing had failed to highlight any failings of the beacons, the 4 beacons were sent to Horsea Island, where a practical test of their functionality was made at sea in a single man life raft in order to replicate, as closely as possible, the conditions experienced by the crew of ZG792. The pilot's beacon operated as expected when activated and its transmissions were detected. The WSO's beacon was placed on its side in the liferaft, as the WSO in ZG792 had done, but its signal was not detected. When the beacon was re-positioned, according to the manufacturer's recommendations, its signal was detected. Following the sea trial the beacons from the crew of ZD741 were activated simultaneously, 1m apart, on dry ground. Whilst the beacons' signals were detected, the received signals were not as expected as per the manufacturer's specification. Further testing by the manufacturer revealed that if the beacons were operated simultaneously, then only one beacon's signal would be detected. The beacons were then re-activated, this time with a 25s split, and both signals were received. This did not, however, completely explain the failings of the beacons as a randomisation circuit built into the beacons should have offset the signals after several minutes of continuous operation. Annex G

53. **Defence SERE Training Organisation (DSTO) Trial.** DSTO conducted trials to ascertain if operation of the Fastfind, G2R and PLB simultaneously could interfere with each other and reduce signal strength. The trials were conducted in single and multi-man liferafts at sea on the Moray Firth. Both Fastfind and G2R operated as expected, with the signals being received, both with the life rafts cover up and down. However, the PLB signal was not detected. The trial concluded that Fastfind and G2R would not interfere with each other. Annex G

54. **Conclusions.** The McMurdo Fastfind beacon performed successfully, as per its specification, in all of the trials conducted, when operated in accordance with the manufacturer's advice. The Horsea Island trial proved that, in the case of the WSO's beacon, if the beacon was placed on its side, thereby obstructing a clear view of the GPS zone at the front of the beacon, its signal would not be detected. The pilot's Fastfind passed all the tests placed on it. Whilst the Panel accepted that the WSO's beacon performance could be attributed to the way it was placed, this could not Annex G

explain the pilot's beacon performance at the time of the accident. As such, the Panel considered that further investigation was required. **The Panel could not positively determine why the Fastfind beacons did not perform correctly immediately post the ejection from ZG792. The Panel concluded that had recovery been required in different circumstances, the consequences could have been severe; therefore the Panel concluded that SE was an OTHER factor in the accident.**

Safety Case Management

55. **Introduction.** The Panel reviewed the current GR4 hazard log and interviewed the current hazard log manager. In order to gain an appreciation of the level of risk being held, an identified hazard (or accident as defined in the GR4 hazard log) is awarded a risk rating. This risk rating is defined by a number of variables, but specifically the likelihood of the accident happening over the life of the ac. An 'A' risk defines an unacceptable risk. A 'C' risk would be described as broadly acceptable. A number is associated with the risk to define its priority amongst the other risks in its category. Within the hazard log, there is the opportunity to enter controls into the log. A control is a mitigation of the risk, typically an amendment or modification. Having entered a control to mitigate the risk, the Engineering Authority (EA) can assess the effectiveness of the control and report back to the hazard log manager, so that a new appreciation of the risk can be seen within the Post Control Status box.

56. **Tornado hazard log.** Having determined the likely sequence of actions that led to the loss of ZG792, the Panel were interested to see if the Tornado hazard log accurately identified and mitigated the various hazards highlighted in this accident. The Panel focused its investigation into the following specific areas of the hazard log; uncontrollable engine fire, critical or uncontrollable oil fire, critical or uncontrollable hydraulic fire, uncontrollable fuel fire and uncontrollable engine Ti fire. The Panel noted that in all these emergencies/accidents listed, there were no Post Control Status indications, implying that there was no control analysis in the areas the Panel focussed. In order to enable the Panel to provide a more focused analysis, the Panel elected to pick 2 of the emergencies that it considered were the most severe within the ZG792 accident sequence and focus on them.

57. **Uncontrollable Engine Fire (A143).** The Panel noted that in the case of A143, this hazard had no risk rating associated with it. By examining the Tornado Hazard Working Group (HWG) minutes, the Panel ascertained that the accidents that made up this emergency had been split between uncontrollable Ti Fire and uncontained engine breakout. Despite this, A143 still existed on the hazard log. Exhibit 20

58. **Uncontrollable Ti Engine Fire (A146).** Having ascertained that some of the hazards from A143 had been moved to A146, the Panel focused on this accident. The risk rating, C10, had been derived from 3 previous accidents caused by Ti fires that took place between 1990 and 1999. Since 1990, the Panel is aware of a number of Ti fires in addition to those listed within A146[1]. Three Ti fires in Tornado GR4 ac stood out from these post Exhibit 20

1999; ZD714 25 Feb 08, ZA446 23 Sep 09 and ZG792 – the accident ac. The Panel were interested to find out if these accidents had been taken into account in determining the risk rating for the Ti fire. To be classed as an accident there must be a fatality, serious injury or Cat4/5 damage sustained to the ac. In the case of the three Ti events listed above, they either had not sustained the damage to be considered in the hazard log or the accidents/incidents were subject to ongoing inquiries and as such had not been incorporated. The Panel noted that one of these accidents had happened on the ground and so the severity of the potential airborne consequences could not be determined. Another ac had successfully landed after the event, although the Panel noted that the crew were fortunate that this incident had not been an accident, as was the case with ZG792. The hazard log manager stated that it was standard practice to wait for UIs/SIs to report before considering the accident within the risk rating. Given the additional number of actual Ti fires affecting that GR4 ac, the hazard log manager conceded that had these accidents/incidents been included within the hazard log, then the risk rating might have changed. During interview he stated that he could only work with the information that was given to him by the Engineering Authority (EA).

59. **Post Control Measures.** Having looked into the processes of determining the risk rating, the Panel then sought to find out how the Tor PT managed the Post Control Status in the hazard log. The Panel ascertained that a number of improvements to the GR4 engine had been made in an attempt to reduce the number of Ti fires under Tor/C9: Mods 41206, 41168 and 41278. These controls had been entered into the controls section of the hazard log, and yet there was still no Post Control Status. In interviews with the hazard log manager the Panel discovered that the manager had correctly entered these controls into the log, but had not received any feedback from the EA as to their effectiveness. These controls had been entered on 8 Feb 2005. The hazard log manager stated that until he received feedback from the EA, he was unable to update the Post Control Status. The Panel therefore sought to determine why it had been 6 years since the controls were entered, and yet the hazard log manager had received no feedback. The hazard log manager stated that because the risk associated with the accident, C10 was low, the importance placed on reviewing the controls was similarly low and he used this to explain the lack of feedback. The Panel were concerned that until additional Tornado accidents/incidents were included in the hazard log, it was unlikely that the overall risk rating would change, and the review of controls would continue to remain a low priority. The Panel established that the hazard log was not a 'live document', because not all of the significant Ti fire events had been included. The Panel noted that because the majority of these incidents had not resulted in the loss of the aircraft or crew, then there was a degree of justification in this. However, the Panel considered that in some of these incidents, there was an extremely thin line in the difference between incident and accident. This directly affected the Tor PT's ability to be aware of the extant risks facing the ac, and crucially to be able to manage the controls put in place. The Panel concluded that there was no single point of failure, but rather a wider organisational issue that resulted from the hazard identification process, analysis of controls and the time taken to incorporate additional accidents/incidents into the hazard log.

Witness 22

Witness 22

60. **Manpower.** The Panel noted that a number of posts within the Safety Management Group were gapped, and the hazard log manager rated the amount of support given to him as poor. Witness 22

61. **Review of control measures.** The Panel determined that there was evidence to suggest that some of the Mods incorporated to reduce Ti fire risks had not been as effective as originally devised. Despite this, the Panel noted that there was no record of this within the hazard log. Mod 41278 was still entered as a control in the hazard log, yet the panel were aware that it had not been as effective in reducing Ti fires as had been envisaged. The Panel determined that the EA were aware of this, and were actively attempting to mitigate it, but this was not reflected in the hazard log. Exhibit 19

62. **Risk awareness.** Given the concerns raised from its initial investigation into the hazard log, the Panel were interested to ascertain the level of risk awareness ultimately held by the Operational Duty Holder (ODH) and the Delivery Duty Holder (DDH). The Panel inspected both the HQ 1 Gp risk register and their new draft risk register. In both cases there was no mention of Ti fires. These risk registers are mainly focused at Risk to Life (RtL) risks. However the Panel opined that there was a potential RtL associated with Ti fires that is presently not accounted for.

63. **Conclusion.** The Panel concluded that the current GR4 hazard log had the potential to not accurately reflect the level of risk being held by the ODH, and the post control status did not accurately reflect the effectiveness of the controls. The Panel determined that the exclusion of some significant Ti fire events could have an impact on the overall risk rating. It also noted that the process for reviewing the controls was not effective enough to enable to hazard log to reflect a current, up to date appreciation of the risk. Whilst the Panel noted that, within the EA, there was an awareness of the risk posed by Ti fires, and controls were being actively sought, it determined that the process for reflecting this within the hazard log was undefined, and as such there was potential for the risks not being fully appreciated by higher authority. Because the ODH was not aware of the risk, he was unable to understand or mitigate it. **The Panel concluded that the current state of the GR4 hazard log was a CONTRIBUTORY factor.**

SUPERVISION

64. **Ac State.** The ac was fitted in an acceptable role fit in accordance with the release to service (RTS). The Panel found no evidence suggesting that ZG792 was operated outside of the parameters set within the RTS. **The Panel concluded that the ac state was NOT a factor in the accident.**

Exhibit 9

65. **Engineering Practices.** Throughout the interview process, engineering paperwork audit and interviews with Sqn engineering personnel, the Panel found no evidence to suggest that engineering practices were a factor in the accident. **The Panel concluded that engineering standards and practices on XV(R) Sqn was NOT a factor in the accident.**

66. **Supervision, Authorisation and Planning.** The levels of supervision and authorisation are clearly defined in 1 Gp GASOs and the RAF Lossiemouth Flying Order Book. During an audit of the Sqn's documentation post the accident, the Panel found these documents to be at the correct amendment state and well kept. A couple of minor errors were noted in the recording of amendment states, about which the Sqn was informed. The Sqn employed a supervisory chain including a Sqn Duty Auth and Duty Executive, as well as a Duty Controller Flying (DCF). The sortie was correctly authorised by the senior auth in the formation. Due to a previous programmed PCON phase brief, the pilot was not present at the beginning of the sortie planning process, because the previous commitment overran, however he joined the plan as soon as he could and he was present for the brief. The Panel considered whether the pilot felt rushed and whether this had any effect on his state of mind, or his ability to react to unforeseen circumstances. Given his experience, the Panel concluded that he would be able to transit from the PCON phase brief straight into the plan, and his attendance at the brief was sufficient to enable him to carry out his tasks adequately. Likewise, the Panel considered whether the student WSO was adequately prepared for the task. The plan was supervised by the formation auth, and the proposed sortie profile was realistically achievable. Although the student WSO commented that he felt rushed and had forgotten most of the plan by take off, the Panel concluded that this was more likely down to his lack of experience rather then any failings in the planning cycle. **The Panel concluded that supervision, authorisation and planning were NOT factors in the accident.**

Witness 15, 16, 21

Exhibit 23

Witness 1, Part 3, Pg 4

Annex A. Pg 11

67. **Operational tempo.** XV(R) Sqn is a busy Operational Conversion Unit. The Panel considered whether the task placed on it was achievable, and whether the current operational demands to produce qualified TGRF aircrew had any impact on the Sqn's daily routine. In his formal interview with the Panel, OC XV(R) commented that he considered the Sqn to have been working hard, as was everyone in the RAF. He also considered that the OCU was not resourced to the correct levels, specifically in terms of manpower, and that this increased the pressure on his Sqn to achieve the task. The Panel considered whether these factors had a detrimental effect on the personnel working on XV(R), and whether there were any associated flight safety trends emerging from it. The Sqn had recently implemented a Continuous Improvement (CI) programme to increase the availability of ac for the flying programme. However, OC XV(R) was keen to point out that despite an increase in ac availability, the Sqn manpower, from an

Witness 20, Pg 2

Witness 20, Pg 2

Witness 20, Pg 4

engineering perspective, was being closely monitored to ensure that people were not being worked to a level where their actions became unsafe. Management of that risk was one of OC XV(R)'s greatest priorities. The Panel then focused its attention on the engineers to ascertain whether they felt the task was achievable, and any pressure, perceived or not, that they were subjected to. Throughout the interview process, the general impression given to the Panel was that the Sqn was working hard, but that it was being well managed.

Witness 20, Pg 3

Witness 5, 6, 7, 8, 9, 10, 11, 12, 13, 14

> *"it's well balanced and well managed, there is pressure but its never undue".*

At the JNCO and airman level the Panel found that, whilst the engineering team was working hard, the perceived successes at generating ac were just rewards for their hard work, and morale was high:

> *"Yeah it's good it's busy... I think it's spot on to be honest the right amount."*

From the aircrew perspective the Sqn was operating at 3 WSO's and 7 pilots below its LUE. The Panel concluded that, whilst there was a considerable task being placed on XV(R) Sqn, it was achieving this task helped by its implementation of CI and morale was high. **The Panel concluded that op tempo was NOT a factor in the accident.**

Witness 20, Pg 4

68. **Competency, qualifications and fitness to complete the task.** The Panel considered whether the crew were adequately qualified to fly the sortie, whether they were competent to do so and whether they were fit to fly. A review of the pilot's F5020, other supervisory documentation held on the Sqn and interviews with the crew's supervisory chain confirmed that he was competent both to fly the sortie and to supervise the student WSO. He was also in date for all periodic and supervisory checks and as such was qualified to fly the sortie and act as ac captain. Although a student, the Panel concluded that the WSO, whilst not yet qualified on the GR4, was sufficiently competent to complete his task, and was in-date for all his periodic and supervisory checks. Interviews confirmed that the pilot had been ill the day before the accident, and the WSO reported being under pressure to perform. The Panel considered whether either of these factors affected the crew's ability to carry out the task. The pilot had been ill the day before the accident, but had not sought medical advice electing to declare himself un-fit to fly and went home. In the morning the pilot felt better and so reported for duty. The pilot was under no obligation to seek medical advice, although the fact that he was physically sick by the side of the ac could have warranted it. The pilot confirmed that he was fit to fly the sortie both to the Panel, but also to the Duty Authoriser (Auth) at the out brief, who agreed. The WSO commented that he felt under pressure, but that this was normal for this stage in the course and was not unusual. The Panel also determined that he had adequate rest prior to reporting for work. **The Panel concluded that the crew were competent, qualified and fit to fly the sortie and these considerations were NOT factors in the accident.**

Exhibit 24

Witness 1, Part 3, Pg 3

Witness 2, Part 1, Pg1

Witness 1, Part 3, Pg 5

Witness 21, Pg 1

Witness 2 Part 1, Pg 1

69. **Engineering documentation.** The ac's in-use and archived paper and electronic documentation set was impounded and quarantined as part of

the PCMP and subsequently sent to RAF Marham EP&R, for formal review. The full report can be found at Annex H. However, in summary, the documentation set was generally found to be in good order, with all maintenance and servicing requirements correctly annotated and in date. A significant number of administrative discrepancies were identified, but did not affect the serviceability of ZG792. Of particular note, the Panel observed a significant number of forms that were out of date. The results of the audit were passed to SEngO XV(R) for review. **The Panel concluded that the standard of engineering documentation was NOT a factor in the accident.**

Annex H

PRECONDITIONS

70. **FOD/Fatigue.** The Panel concluded that the initial failure that led to the Ti fire was caused by either FOD or fatigue leading to failure of a compressor blade or stator vane within the right engine. Investigation to date has not provided the Panel with the substantive evidence to support either theory at this point. **The Panel could not positively determine the cause of the initial blade or vane failure. However, FOD or fatigue would have been the initiator that led to the Ti fire and therefore was a CAUSAL factor.** Para 9

71. **Ti fire.** The Panel concluded that debris, potentially from a failed stage 2 vane/blade, became lodged in a HPC stage 2 stator vane. This was frictionally heated by each HPC stage 3 blade in turn striking the debris. The heat generated eventually led to a localised Ti fire. **The Panel concluded that the Ti fire in the HP2 stator/HP3 blade area was a CAUSAL factor in the accident.** Para 10

72. **Breakout.** Evidence concluded that the Ti fire broke through the HPC casing, the CCOC and the engine outer casing. As the engine casing could not contain the Ti fire breakout, the fire broke through the reheat fuel line. **The Panel concluded that the breakout of the Ti fire was a CAUSAL factor in the accident.** Para 11

73. **Fuel line failure.** Given all the available evidence and supporting analysis, the Panel was unable to positively determine the exact cause of the fuel line rupture. However, it is highly probable that the Ti engine fire penetrated the reheat fuel line causing it to rupture at a hot-spot, or violently ejected heated material impacted the line causing failure at a hot-spot. The Panel noted that the current level of protection for the reheat and main supply lines was insufficient for this failure mode. **The Panel concluded that the failure of the reheat fuel line was a CAUSAL factor in the accident.** Para 11

74. **Right engine bay fire.** The damage to the reheat fuel line led to a fuel leak. Fuel vapour contained in the engine bay ignited on the hot surface of the NCU. This initiated a fuel fire in the right engine bay which reached a temperature between 635 and 1667°C. **The Panel concluded that the right engine bay fire was a CAUSAL factor in the accident.** Para 22

75. **Fuel transfer.** A BAE Systems test carried out in 1980 assessed the engine bay venting and draining systems. It highlights that small amounts of fuel drained from the right engine bay can transfer and enter through the left thrust reverse air motor exhaust, confirming that positive pressure gradients do exist in parts of the flight envelope. The RR RB199 Engine Nacelle Fire Hazard Review in 2001 also states that purged fuel exiting the ac upon re-heat de-selection may re-enter the engine bay during flight through either the NCU exhaust, TRCU exhaust, or the combined drain/overboard purge outlet. The Panel concluded that, given the lack of physical evidence to suggest an alternative fuel transfer route, re-ingestion was the most likely scenario. **The Panel concluded that the fuel transfer from right to left engine bay was a CONTRIBUTORY factor in the accident.** Annex F; Para 33

76. **Left engine control.** Evidence highlighted that the wiring looms to the left engine were significantly damaged in the left engine bay fire. The Panel concluded that this damage resulted in the pilot's loss of throttle control in the left engine. Along with his loss of taileron control, the pilot's decision to eject was based upon his loss of left engine control. **The Panel concluded that the loss of throttle control of the left engine was a CONTRIBUTORY factor in the accident.**

Para 31

77. **Hot Spots**. The NCU is fed by 4th stage HPC air which is approximately 400°C. Testing by Turbo-Union has shown that the NCU supply pipe and air motor can reach surface temperatures from 300-375°C. This provides the environment for spontaneous ignition, for which the probability is increased when there is an air/fuel/gas mixture. Recognition of the NCU as an ignition source dates back to 1978 in a report by Turbo-Union heat transfer department. **The Panel concluded that hot spots were a CONTRIBUTORY factor in the accident.**

Para 34

78. **Fire detection.** The Pilot did not receive a R FIRE indication until T1:33. This indication followed the L FIRE indication. Had the fire detection system alerted the pilot to the right fire that he was experiencing, the Panel concluded that there was a higher likelihood that the pilot would have shut down the right engine sooner. This act in itself may have prevented the fire in the left engine bay. The Panel is of the opinion that the fire wire was submerged under the fuel pool, preventing a fire indication, and then subsequently damaged by the fire. A BAE Systems led study into the fire detection and suppression system of the Tornado in June 2010 states that the current fire detection system can fail to provide a fire warning if the flame from a fire burns through the fire wire and causes a short-circuit. It also states that the current system is prone to spurious warnings and suffers from contamination. It suggests that a new pneumatic fire/overheat detection system, as used in the Typhoon, would provide redundancy as the system can be installed as a dual loop system and also provides feedback to the pilot through the integrity monitoring unit, should the wire become damaged. This could then be used by the pilot as evidence for a Ti fire and hence aid a clearer diagnosis of the fault. The Panel noted that the recommendation from the Board of Inquiry for ZE830, in Nov 99, for the Tornado engine bay fire detection system to be modified remains outstanding. **The Panel concluded that the limitations of the fire detection system was a CONTRIBUTORY factor in the accident.**

Exhibit 1

Witness 1, Part 3, Pg 8

Exhibit 26

Exhibit 16

79. **GR4 Fire Suppression.** Following the shut down of the right engine, the pilot was then faced with the contradictory left engine fire caption. Although confused initially, he elected to press both fire buttons iaw the FCC advice for Mech fail. He could not remember how long he waited from shutting down the right engine to pressing the fire buttons. The fire suppression system in this event was not sufficient, as the fire continued following his selection. The Tornado GR4 currently uses Halon 1121: one dual headed fire bottle capable of delivering bromochlorodifluoromethane (BCF) to either of the engine bays, or both simultaneously via fire extinguisher buttons in the cockpit. A BAE Systems report states that Halon 1211 (BCF) is one of the best agents available to extinguish fires. Clearly, the timing of the closure of the LP cock would have been critical. If it was left

Exhibit 14

Witness 1, Part 4, Pg 2

open, thereby providing a steady supply of fuel to the fire, the Panel reasoned that any fire suppression system would have been ineffective. However, if the LP cock was closed during the initial right engine shut down drill, as the pilot reported, the Panel reasoned that the current fire suppression system was ineffective in this case. The Panel observed that the ability to have been able to fire more then one shot of extinguishant into the affected engine bays may have provided a greater level of fire suppression. **The Panel concluded that the Tornado Fire Suppression System was a CONTRIBUTORY factor in the accident.**

Exhibit 26

80. **FS FIRE caption.** Although a FS FIRE caption was reported by the WSO, there was no physical evidence of fire discovered in the vicinity of the FS FIRE RFODS fire wire Nor was there any evidence of a 4th stage HP air leak. The FS FIRE caption illuminates when the RFODS detection system senses a temperature in excess of 200°C. Therefore, the Panel concluded that the FS FIRE caption was most likely illuminated as a result of heat transfer from the engine bay through the heat shield into the rear fuselage bay containing the RFODS fire wire. The average temperature within the FS FIRE fire wire bay during flight is approximately 100°C, and with a temperature in excess of 635°C on the other side of the heat shield, it is highly probable that the ambient temperature was raised above the trigger of 200°C. **The Panel concluded that the FS FIRE caption was NOT a factor in the accident.**

Witness 2, Part 1, Pg 2

Annex D Para 1.6

81. **ECS.** All of the fire damage discovered was aft of the engine forward bulkhead, frame X 12737. All of the ECS pipes recovered indicated no fire or heat damage. The Panel did not find any evidence linking the ECST captions and the accident. Anecdotal evidence suggests that ECS captions are common in the GR4 and are generally cured by recycling the system. **The Panel concluded that the ECS system was NOT a factor in the accident.**

Annex D Para 2.2.1

82. **Pitch feel accumulator.** During the initial ac walk-around, the pilot highlighted a pitch-feel accumulator gauge at the level of 100 bar as opposed to 60 bar, which is usually expected. The high reading on the pitch feel accumulator was attributable to the residual pressure from the previous sortie. The pitch feel accumulator gauge is only checked by engineering personnel on a before-flight servicing and not on a turn-around or after-flight servicing due to this fact. **The Panel concluded that the pitch feel accumulator gauge reading was NOT a factor in the accident.**

Witness 1, Part 1, Pg 3

Witness 11, Pg 1

83. **Weather conditions at the time of the accident.** The Panel had access to both the RAF Lossiemouth daily met brief slides and the TAFs for the North coast on the day of the accident. Weather conditions were benign and fit for VFR recoveries at both the home base and diversions. The crews did not report experiencing any difficulties associated with the weather. **The Panel concluded that weather conditions were NOT a factor in the accident.**

Exhibit 22

ACTS

84. **Right hydraulic bay fire.** The Panel confirmed that the fire within the right engine bay reached temperatures of over 635°C, and may have reached temperatures as high as 1667°C. The Panel concluded that the path of the fire focussed the heat intensity on the outer firewall, adjacent to the hydraulic bay. Heat transfer through the titanium firewall led to a hydraulic leak from a aluminium/steel union or flexible pipeline, which took place approximately 49 - 77 secs after the initial failure. Ignition of the hydraulic leak either took place by hot-plate ignition on the titanium firewall, or the degradation of the CSAS wiring within the bay leading to a short circuit, providing the required spark. **The Panel concluded that the right hydraulic bay fire was a CAUSAL factor in the accident.** Para 25

85. **Flying control failure.** The fire in the right hydraulic equipment bay burnt through the CSAS wiring looms, leading to the reversion into Mech mode at T2:50. The fire then continued to heat the right taileron mechanical control rod, leading to the gradual deformation of the rod and eventual loss of control. **The Panel concluded that the loss of right taileron flying controls was a CAUSAL factor in the accident.** Para 29

86. **Pilot emergency handling**. The pilot of ZG792 was faced with a complicated emergency. On recognising the surge, he brought both throttles back to idle and maintained less than 10 units AOA. T0:14 is the first indication that he has diagnosed a Mech fail. He informs his WSO, flies the ac away from the ground and transmits to his wingman. At T0:31 he concludes that he is going to shut down the right engine and at T0:39 he shuts the HP cock. At this stage the Panel concluded that there were sufficient symptoms available to allow the pilot to diagnose the nature of the emergency and action the full Mech fail/Ti fire drill. The Panel noted that, having made the decision to shut the engine down, there was doubt in the pilot's mind whilst he re-considered, but then having shut the HP cock nothing more is heard for a further 8s until the L FIRE caption illuminates. The Panel were able, from witness testimony, to determine that the LP cock was not closed until sometime after the L FIRE caption. The pilot stated that it was the emergence of the L FIRE caption that delayed his actioning of the full Mech fail/Ti fire drill and that this was coincident with shutting the HP cock. As such the Panel were unable to account for this 8s gap in the pilot's immediate action drills. The Panel could not identify any factors that would have prevented the LP cock being closed in the 8s period after the HP cock was closed. The Panel also noted that at this point the pilot stopped verbalising any of his Mech fail/Ti fire immediate actions. The pilot was an experienced GR4 operator and the Mech fail/Ti fire symptoms presented to him were exactly as described in the GR4 FCC drills. As such, the Panel concluded that although his diagnosis was ultimately correct, his actioning of the Mech fail/Ti fire drill, and specifically the initial doubt in the pilot's mind prior to closing of the HP cock, the 8s pause and lack of verbalisation of the drills, was not consistent with his experience. Given that the reheat fuel pipe was found to be perforated, then an open LP cock would provide a steady supply of fuel into the engine bay, feeding a fire. The Panel were able to ascertain an approximation of the time taken for the heat transfer to lead to a hydraulic leak was between 49-77s from the initial failure. As such, isolating

Exhibit 6

Exhibit 6

Exhibit 6

Annex A Part 2, Pg 6

Witness 1, Part 3, Pg 8

Annex D, Para 1.5.1

the fuel supply to the engine was critical. Had the LP cock been closed before this point, it is the Panel's opinion that it is unlikely that the fire would have been able to reach the temperatures necessary for the Hydraulic lines to fail, and then ignite. The Panel noted that the technical evidence suggested that this action had probably not occurred until approx T4:37. It also noted that better CRM would have made the probability of closing the LP cock sooner more likely. The Panel conducted a full review of the pilot's Training Folder to see if any obvious trends existed. Whilst the Panel found that the total number of specific HIEST (High Intensity Emergency Simulator Training) serials carried out by the pilot since his arrival on XV(R) was comparatively low (6 full HIESTs), it did not note any obvious concerns raised over the pilot's standard of emergency handling. The Panel also considered whether the pilot's illness the day before had any effect on his performance. Aircrew can declare themselves un-fit to fly without seeking medical opinion, and the decision as to when they are fit again rests with the pilot, as long as he has not been specifically grounded by a MO. The Panel were unable to determine if the pilot's illness the day before had any detrimental effect on his performance. Ultimately, the Panel determined that the supply of fuel to the fire was a critical factor. However, as the Panel were unable to determine a specific point at which isolating the fuel would have allowed the ac to be recoverable, **the Panel concluded that the pilot's emergency handling was a CONTRIBUTORY factor.**

Annex K

Para 21

Para 88

Exhibit 33

87. **WSO emergency handling**. The TGRF SOP is for the WSO to monitor the pilot's immediate actions and confirm each action from the FCCs, then to read out any 'subsequent actions' and advice. The WSO did not do this. At no stage did he question the lack of "LP Cock" in the pilot's verbalization of the Mech fail immediate action drill and he remained passive for most of the emergency. **The Panel concluded that the WSO's emergency handling was a CONTRIBUTORY factor.**

Exhibit 6

88. **CRM.** The Panel noted that it was the pilot of ZG792 who played the most active role in the emergency, while the WSO was comparatively quiet. Throughout the preceding portion of the sortie, both pilot and WSO conduct themselves in a calm, relaxed manner in a professional cockpit environment. At the onset of the emergency, the pilot communicates his diagnosis to the WSO, talking through the captions he can see and what his action is going to be i.e. "*I am going to shut down the right hand engine*". As the pilot completes his shut down, SOPs dictate that the WSO should have confirmed each action from the FCC and be ready to read out any 'subsequent actions' that the pilot would not necessarily know from memory. Whilst the pilot does verbalize his initial drills, at no stage does he mention the LP cock, nor does his WSO question him over this. Likewise, contrary to what might have been expected, the pilot did not direct the WSO to back his actions up by confirming the FCC advice during his initial actions. The HF report comments that this would increase the possibility of an action being missed. In the context of LP cock closure times, this may have been a vital action. Ultimately, if the LP cock was not closed until approx T4:30, then this breakdown in CRM would have been a major factor in this omission. However, if the pilot did close the LP cock at T1:00, as he claims, it is possible that he felt he did not need the WSO to read out the FCC advice as, by then, he would have been occupied with the potential rear fuselage fire and left engine fire. Of note, the pilot uses the WSO in CACTUS 1

Annex A

Exhibit 6

Exhibit 6

Annex A Part 2, Pg 7

significantly (a fellow staff instructor) and the Panel reasoned that this may have caused his own WSO to play a less active role in the emergency. The Panel also noted that, given the WSO's inexperience, he may not have been best placed to appreciate or deal with the contradictory captions presented to him. The Panel also noted that had the crew received a R FIRE caption from the onset of the emergency then this may have provided the crew with the additional information they needed to gain a clearer picture of what was happening to the ac. At T2:57 and T3:35 the pilot asked both the WSO in CACTUS 1, and his own WSO, to back him up with the cards. As with emergency handling, the CRM aspects were linked to the closure of the LP cock, however the Panel determined that the action of closing the LP cock could have been achieved faster if the CRM between the crew had been more effective. **The Panel concluded that CRM was a CONTRIBUTORY factor in the accident.**

Annex A, Part 1, Pg 12

Exhibit 6

Exhibit 1

89. **Malicious Intent.** The Panel found no evidence to suggest that malicious intent, from either aircrew or engineering, played any role in the accident. **The Panel concluded that malicious intent was NOT a factor in the accident.**

90. **Birdstrike.** Neither crew member of ZG792 was aware of any birds prior to the accident, and no initial birdstrike impact was felt by the crew. Extensive investigations by the MilAAIB and RR have found no evidence of birdstrike. Given the lack of any evidence pointing towards a birdstrike**, the Panel concluded that birdstrike was NOT a factor in the accident.**

Witness 1, 2, 3, 4

91. **Post Crash Management Plan (PCMP).** The Panel reviewed the XV(R) Sqn PCMP and reviewed the actual actions of those implementing it during the day of the crash. The Panel ascertained that the PCMP had been correctly activated and had worked effectively. The Panel noted that XV(R) Sqn had recently practised their PCMP and were able to implement the recommendations that had arisen from that exercise. The only area for comment came from OC XV(R) Sqn, who felt that greater training was required of supervisors in the kinforming process. OC XV(R) noted that when undertaking kinforming, where family circumstances were complex, potential for confusion existed. **The Panel OBSERVED that the PCMP had been correctly activated and managed.**

Witness 20, Pg 3, 5

92. **Post Incident Drug and Alcohol Testing (PIDAT).** Following transfer to Raigmore Hospital, both pilot and WSO were interviewed by the RAF Lossiemouth Senior Medical Officer (SMO). He had no reason to believe that either crew member was under the influence of drugs or alcohol and as such PIDAT was not initiated. In their formal interviews, both crew members confirmed that they had not consumed any alcohol in the 24hrs leading up to the accident. **The Panel concluded that drugs and/or alcohol were NOT a factor in the accident.**

Annex C

Witness 1, Part 3, Pg 2

Witness 2, Part 3, Pg 2

SUMMARY OF FINDINGS

93. **Cause(s).** The Panel concluded that the cause of the accident was the failure of a blade or stator vane caused by FOD or fatigue. This led to an uncontrollable rear fuselage fire, which ultimately resulted in the loss of ac control, and ejection.

a. Following an undetermined failure within the right engine HPC, a Ti fire broke out through the HPC casing, the engine outer casing, and the reheat fuel line. It is likely that the breakout did not have sufficient energy to penetrate the engine bay firewall. Para 71/72

b. Following the rupture of the reheat fuel line, fuel leaked into the right engine bay, pooling at the base of the bay. Ignition of the fuel vapour occurred via the NCU hot surface, leading to a right engine bay fuel fire, which was continually fed by the pool of fuel. The fire was also fed by the leaked fuel from the perforated fuel line, the time period for this is dependent on the 2 theories of the LP cock closure time. Paras 73-75

c. As the fire in the right engine bay increased in temperature, thermal heat transfer occurred through the engine bay firewall into the adjacent right hydraulic component bay. This caused different rates of heat expansion in hydraulic unions and pipelines, leading to hydraulic leaks. Hydraulic oil ignition is believed to have been caused by the degradation of electrical looms, caused by heat intensity in the area, leading to an electrical short, and/or hot-plate ignition caused by the hydraulic oil spray hitting the hot firewall and igniting, leading to a hydraulic fire in the right upper rear fuselage bay. Paras 76-77

d. The hydraulic fire burned through the CSAS wiring looms and caused the heat deformation of the right taileron control rod, leading to eventual loss of control. Para 85

94. **Contributory Factors.** The Panel identified the following contributory factors that did not directly cause the crash, but made the outcome more likely:

a. Concurrently, pooled fuel drained through the exhaust outlets, and leaked through panel latches, hinge seals and fasteners in the right engine bay doors. Due to a pressure gradient, fuel was re-ingested into the left engine bay, through the same apertures and ignited on the nozzle air motor. This led to a subsequent left engine bay fire, which remained relatively contained in the rear of the left engine bay. This fire continued until the exhaustion of aviation fuel from the right engine bay and damaged the wiring looms, leading to the loss of throttle control to the left engine. Para 75

b. Within the cockpit, the crew did not receive a R FIRE caption. As such, neither crew member were aware of the severity of the right engine fire, and the fire suppression system was unable to extinguish Para 78 the fire.

c. The Panel were unable to determine the exact time that the LP cock was closed. Based on the weight of technical evidence it opined that this was, most likely, not to have been until sometime around T4:30 (after the aborted re-light attempt). As such, it concluded that it was likely that incomplete initial drills, and a breakdown in CRM, allowed a continual source of fuel to both the right engine fire, and subsequent left engine fire. Paras 86/88

d. Although safeguards had been put in place to reduce the risk associated with Ti fires, these modifications were not effective enough to contain the failure and fire. Para 61

e. The Panel found a wide variation of emergency handling drills across the TGRF. It also discovered a number of errors by Force aircrew in the handling of the Mech fail/Ti fire drill, and as such more detailed emergency training was required to equip crews with the knowledge to deal with Mech fail/Ti fires. Para 46

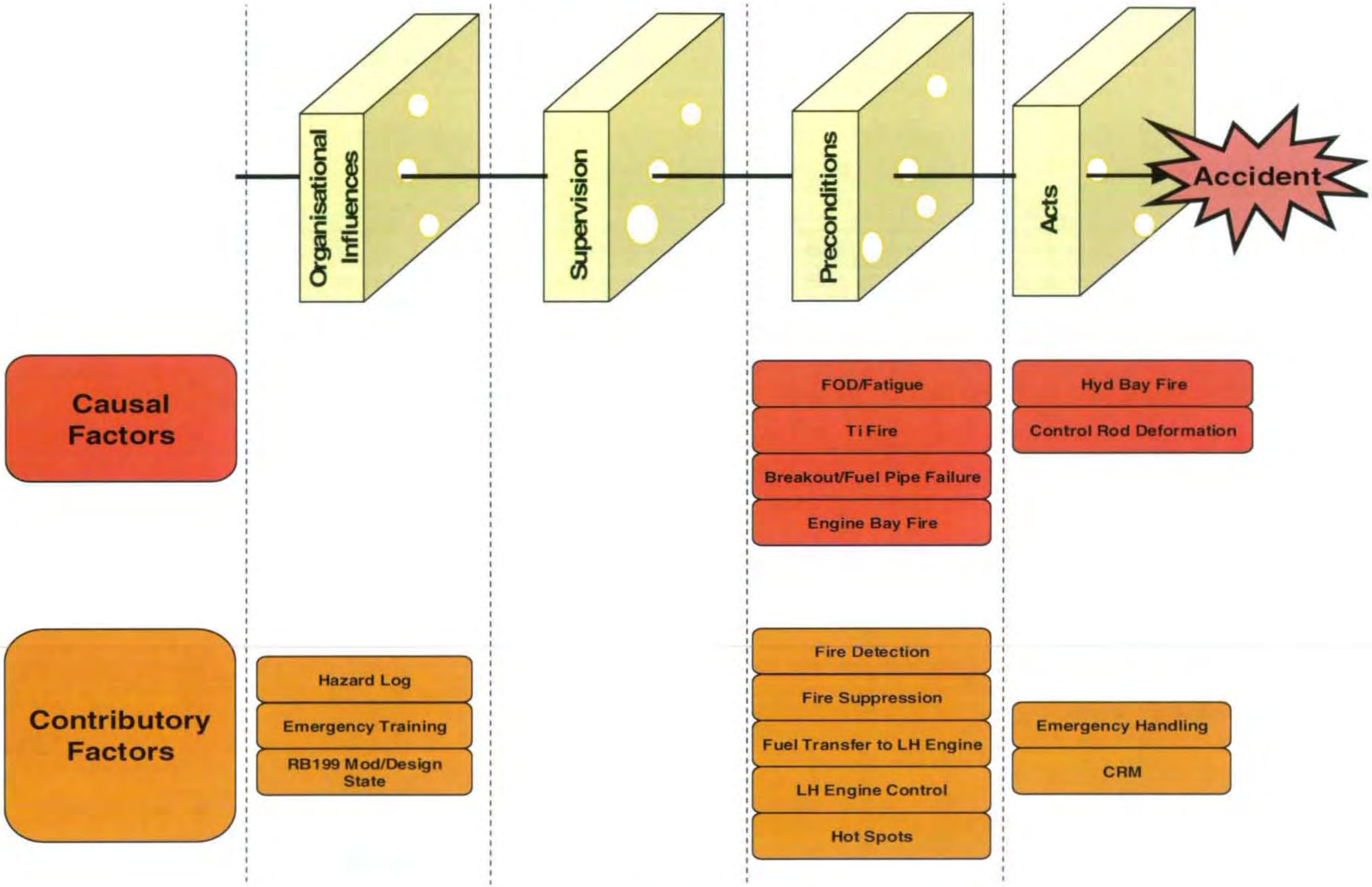
f. The Tornado Hazard Log does not reflect a current, up to date appreciation of the risk being carried. As such, it should be updated to account for recent Ti fire events, and the Post Control Status should reflect more plausibly the effectiveness of the controls placed within it. Para 56/63

95. **Other Factors.** The Panel concluded that if the following factors are actioned, future accidents may be prevented:

a. The failure of the Fastfind location beacons to provide an accurate position to aid the recovery of the crew could have severely impacted the crew's chances of survival once in the water. The ODH should seek measures to mitigate this risk. Ultimately, all fast Jet aircrew should be fitted with automatic PLBs. Para 49

96. **Observations.** The Panel observed the following factors which did not impact on the accident, but are worthy of comment:

a. There did not appear to be an effective process for transporting ejectees back to their home units following hospital admission, and where this responsibility lies appears to be undefined, or misunderstood. Part 1.3 Para 24


Organisational Influences
Supervision
Preconditions
Acts
Accident
Causal Factors
FOD/Fatigue
Ti Fire
Breakout/Fuel Pipe Failure
Engine Bay Fire
Hyd Bay Fire
Control Rod Deformation
Contributory Factors
Hazard Log
Emergency Training
RB199 Mod/Design State
Fire Detection
Fire Suppression
Fuel Transfer to LH Engine
LH Engine Control
Hot Spots
Emergency Handling
CRM

GLOSSARY

AAIB	Air Accidents Investigation Branch
ac	Aircraft
ACM	Aircrew Manual
APS PT	Air Platform Systems Project Team
CBLS	Carrier Bomb Light Store
CCOC	Combustion Chamber Outer Casing
CI	Continuous Improvement
CRM	Crew Resource Management
CSAS	Command and Stability Augmentation System
CSW	Combat Survival Waistcoat
CVR	Cockpit Voice Recorder
DCF	Duty Controller Flying
DDH	Delivery Duty Holder
DSTO	Defence SERE Training Organisation
EA	Engineering Authority
EHUMS	Engine Health and Usage Monitoring System
ENC	Emergency Nozzle Close
EP&R	Engineering Publications and Records
ERA	Emergency Ram Air
FCC	Flight Crew Checklist
FCU	Fuel Control Unit
fg hrs	Flying Hours
FOB	Flying Order Book
FOD	Foreign Object Debris
GASOs	Group Air Staff Orders
HIEST	High Intensity Emergency Simulator Training
HF	Human Factors
HP	High Pressure
HPC	High Pressure Compressor
HWG	Hazard Working Group
IA	Immediate Action
ICAO	International Civil Aviation Organisation
IP	Intermediate Pressure
IPC	Intermediate Pressure Compressor
JARTS	Joint Aircraft Recovery and Transportation Squadron
kg	kilogram
KCAS	Knots Calibrated Air Speed
LP	Low Pressure
LPC	Low Pressure Compressor
LRU	Line Replaceable Unit
MAAIB	Military Air Accident Investigation Branch
Mech fail	Mechanical failure
Mech mode	Mechanical mode
MECU	Main Engine Control Unit
MIG	Materials Integrity Group
MO	Medical Officer
mm	millimetres
NCU	Nozzle Control Unit
NH	High Pressure Compressor Speed
ODH	Operational Duty Holder
ODM	Operating Data Manual

PCMP	Post Crash Management Plan
PCON	Pilot Conversion
PELS	Personal Equipment Location System
PFCU	Primary Flying Control Unit
PIDAT	Post Incident Drug and Alcohol Testing
PLB	Personal Locator Beacon
POL	Petroleum, Oils and Lubricants
PT	Project Team
QFI	Qualified Flying Instructor
QQ	QinetiQ
R-ADR	Replacement-Accident Data Recorder
RAF	Royal Air Force
RAFCAM	Royal Air Force Centre of Aviation Medicine
RFODS	Rear Fuselage Overheat Detection System
RR	Rolls-Royce
RtL	Risk to Life
RTS	Release to Service
s	seconds
SI	Service Inquiry
SMO	Senior Medical Officer
SPS	Secondary Power System
STM	Simulator Training Manager
TAF	Terminal Area Forecast
TBT	Turbine Blade/Bearing Temperature
Ti	Titanium
TGRF	Tornado GR Force
TIALD	Thermal Imaging Airborne Laser Designator
Tor PT	Tornado Project Team
TRCU	Thrust Reverse Control Unit
UK MCC	United Kingdom Maritime Co-ordination Centre
UI	Unit Inquiry
VFR	Visual Flight Rules
VRS	Video Recording System
WSO	Weapon Systems Operator

PART 1.5 RECOMMENDATIONS

RECOMMENDATIONS MADE DURING THE SERVICE INQUIRY (FOR FOLLOW UP ACTION)

1. **Survival Equipment.** AOC 1 Gp ensures that:

a. The cotton ties used to secure the zips of the CSW are removed. — Exhibit 32

b. The length of the cord attaching the beacon to the CSW is increased by 12". — Exhibit 32

c. All Sqn SERE Os re-brief their Sqn on the correct use of Fastfind and G2R. In the long term the panel recommends that formal training be given by the SERE School at RAF St Mawgan. — Exhibit 32

2. **Aircrew Training.** AOC 1 Gp ensures that TGRF aircrew are reminded of the advice given within the GR4 ACM Book 1, Part 3, Ch 2, para 72-75. Specifically, that:

a. Crews should be aware that if they suffer a surge in a benign environment i.e. an apparent engine surge outside typical surge parameters, the drills for **ENG MECH FAIL/TI FIRE (E-31R)** should be carried out. Moreover, this drill should also be actioned if any surge is accompanied by additional engine CWP captions. — Exhibit 32

b. When actioning the **ENG MECH FAIL** drill, <u>both</u> fire buttons should be pressed 15s after the LP cock has been closed, regardless of which Fire caption is or is not illuminated. This accounts for the possibility that either engine may be subject to a fire, but that the fire warning may not have been triggered. Crews are also reminded that the fire suppression system fitted to the GR4 is not an engine fire extinguisher but an engine <u>bay</u> extinguisher, used to account for the possibility of ancillary engine bay fires following an **ENG MECH FAIL/TI FIRE**. — Exhibit 32

c. Having made a reasoned decision to shut an engine down, taking into account the above advice, sensible airmanship and good CRM, crews should carry out the **ENG MECH FAIL/TI FIRE** drills ASAP. Crews are reminded that the fuel supply to an affected engine, and/or any associated fire, is only isolated when <u>both</u> HP and LP cocks are closed. — Exhibit 32

ADDITIONAL RECOMMENDATIONS

3. **Causes**. The Panel recommend that:

a. Hd MilAAIB, through Rolls-Royce, continues to investigate the cause of the initial failure in the right engine. — Part 1.4 Para 71/72

b. FAST PTL, through Rolls-Royce, carries out a full review of all critical components in the line of breakout, in particular the engine casing and the main and reheat fuel lines. All components identified to be assessed for additional protection from Ti fire breakout and conclusions reported to the — Part 1.4 Para 71/72/73

ODH.

c. FAST PTL conducts further investigations to seek additional modifications that will mitigate the risk of Ti fire breakout in the RB199 and reports his conclusions to the ODH.	Part 1.4 Para 72
d. FAST PTL reviews the survivability requirements of Tornado GR4 flexible hydraulic hoses, assesses the potential fire hazard risk and associated control measures, and reports his conclusions to the ODH.	Part 1.4 Para 27 Annex M

4. **Contributory Factors**. The Panel recommend that:

a. Hd MilAAIB continues to engage with the fire detection manufacturers in order to assess the effects of fuel cooling on the firewire and the effects of radiated heat on the firewire controller.	Part 1.4 Para 23
b. AOC 1 Gp conducts a review into the teaching of the Mech fail/Ti fire drill. Specifically, focussed attention should concentrate on understanding the symptoms of mechanical failure, the likely sequence of events following mechanical failure, aircrew immediate actions and the reasons behind these actions.	Part 1.4 Para 46
c. AOC 1 Gp ensures that greater emphasis, during initial and recurrent training, is placed on the importance of isolating the fuel supply to engines that have suffered mechanical failure/Ti fires. Specifically, TGRF aircrew should be made aware of the importance of closing the LP cock as well as the HP cock.	Part 1.4 Para 46
d. AOC 1 Gp ensures that greater emphasis, specifically during initial training, is placed on the importance of effective CRM in emergency situations. Training should focus on effective use of crew resources in emergency situations.	Part 1.4 Para 88
e. FAST PTL conducts further investigations to seek modifications to the Tornado engine bay fire detection system in order to provide an increased probability of detection of localised fires.	Part 1.4 Para 78
f. FAST PTL undertakes investigates potential improvements to the Tornado fire suppression system and makes recommendations to the ODH.	Part 1.4 Para 79
g. The Tor PTL implements a system to ensure the process for incorporating incidents/accidents into the hazard log is improved in order to ensure a timely, up to date risk rating exists.	Part 1.4 Para 56
h. The Tor PTL conducts a full review of the Tornado hazard log to ensure that the Post Control Status accurately reflects the effectiveness of controls placed in it.	Part 1.4 Para 58

5. **Other Factors**.

a. ODHs seek ways to mitigate the risk being carried by PLBs not functioning correctly.	Part 1.4 Para 51

b. AOC 1 Gp reviews the requirement for a fully automatic personal locator beacon fitted to all crew members of fast jet ac.	Part 1.4 Para 50
c. FAST PTL and the APS PTL conduct further investigation into the performance of the Fastfind personal locator beacon.	Part 1.4 Para 52 and 53
d. ODHs ensure that formalised annual training is given to aircrew in the operation of the Fastfind and G2R beacons.	Part 1.4 Para 54
e. FAST PTL investigates ways to improve the Tornado R-ADR to capture more parameters, specifically CWP captions and LP cock positions, and makes recommendations to the ODH.	Part 1.4 Para's 12, 14, and 36a

6. **Observations**.

a. COS Health reviews the process, and responsibilities, for transporting ejectees back to their units following hospital admission, and ensures that these responsibilities are clearly defined.	Part 1.3 Para 24
b. FAST PTL conducts a review of engine bay fuel pooling and drainage characteristics, assesses the potential fire hazard risk and associated control measures and reports his findings to the ODH.	Part 1.4 Para 22 Annex M
c. Stn Cdr RAF Lossiemouth conducts a full review of F700 documentation to ensure it is at the correct amendment state.	Part 1.4 Para 69 Annex H
d. FAST PTL reviews the specific recommendations made by BAE Systems reports to the Boards of Inquiry into Tornado GR4 ZA599 and Tornado F3 ZE830 accidents, and highlighted to this SI Panel and makes recommendations to the ODH.	Annex M section 7.0. Para 4 and 5

PART 1.5 RECOMMENDATIONS

RECOMMENDATIONS MADE DURING THE SERVICE INQUIRY (FOR FOLLOW UP ACTION)

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c. Having made a reasoned decision to shut an engine down, taking into account the above advice, sensible airmanship and good CRM, crews should carry out the **ENG MECH FAIL/TI FIRE** drills ASAP. Crews are reminded that the fuel supply to an affected engine, and/or any associated fire, is only isolated when <u>both</u> HP and LP cocks are closed. Exhibit 32

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ODH.

c. FAST PTL conducts further investigations to seek additional modifications that will mitigate the risk of Ti fire breakout in the RB199 and reports his conclusions to the ODH. — Part 1.4 Para 72

d. FAST PTL reviews the survivability requirements of Tornado GR4 flexible hydraulic hoses, assesses the potential fire hazard risk and associated control measures, and reports his conclusions to the ODH. — Part 1.4 Para 27 Annex M

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g. The Tor PTL implements a system to ensure the process for incorporating incidents/accidents into the hazard log is improved in order to ensure a timely, up to date risk rating exists. — Part 1.4 Para 56

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5. **Other Factors**.

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c. FAST PTL and the APS PTL conduct further investigation into the performance of the Fastfind personal locator beacon.	Part 1.4 Para 52 and 53
d. ODHs ensure that formalised annual training is given to aircrew in the operation of the Fastfind and G2R beacons.	Part 1.4 Para 54
e. FAST PTL investigates ways to improve the Tornado R-ADR to capture more parameters, specifically CWP captions and LP cock positions, and makes recommendations to the ODH.	Part 1.4 Para's 12, 14, and 36a

6. **Observations**.

a. COS Health reviews the process, and responsibilities, for transporting ejectees back to their units following hospital admission, and ensures that these responsibilities are clearly defined.	Part 1.3 Para 24
b. FAST PTL conducts a review of engine bay fuel pooling and drainage characteristics, assesses the potential fire hazard risk and associated control measures and reports his findings to the ODH.	Part 1.4 Para 22 Annex M
c. Stn Cdr RAF Lossiemouth conducts a full review of F700 documentation to ensure it is at the correct amendment state.	Part 1.4 Para 69 Annex H
d. FAST PTL reviews the specific recommendations made by BAE Systems reports to the Boards of Inquiry into Tornado GR4 ZA599 and Tornado F3 ZE830 accidents, and highlighted to this SI Panel and makes recommendations to the ODH.	Annex M section 7.0. Para 4 and 5