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. (Annex D Para 1.4) 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. (Annex D, Para 1.4) 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.

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. (Exhibit 2) At 0815 on 27 Jan 11, ZG792 completed a 1:30hrs sortie, returning with no faults reported by the crew. (Exhibit 4) A turn-around servicing was completed by XV(R) Squadron engineers with no faults documented. (Exhibit 8) The flight servicing was coordinated at 1200, and the ac was signed out by the pilot at 1310. (Exhibit 2) 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 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 Annex I 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 Annex D Para 1.5.5 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 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 Annex D Para 1.5.1 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 Annex D Para 1.5.1 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 Annex I line rupture:

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

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.

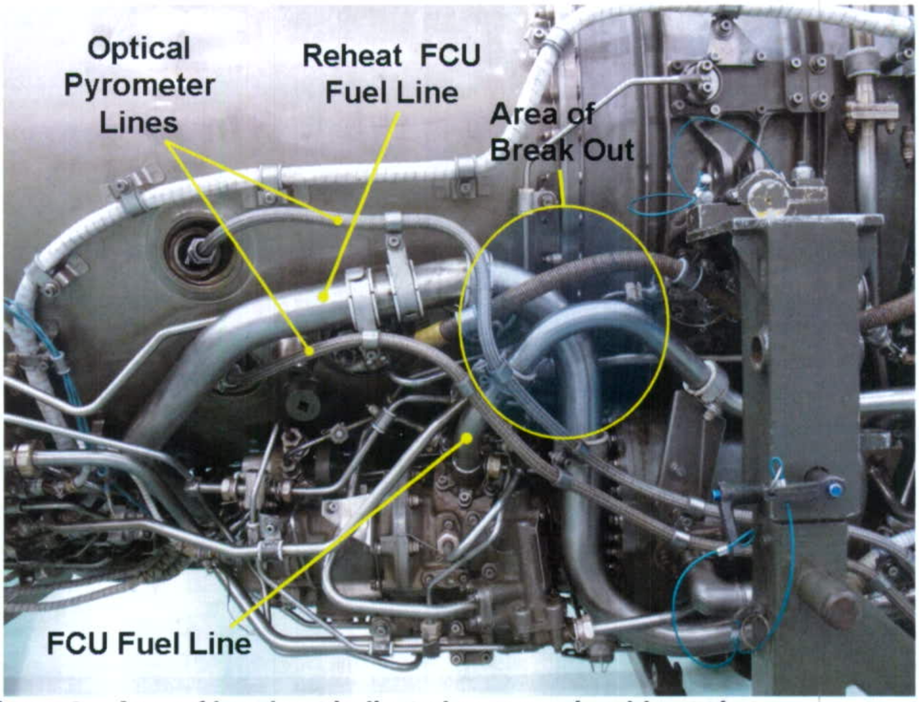

Figure 2 – Area of breakout indicated on a serviceable engine

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

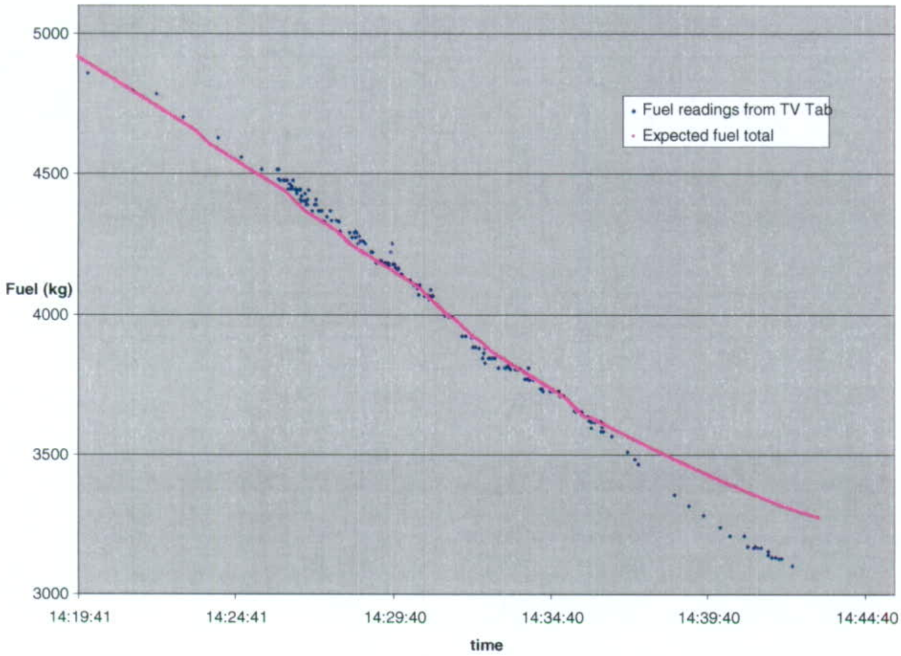

Figure 3 - Predicted and actual fuel use

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.

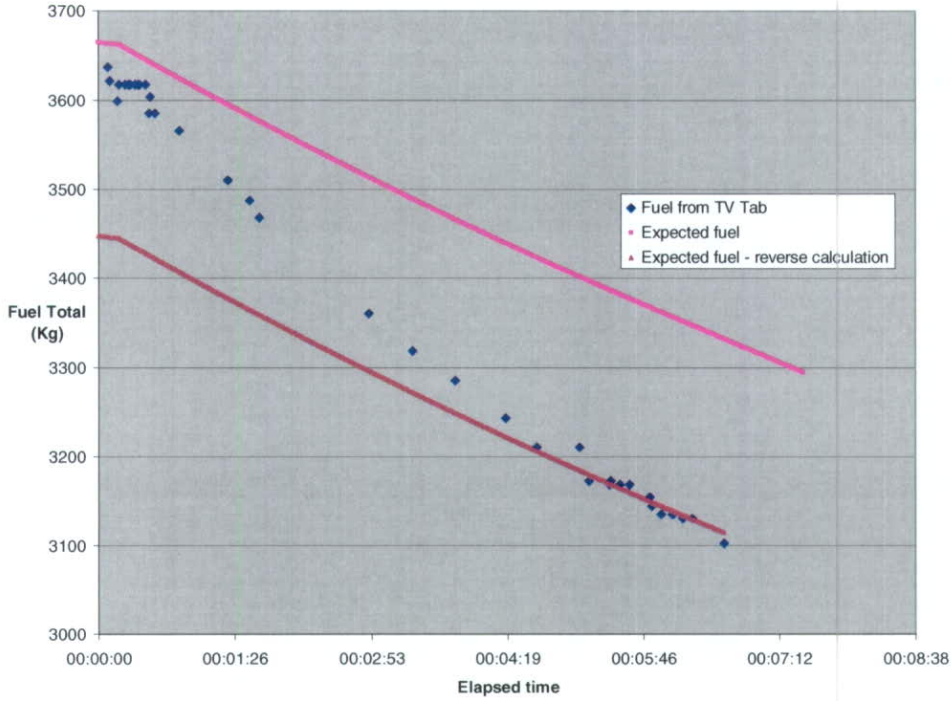

Figure 4 - Predicted and actual fuel use during accident sequence

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

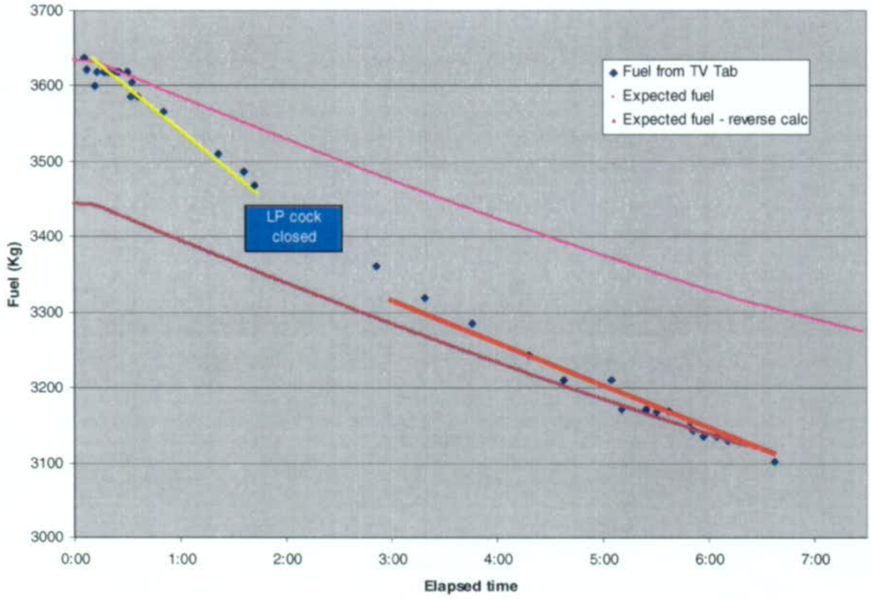

Figure 5 - Fuel Flow graph - LP Cock closure at T1:00 theory

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

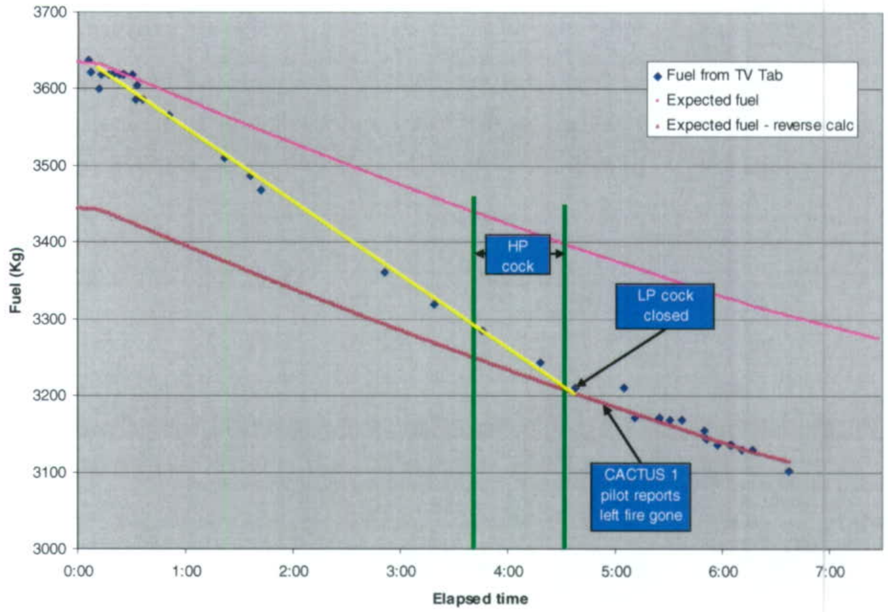

Figure 6 - Fuel flow graph - LP Cock closure at T4:30 theory

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

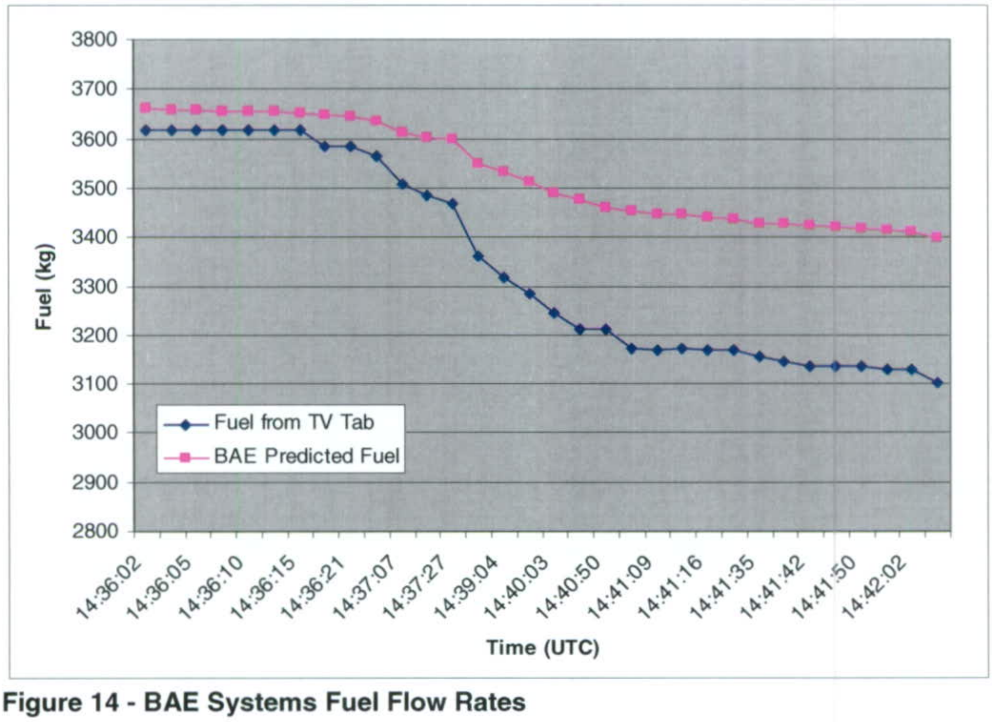

Figure 14 - BAE Systems Fuel Flow Rates

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

b. Hotplate ignition

Annex D Para 2.2.1

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. Annex D Para 1.6
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.

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

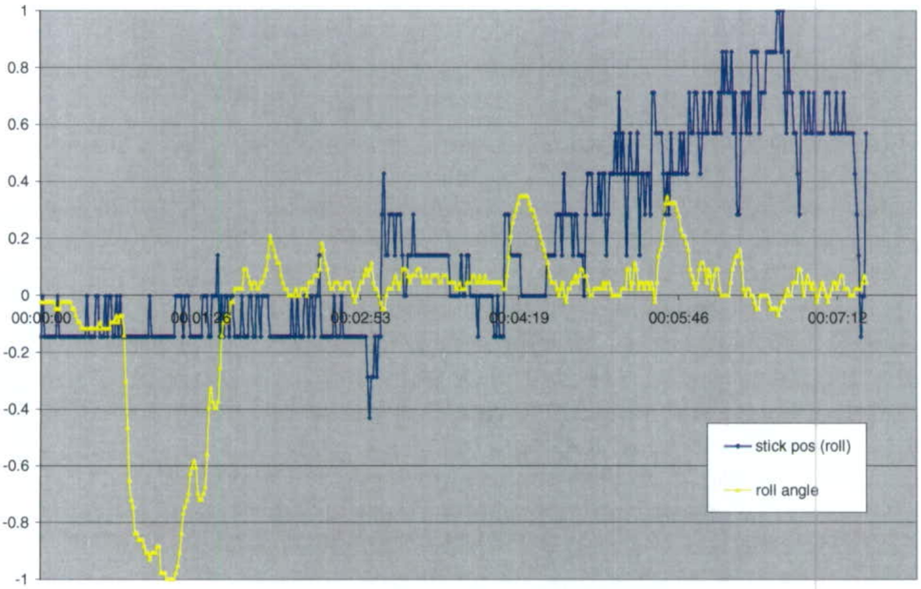

Figure 16 - Normalised lateral control data (+ve = right)

Military Aviation Authority MAA

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