FAST/Tor/5/2/28

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Tor EA
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CEST 1
Tor ESM 2

TORNADO AAES HAZARD REVIEW OF A16 – UNINTENDED ESCAPE SYSTEM OPERATION AND H46 – ESCAPE SYSTEM FAILS WHEN REQUIRED OR ACTIVATED

References:

A. FTLM, V5, dated Dec 13.
B. Fault Tree Analysis For Mk 10A Safety Case, Martin Baker Doc No: MBA-DS-S-05-06, Issue A, dated Mar 05.
C. Tor Crew Escape System hazard Identification Report, Cowell & Cowin, QQ/TIS/S&AS/TR1303389\1.0A, dated 7 Jan 14.
D. RAF Flight Safety Ac Accident Summary & Selected Incident Reports, Tor Accident Database, Work In Progress, http://cui6- uk.diif.r.mil.uk/r/329/Tor_Safety_and_Env_LTD/Tor_Haz_Mgmt_LTD/02_Tor_Hazard_Log_LTD/20121119-Tornado%20Accident%20Summary%20Draft R.xls
E. TESMP, Issue 8, Annex C, TEHRM, dated Dec 12.

Aim

1. To capture the hazards posed by the Tornado MK10A AAES and identify the mitigations and hazard analysis for operation of the seat.

Introduction

2. Recent investigations have led to a review of the evidence used to support the AAES Safety Case. Contained within this document are the known identified hazards posed to the crew by the AAES and the evidence to support the mitigation procedures/activities.

3. Ref A is utilised by the Tor EA to identify known Tornado platform hazards, their mitigations and probabilities (P) of occurrence and is primarily focussed on factors leading to the loss of the Tornado platform. In some circumstances, the AAEs is employed by the crew once loss of the platform has been established and this review considers the P of AAES failure in addition to the P for the loss of the Tornado platform. Ref A cites three streams concerned with the failure of the AAES:

a. A16. Crew Escape System Unintended Operation.

b. H14. AAES Unintended Operation.

c. H46. AAES Fails When Required or Activated.

4. Ref B is the FTLM produced by the AAES OEM which is used to identify the individual factors, and their associated P of occurrence leading to failure of the system. It should be noted that Ref B cites HF failures as contributory factors whereas the Tor EA considers equipment-only failures leading to the loss of the platform. This analysis uses data from Ref B but excludes operator HF issues and therefore, the calculated Ps in this review differ to the OEM's analysis.

Assumptions

5. For all hazards, the assumptions and parameters in which the AAES operates are:

a. **Maintenance Error**. The AAES is maintained iaw the ADS. This supports the criteria in which HF are not considered as a fault in this analysis. This review considers a correctly installed and serviceable seat and that maintenance errors have not occurred.

b. **Human Factors (HF)**. The Tor EA's FTLM focuses on equipment risk but it is worth highlighting HF errors. Due to the criticality of the system, vital and independent inspections are conducted during AAES maintenance to reduce the risk of HF-related maintenance failures. Whilst it is recognised that HF cannot be reduced to zero, it is considered that the residual HF risks are considered to be ALARP.

b. **Design Envelope**. The AAES is operated within the OEM's design envelope. It is identified that instances in which the AAES is employed can occur when the Tornado platform in either approaching or outside of the AAES's limits. Therefore the AAES may still operate correctly and remove the occupant from the platform; however, at the limits of the envelope additional factors have a greater influence on the crew's survivability factor during the ejection sequence.

AAES A16 Hazard Breakdown

6. Following a review of the AAES, the EA proposes the following Hazards (H):

a. H(46). The seat fails to operate correctly when required.

b. H(14). The seat operates when not required. (Spontaneous initiation of the AAES).

c. H(x). The seat fails to retain the occupant.

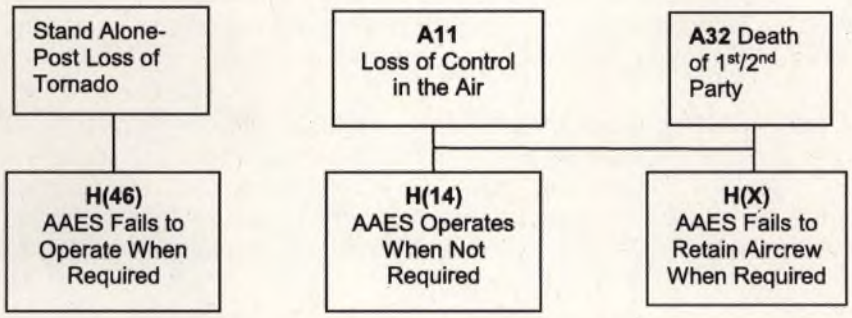

Fig 1. Hazards H(46), H(14) and H(X) contributing to A11 and A32.

H(46) AAES Fails To Operate When Required - Qualitative Analysis

7. For the AAES to be required, the crew must be in a situation whereby the platform has failed. Whilst it is possible to identify the root causes at the cause level, sensible analysis cannot be conducted for each cause individually therefore this analysis is restricted to the hazard level.

8. AAES failure to operate when required is an event-based hazard as the AAES is only employed when it is necessary to eject from the platform. Occurrences of ejections occur at an insufficient frequency to generate a comprehensive statistical analysis and therefore the reliability of the AAES in terms of H(46) is also subject to qualitative analysis. Analysing Ref B, the EA

identified the following causes (Z) leading to H(46) as shown in Fig 2.

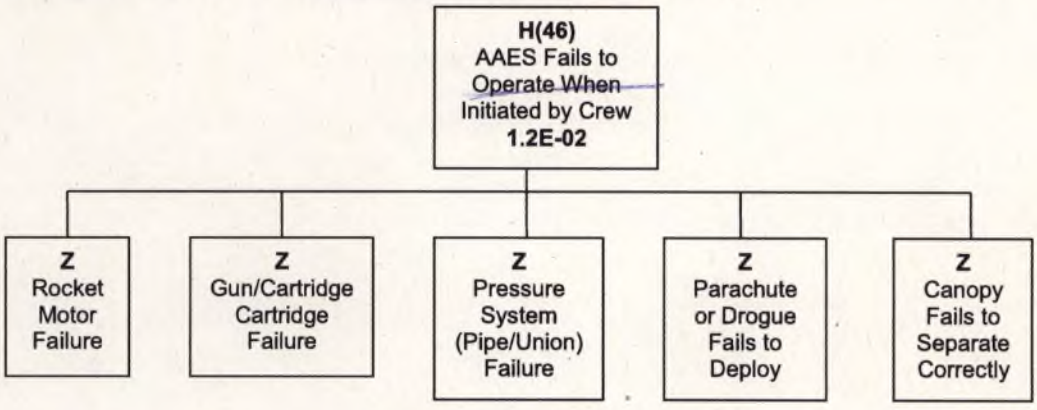

Fig 2. H(46) Failure Causes.

9. **Cause Z - Rocket Motor, Gun/Cartridge Failure, Parachute/Drogue Failure**. Despite similarities in their operation, the rocket motor and gun cartridges have been separated to identify their separate functions within the AAES. Failure of the parachute or drogue assembly is also considered as they are fundamental to the successful ejection sequence.

10. **Cause Z, Pressure System Failure**. The AAES relies on gas pressure from the activated cartridges to initiate the ejection sequence. Failure of the pressure systems can lead to a system failure for H(A) when the AAES is required. Failure of the pressure system under H(14) conditions complements an already failed system and therefore is not a factor during un-commanded initiation. Pressure system failure is not included in Ref B hence; the Tor EA's FTLM will differ from the OEM's.

11. **Cause Z, Canopy Fails to Separate Correctly**. The canopy jettison system has two modes to enable the crew to pass clear from the canopy. The first covers rocket-assisted separation of the canopy and the second is the back-up MDC system which shatters the canopy via a mechanical initiation system as the seat travels upwards. There have been no reported instances where the MDC was required however there is one incident[1] resulting in a fatality where, potentially, the navigator impacted the canopy during the ejection sequence though this was not positively determined.

H(46) AAES Fails To Operate When Required - Assessment

12. Ref D[2] details all 69 recorded RAF Tornado air accidents. Of these 69 accidents, 42 accidents provided an opportunity for ejection for at least one of the crew, with 83 attempted ejections.

13. Following analysis of previous Tornado ejections detailed at Annex A, the loss of ZE789 where the Navigator is believed to have impacted the canopy upon ejection is the only recorded death following a demanded ejection [1].

$$P_{(\text{AAES Fails on Demand})} = 1 / 83 = 0.012. \text{ or } 1.2\%$$

14. The EA assess that provided the AAES is initiated within the limits defined within the RTS then a successful probability of at least 98%(1 - 0.012) may be assumed. This, when combined with the probability of a situation to which an ejection may be attempted, reduces the likelihood of

[1] RAF BOI, Tor F3, ZE789, 10 Mar 1995 – 1 Fatality, 1 Minor Injury. It is not known whether initiation of the AAES occurred when the ac was within RTS limits for safe ejection.
[2] Note Ref D also includes the loss of a GAF ac (G4324) operated by TTE on 17 Jun 86. Due to lack of clarity in the subsequent BOI this incident is not included in this report.

1st party death from H46 to be 'unlikely to occur in 10 years' therefore 'Improbable' with a 'Critical' severity. This equates to a C15 HRI at the Accident level - iaw Ref C.

H(14) AAES Operates When Not Required - Quantitative Analysis

14. The seat component of the AAES is in constant use by the occupant and therefore AAES operation when not required can be calculated over the exposure time of the Tornado fleet. Since H(14) is a constant hazard, so long as the seat is occupied, the hazard is persistent during normal operations. The EA therefore proposes the causes cited in Fig 3.

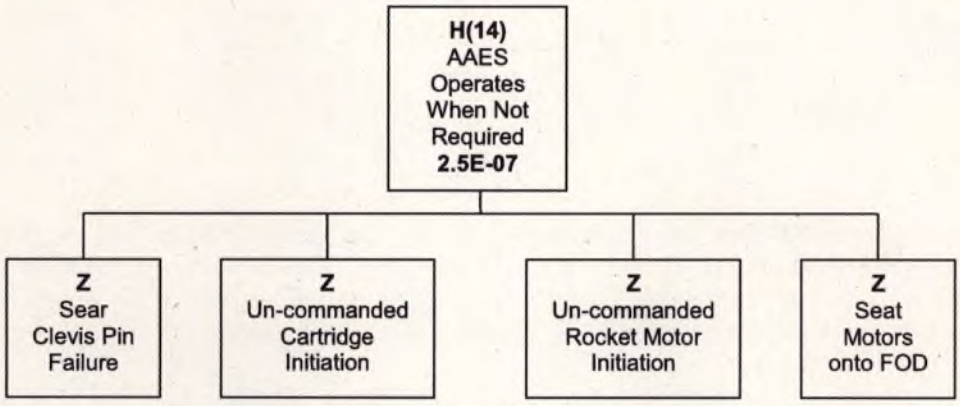

Fig 3. H(14) Failure Causes.

15. **Cause Z - Sear Clevis Pin**. This pin connects the seat pan firing handle to the initiation cartridge firing pin. There is no redundancy should the clevis pin fail and there have been no reported pin failures.

16. **Cause Z - Un-commanded AAES Cartridge Firing or Rocket Motor Initiation**. There have been no recorded instances of the AAES cartridges or rocket motors firing without deliberate initiation. However, un-commanded cartridge/rocket initiation could be caused by exposure from either EMF or manufacturing defects.

17. **Cause Z - Cockpit FOD**. Modifications to Aircrew clothing and their carry-on equipment, particularly during sorties in Th, have led to increases in the weight of the occupant and additional items of equipment in the cockpit. Such items can be stowed/migrate underneath the seat and potentially damage or cause initiation of the seat should the occupant decide to 'motor-down'.

H(14) Assessment

18. Exposure to H(14) is greater than the fleet FH as it is present whenever the AAES is occupied. As the Tornado Fleet has exceeded 1.5E06 FH it is assessed to be on average an additional 30 mins of expose time per sortie (crew pre flight checks, see-off, see-in etc). Assuming a 90 min average sortie length this provides an exposure of 2E06 Hours. Moreover as there are 2 ejection seats, assuming that the unintended initiation of one seat is unlikely[3] to result in the initiation of the other seat, the exposure to this hazard per seat can be assessed to be double this figure, i.e. in the region of 4E06 Hours. It should also be noted that the nature of the safety devices (pins), whilst effective against human error, are assessed to be largely ineffective against preventing hazards from other factors e.g. EMC .

19. There have been no AAES operations when not required on Tornado ac and therefore, should H(14) occur during the next FH, quantitative analysis calculates the occurrence $P_{H(14)}$ as 1/(4E06) = 2.5E-07. The Causes contributing to H(14) are shown in Fig 3.

[3] While the command eject system provides functionality for one seat to initiate the other, only an unintended initiation of the seat pan firing handle cart is likely to result in a double ejection.

20. For comparison the Hawk Service Inquiry involved un-commanded / un-intended initiation of the AAES. The Hawk fleet operate a very similar AAES system and have also flown approximately 1.1E06 FHs and using this incident as the only such occurrence similar to H(14) then the P(Hawk) equates to 9.1E-07. While the cause was assessed to be HF-related and not a technical fault, this is further evidence to the high reliability of the system.

21. If H14 is related to the front seat, it is a factor to A11, Loss of Control in the Air. Thus as each seat is assessed as having a probability of uncommanded operation of 2.5E-07, a proportion of this hazard should feed into A11. As H14 only results in loss on control in the air for the proportion of time that the ac is in the air, ¾[4] of H14 should apply to A11 with the remaining ¼ of H14 not leading to loss of ac[5] being applied to A32 – Loss of 1st/2nd Party life. Equally there is an argument that a small proportion of H14 could also feed into A12, loss of control on the ground. However, considering the relative proportions of time at risk (Ground taxi vs Flight) and the likely comparative severities, this small proportion[6] (i.e. less than 1/100) of H14 is assessed to be comparatively small when assessed against the current probability of A12 (1.8E-06) and thus can be discounted from the FLTM.

22. Relating H14 to the rear seat only, while far less likely to contribute into A11 - as the loss of navigator / rear seat pilot is unlikely to result in loss of control of the ac in the air[7]- H14 for the rear seat feeds into risk to A32, Loss of 1st/2nd Party. Thus, as each seat is assessed as having a probability of uncommanded operation of 2.5E-07, this hazard should feed also feed into A32. Fig 1 refers.

H(X) AAES Fails To Retain Aircrew When Required - Qualitative Analysis

23. The seat is in constant use during sorties and potentially the AAES may fail to retain the occupant. This could occur, though is not limited to, failure of the QRF, Harness, Top Latch Plunger (TLP) or the structural attachment of the seat system to the Ac's structure. Caution needs to be exercised to prevent double-accounting of causes such as the harness and the TLP failures. The EA proposes the causes contributing to H(X) as shown in Fig 4.

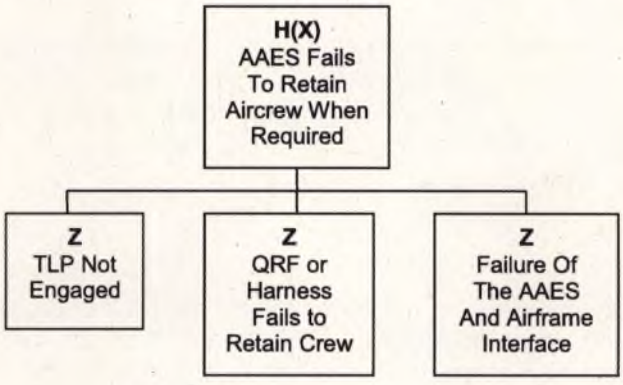

Fig 4. H(X) Failure Causes

[4] Ave sortie flight time of 90 Mins of a total exposure time of the 120 Mins total time at risk from aircrew strap in to leaving the cockpit; thus 90/120 is ¾ of the risk.
[5] It is assumed that unintended initiation of the AAES on the ground, when related to the pilot will not lead to loss of ac but is likely to result in loss of life of the pilot.
[6] H14 is only likely to lead to loss of control on the ground and subsequent loss of ac at high speed on the ground, i.e. during take-off and landing phases. This time can be measured in tens of seconds against the total average time of risk of 120 mins, and as it less than 1/100 of the risk can therefore be discounted.
[7] Unless caused by unintended initiation of the Seat Pan Firing Handle Carts as unintended initiation of these carts is in effect a correctly initiated ejection sequence. This is likely to result in a double ejection, and could strictly be a very small factor of A11 - Loss of control in the air. As this probability is so small it is not considered any further.

24. **Cause Z - Top Latch Plunger (TLP).** The TLP and its associated ancillaries retain the seat in position during operational use which is fundamental to securing the seat during negative g. While it is acknowledged that pulling significant negative g is not common, following liaison with Tor STANEVAL, and noting that the RTS provide clearance for upto -0.5G, exposure to limited negative G is considered to be a credible hazard which can cause crew exposure to TLP failing to retain aircrew when required. It is a single point of failure to correctly retain the occupant and has been assessed as the cause of the loss of a Navigator from ZA554[8].

25. **Cause Z – QRF/Harness Failure.** This cause is concerned with the failure of the AAES harness component to correctly restrain the occupant. While several F760 investigations into the failure of a QRF to release the harness are noted, there have been no recorded instances of the QRF failing to secure the harness and retain the aircrew on the RAF Tornado fleet[9].

26. **Cause Z - Failure of the AAES & Airframe Interface.** Failure of the attachment points between the AAES and the Ac's structure can lead to loss of functionality of the AAES during the ejection sequence and inhibit the crew to conduct normal flying operations. No such instances have occurred on the Tornado fleet.

H(X) Assessment

27. Assuming each seat to be equally susceptible to this failure mode, thus as each seat position has been exposed to 1.5E06 FH a combined exposure of 3E06 FHs to this hazard can be assumed. Noting that a TLP failure is the only occurrence of this hazard resulting in loss of life, then this results in a failure rate of 1 / 3E06 = 3.33E-07 which is a C15 (Critical, Improbable) risk.

28. Similarly to the assessment of H14, H(X) is assessed as contributing to both A11 loss of control in the air (when H(X) is assessed against the front seat) and A32 - loss of 1st/2nd Party (when assessed against the rear seat). Therefore a factor of 3.33E-07 from H(X) should feed into both these accidents equally at detailed at Fig 1.

Single Points of Failure

29. Ref B contains the hazards identified by the OEM. As stated in para 5.b, Operator HF is not considered as the Tor EA is concerned with equipment risks only. Following analysis of Ref C, the EA Arm Elec deems the TLP, Sear Clevis Pin and the Pressure System as AAES single points of failure with no redundancy. It should be noted that particular attention should be given to any reported failures to these systems.

Ejection Survivability

30. H46 assesses the probability of a 'safe' ejection initiated within the limits of the RTS. However when considering a survival factor for Cost Benefit Analysis, a wider spectrum of events must be considered. Thus when assessing the reliability of the AES following a Accident caused by a aircraft technical failure (TF), regardless of whether ejection sequence was necessarily initiated by the aircrew.

31. There have been 17 Ac losses due to aircraft TF and one fatality[10] giving a P of survivability during the AAES sequence resulting from Ac TF as:

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[8] ZA554 BOI report - accident dated 14 Nov 07. Note it was not positively determined whether the TLP not being engaged was caused by component failure or maintenance error.

[9] The EA is aware of discussion surrounding the Typhoon QRF and the possibility to release the harness on ejection however the Typhoon QRF is significantly different in operation to that used on Tornado.

[10] Incident ZA789, 10 Mar 95. This incident resulted in one fatality with the rear ejection seat being judged to have impacted the canopy upon ejection. Note the loss of ZA558 in 28 Oct 83 is discounted as the pilot was likely to have been incapacitated or dead prior to ejection.

$P_{(Survival\ from\ TF\ Accident)}$ = 1-(1/17) = 1-0.059 = 0.0941 (94%.)

32. In comparison from all accidents including CFIT and MAC the survival rate drops to 39 fatalities in 69 Air Accidents resulting an overall probability:

$P_{(Survival\ from\ Any\ Accident)}$ = 1-(39/69) = 1-0.565 = 0.435 (43%.)

33. Survivability of any accident is highly dependent on the scenario and as far as possible should be individually assessed in the likely context of occurrence e.g. flight characteristics/envelope. However, it can be seen that the survivability from an Ac accident caused by Technical Failure is significantly higher than the fleet survivability average of 0.435 from all accidents. It is noted that this figure is derived from a relatively small sample size of 17 air accidents and is highly sensitive to further data; it is therefore subject to error. When further case specific assessment cannot be carried out, it is recommended a more conservative survivability factor of 90%, which equates to a 10% probability of death, should be used when conducting CBA iaw Ref E, Annex C, Pt 4 for accidents resulting from TF. Further advice may be sought on an individual basis from the EA Arm Elec.

Recommendations

34. Ref A be updated as detailed in the figures and probabilities included within this document.

35. Ref E be updated as detailed in Para 33.

[redacted]
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[redacted]

Annex

A. Tor AAES Hazard Review Of A16, Ref D, dated 28 Feb 14.