FACTORS CONSIDERED BY THE BOARD

30. The Board considered that the following factors may have had a bearing on the accident:

a. Age of the Nimrod MR2 fleet.

b. Maintenance policy.
   (1) Maintenance of fuel system.
   (2) Maintenance of engine hot air bleed system.
   (3) Nimrod Safety Case.

c. Maintenance.

d. Servicing.

e. Operational pressures.

f. Enemy action:
   (1) Improvised explosive device.
   (2) Surface-to-air missile.

g. Weather.

h. Hot air leak.
   (1) Damage to fuel tanks.
   (2) Damage to fuel pipes and couplings.

i. Fuel system.
   (1) Fuel pipe leaks.
   (2) Fuel coupling and seal leaks.
   (3) Fuselage tank leaks.
   (4) Wing tank leaks.

j. Air-to-Air Refuelling (AAR):
   (1) AAR system incorporation.
(2) Frequency of use.

(3) Over pressure of MR2 fuel system.

(4) Overflow phenomena during AAR.

(5) AAR Procedures.

k. Electrical components as an ignition source.

l. Hot air system as an ignition source.

m. Lack of fire detection/suppression system in No 7 tank dry bay.

n. The aircraft’s final flight path.

DISCUSSION OF FACTORS

31. Age of the Nimrod MR2 Fleet

a. Prior to XV230’s crash, only 3 Nimrod aircraft had been lost in 36 years of operations: of these, one was caused by multiple bird strikes shortly after take-off; one by the mechanical failure of an engine starter motor, which, by chance, perforated a fuel tank resulting in a fire; and one was occasioned by human factors. Thus, only once has a mechanical failure caused the demise of an aircraft. Indeed, in another incident, an airframe successfully carried its crew to safety after a major bomb bay fire, which damaged the aircraft beyond economical repair. Despite a long period of operational flying, there is no evidence of increasing losses due to mechanical failure as the aircraft has aged.

b. The increasing age of the Nimrod fleet has been recognised and, in accordance with extant policy, an Ageing Aircraft Audit (AAA) was conducted in 1993 and reviewed in 2003. However, in common with both civilian and military practice, the AAA focussed on the structural integrity of the airframe, although it was expanded in Sep 06 to incorporate aircraft systems as well; formal guidance on implementation has yet to be issued. Nonetheless, the AAA review of 2003 specifically addressed the delay in Nimrod MR2 Out of Service Date (OSD) to 2012 and made a number of recommendations in response to that delay. The Nimrod IPT has enacted all of the recommendations, with the exception of a Mini Life Extension Programme (MLEP); it was decided that this was not necessary as the major driver of platform life is the fatigue index (FI) which has been extended through a structural sampling programme and through an analysis of the tear-down of the fatigue
test specimen. The Board was presented by the Nimrod IPT with evidence of other processes and documents initiated to oversee aircraft safety; in particular a Safety Working Group, which meets every 6 months and is open to all stakeholders. The Board concluded that, the increasing age of the Nimrod had been recognised and that the measures taken followed existing practice, within both the civilian and military sectors: an age-related audit of the aircraft’s structure had been completed and there was evidence of regular oversight of fatigue and safety issues. Although there was no evidence to indicate that all of the aircraft’s ageing internal systems had been comprehensively reviewed, this was not mandated by MOD regulations prior to the crash and, indeed, guidance has yet to be issued to describe how the policy initiated in Sep 06 should be implemented. Nonetheless, and despite the MOD’s compliance with all extant requirements for the operation of an ageing aircraft, the Board’s analysis of both fuel system (para 32a(4)) and hot air system (para 32b) maintenance policies leads it to the conclusion that age was a possible Contributory Factor in the loss of XV230.

32. Maintenance Policy.


(1) Current Maintenance Regime. The Nimrod fuel system (described in detail at Annex H) is maintained under a process of Corrective Maintenance (as defined in JAP 100A-01) in which components are replaced when they are observed to have failed: such replacement usually occurs following visual detection of a fuel leak in flight or on the ground. The process is supplemented by the zonal survey of areas of the fuel system during periodic maintenance, in which components observed to be in an unacceptable condition due to damage, deterioration or corrosion are replaced. However, these inspections are completed with the fuel system empty and thus are unlikely to provide evidence of leaking pipes or couplings. Moreover, unless they are physically leaking, damaged, or disassembled for access, the couplings used to connect fuel pipes are not dismantled to check the condition of their rubber seals.

(2) Designer’s Recommendations. The Declaration of Design and Performance (DDP) issued in 1968 for the original FRS Series 1 elastomeric fuel seal (used up until approximately 2002) states that, if subject to a 5-yearly inspection regime, they have an unlimited service life. This was based on 15 years experience of use of these seals at that time. A 5 year inspection schedule is also referred to in the seals’ design specification. However, no Nimrod seals
have been removed solely for the purpose of the examination scheduled in the DDP. The Board has been unable to determine any formal record explaining the apparent dichotomy between the manufacturer’s recommendation and MOD practice, but the Nimrod IPT has stated that such examination would be impractical, as it would effectively require the replacement of the seals every 5 years (standard engineering practice would be to replace the seal if it had been removed from its housing for inspection). At a meeting between MOD staffs and the current seal manufacturer, Eaton Aerospace, the latter stated that, in view of their current experience of elastomeric seal manufacture and use, if seals were subject to the specified inspection regime, they would recommend their replacement after they had been fitted to a coupling for 25 years. However, the seal could now be inspected in situ, without disturbing the coupling. The inspection should be conducted with the fuel system under pressure and should check for leaks and seal extrusion. If a customer decided to retain the seals past 25 years of age, then the inspection regime must continue, but the seals would have a greater tendency to leak. Eaton Aerospace agreed that this advice had not previously been conveyed to MOD or BAE Systems.

(3) Effect of Disturbing Seals. MOD expert advice has stated that the act of replacing fuel seals might actually increase the number of fuel leaks due to disturbance of the system. A BAe document highlights that a ‘catalogue of problems causing fuel leakage due to airframe build difficulties when using FRS110 couplings (as used in the Nimrod) relate back to the Lancaster, Vulcan, Lightning, AEW Mk3, and VC 10 CMk1’. It notes that ‘each (Nimrod) production aircraft has build differences that exceed the permitted tolerance banding for the couplings’ and that ‘during production build the correct gap between each production pipe on every aircraft was reached by a careful build up of the system as a whole’. The report notes that when couplings are replaced ‘assembly stresses are built into the system’ which could provoke further leaking. Thus, any maintenance policy requiring, for example, regular seal replacement would require careful management to ensure that it did not itself degrade the fuel system’s integrity. Nonetheless, there has been no scientific study of elastomeric seal behaviour beyond 40 years of age and it is possible that some Nimrod seals have been in place for up to 38 years.

(4) Analysis of Maintenance Data. Analysis of Annexes I&J
Nimrod fleet maintenance data from 1983 to 2006 indicates that there has been a continual increase in fuel leaks over time: the average for the fleet per annum in the 1980s was 10, it had risen to 40 per annum between 2000 and 2005, despite the reduction in Nimrod fleet size. The great majority of fuel leaks are from couplings. In the absence of other factors, the reason for the increase in leaks over time might be that the seals are proving less effective as they age. The 2 aircraft that have been Nimrod R1s since their construction show no increase in fuel leaks over time. While this might be attributable to their operating in a more benign, higher-level, environment than the MR2, the small size of the Nimrod R1 fleet makes it difficult to draw meaningful comparisons.

(5) Maintenance Regulations. An interim report into maintenance policies for aircraft system seals suggests that the Nimrod policy for seal replacement is not unusual and is replicated in many other military aerospace organisations. Although life extension documents for the Tornado require the replacement of some O-ring seals and self-sealing couplings, those for the Hercules CMk1 make no reference to a need to replace seals. However, JAP 100A-01 notes that it is important that corrective maintenance trends are analysed and, where appropriate, reflected in changes to preventative maintenance schedules; this is reflected in civilian maintenance procedures defined in CAAIP leaflet 1-7. There is no evidence that the maintenance data for the fuel system at component level was ever analysed in order to inform maintenance policy. It is impossible to prevent completely fuel leaks within any fuel system, but the threat of fire inherent on such occasions, requires a policy that reduces the number of leaks to the minimum reasonably practicable. The current Nimrod fuel policy attempts to meet this requirement by imposing as little disturbance on the system as possible, but appears not to have balanced this risk with a growing risk of fuel leaks from other causes.

(6) Conclusion. Although the maintenance policy for the Nimrod’s fuel system broadly followed common practice within the aviation industry, the policy did not prevent a gradual increase in fuel leaks within the aircraft over time and was not revisited to take account of the implications of the increasing number of fuel leaks exhibited by the system. The Board was, thus, of the opinion that the fuel system’s maintenance policy was a Contributory Factor in the loss of XV230.
b. **Maintenance Of Engine Hot Air Bleed System.** The Nimrod hot air engine bleed system (described at Annex K) is also maintained under corrective maintenance. The construction of the system’s insulated pipes consists of an inner steel pipe covered by a 12mm thick glass fibre blanket which is protected by an outer dimpled stainless steel jacket. Observation of the hot air pipes’ insulation on various aircraft revealed some areas where the outer jacket was badly compressed and in one case cracked. The damage to the outer jacket is likely to have occurred over time, during maintenance activities. The Aircraft Maintenance Manual (Topic 1) gives clear guidance on the correct assembly of the V-band clamps, which join individual lengths of pipe, and leak checking, but gives no guidance on the condition and acceptable damage limits of the insulated pipes. Any areas of poor insulation of a pipe would reduce its effectiveness and its ability to prevent it becoming a source of ignition. One experiment, conducted by the Board on an area of compressed insulation indicated only a 16 ºC temperature difference between an exposed section of hot air pipe and the exterior of the insulated blanket. Those elements of the hot air system, such as expansion bellows, which cannot be encompassed within the standard insulation blanket, are covered with muffs or individual insulating blankets, secured with laces and abutted to the principal insulation. In some areas on other aircraft it was noted that the laces have loosened and there are visible gaps between the blanket edge and the edge of the main pipe insulation, leaving exposed sections of pipe surface; indeed, an expansion bellows in each of the No 7 tank dry bays possesses no lagging whatsoever (the Board has been unable to determine any risk assessment for the non-insulation of these components). The Board believes that a lack of guidance on the allowable condition for hot air pipe insulation contributed to its gradual deterioration in some areas and that gaps between different types of insulation provided points of weakness in the system, making it possible for leaking fuel to touch bare pipe metal at operating temperatures in excess of 400 ºC. Thus, the Board was of the opinion that the hot air system’s maintenance policy was a Contributory Factor in the loss of XV230.

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**Nimrod Safety Case.**

(1) The Nimrod Safety Case (NSC) is the body of evidence that assures that the aircraft is safe to operate within the Statement of Operating Intent and Usage. It is a suite of documents providing a written demonstration that risks have been reduced to As Low As Reasonably Practicable (ALARP). It is intended to be a living dossier, which underpins every safety-related decision made. The NSC incorporates the Hazard Log, held within the Cassandra Database, which is installed on the BAE Systems
Chadderton computer system and managed, on the Nimrod IPT’s behalf, by the company. Data to populate the Hazard Log was obtained by BAE Systems and MOD personnel conducting Fault Tree Analysis, as well as dividing the Nimrod airframe into zones and physically surveying each zone to determine both singular and interacting hazards; a number of non-zonal hazards, such as failure of aircraft structure, were also investigated. From this analysis the hazards were given a ‘hazard probability’. Each hazard was then considered, in conjunction with all other hazards, in the context of one of 6 possible accident scenarios, allowing a probability to be assigned to each potential accident. That probability, when considered with the accident severity rating, produced a Hazard Risk Index for each accident sequence.

(2) The NSC analysis of Zone 614 (which contains the No 7 tank dry bay) identifies almost identical hazards to those determined by the Board. However, the NSC assessment of the risk imposed by those hazards is significantly different to that assessed by the Board. The NSC quotes the potential for fuel system leakage as ‘Improbable’, which is defined as ‘Remote likelihood of occurrence to just 1 or 2 aircraft during the operational life of a particular fleet’. The Board’s analysis of fault data indicates an average of 40 fuel leaks per annum for the Nimrod MR2 fleet between 2000 and 2005. Even in the absence of such data (which is not easily extracted from the sources) a number of incident reports occasioned by fuel leaks have been raised over the years, including one in which leaking fuel falling on the cross-feed duct began to smoke. The NSC states that the cross-feed duct is only pressurised during engine start, not taking into account the lengthy periods it can be pressurised (at a working temperature of up to 420 °C) when feeding the SCP. Furthermore, the NSC notes, as mitigation for the Zone 614 hazards, the provision of an aircraft fire detection and suppression system: neither exist within Zone 614. These inaccuracies led to an overly optimistic assessment of the hazards related to Zone 614, which in turn affected the assessment of the probability of the loss of an aircraft to an uncontrolled fire/ explosion – given as ‘Improbable’. In its examination of the NSC the Board focussed principally on those areas of relevance to XV230’s loss, but noticed a number of other inaccuracies, not directly related to the investigation. Had the NSC’s inaccuracies been noticed earlier, the Board considers that a more intense review of the hazards concomitant on airframe fuel leaks might have been instigated. Moreover, the higher assessed risk, which
necessarily would have been attributed to such a hazard, would have required sanction at a higher level of management, or active mitigation, such as not using the SCP.

(3) The NSC, released in 2005, reflects a positive desire to identify and reduce the risks of operating the Nimrod. Indeed, the risks highlighted in this discussion have been present since the Nimrod entered service (although the SCP was only introduced when the Nimrod MR2 entered service). Nonetheless, the Board considers that the overly optimistic hazard/risk categorization of the potential threat to the aircraft caused by the collocation of fuel and hot air system components within the No 7 tank dry bay was a Contributory Factor in the loss of XV230.

33. Maintenance.

a. XV230 underwent a Major maintenance at the end of 2004. The aircraft had a Primary maintenance in 2005 and was the first Nimrod MR2 to undergo Equalised One maintenance in May/July 2006. As a result of the introduction of the new Equalised maintenance schedule XV230 underwent an earlier maintenance intervention than would have occurred under the previous regime. Analysis of the aircraft maintenance records since the Major did not highlight anything out of the ordinary. Nine maintenance work orders were missing from the records, but the Board was able to determine that they were not related to work on fuel or air systems. Indeed, the only significant work to be undertaken on these systems was the reassembly of the fuel tanks and pipe work post Major and the rectification of leaks from the integral wing tanks (see para 39d). Only minor routine rectification work was conducted on the fuel or hot air systems in the intervening period up to the crash (with no work conducted post Equalised maintenance).

b. The Aircraft Maintenance Manual (Topic 1) does not contain guidance for the identification and fitting of elements of the fuel system. No instructions exist for the correct fitting of the locking rings to fuel couplings; it is possible to fit these incorrectly, such that the 2 metal halves of the coupling can partially undo and potentially leak. Two examples of an incorrectly aligned and locked fuel coupling were seen by the Board during a hangar inspection of Nimrod XV236. Local management and the IPT were notified of this fact and ground crew have been advised formally by the IPT of the possibility for error; the IPT is taking action to include assembly and security of fuel couplings within the aircraft Topic 1 publication. Furthermore, the aircraft Illustrated Spares Catalogue (Topic 3) does not comprehensively identify every coupling and its component parts. In many cases it is only possible to identify the
replacement items by noting the reference numbers of replaced equipment; this practice could lead to the fitting of incorrect parts due to misreading of eroded identification details and even the perpetuation of that misidentification during future maintenance.

c. Despite concern over some individual maintenance procedures, the absence of significant work undertaken on XV230’s fuel and hot air systems means that the Board can find no evidence that maintenance was a Cause or Factor in the loss of XV230.

34. Servicing. Interviews with ground engineering personnel in and analysis of engineering work records shows that the pre-flight preparation of the aircraft was conducted correctly. No significant engineering rectification had been undertaken on what was reported as a particularly serviceable airframe; in particular, no work had been undertaken on the fuel or hot air systems while the aircraft was on detachment. However, the MOD Form 700 (Aircraft Maintenance Log) for XV230, with all original signatures removed, was carried on the aircraft, as is standard practice within the Nimrod fleet, and was destroyed in the crash. As a result, the Board had to reconstruct the MOD Form 703 s (Limitations Log) and 704 s (Acceptable Deferred Faults) record sheets from the Maintenance Work Orders. This required extensive research, as a number of specialist Service modifications had been fitted to XV230 for Out of Area operations, and several gaps remain in this reconstruction. Nonetheless, from the data available no entries on Forms 703 or 704 contain information of relevance to the Board’s inquiry. The Board considered that there was no evidence to suggest that servicing was a Cause or Factor in the aircraft’s loss.

35. Operational Pressures. XV230 was lost Witness 4. However, in the period leading up to the aircraft’s final flight, the crew had not been required to work excessively long hours and neither did operational requirements necessitate the completion of an unusual or difficult flight profile on 2 Sep. While there were certainly significant pressures at times to achieve operational tasking, Crew 3 had not faced these pressures on this detachment. Requirements for the Nimrod MR2 force to man a Main Operating Base (RAF Kinloss) and 2 DOBs ( and Basra, Iraq) during a period of reorganisation of RAF structures and reductions in manpower had placed pressures on, in particular, the ground crew: it was difficult to maintain Harmony guidelines and it was necessary to deploy personnel with lower than optimum experience levels. In particular the engineering deployment contained 2 individuals with minimal recent experience of Nimrod operations, and one of these was the Engineering Officer. However, in both cases, the individuals had been given appropriate pre-deployment training and support to fulfil their roles in what was admittedly a challenging environment. The continued commitment to long-term operations from disparate locations is undoubtedly placing pressure on the Nimrod force, and diluting experience levels, but there is
no evidence that either its long or short-term effects were a Cause or Factor in the loss of XV230.

36. **Enemy Action.**

   a. *Improvised Explosive Device (IED).* Security provided by is extremely thorough Witnesses 19&20

The only occurrence which attracted comment on 2 Sep was the fact that the civilian escort to the van delivering rations to XV230 was reported to have left earlier than usual; however, as the rations driver was seen to remain in his cab and the rations were subsequently loaded successfully, this was not assessed as significant. It was confirmed that there were no reported security incidents on 1 Sep or 2 Sep. Witnesses 8&15

Furthermore, no explosion was reported by the crew and those elements within the bomb bay which survived the crash showed no evidence of explosive damage. Although the physical evidence is limited, the Board determined that there was no evidence of an IED having destroyed Nimrod XV230 and it was not a Cause or Factor in the loss of the aircraft. Exhibit 42

b. **Surface to Air Missile (SAM).** Although, as might be expected, a number of Taliban commanders claimed responsibility for the Nimrod’s loss, there is no evidence, from visual observations, of a SAM firing in the area. The Nimrod was observed by the Tristar tanker crew as it departed and that crew reported nothing untoward. The aircraft’s underside was scanned by Crew 3’s operator and he did not report any damage, other than the fire from the rear of the aircraft’s engines. Witnesses 29-31/ Exhibit 83

Furthermore, no explosion was reported by the crew. There is no evidence from the DARU of any damage to the aircraft’s engines. Examination of the evidence (photographs and available remains) has not shown any indication of missile strike. The Board determined that there was no evidence that a SAM was responsible for the fire which caused XV230 to crash and it was, thus, not a Cause or Factor in the loss of the aircraft. Exhibit 1

37. **Weather.** The possibility of weather either initiating the fire through lightning strike or contributing to the aircraft crash through poor visibility was discounted by the Board in view of pilot in-flight reports indicating extremely good weather conditions. Thus, the Board considered that weather not a Cause or Factor in the loss of XV230. Exhibit 7

Exhibits 44 and 45
38. **Hot Air Leak.** Bleed air from the port and starboard engines is connected by a crossfeed air pipe which runs through the bomb bay, just forward of the aileron bay. The crossfeed air pipe is routed from the engines to the bomb bay via the No 7 tank dry bays. From this crossfeed air pipe, a junction, in the starboard side of the bomb bay, takes air to the SCP system. This junction is immediately below the entrance from the bomb bay to the starboard No 7 fuel tank dry bay. When the SCP is switched on, valves at either end of the crossfeed air pipe and the PRSOV open to allow engine-bleed air into the pipe to supply the SCP. Evidence from the mission tape audio shows that the SCP was in use at the time of AAR and, therefore, probably since take off; thus the crossfeed air pipe was open along its entire length. The Board considered the possibility that a leak from this system could have disrupted part of the fuel system prior to AAR. The potential for extensive damage by engine bleed air was demonstrated following an incident in which a hot air pipe fractured on XV227. However, a repeat of the fault on XV227 is improbable, as the pipe which failed on XV227 was replaced throughout the fleet. Moreover, a leak of similar magnitude, from a different area, is unlikely to have gone unnoticed by the experienced FS Davies; indeed, at the altitude at which XV230 transited, the crew would all have noticed the pressure change concomitant on the loss of conditioning air. It is possible, however, that a smaller hot air leak from the crossfeed pipe could have degraded a part of the fuel system. Due to the large volume of hot air available from the engines such a leak could easily go unnoticed as it would not cause any loss of pressure to the cabin air supply systems. There is no evidence of any maintenance or repair work carried out on the crossfeed air system of XV230, which might have disturbed joints between sections of pipe. Although an adjacent hot air leak should be detected by the centre section overheat sensors, these did not activate during the XV227 incident, despite a proven large air leak. Nonetheless, the Board concluded that, while a large hot air leak was unlikely, a small leak could have caused the necessary disruption, but would have needed a considerable time to do so. Possible disruption to the following parts of the fuel system was considered:

a. **Fuel tanks.** The No 1 and No 6 tanks are close enough to the crossfeed air pipe to be potentially affected by a hot air leak. Both tanks consist of an outer aluminium shell within which a strong rubber bag holds the fuel; No 6 tank also possesses a double skin of aluminium and is within the pressure hull. Even at its highest temperature, hot air from the crossfeed air pipe would take a considerable time to disrupt the aluminium tank structure, particularly as any air leak is likely to have been small and the tank’s fuel would delay the effects of heating. Should the fuel tanks remain sound, but heat damage the internal bags, then the leaking fuel would drain either into the bomb bay, away from sources of ignition, or overboard through the interspatial drain, well aft of the seat of the fire. Similar conclusions can be drawn for the No 7
tank, which is an integral tank with no inner bag. The Board considered that, although possible, hot air damage to the fuel tanks was unlikely to be a Cause or Factor in the loss of XV230.

b. **Fuel pipes and couplings.** It is possible that a hot air leak could impinge on one of the fuel pipes or couplings in the No 7 tank dry bay. Each FRS fuel coupling, joining 2 pipes, consists of 2 metal halves with a rubber seal and 2 compression rings between them. Both the coupling shell and fuel pipes are constructed of steel, leaving the rubber seal as the weak point most likely to be compromised by a hot air leak. On XV227, these rubber seals suffered significant damage and were almost destroyed. The fuel feed system pumps for the No 6 and 7 tanks would have been off during XV230’s AAR; thus, with little pressure in the feed system, a feed system coupling leak is not considered a potential source of fuel. However, the refuelling gallery and all associated couplings in the dry bay area would have been pressurised during AAR, such that any seals which had suffered degradation due to a hot air leak would probably leak. Whilst the No 7 tank itself is unlikely to suffer structural damage from a small hot air leak, the seals on the front face (in the dry bay) which seal pipes and components entering the tank, would suffer the same fate as a pipe coupling if subjected to a hot air leak. The Board concluded that a leak of engine bleed air could have caused disruption to the fuel system, either to a fuel coupling on the refuel pipe work or to a seal on the front face of No 7 tank, leading to a fuel leak when AAR pressurised the system: thus, such a fault is a possible Cause of XV230’s fire and, thus, of the loss of the aircraft.