CONSIDERATION OF HUMAN FACTORS

58. The Board considered human factors with regard to the crew’s handling of the emergency and Annex P contains a detailed analysis of the Board’s reconstruction of possible crew actions from mission tape evidence. Crew 3 were faced with a series of complex and demanding emergencies. Throughout these events they acted logically and calmly, performing drills initiated by their captain in an attempt to save their aircraft. Although the need to use oxygen masks, following the aircraft’s depressurisation, complicated the means by which they could address the multiple emergencies, the crew persevered with every means at their disposal to quell the fire. Despite the seriousness of the situation they also ensured that their 2 army and marine colleagues were provided with oxygen. Nonetheless, this emergency illustrated the difficulty of conducting aircraft drills when crewmembers are restrained in their movements by the need to connect to an oxygen supply. The speed with which the pressure hull was breached highlights the need for all crews to consider seriously the potential problems when conducting emergency drills in such situations. The report from , which provided information about the fire on the wing, emphasises the need to gather data from all sources, to provide information on damage to aircraft external surfaces. Crew 3 needed only to assist 2 non-crew members; the complications imposed by being on oxygen could restrict another crew’s actions in dealing with a larger number of passengers. Furthermore, the same restrictions would make it extremely difficult to retrieve the spare oxygen bottle at the rear of the aircraft. The loss of the air engineer’s intercom for approximately one minute during the emergency removed a key element from the crew’s ability to analyse the emergency and conduct appropriate drills. However, the remainder of the crew clearly began to conduct the correct drills while he cured his intercom problem. The Board considers that Crew 3 acted in a most professional manner throughout and none of their actions contributed to the incident.

COMPLIANCE WITH ORDERS AND INSTRUCTIONS

59. All relevant orders and instructions were complied with.

SUMMARY OF CAUSES AND FACTORS

60. Causes. As the Board was unable to investigate XV230’s wreckage at the crash site and it proved impossible to recover more than a few small components from the aircraft, the Board has been unable to determine positively the source or cause of the fire which led to the loss of XV230 and its crew. Nonetheless, through investigation of the limited data available, the Board was able to deduce the most probable location of the fire, a number of probable causes of that event and factors which possibly contributed to it:

a. The escape of fuel during AAR, occasioned by an overflow from No 1 tank, or a leak from the fuel system (fuel coupling or
pipe), led to an accumulation of fuel within the No 7 tank dry bay. Although of a lower probability, the fuel leak could have been caused by a hot air leak damaging fuel system seals.

b. The ignition of that fuel following contact with an exposed element of the aircraft’s crossfeed/SCP pipe work.

61. **Contributory Factors.**

   a. The age of the Nimrod MR2’s non-structural system components.

   b. Nimrod MR2 maintenance policy in relation to fuel and hot air systems.

   c. The lack of a fire detection and suppression system within the No 7 tank dry bay.

   d. The fact that hazard analysis did not correctly categorize the potential threat to the aircraft caused by the collocation of fuel and hot air system components within the No 7 tank dry bay.

   e. The formal incorporation of AAR capability within the Nimrod did not identify the full implications of successive changes to the fuel system and associated procedures.

62. **Aggravating Factor.**

   a. The loss of flying controls through fire damage to the hydraulic systems or cables and pulleys.

63. **Other Factors.** Nil.

**OBSERVATIONS**

64. The Board observed that:

   a. The recovery operations at XV230’s crash site by the Canadian and UK contingents, assisted by US personnel, were conducted with considerable skill and fortitude in an exceptionally demanding and distressing situation.

   b. Changes to RAF Kinloss’ management structure as a result of Project Trenchard removed the So1 engineer (OC Engineering Wing) from the station structure. Engineering personnel are now distributed between the station’s 2 remaining wings under non-specialist leadership; QR640 responsibility is delegated to a squadron leader. Both operational and engineering witnesses believed that this change had had a negative effect on availability.

Witnesses 32-34
c. Service training courses were perceived by a number of witnesses no longer to impart the skill of hand and depth of knowledge necessary to maintain an aircraft built around a design philosophy now some 40 years old. This, combined with a tautly-manned engineering establishment and a recent outflow of skilled personnel, has led to an effective dilution of engineering skills, although there is no evidence that this contributed to the loss of XV230.

d. Some Nimrod aircraft at both DOB and RAF Kinloss had elements of the acoustics mission equipment removed and the resultant voids had been masked with cardboard, held in place with tape. The Nimrod IPT has stated that there are sufficient acoustics systems to make such removal unnecessary, thus there is no need to provide blanking plates.

e. Following the loss of XW666 the BoI recommended the incorporation of position and voice recording within the Nimrod DARU. This was not enacted.

f. Other aircraft types in the MOD inventory use fuel seals similar to those fitted on the Nimrod.

g. The body bags, which had been provided by the US mortuary at Kandahar and manufactured in the USA (NATO Stock No 9930-01-3316244), were not provided with impermeable membranes.

h. AAR refuel rates in the dynamic simulator are not realistic as they give a fixed refuel rate to each tank, regardless of the number of tanks being filled. This leads to a false impression of real time refuel rates towards the end of an AAR uplift.

i. The Board noted that, while BAe had concluded that individual pressure surges of less than 120 psi were not significant, no studies had been conducted on the cause of pressure surges or on their potential cumulative affect on an aircraft’s fuel system.

j. The Board had to travel to theatre without a DASC post-crash pack-up thereby placing great strain on IT and secure communications during the initial investigation. Valuable time was lost resolving the resulting problems.
65. **RECOMMENDATIONS**

a. **Policy.**

(1) The Nimrod Maintenance Policy is reviewed to ensure that maintenance procedures reflect the increasing age of the aircraft.

(2) The Nimrod Ageing Aircraft Audit is reviewed to include aircraft systems. This work should be incorporated within the review of Nimrod maintenance policy.

(3) The Nimrod Safety Case is reviewed, reassessing the factual data used for interpretation and categorisation of hazard and risk. The review should include widespread operator (air and ground crew) involvement. This work should be incorporated within the review of Nimrod maintenance policy.

(4) A safety review of the Nimrod fuel and hot air systems is completed. In particular the safety review should consider the suitability of corrective maintenance for these systems. The review should also consider mitigation of the risk of fire and hot air leaks within airframe hidden compartments, such as the No 7 tank dry bay and the Rib 1 landing; mitigation might involve introduction of fire detection and suppression systems, fire retardant coatings, or a change in procedures, which reduces the risk of fire. Nimrod operators (air and ground crews) should be involved closely with the review. This work should be incorporated within the review of Nimrod maintenance policy.

d. **Fuel System.**

(1) A life for the FRS Series 1 fuel seal be determined, based on the designer’s recommendation that fitted seals are replaced after 25 years.

(2) A maximum installed life for fuel seals of other material types is determined.

(3) A one-off inspection of the integrity of each Nimrod’s fuel system, between Ribs 3 starboard and port, be conducted with access panels removed and the system pressurised. The inspection is to check for leaks, physical damage and is also to include visual confirmation that fuel couplings have been assembled and locked correctly. This inspection will establish a baseline pending action on other recommendations.
(4) An inspection regime for fuel seals be initiated as recommended by Eaton Aerospace (para 32a(2)). The inspection should be a visual check of the fuel coupling, in-situ and under pressure, with panels removed. In view of the potential age of some Nimrod fuel seals this inspection should be annual, until a life is determined for the seals and any seal replacement programme is complete.

(5) A procedure is developed to pressure test the fuel vent system at the fuselage to wing interface.

(6) Detailed instructions for the correct fitting and locking of FRS couplings and seals be incorporated formally within the Nimrod AMM and publicized widely.

c. **Hot Air System.** Existing limitations, prohibiting the use of the SCP and of the cross-feed pipe in the air be continued, unless: the pipe insulation is modified in such a way that the pipe cannot act as an ignition source; the study into corrosion within cross-bleed pipes, undertaken following the hot air leak on XV227, is completed and its recommendations acted upon; a hot air leak detection system capable of detecting any leak within the cross-feed pipe and SCP (to the venturi) is fitted.

d. **AAR.**

(1) Nimrod AAR procedures are reviewed in the light of the Board’s report, to establish appropriate levels and rates of refuel, which will prevent overspill of fuel from tanks.

(2) A study be initiated to determine the cause of pressure surges during AAR and their long-term effect on aircraft fuel systems.

(3) A statement specifying that the maximum normal operating pressure of 50 psi during AAR be reintroduced into the Nimrod ACM.

(4) AAR refuel rates in the dynamic simulator are changed to reflect actual refuel rates to provide more realistic training.

e. **Operational.**

(1) Existing limitations, prohibiting the use of the No 7 fuel tanks, introduced following the loss of XV230, be discontinued.
(2) A study be undertaken into the utility of parachute escape on the Nimrod MR2.

(3) Nimrod STANEVAL consider the lessons identified at Annex P and their potential impact on crew emergency procedures.

(4) The port rear emergency oxygen bottle is relocated to a more central position, or another oxygen bottle is provided in this position.

(5) Nimrod STANEVAL consider the lessons identified at Annex P and their potential impact on crew emergency procedures.

f. **Aircraft Modification.**

(1) The design of No 1 fuel tank is reviewed to reduce the effect of asymmetric filling.

(2) The outlet pipes for fuselage fuel tank blow-off valves be modified to ensure that blown-off fuel cannot run down the exterior of the fuselage.

(3) The connections of the No 1 tank vent pipes be modified to reduce the risk of fuel leakage.

(4) The drainage of the lower panel in the No 7 tank dry bay be improved to prevent any accumulation of fuel.

(5) A crash-protected means of recording aircraft position and intercom voice is introduced to the Nimrod.

g. **Post Crash Management.**

(1) The Defence Aviation Safety Centre (DASC) should investigate the provision of details of type specific emergency equipment (ADR, etc) and key internal components (for example the ADR tape unit and housing) on their website to enable Post Crash MOD Incident Officer (PCMIO) to provide guidance to search teams.

(2) Instructions for PCMIO are revised to provide guidance when attending crash sites that are likely to become inaccessible.

(3) Instructions for PCMIO at crash sites which are likely to become inaccessible should include advice to make every effort to ensure the widest possible photographic
coverage of the crash site, at the highest possible resolution. This should take priority over all other tasks for any photographic team.

(4) DASC should increase their current stock of post-crash BOI kits.

(5) Body bag fluid proof liners should be stored within the outer ruggedised bags in crash kits to ensure that they always arrive on scene together.

h. Engineering.

(1) The Nimrod Mod Form 700 Sections 2 and 3 (F703/F704) should be copied and retained before the document is carried on the aircraft.

(2) The use of non-approved mission system panel blanks be discontinued.

i. Personnel.

(1) Consideration be given to reinstating the SO1 engineering post in Forward at RAF Kinloss to provide senior oversight of station engineering matters.

(2) A review of engineering training is undertaken to identify those areas which, while relevant to Nimrod capability, are not encompassed within existing formal training courses.

ACKNOWLEDGEMENTS

66. The Board wishes to acknowledge the extensive assistance given by all of the organisations and individuals identified at paragraph 20. Their expertise and commitment have been fundamental to the Board in their attempts to explain the tragic loss of XV230 and its crew. The Station Commander and personnel of RAF Kinloss, who, at a time of great strain and considerable workload, were unstinting in the support of the Board’s activities, were also central to the compilation of this report.

President  Wg Cdr
Members  Sqn Ldr
                Sqn Ldr  Date
Annexes:

A. Diary of Action.
B. Details of Aircrew Occupants.
C. Details of Aircraft.
D. Cockpit Warnings.
E. Previous Nimrod Accidents and Incidents.
F. Analysis of Canadian Sighting of Nimrod XV230.
G. No 7 Tank Dry Bay.
I. Fuel System Maintenance History Analysis.
J. Fuel Coupling and Seal Consumption.
K. Air Systems.
L. AAR System Incorporation.
M. Technical Description of No 1 Fuel Tank and Ground Refuelling.
N. Analysis of the AAR Refuel of XV230.
O. Flying Control and Hydraulic Systems.
P. Description of Crew Actions during the Emergency.
Q. List of Exhibits.
R. List of Witnesses.
S. Glossary.
BOARD’S FURTHER INVESTIGATION INTO SPECIFIC ISSUES

PART 2A

CONVENING AUTHORITY DIRECTION TO THE BOARD FOR FURTHER WORK

INTRODUCTION

1. Following a meeting of subject matter experts held at HQ 2 Gp on 24 May 07 to discuss the findings of the Board of Inquiry and ensure all possible avenues of investigation had been explored, AOC 2 Gp determined that there were several areas that would benefit from further examination. Accordingly, the Board was tasked to amplify and clarify the findings presented to the Convening Authority on 20 Apr 07 paying particular attention to:

a. Determining, in the light of new information, whether fault trends associated with fuel system components had been analysed effectively, to validate the suitability of the Nimrod maintenance policy.

b. Clarifying why electricity was discounted as the likely source of ignition that led to the fire suffered by XV230.

c. Providing a more explicit argument regarding the most probable sources of fuel and ignition.

d. Presenting the Nimrod fuel seal failure rate against flying hours rather than as a simple chronological plot.

e. Identifying those components whose age, in the Board’s opinion, had been a possible contributory factor to the accident; and clarifying the relationship between the age of the components and their condition.

f. Amending the conclusions as appropriate, if different causes and/or contributory factors were identified as a result of this additional work.

The findings were to be an addendum to the original F412 and be contained within the BOI as Part 2A.

2. **Composition of the Board.** The membership of the Board remained as originally convened.

MATTERS ARISING FROM ADDITIONAL TASKING
3. **JAP 100A-01 Analysis of Fault Trends.** In its main report the BOI noted at para 32a(5) that ‘there is no evidence that the maintenance data for the fuel system at component level was ever analysed to inform maintenance policy’ in accordance with JAP100A-01. On 7 Jun 07 the Board was provided with fresh evidence that a full Nimrod maintenance schedule review had been carried out in 2001 using Reliability Centred Maintenance (RCM) methodology and had been used to inform maintenance policy. The RCM review searched maintenance records for the Nimrod fleet for the period 1995 to 2000, to identify failure trends, in order to confirm the appropriate level of maintenance required for the Nimrod. The analysis team not only examined formal records, but also interviewed maintenance personnel in an attempt to identify areas of concern. Despite this widespread consultation, the team did not identify any fault trends within the Nimrod fuel system. Although the RCM team used similar data to the BOI, it had a much wider remit and the increase in fuel seal leaks may have been masked by the sheer quantity of other data (in the BOI’s analysis fuel system leaks represented only 10% of the total faults recorded with the fuel system over a period of 23 years). The Board acknowledges, however, that this new evidence confirms that maintenance data for the fuel system was analysed as required by JAP100A-01.

4. **Fuel System Inspections.** Work undertaken by the Board to investigate the analysis of maintenance data above revealed 2 additional checks of the fuel system undertaken during periodic maintenance. Although not specifically tasked to consider this matter the Board was of the opinion that the fact that a greater range of fuel system inspections are conducted was of relevance in that it illustrated a wider range of such checks than suggested by the main report; the additional inspections are:

   a. **Fuel leak mapping.** Before entering periodic maintenance a Nimrod’s fuel tanks are filled with fuel and left for 24 hours, to see if fuel leaks become evident. Known as fuel leak mapping this technique is aimed primarily at detecting fuel tank leaks, but the procedure can identify leaks in other areas of the fuel system. This process is followed by the zonal inspections described at para 32a(1) of the main report.

   b. **Nitrogen pressure testing.** Following periodic maintenance in which elements of the refuel/defuel system are disturbed pressure tests using nitrogen are performed to confirm correct assembly and detect system leaks.

5. **Combustion Report – Electrical Ignition.** The main BOI report and supporting QinetiQ combustion report do not explain in detail the full rationale behind discounting electricity as a likely source of ignition. QinetiQ was tasked with providing a more detailed explanation for this decision, which is contained in Annex B to Issue 3 of the QinetiQ Combustion Analysis. In summary, electrical ignition requires either a
low-energy spark with a very precise mixture of fuel vapour and air, or a very high-energy spark within a less well prepared mixture (the energy required from the spark will increase with altitude). While the former has occurred in sealed containers such as fuel tanks, it is unlikely in an area such as the No 7 tank dry bay, which is vented and open to the much larger bomb bay. The latter scenario is very unlikely at the altitude XV230 was flying as there are no electrical components with sufficient energy within the No 7 tank dry bay.

6. **Sources of Fuel and Ignition.** The BOI F412 Main Report Discussion of Factors is arranged in chronological order and thus the central discussion of the means by which the Board determined the most likely sources of fuel and ignition is dispersed over a number of paragraphs. In view of the complexity of the argument, a short summary of the means by which the Board determined the most likely sources is contained below:

a. **Sources of Fuel.** Only 2 possible sources of fuel were evident: overflow from No 1 tank during AAR or a leak from the fuel system. Circumstantial evidence suggested that the former was a probable fuel source: the fire’s proximity in time to XV230’s AAR serial, the conjunction of the SCP’s failure with the predicted time for blow-off and the fact that No 1 tank overflow had occurred during recent sorties on XV230 (although the first 2 events could also indicate a significant leak from a fuel pipe or coupling).

However, none of the evidence suggesting No 1 tank overflow was conclusive and the Board, therefore, also considered the 3 elements of the fuel system (fuel tanks, pipes and couplings) as possible sources of fuel. Fuel tank leaks were eliminated, as such leaks tended to vent to atmosphere, or to the bomb bay, which contains no viable ignition sources; a leak from a pipe was possible, but statistically unlikely; fuel couplings had shown an increase in leakage rates and were present in and close to the No 7 tank dry bay, in locations which would easily supply fuel to the likely ignition point. Although couplings rarely suffered catastrophic failure, significant leaks had been known and such an occurrence during refuelling could have allowed the escape of sufficient fuel to support the fire, particularly from the refuel gallery whilst pressurised during AAR. The disruption of an element of the fuel system by the failure of a hot air pipe was also considered possible, but unlikely. After much consideration the Board decided that the 2 probable sources of fuel were either No 1 tank overflow or leakage from a fuel coupling, but it was unable to determine objectively which of the 2 was the most likely. The proximity in time of the fire’s ignition to the AAR serial supports either as being probable sources of fuel.

b. **Ignition Scenarios.** The Board was only able to identify 3 possible ignition scenarios: the cross feed pipe failing, allowing hot air to disrupt a fuel coupling and then the leaking fuel being ignited.
by the fractured ends of the cross feed pipe; a faulty electrical component causing a spark which ignited fuel vapour concomitant on one of the leaks described above; or escaped fuel touching the SCP/cross feed hot air pipe and spontaneously igniting. The first ignition scenario was discarded on the grounds that the crew would have detected a major hot air leak and that a minor leak would have had to occur in close proximity to a fuel coupling to cause sufficient damage. While considering the second scenario the Board noted that electrical wiring in the No 7 tank dry bay on other Nimrods was in good condition. Moreover, the Board was advised that a high-energy electrical spark would be necessary to ignite a fuel/air mix in the No 7 tank dry bay and there were no such sources within this area. Also, achieving the correct fuel/air mix in the vented No 7 tank dry bay, especially at the altitude at which XV230 was flying, made electrical ignition very unlikely. On balance the Board decided that while an electrical source of ignition was possible, though unlikely, a more likely source lay within the No 7 tank dry bay. The cross feed/SCP pipe in the No 7 tank dry bay can reach temperatures in the order of 400 °C when operating, which can cause auto ignition of fuel in under a minute. Although the majority of this pipe is insulated there are short sections in some aircraft not covered by insulation and also insulating blankets in which it is possible for fuel to accumulate and be held against the pipe. The SCP had been operating during XV230’s refuelling operation and a section of the SCP pipe lies at the lowest point in the No 7 tank dry bay; this section is covered by an insulating blanket, although in most aircraft there is a short section of exposed pipe immediately adjacent to the blanket. The Board believed that fuel leaking in this area would gravitate towards this point and ignite against the pipe, possibly after soaking under the insulation blanket; thus the SCP/cross feed pipe represented the most probable point of ignition.

Note that the Board is not using the term ‘most probable’ in any specifically defined engineering/scientific sense. It should be seen as being synonymous with the phrase ‘most likely’.

7. Seal Failure Rates. The Board was asked to present the fuel seal failure rate in terms of flying hours, in order to inform studies into the failure mechanism, and this information is attached at Annex A to this report. The data supports previous conclusions, showing an increase in fuel coupling leaks.

8. Age as a Factor. The Board was tasked to identify those components for which it considered their age to have been a possible Contributory Factor to the accident. The Board noted that the only 2 components in which it had identified age as a possible contributory factor were the fuel system seals and the SCP/cross-feed pipe insulation; the age
of the airframe was not a factor in the loss of XV230.

9. **Clarification of the relationship between the age of the components and their condition.** The Board was asked to clarify the relationship between the age and the condition of the 2 components identified in the previous paragraph. Analysis has shown that there has been an increase in leaks from the Nimrod’s fuel system elastomeric seals over time. This had not been realised prior to the Board’s Inquiry. The Board found no evidence of studies indicating that elastomeric seals were susceptible to failure due to age, although the manufacturer of the most commonly used elastomeric seal on Nimrod has recently stated that they should be considered for replacement after having been fitted for 25 years. Both the manufacturer and MOD expert advice noted that there might be a number of reasons for the increase in seal leakage. An investigation into this issue was outside the Board’s resources, but, in view of its importance and wider implications, the Nimrod IPT has commenced an investigation into the life of such seals; this investigation is not yet complete. The other component considered by the Board was the cross feed pipe insulation, which was observed in some areas of other Nimrods to be compressed; this may have been caused by manual means (physical contact during maintenance), or possibly because of thermal or pressure cycling. The compression would appear to have occurred over a period of time; however, this condition does not appear to be the result of a natural ageing process, but of the length of time that the component has been fitted. The Board’s conclusion is that the condition of the 2 components was linked to their age in terms of “showing the effects of the passage of time”. The Board believes that this could equally be expressed as “the condition of the components associated with the time fitted”.

10. **Amendment to Conclusions.** The Board considered that it should reconsider 2 Possible Contributory Factors following its additional work:

   a. **Fuel System Maintenance Policy.** The additional information presented to the Board illustrated clearly that fault trends had been analysed to inform maintenance policy and that a more comprehensive system of fuel leak checks existed than was previously considered by the Board. Nonetheless, none of the new data altered the fact that the rate of fuel leaks had increased and that the increase had not been detected; thus, in this one area, fuel system maintenance policy remained a possible Contributory Factor. It should be noted that fuel system maintenance policy is only a Contributory Factor if the fuel release was occasioned following a fuel system leak.

   b. **Age.** The Board considered that the condition of the fuel seals and crossfeed pipe insulation was linked to the length of time that they had been fitted and through this fact, to their age. The

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Board had been tasked specifically to consider age and was unable to exclude it as a possible Contributory Factor. Therefore, acknowledging the close linkage with the components’ condition as a result of time fitted, the Board believed that the age of the aircraft’s fuel seals and crossfeed pipe insulation remained a possible Contributory Factor.

President ___________________________ Wg Cdr
Members ___________________________ Sqn Ldr
_______________________________ Sqn Ldr Date

Annex:

A. Fuel System Leaks Per 1000 Flying Hours.

Exhibits:

A3. Minutes of a Meeting held at AAIB on 29 Mar 07.
A4. Revised Declaration of Design and Performance FRS110 Pipe Connection (Coupling) Series 1 dated 7 Jun 07.