FUEL SYSTEM LEAKS PER 1000 FLYING HOURS

1. **Introduction.** Annex I of the main BOI report details the analysis of the fuel system maintenance history for the years 1984 to 2005\(^1\). This Annex illustrates fuel system leaks per 1000 flying hours (FH).

2. **Analysis of Data.** With the decrease in fleet size over the sample period, the number of total fleet flying hours has also reduced. When the fuel leak rate per 1000FH for fuel system couplings and seals (Table 1 and Figure 1) is examined, there is a continual increase from 0.5 leaks/1000FH in the 1980s, increasing to 1.5/1000FH in the 1990s and to 3.5/1000FH in the 2000s. The data for pipe leaks shows a low and stable rate of less than 0.5/1000FH. The leak rate from tanks has also shown an increase (Table 1 and Figure 2), which appears to have stabilised over the past 10 years at 2/1000FH. However, it must be cautioned that although the data was filtered to exclude wing tanks, this cannot be guaranteed and there has been significant work carried out to reduce wing leak on the MR2 fleet over the past couple of years.

3. **Conclusion.** The data shows the same increasing trend (as identified in the main report) in fuel leaks from couplings and seals.

Appendix:

1. Fuel System Fault Rate per 1000FH.

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\(^1\) Data from 1983 to 2006 was supplied from the Maintenance Data System, although as the data for 1983 and 2006 appeared incomplete only that for the period 1984 to 2005 was used for analysis.
Figure 2 - Graph of Fuel Leak Fault from Fuselage Tanks per 1000 Flight Hours by Year

EMBARGOED UNTIL 1330 4 DECEMBER 2007
INTRODUCTION

1. The Board of Inquiry (BOI) were confronted with a significant challenge in establishing the events that lead up to the crash of XV230. Their inability to examine the crash site, coupled with an almost total lack of mechanical evidence, imposed severe constraints on the lines of enquiry that were open to them. Their achievements are, therefore, notable for their completeness, tenacity and determination to ascertain as best as possible what might have caused the fatal accident on 2 Sep 06. That said, given the limitations under which they were working, I believe establishing with absolute certainty the precise source or cause of the fire, to be impossible.

COMMENT ON FINDINGS

2. Comment on the BOI’s findings in terms of causes and factors, is, in this instance, necessarily predicated on acceptance that the seat of the fire has been correctly identified. Having examined the available evidence, I am content the Starboard No 7 Tank Dry Bay is the most likely origin of the fire; furthermore, I believe both the bomb bay and the No 3 engine can be discounted and that the starboard Rib 1 landing is highly unlikely to be the seat of the fire. Hence, I am content that the Board’s route of investigation was sensible and I am also happy that their analysis of causes and factors is logical, although I do not fully agree with their findings.

3. Causes. I concur with the BOI’s findings in their determination of the probable and possible causes. Now that the mechanics of the No 1 Tank are fully understood, it is evident that overflow of fuel during AAR from the No 1 Tank Blow-Off Valve is a phenomenon that may have occurred since the inception of AAR on the Nimrod MR2. I would also reinforce the BOI’s assessment that a fuel leak occasioned by a hot air leak damaging a fuel seal seems the least probable source of fuel for the fire. When placed against the No 7 Tank Dry Bay as the origin of the fire, the QinetiQ combustion analysis at Exhibit 30 is compelling evidence that leaves little room for doubt that the cross feed or SCP pipe assembly was the probable source of ignition.

4. Contributory Factors. I agree with the BOI findings with respect to the lack of a fire detection and suppression system in the No 7 Tank Dry Bay. I would also note, however, that the portion of the bomb bay fire detector wire that runs close to the 7 Tank Dry Bay (which provided the first indication of a problem with the aircraft) can in no way be considered an integral fire detection system for the 7 Tank Dry Bay: this fire detection system is incapable of providing a location of a fire within or around the bomb bay. I also have a number of observations and comments over the other possible contributory factors identified by the Board.

   a. **Age of Non-Structural Components.** While noting in the addendum to their report that the BOI have clarified their conclusions on this question, I disagree that age was a contributory factor. The Board’s additional work, which again focuses on fuel seals and the SCP/cross-feed pipe insulation, draws the conclusion that ‘condition’ is
linked to the length of time such seals are in situ. While I agree that age will not
improve the condition of these components, condition remains the central piece in this
argument and the condition of fuel seals and insulation could be affected at any time
during the aircraft or a component’s life. I can not, therefore, agree with the BOI; my
assessment is that the ‘condition’ of the Nimrod MR2’s non-structural components,
specifically fuel seals and the SCP/cross-feed pipe insulation, was a possible
contributory factor.

b. Nimrod Safety Case/Hazard Analysis. From the evidence presented by the
BOI, I believe the Zone 614 portion of the NSC the most important possible
contributory factor in the loss of XV230. The BOI has correctly identified a number
of fundamental errors in the hazard analysis and I would add that even when the SCP
was not operating, standard procedure was for the engine cross-feed pipe to remain
pressurized, whenever engines were shut down for fuel economy, in order to affect an
immediate air-assist engine start should an emergency make it necessary. The errors
contained within this portion of the NSC, be they over operating practice, aircraft
design or the probability of fuel leaks are fundamental, and without doubt lead to an
incorrect assessment of risk that perpetuated the likelihood of fuel coming into contact
with an ignition source in Zone 614 – that is, the SCP/cross-feed pipe.

c. Nimrod MR2 Fuel System Maintenance Policy. Subsequent to their initial
findings, the BOI were asked to determine whether fault trends within the Nimrod
MR2’s fuel system components had been analysed effectively, in order to validate the
suitability of Nimrod maintenance policy. New evidence clearly indicated that fault
trends had been analysed and hence, the direction contained within JAP 100A-01 has
been followed. That said, the analysis was not effective as it did not identify the
increase in fuel leaks that the BOI uncovered. Given that the Nimrod MR2
maintenance policy was, in part, based on an incorrect hazard analysis in the NSC
(paragraph 4b), the probability of fuel coming into contact with the SCP/cross-feed pipe was
therefore increased. In the instance that the source of the fuel for the fire on XV230
was a fuel system leak, the Nimrod MR2 maintenance policy is a clear contributory
factor.

d. Incorporation of the AAR Capability on to the Nimrod MR2. Prior to
2 Sep ’06, the AAR capability on the Nimrod evolved through a number of equipment
installations and modifications, and procedural changes. In parallel, the Tristar tanker,
with an increased refuel rate, arrived in 1989. Annex L to the BOI’s report identifies a
number of important pieces of information that, while relatively innocent in isolation,
when linked together have serious implications. Hence, the Board found that formal
incorporation of the AAR capability was a possible contributory factor. Their
assessment, however, contains the caveat ‘did not identify the full implications of
successive changes’. Although I have no doubt that each stage of the development of
the Nimrod AAR capability as described in Annex L was appraised, at no point was a
holistic view, which looked to the past as well as the present, taken. I believe,
therefore, that a more correct caveat would be ‘did not identify the compound
implications of successive changes’. Although a subtle change, I believe it better
reflects the need for comprehensive monitoring of, and responsibility for, through life
aircraft development.
5. Aggravating Factor. I agree with the BOI.

COMMENT ON OBSERVATIONS

6. Many of the observations fall out with my remit. However, it is right that I comment on 3, if only to present an up to date picture.

a. RAF Kinloss Management Structure. The Kinloss management structure has now been revised to include an SO1 engineer. This individual now commands the Station’s Forward Support Wing and holds QR 640 responsibilities.

b. Non-Standard Blanking Plates. While the IPT is correct in it’s assurance that there are sufficient quantities of acoustics systems, the instance in question was wrapped up in the peculiarities of specific role equipment and insufficient acoustics systems being available in theatre. This is only offered as an explanation of the occurrence, and procedures have now been put in place to ensure that this does not happen again.

c. AAR Refuel Rates. All AAR qualified Air Engineers have been re-trained on AAR procedures by STANEVAL Air Engineer and reminded that refuel rates in the dynamic simulator are not fully representative. A software update will be required to provide more accurate simulation.

COMMENT ON RECOMMENDATIONS

7. I have a number of comments and observations on the recommendations made by the BOI. Where I have not commented, it can be assumed that I support the recommendation.

8. Policy. I agree with all of the BOI’s recommendations with respect to maintenance policy. In particular, I strongly support the recommendation that the NSC be reviewed with widespread ground and aircrew input. This approach should be adopted for all aircraft fleets in order to avoid misinterpretation or misunderstanding of operating practice and aircraft design leading to incorrect hazard analysis. As to the recommendation for a review of fuel and hot air systems, I would press that the main aim of any such review should be to remove or isolate potential ignition sources. All aircraft will leak fuel at some stage. The only feasible approach is, therefore, to focus on removing potential ignition sources.

9. Fuel System. While supporting the recommendation that a life for the FRS Series 1 fuel seal be determined, such a life should be based on an understanding of the failure mode and factors that promote degradation as these will determine when a seal is not fit for purpose rather than simply installed or shelf life.

10. Hot Air System. Given the limited life remaining for the Nimrod MR2, existing limitations on the use of the cross-feed pipe and the SCP should remain in place until the aircraft goes out of service.
11. **AAR.** AAR procedures have already been modified to more benign limits in terms of refuel flow rates and pressure, and tank refuel levels. Since these procedures were introduced, more than 35 sorties have conducted AAR without incident. That said, I agree these procedures should be formally reviewed against all AAR scenarios. While a study into the effect of pressure surges and their long term effect will have limited utility for the Nimrod MR2, if widened, such a study would benefit all AAR receiver fleets and should therefore be undertaken.

12. **Operational.** I do not believe that the fitting of parachutes on the Nimrod MR2 is practical. Available stowage space and, from personal experience of flying a multi-crew aircraft equipped with parachutes, sheer physical space to don a parachute are in my opinion insurmountable limiting factors for the Nimrod MR2.

13. **Aircraft Modification.** Given that AAR procedures have been modified in order to avoid the potential for No 1 Tank blow off valve operation or fuel to enter No 1 Tank vent pipes, and assuming the review recommended at para 11 provides full assurance over these, I see no reason to pursue the relevant modifications proposed. Likewise, the problems associated with asymmetric filling of the No 1 tank have also been mitigated. Given the source of ignition in the 7 Tank Dry Bay area has also been removed, I see no justification for modifying the 7 Tank Dry Bay lower panels.

**ADDITIONAL RECOMMENDATIONS**

14. **AAR restrictions.** Subsequent to 2 Sep 06 Service Deviation (SD) 132, which restricts the occasions under which AAR can be used on the Nimrod MR2, was issued. Given that all potential sources of ignition have been removed from around the refuel gallery and that AAR has been completed successfully on some 35 sorties without any activation of the No 1 Tank Blow Off Valve, consideration should be given to updating SD 132 such that AAR can take place on a routine basis. However, the 50 psi pressure test of the refuel system, articulated within Routine Technical Instruction 170, should remain in place.

**HUMAN FACTORS**

15. Crew 3 was an unusually experienced crew with 2 of the Nimrod Force’s most capable and knowledgeable aviators, Flt Lt Squires and FS Davies, on the flight deck. I knew and had flown on many occasions with both of them, as well as a number of the remainder of the Crew, and am not surprised that the evidence shows they all reacted in a highly professional and determined manner to the complex and demanding set of emergencies they faced.

**CONCLUSION**

16. Circumstance dictates that the BOI has been unable to positively determine the exact chain of events that lead to the loss of XV230. But for the fire on XV230 to occur, an ignition source and fuel had to be brought together. The genesis of the ignition source – the SCP/cross-feed pipe – can be traced back to the very origins of the aircraft. The Nimrod MR1 design introduced the cross-feed pipe for engine starts on the ground and in the air, while the Nimrod MR2 aircraft update brought the SCP into service. Subsequently, errors in the NSC/hazard analysis lead to an incorrect assessment of risk over the Starboard No 7 Tank...
Dry Bay and hence, an unprotected potential ignition source was not mitigated. The exact route of the fuel will never be determined absolutely. However, the incorporation of the AAR capability on the aircraft, combined with the lack of effective analysis within the Nimrod MR2’s maintenance policy, increased the likelihood of fuel coming into contact with the SCP/cross-feed pipe and a fire igniting in an area which is both unprotected and impossible to diagnose in the first instance.

17. The BOI are to be congratulated for the completeness they have achieved. Given the constraints that were forced on them, I am entirely content that they have met their Terms of Reference as best as possible. Subject to my comments above, their findings, while not absolute, are on the whole logical and supported by credible and compelling expert evidence which goes a long way towards removing doubt as to the precise cause and factors that lead to the loss of XV230 and its crew.

J B KESSELL
Group Captain
Station Commander

Date ____________________________
BOARD OF INQUIRY INTO THE LOSS OF NIMROD MR2 AIRCRAFT XV230 ON 2 SEP 06 – AIR MEMBER FOR MATERIEL’S COMMENTS

INTRODUCTION

1. The Board of Inquiry (BOI) has produced a very thorough report and has made significant progress towards identifying the cause of this tragic accident. I can endorse their overall conclusion that the probable cause of the crash was the loss of structural integrity and controlled flight following a severe fire in the starboard wing root that did not arise from hostile action. However, given the very limited access to the crash site, it is clear that we will never know the cause of the fire with any certainty.

2. In my role as the Royal Air Force’s Air Member for Materiel and its most senior Engineer, I am therefore keen to ensure that in the absence of such certainty, and given the remaining in-service life of this aircraft, we exercise sound judgement to target those measures most likely to assure the integrity of the current Nimrod fleet, accepting that some measures will be across a broad front to cover a range of perhaps less probable, but still possible causes. Whilst I concur with the general thrust of the BOI findings I am unable to agree with all of their conclusions or all of the Station Commander’s remarks, to the extent detailed in the following paragraphs. Where I make no comment either I concur with the findings, or they are out with my remit.

GENERAL POINTS

3. As with all other aircraft, combustible material (such as fuel) and potential ignition sources are present throughout the Nimrod and the avoidance of fire is dependent upon one being kept from coming into contact with the other. Reducing the occurrence of fuel leaks is clearly desirable and the increased leak rates indicated by the data considered by the BOI are worthy of further examination to substantiate the trend, determine possible causes and effect remedial action. However, as the Station Commander remarks, fuel leaks on aircraft are inevitable and we cannot depend upon eradicating them entirely. We must not, therefore, allow ourselves to be seduced into a belief that reducing fuel leaks, for instance by applying a finite life to installed seals, would necessarily yield improvements in aircraft safety unless there is clear evidence to support this. Indeed, through the necessary associated disturbance to other aircraft systems (for example electrical, hydraulic, flying control) as well as disturbance to the fuel system itself, experience shows that such action may actually introduce more problems than it solves, thereby having a detrimental effect on safety. Instead, primacy should be afforded to taking action to mitigate any consequential hazard to the aircraft arising from a leak.

COMMENTS ON FINDINGS

4. I am satisfied that the BOI has presented sufficient evidence to discount the Port Wing, the Bomb Bay and the Starboard Engine Bay as locations for the origin of the fire and to substantiate their finding that the source of the fire was most probably in the area of the Starboard Number 7 Tank Dry Bay.
Causes

5. The BOI concluded there to be two probable sources of fuel, a leak from a fuel coupling seal failure or Air-to-Air Refuelling (AAR) overflow via the No 1 Tank Blow-off Valve, but were unable to determine which of these is the most likely. Having considered the evidence presented by the BOI, I believe AAR overflow to be the most likely for the following reasons:

   a. AAR overflow is a design characteristic which is not predicated on the presence of a fault.

   b. The close proximity of the time of the fire with the completion of AAR and the observed Supplementary Conditioning Pack (SCP) shut down.

   c. Other cases of apparently similar fuel overflow during AAR in similar circumstances shortly before and after the loss of XV230.

6. I am satisfied that actions now taken to change AAR procedures are sufficient to ensure that the conditions needed for overflow to occur are avoided.

7. Whilst it is in my view the less likely of the two sources of fuel, I agree that a fuel leak from either a coupling or fractured pipe (or indeed as a consequence of a hot air leak) cannot be excluded as a possible source of the fuel. Inspections introduced by Routine Technical Instructions (RTIs) are being undertaken to confirm the integrity of the fuel systems and possible sources of ignition, and further activities are underway to determine whether changes to the maintenance of fuel seals would reduce the likelihood of leaks.

8. As to the ignition source, I agree that the hot air pipe bellows coupling associated with the SCP located in the pannier fairing immediately below the Starboard No 7 Tank Dry Bay is the most likely source of ignition. It must be recognised, however, that for auto-ignition to occur would have required the sustained presence of fuel giving rise to vapour within the No 7 Tank Bay. This would tend to rule out minor fuel system leakage. Prohibiting use of the SCP removes this ignition source but we must not allow ourselves to be convinced that consideration of other potential sources of ignition can thereby be excluded. This is especially important because ignition sources are more readily avoided than fuel leaks and therefore have a more prominent influence on improving aircraft safety. The current enhanced inspection regime is designed to mitigate any hazards arising from these, pending completion of an independent fuel system safety analysis.

Contributory Factors

9. I can find no direct evidence to support the linkage between aircraft integrity and the age of non-structural components (notably fuel seals and hot air duct insulation) ascribed by the BOI, or their condition as ascribed by the Station Commander. Equally, I accept that neither is there evidence that they can be entirely discounted as a contributory factor in the loss of XV230. Further work will therefore be necessary to enable informed
decisions on the long term remedial measures which might be necessary to supplement or relax those measures already put into place to assure the aircraft's safe operation.

10. Although the BOI has shown data that indicates that the rate of fuel leaks has increased, I do not agree that this supports the conclusion that fuel system maintenance policy is a contributory factor. Even if the fire had been occasioned by a fuel leak, as opposed to AAR overflow, concluding that the loss of XV230 would have been avoided by a preventative maintenance regime is flawed without evidential linkage between this, seal deterioration with age and a demonstrable ability to determine, with confidence, a finite seal installed life. Furthermore, even a finite installed life for seals could not guarantee eradication of fuel leaks because many factors contribute to seal failure. Despite ongoing investigations, we have no evidence with which to correlate installed fuel seal degradation with age. The Station Commander suggests that the fault trend analysis conducted as part of the maintenance policy review was not effective as it did not identify the increase in fuel leaks identified by the BOI. I do not agree with this conclusion. During the period reviewed, 1995 to 2000, there was a reported annual average arising rate of between 1 and 2 leaks per 1000 flying hours from fuel seals and couplings; a review of the data provided by the BOI for the previous 5 years would have given a similar overall result. Although this rate is an increase over that reported during the 1960s (between 0.4 and 1 leak per 1000 flying hours), it would not have been considered to be a high leak rate in an absolute sense considering there are over 400 fuel seals fitted to each aircraft. Moreover, in the absence of any air incident or serious fault reports to highlight any cases that were hazardous, the review would have made its recommendations purely on the basis of system reliability. It was therefore unlikely to have recommended a review of the fuel system maintenance policy, even if data had been reviewed over a 10- or 15-year period. As explained in my introduction, it should also be borne in mind that the very act of disturbing aircraft systems to replace fuel seals could, itself, be detrimental to system integrity and therefore on the evidence available to date, I am of the opinion that a corrective maintenance policy bolstered by the current enhanced inspection regime remains appropriate while more evidence is gathered.

11. The BOI has shown that hot air refraisal insulation has been allowed to deteriorate: this was not compliant with extant maintenance instructions in that no acceptable damage limits are defined. The correct procedure on finding damage would therefore be for a concession to be sought; clearly this has not been happening. In this respect this was a maintenance, rather than maintenance policy shortcoming. Although the BOI considered a hot air leak damaging a fuel seal as a possible but less probable cause, it should be noted that the insulation is there to reduce heat transfer rather than prevent hot air leaks. Nevertheless, I do agree that there is insufficient evidence to allow the hot air system maintenance policy to be dismissed as a possible contributory factor.

12. Whilst the proximity of the bomb bay fire detection system to No 7 Tank Dry Bay led to this providing the first indication of a fire to the crew, it is unclear whether the presence of a dedicated fire detection system in the No 7 Tank Dry Bay would have made a material difference to the crew’s ability to recover the aircraft. The difference that the presence of a fire suppression system within the Bay might have made is even more difficult to determine. Such a system would only be effective if its capacity exceeded the persistence of a fuel supply and any ignition source; expert evidence stopped short of concluding whether or not, in this case, its presence would have granted the crew the additional time
needed to land the aircraft. Given that the catastrophic failure occurred when only 14 miles or so from Kandahar airfield, I do agree, however, that the lack of fire detection and suppression systems within the No 7 Tank Dry Bay cannot be excluded as a possible contributory factor. Prohibiting use of the SCP and engine cross-feed removes the most likely source of ignition, thereby reducing the likelihood of fire in the No 7 Tank Dry Bay.

13. I do not agree with the BOI’s understanding of leak rates being synonymous with hazard likelihood. Fuel leaks vary in nature and not all will hazard the aircraft. Furthermore, whilst the presence of aircraft fire detection and suppression is documented in the safety case as a generic mitigation, BAE SYSTEMS has confirmed\(^1\) that the IMPROBABLE likelihood categorisation in the No 7 Tank Dry Bay did not arise out of any erroneous assumption of fire detection and suppression within the bay. However, I would agree that if, as seems likely, the SCP coupling was the source of ignition, then the failure of the hazard analysis properly to identify the threat represented both by the design of the SCP system and its operation in flight, was a contributory factor.

14. It is particularly disturbing that the undesirable overflow characteristic of the AAR system design appears to have been identified during development trials in the mid 1980s for the Nimrod Airborne Early Warning (AEW) aircraft, yet (although corrective action was taken for No 5 Tank) no corrective action was taken for the No 1 Tank despite recommendations that the phenomenon be investigated further. It is unlikely that the reasons why the development trials recommendations were not acted upon can be established given the passage of time, but I agree that this was probably then further exacerbated by the progressive nature of the introduction of the final AAR installation and the subsequent development of AAR operating procedures. More recently, it appears that the situation has been further exacerbated because the intensity of AAR operations was greater during 2006 than at any time during the life of the aircraft. Whilst the overflow phenomenon had been noticed during some sorties shortly before the accident, it is unfortunate that no aircraft incident reports were raised as a result of these events. As a result, the linkage between overflow and the maximum fill level for No 1 Tank had not been determined prior to the accident. Changes introduced to AAR procedures since the loss of XV230 will ensure the conditions necessary for overflow to occur are avoided.

**OBSERVATIONS**

15. Whilst I understand that there is concern that the removal of the SO1-level Engineer (Officer Commanding Engineering Wing) has had a negative effect on aircraft availability, there is no evidence to suggest that safety has been compromised. Equally, whilst the Station has had an outflow of skilled personnel, there remains a core of engineering tradesmen who are highly experienced, and engineering standards continue to be maintained through a rigorous system of competency certification and supervision. That said, we clearly need to remain vigilant to ensure that there is no erosion in safety standards.

\(^1\) Letter from BAE SYSTEMS to MOD, Reference: IH/003-07-06-07/cpw dated 8 June 2007.