with the symptom is raised to 90% for 30 secs[20]; this is repeated a second time if necessary. This could previously have been done with the cross-feed valves open (depending on when the fluctuations occurred) and, possibly, air-conditioning selected. The precautionary advice recommended closing the cross-feed valves before initiating the increase in RPM.

b. Conditioning System Fails to Initiate. When an air-conditioning system fails to initiate, one of the engines on the same side, generally the inboard, is increased in RPM until the air-conditioning initiates; on very rare occasions, this could require full power. The precautionary advice recommended closing the cross-feed valves before initiating the increase in RPM.

c. Air-Start Valve Fails to Open. When an engine air-start valve fails to open, the engine supplying the air is increased in RPM until the air-start valve opens. The precautionary advice suggested failing the cross-feed valves in the closed position by tripping a circuit-breaker, then starting the adjacent engine to the one with the symptom. RPM is then increased on the adjacent engine to open the stuck air valve.

19. ADR data was available for the engine start and flight on the 28 Jan 08. The recorder had over-written data from the previous engine ground runs on the 23 and 25 Jan 08. This data showed that the engine RPM did not rise above 81% during the start sequence on 28 Jan 08. Evidence from the ground runs carried out between 1 and 6 Feb 08[21] suggests that this would lead to a maximum cross-feed ducting temperature of less than 172 degrees Celsius.

ANALYSIS OF COMPONENTS

20. The Number 3 engine that had been removed from the aircraft on 24 Jan 08 was bench-tested by Rolls Royce to confirm that the engine bleed air was not at an unusually high temperature. Apart from an out-of-limits vibration, for which the engine was removed from the aircraft, the bleed-air temperatures were not unusual; the full Rolls Royce report is included at Enclosure 9.

21. The cross-feed valves were removed for bay testing at RAF Kinloss. Although the valves had appeared to work on the aircraft, they were found to be ovalled[22] on removal, which could allow some hot air flow past a closed valve. The Nimrod IPT are investigating the cause of this ovalling and will report separately, but the instrumented engine ground runs carried out during the investigation had shown that the valves were effective when selected closed. However, air leaks through the valve shafts (rather than across the valve itself) caused both valves to fail bay testing; a copy of the bay report is included at Enclosure 10. These air leaks are unlikely to have contributed to the fire in this instance because the cross-feed valves themselves are located away from the fire area. However, the valve failure is the subject of a separate Nimrod IPT investigation to determine the consequence of hot air leaking from the valve shafts.

22. The cross-feed ducting was removed so that the Refraisal covering could be carefully examined for cracks under magnification. Gaps in the joins between Refraisal panels were found as is common on this type of insulation but nothing of significance was identified. Finally, all electrical items relating to the cross-feed valves were also tested, as detailed in Enclosure 11, with no problems found.

[20] AP101B-0502-15B Part 2 Chap 11 Para 20.
[21] Simulation of the engine start of 28 Jan 08 carried out on 1 Feb with max RPM of 83% as described by witnesses rather than 81% as recorded on ADR gave maximum duct temperature of 172.3 degrees Celsius.
[22] The vertical measurement of the ducting connection face varied from the horizontal measurement by 2mm.

HUMAN FACTORS

23. The investigation thus far had concluded that the cross-feed ducting was the likely heat source for the fire, and that for the ducting to get hot enough, the cross-feed valves would need to be open (see Para 17a). However, all personnel were adamant that the cross-feed valves were closed when appropriate, so a human factors expert was consulted. XXXXXXX, from RAF Aviation Psychology/Human Factors at RAF Henlow interviewed 11 aircrew and groundcrew personnel over a 3-day period in Mar 08. The full report is included at Enclosure 12. It concluded that the second and third ground-runs were the most likely time for mistakes to have occurred, with the first ground-run next most-likely, and the test flight least likely. The report also raised important issues concerning the employment of groundcrew on 51 Sqn, and made several recommendations to reduce the risk of the cross-feed valves being incorrectly selected open in the future. Significantly, the report questioned the assumption that the fire did not occur prior to 21 Jan 08, as the last inspection on 21 Jan 08 was carried out at dusk with the focus being on fuel leaks rather than evidence of smoke or soot. However, the pannier bay had also been inspected earlier that day under natural daylight conditions following an earlier test flight. 5.40

FURTHER ASSESSMENT OF CROSS-FEED DUCTING TEMPERATURE

24. A series of further instrumented ground runs were carried out on 12 and 13 Mar 08 using a Nimrod MR Mk 2 aircraft at RAF Kinloss. One of these runs was intended to determine the temperature that the cross-feed ducting reaches during a start when there is ~~air~~ in the fuel, as described in Para 5a. This was chosen since it had not been previously analysed, and because the start prior to the test-flight (when the No 3 engine was taken up to 83%[23] because of the stbd air-conditioning problem) had already been simulated. Although there was no air in the fuel between 21 and 28 Jan 08, the human factors expert had suggested that the fire might have occurred before that time. The highest temperature that the cross-feed ducting reached during the trials of 12 and 13 Mar 08 was 240 degrees Celsius, which is high enough to auto-ignite AVTUR[24] and vaporise the suspected accelerant within the shroud.

FURTHER WORK

25. The Nimrod IPT has tasked BAES with the following work, the results of which will be published separately:

a. Investigation of whether the ducting clamp suffered fire damage rather than sooting.

b. Confirmation of the auto-ignition point of an AVTUR/rubber bonding compound mixture.

c. Confirmation of the ignition temperature of an AVTUR/hydraulic fluid vapour.

d. Further investigation of the residues within the shroud assembly.

CONCLUSION

26. The cause of the fire on XV249 could not be positively determined or replicated during tests. The options for heat source and accelerant were the focus of the investigation because of the known presence of

[23] The simulation on 1 Feb 08 took the Number 3 engine up to 83% based on aircrew testimony although analysis of ADR subsequently showed that the engine had only been taken up to 81% on 28 Jan 08.
[24] Enclosure 2

oxygen in the pannier bay area. AVTUR and OX-87 are the most likely accelerants because of their known proximity to the fire site and because their auto-ignition temperatures are below the maximum possible operating temperature of the cross-feed ducting. The only credible heat source is the cross-feed ducting; mechanical failures, chemical reaction and electrical sources of ignition can all be discounted with a high degree of surety. The likely presence of AVTUR on a cross-feed ducting mounting block, the fact that liquid was found in the cross-feed ducting shroud assembly and the patterns left by the smoke all lead to the conclusion that the cross-feed ducting reached sufficiently high temperature to ignite AVTUR that was in contact with the ducting on or around the clamp assembly. This small flame ignited vapour emanating from the nearby shroud assembly which contained a clear liquid, likely to be OX-87 hydraulic fluid. The temperature at which this occurred, the precise source of ignition, and the type of liquid remain unproven. For the cross-feed pipe to reach a sufficiently high temperature for this to occur, at least one engine would have to be operating at over 80% with both cross-feed valves open. Three potential scenarios emerge:

a. Fire During the Test-Flight. If both cross-feed valves were open during the test-flight, simulation showed that the temperature of the cross-feed ducting could reach 300 degrees Celsius. However, crew procedures for correct selection of the cross-feed valves are robust, and as the valves were effective during all of the on-aircraft instrumented ground tests, it is reasonable to assume that the cross-feed valves were operating correctly during the flight. **It is considered highly unlikely that the fire occurred during flight.**

b. Fire During Start-up Prior to Flight. A fire during engine start prior to flight could have occurred prior to 21 Jan 08. It has been shown that the cross-feed ducting temperature could reach 240°C during the procedure to clear air in the fuel during engine start. Whilst possible, there is no specific recollection of an 'air in the fuel' problem and the two inspections of the pannier bay on 21 Jan would have had to have missed the soot that was evident around the cross-feed pipe. The Human Factors report suggests this is possible, but the nature of the inspection being non-routine and specifically in the cross-feed pipe area makes this oversight unlikely. **Therefore, this scenario is considered to be unlikely.**

c. Fire During Ground Runs. A fire during one of the 3 ground runs between 23 and 25 Jan 08 would have required the cross-feed valves to be left open and the aircraft to have been operated in a configuration other than that described and documented (the port air-conditioning being selected for fault diagnosis instead of the stbd, for example). Importantly, the human factors report suggested that groundcrew might be reluctant to admit to mistakes because of a perception of a 'blame culture' on 51 Sqn. **It is considered possible that the fire occurred during ground runs.**

27. Unless further work identifies a lower auto-ignition temperature for AVTUR when combined with adhesive of the cross-feed ducting clamp, it is likely that residual AVTUR on that clamp ignited during one of the 3 Engine Ground Runs between 23 and 25 Jan 08. However, at this time, the cause of auto-ignition has not yet been completely determined.

RECOMMENDATIONS

28. It is recommended that:

a. The Nimrod IPT advertises the importance of removing AVTUR and OX-87 leakage or spillage from the area of the air cross-feed pipe.

b. The Nimrod IPT considers replacing all cross-feed pipe clamp blocks and mandating their replacement if fuel or OX-87 contamination is suspected.

c. The Nimrod IPT tasks further investigation to determine the auto-ignition temperature of AVTUR when combined with the bonding compound within the cross-feed pipe mounting block.

d. The Nimrod IPT continues the current RTI requirement to inspect pannier bays and MR2 bomb bays after every flight.

e. The Nimrod IPT considers the Human Factors report advice on modification to the cross-feed valve switches and indicators.

f. OC 51 Sqn takes action to investigate the perception of a blame-culture within 51 Sqn engineering personnel.

g. STANEVAL liaise with the Nimrod IPT prior to issue of advice to aircrew in order to ensure consistency of advice to aircrew and groundcrew.

h. The Nimrod IPT reviews the need for challenge and response checks to be part of engine ground running procedures and TQA training[25].

i. The Nimrod IPT tasks NAEDIT to identify the timing requirements to be followed for engine starts and amend the ground-crew ground running procedures[26].

Original Signed

XXXX S.40
XXXXX S.40
Investigating Officer
Ext XXXX S.40 DATE: 19 May 08
Enclosures:

1. Summary of Ground-runs and Flights Undertaken on XV 249 Since Returning From Theatre.
2. Initial Combustion Specialist Report.
3. Initial Fuels and Lubricants Specialist Report.
4. Qinetiq Fuels and Lubricants Specialist Report.
5. Qinetiq Combustion Specialist Report.
6. Summary of Meeting to Determine Possible Sources of Ignition – 11 Feb 08.
7. Overview of Ground-runs Carried out During Investigation.
8. Advice to Aircrew From Nimrod STANEVAL – 11 Feb 08.
9. Rolls-Royce Performance Report on Spey Mk 251 Engine Ser No 748.
10. RAF Kinloss Bench-test Report on Cross-feed Valves Removed From XV 249.
11. Details of Cross-Feed Valve Electrical Component Checks.
12. Human Factors Report.

[25] Recommended in Human Factors Report at Enclosure 11.
[26] Recommended in Human Factors Report at Enclosure 11.

OC FORWARD SUPPORT WING COMMENTS

1. A comprehensive report covering an investigation that has virtually equalled a BOI in its depth of technical analysis. It is disappointing to all that the precise cause could not be found but the investigation sensibly moved to discounting potential causes. The selection of the cross-feed pipe as the only realistic ignition source is well supported. As it could not be proven how this pipe reached auto-ignition temperature of AVTUR or OX-87, there is limited mitigation that can be applied. Similarly, the continual presence of oxygen is a given and no mitigation is practicable. The variable in the 3 elements of the fire triangle (oxygen, fuel and heat) is the fuel element. Mitigation can and must be applied here and the cleanliness of the bay is paramount. Additionally, further investigation of auto-ignition temperatures under aircraft representative conditions, rather than industry standard laboratory conditions, is essential.

2. I am concerned by the comments in the HF report and have already run an engineering standards forum covering forward and depth elements of all ac platforms operating from the Station. 51 Sqn provided an honest discussion piece and I am content that eng standards are being applied sensibly. Further work is required to manage individual perceptions and OC 51 is already engaged in that. Importantly, there is no evidence that the investigation has been hampered by any reticence of individuals to tell the whole story

3. This investigation has enabled a significant step forward in the understanding of the only realistic heat source in an R1 pannier bay. The investigation provides evidence that changes to procedures for the use of the cross-feed pipe have already made the ac safer; following the investigation's recommendations can enhance that further.

Original signed

XXXXXXX 5.40
Wg Cdr
OC FSW
Ext XXXX 5.40 DATE: 19 May 08

STN CDR COMMENTS

1. This was a complex investigation, involving a number of agencies, and I am grateful for the thoroughness and attention to detail with which it has been conducted. Conventional fires require oxygen, fuel and an ignition source, and the design of the aircraft means that the first of these will always be in plentiful supply in the area in question, and hence the focus has inevitably been on the fuel and ignition dimensions. Beginning with fuel, the location of the fire below a hydraulic bay, the proximity to a major hydraulic component, as well as the history AVTUR leaks on XV249, mean that the presence of some form of fuel in this particular area is unsurprising. Indeed, the investigation has been unable to definitively determine the nature and source of the fuel(s) from a choice of AVTUR, OX-87 hydraulic oil or a compound derived from one or more of these. Turning to the ignition source, it does seem clear that there is only one credible candidate, namely the hot cross-feed duct, albeit it is less clear when/how it came to be sufficiently hot. A number of possible scenarios exist, and the input of the human factors specialist is illuminating here. I suspect we will never know precisely what sequence of events occurred to cause the fire, but having exposed a number of weaknesses in our procedures, ergonomics and training, each of which could have contributed to the fire's occurrence, it is more important that we now address these.

2. In my mind, two further issues also remain. Firstly why, in almost 40 years of operation, has this only happened now? Have some of the measures put in place since XV230's accident inadvertently created a new hazard (eg the pooling of hydraulic oil within the refraisal, which under previous operating regimes might have been 'boiled off' before it accumulated?)? Secondly, the human factors investigation has shed light into aspects of the working culture on 51 Sqn that give me concern, and so I will take steps to address this over the coming period.

Original Signed

AD FRYER
Gp Capt
Stn Cdr RAF Waddington
Ext XXXX 5.40

DATE: 20 May 08

2 GP HQ COMMENTS

1. This has been a complex investigation, conducted with notable diligence and thoroughness. Although it is disappointing that neither the accelerant nor the ignition source have been positively identified, I am content that the evidence available and the exhaustive research conducted supports the conclusions of the Investigation. In particular, I am satisfied that this incident did not occur in flight.

2. The Recommendations of the Investigation will minimise the possibility of a similar incident in the future and I look forward to the Nimrod IPTL quickly implementing those which have not already been taken forward. I am further reassured by the outcome of the DGAS-led independent review in Apr 08 into the operational deployability of XV249, which confirmed that there were no issues specific to XV249, or wider Nimrod fleet issues, that compromised the operational deployability of the aircraft.

3. But it is addressing the Human Factors highlighted by this incident which may well offer the greatest potential to avoid repetition. I therefore fully support the Stn Cdr's initiative to engage RAF CAM in completing an independent HF survey which, together with HF training for all Sqn engineering personnel, the issue of anonymous HF questionnaires and a review of the use of Personal Files, should confirm any HF issues that need to be addressed. I know that this work is progressing well, with some aspects already complete and the remainder planned to conclude by the end of Oct 08.

4. Finally, this incident provides a further example of the importance of continued rigour in every aspect of Nimrod operation.

Original Signed

S J HILLIER
AVM
AOC 2 Gp
Ext XXXX 5.40

DATE: 1 Oct 08

HQ AIR/RAF ASG COMMENTS

1. The technical aspects of this incident have been well represented by the preceding reviewers and are being addressed. The Human Factors issues identified within this report are not unique to 51 Sqn. The fallibility of human beings is not a new phenomenon, indeed Human Factors will continue to influence outcomes for as long as people remain in the operation and maintenance chain of events. Operational, personal and resource issues can all lead to situations which do not necessarily belong in the 'Just Culture' that the RAF is trying to develop.

2. The RAF Maintenance Error Management System initiative was started to specifically address issues such as those surrounding this incident. It provides training and clear guidance at both command and 'shop floor' levels to allow all those involved in aircraft engineering to play an appropriate part in a 'Just Culture'. The recently announced 'Can Do Safely' campaign will also play a part in helping to prevent the recurrence of the HF conditions that may have led to this incident.

3. This report exemplifies that the RAF has yet to achieve a universal 'Just Culture'. That said, the current initiatives should go a long way to resolving these types of HF issues by promoting a culture whereby individuals are happy to report genuine mistakes, managers act upon such reports in an fitting manner but all personnel realise that culpable violations will result in appropriate action.

Original Signed

XXXXX S.40
CASO (Ops)
Ext XX S.40 DATE: 07 Nov 08