Investigating No Fault Found in the Aerospace Industry

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SUMMARY & CONCLUSIONS

This paper describes a package of work to investigate the root cause of No Fault found (NFF) events within the Aerospace industry. The project focus is to develop practical guidance for designers and project managers to facilitate a reduction in NFF removal events for both current products and new designs. This investigation forms part of the second phase of the REMM (Reliability Enhancement Methodology and Modelling) project and comprises three diverse investigation activities, below.

- Examination of NFF issues at a system level that can highlight common areas of concern for all partner companies and across the Aerospace industry.
- Classification and Root Cause Analysis of service-data collected by partner companies.
- System modelling the 'softer' NFF issues to determine the effects of intervention.

This paper will describe the formulation of the work package strategy and detail the progress made during the first year of this three-year project.

1. INTRODUCTION

Within the Aerospace industry there is an increasing trend towards the use of alternative reliability requirements such as the Maintenance Free Operating Period (MFOP) in the military field and 'power-by-the-hour' service contracts in the commercial world. Guaranteeing the failure rate of a product may no longer be sufficient to meet these continually evolving reliability objectives, particularly if the product suffers from a high number of No Fault Found (NFF) rejections. In the past, NFF removals have been seen as an unavoidable nuisance. This viewpoint is no longer acceptable if unit removal rate is to be managed effectively

This package of work forms part of the second phase of the REMM (Reliability Enhancement Methodology and Modelling) project. REMM is a United Kingdom, Department of Trade and Industry (DTI), part-funded collaborative programme in the form of an industrial and academic consortium, liasing closely with a military customer via the UK Defence Logistic Organisation, Air Environment Reliability Specialist staff.

During the first stage of the REMM project, a practical data collection, categorisation and analysis system was developed that has already led to improvements in the NFF rate of electronic fuel controls used in large civil aircraft. The intention is to now, widen the scope of this process, to provide a more rounded view of the causes of NFF in the Aerospace industry. This will encompass electrical and mechanical products operating in both a civil and military environment.

2. THE REMM PROJECT

The objective of the REMM research project, carried out between 1998 and 2001, was to develop a methodology to support the reliability enhancement of electronic systems and to incorporate within it, a statistical model that facilitates the assessment of reliability throughout the product life cycle. The research was carried out by a consortium of four industrial and three academic partners, with a focus on those reliability issues associated with electronic products in Aerospace industry (Refs. 1-3).

The second stage of the REMM project, often referred to as REMM2, is a continuation, expansion and extension of the work carried out during the first stage. Further work was considered necessary to ensure that the achievements of REMM were developed to the point of exploitation by the consortium partners and to enable extension to other high reliability sectors of industry. The objectives of REMM2 are built upon the successes and lessons learned from REMM, with a consortium which develop a complementary range of products that operate in diverse application environments and represent the major areas of the Aerospace supply chain.

REMM2 commenced in 2001 for three further years of research activity with broader objectives and an extended consortium, consisting of seven industrial organisations and three universities, listed below. Close liaison with a military customer is provided via the Defence Logistics Organisation, Air Environment Reliability Specialists.

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The output of REMM2 will be an Integrated Reliability Information System (IRIS) which will provide data storage, on-line interactive guidance systems and reliability assessment on a project by project basis. It will use web browser technology, artificial intelligence systems as well as databases to build this system (Refs. 4-5).

REMM2 activity has been formulated as a number of work packages (WPs) that facilitate focus on relevant issues, listed below.

- WP 1: Evaluation, validation and adoption of REMM
- WP 2: Artificial intelligence for decision making
- WP 3: Statistical methods and models
- WP 4: Manufacturing process monitoring
- WP 5: Environmental stress screening
- WP 6: Integration of mechanical systems
- WP 7: Integration of systems that include software
- WP 8: Cost effectiveness
- WP 9: Investigation of No Fault Found (NFF) events
- WP 10:Programme management and dissemination

2.1 *WP9 - Investigation of No Fault Found Events*

During the preparatory activity for REMM2, the objective of the NFF work package, WP9, was clearly defined; To investigate, understand and propose action, to reduce the occurrence of NFF in current product and new designs, throughout the Aerospace industry. The intention was for a task-team to investigate in-service rejection data collected by the industrial partners to assess the effect of NFF on dispatch reliability in terms of cost. For this to be possible it would be necessary to normalise data within the consortium. This would be achieved by agreeing terms of reference and developing a robust failure classification model.

3. REFINING THE PROJECT OBJECTIVES

At the launch of the REMM2 project, representatives from each industrial and academic partner within the consortium were invited to take part in the WP9 task-team to discuss and develop the scope and objectives for the work package. During the inaugural task-team meeting on this subject it was agreed that the work package should reflect a broader objective; to minimise the effects of NFF on an aircraft operation rather than focus one a particular symptom, such as the costs of dispatch reliability. The task team formulated an investigation strategy that they believe to be the most effective way of accomplishing this objective. This strategy attempts to embrace the complex, multi-faceted NFF phenomena by instigating a number of diverse parallel investigation activities, listed below.

1. Examination of NFF issues at a system level that can highlight common areas of concern for all partner companies and across the Aerospace industry.
2. Classification and Root Cause Analysis of service-data collected by partner companies.
3. System modelling the 'softer' NFF issues to determine the effects of intervention.

3.1 *Setting the NFF Investigation Boundaries*

Influence diagrams were used extensively during WP9 task-team meetings to develop the scope and determine the appropriate system level for the NFF investigation. These diagrams were found to be a very useful vehicle for recording and developing ideas. The proposed scope for WP9 activity, developed by the task-team using this technique, is shown in Figure 1.

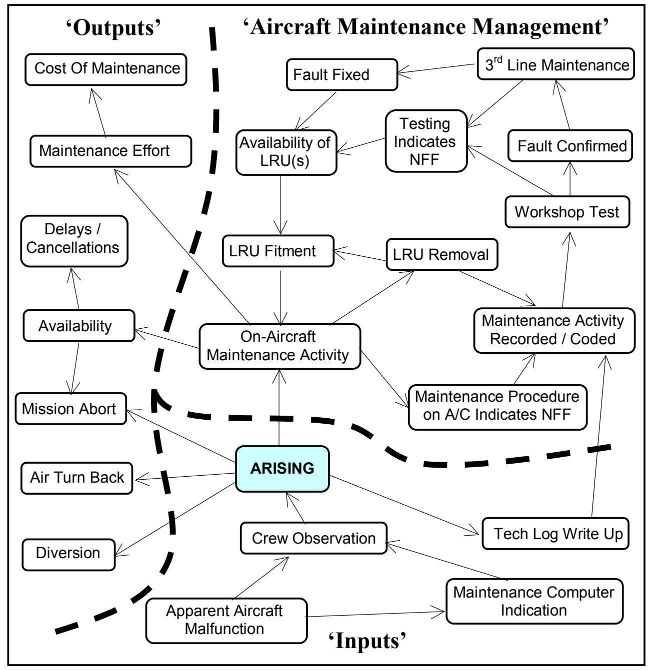

Figure 1: Project Scope Influence Diagram

3.2 *Service Data Classification Process*

It was agreed that a definitive classification scheme would be required to permit a representative review of NFF events across consortium partner products. It was further proposed that the in-service categorisation system developed at TRW Aeronautical systems (Refs. 6-7), used during the initial stage of REMM to categorise the root cause of product removal could be developed further to embrace the widened scope of the consortium product range.

3.3 *Investigating the 'softer' issues*

Past studies carried out on the subject of No Fault Found often highlight the dominating factors to be 'soft' in nature, such as communication and training (Refs. 8-9). To maximise the usefulness of the NFF guidance material, accessible from the IRIS system, it is the intention of the task team to review the softer, more anecdotal, elements of NFF as well as the harder, NFF classification system. To this end, influence diagrams will be developed to capture the softer issues associated with NFF, uncovered by interview, questionnaire and visits to maintenance workshops. It is hoped that these diagrams will provide the necessary relationship data to generate a NFF causal model that can be integrated with the IRIS guidance system.

4.0 SETTING THE INVESTIGATION BOUNDARIES

The bounds of WP9 activity must be developed to ensure that the system level chosen for analysis is high enough to enable participation by all REMM partners, with diverse product types, yet low enough to provide sufficient detail to facilitate effective discussion and analysis.

To achieve this goal, the influence diagram shown in Figure 1 was used to progressively build the major elements of a generic ‘NFF generation’ system. Members of the task-team each suggested factors associated with NFF, that were of relevance to their particular product and its environment. Each of these elements were then discussed within the team to understand the context, agree a common definition and evaluate its importance and relevance to the NFF ‘big-picture’. Following discussion, certain elements were clustered together to form more generic elements, while others were split-out to satisfy specific differences across application environment. As an example, costs associated with mission aborts, flight delays and cancellations, may be better represented by a generalised concept such as availability. The costs of availability could then be assessed for each case without detracting from the common investigation goal.

Referring to Figure 1 it can be seen that the influence diagram can be segregated into three main areas of interest. An ‘inputs’ sub-system observes and records the perceived malfunction while an ‘outputs’ sub-system associates the costs and operational consequences of the perceived failure, a third sub-system represents the management of aircraft maintenance. The task-team believe that the generic components that make up Figure 1 represent a system which generates NFF events, provides enough detail for analysis and is able to represent diverse product type and environments.

Figure 1 shows a number of causal relationships between system elements. Developing an understanding of these relationships will form a large part of this investigation activity and it is anticipated that similar influence diagrams will be developed to a far higher resolution to enable specific issues and relationships to be examined.

5.0 MANAGEMENT OF SERVICE DATA

This section describes the data collection and manipulation process, developed at TRW, used to classify the Root Cause failure mechanism of service events for use with the REMM statistical model. The classification technique provides an opportunity to gain a system level perspective of the reasons for a unit removal. Figure 2 shows a set of removal and investigation data gathered using this process. The data has been mapped into top-level root cause categories to best illustrate the significance of each on the total number of removal events. This mapping technique can be used to display data at varying levels of detail, progressively homing in on the problem areas.

All product removal events are grouped into either ‘Confirmed Fault’ or ‘No Fault Found’ categories. In this case, Figure 2 clearly illustrates the significance of the NFF events upon the overall removal reliability. It can be seen that improving the system to reduce the number of product removals with no apparent failure will have far more effect on the overall reliability than a corresponding improvement in the product failure rate.

5.1 *Confirmed Fault*

The absolute number of removal events that fall into this category indicate the quality of the processes used to design, develop and manufacture the product under review. Carrying out a root cause mapping at a lower level can indicate which processes have most effect on the unit reliability. The areas suggested for a more detailed review may include design, build, test or supplier management as shown in Figure 2. It can be seen how further mapping for a selected aspect may home in on problems in a particular build or test process.

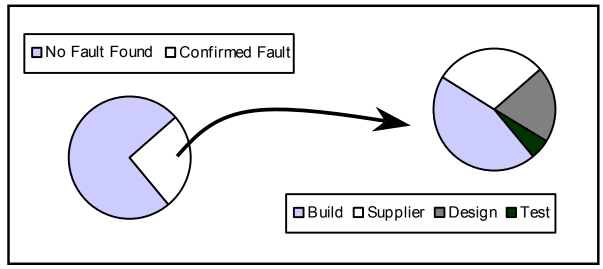

Figure 2: Root Cause Mapping, Highlighting Confirmed Fault

5.2 *No Fault Found (NFF)*

Figure 3 demonstrates how those removal events classified as NFF can be categorised into lower level, more useful, sub-groups. Traditionally, any product removal that exhibits no fault during subsequent acceptance test is classified as NFF. However, for a number of these events, further investigation may conclude that the reason for the removal event was categorically caused by an external effect.

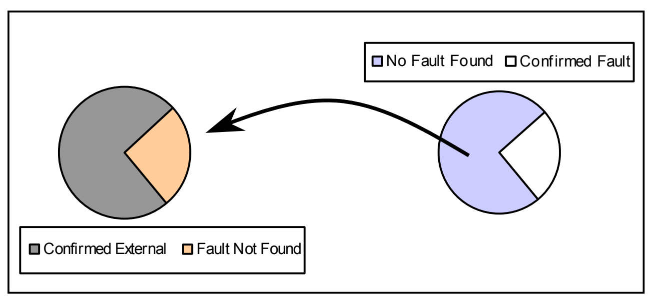

Figure 3: Root Cause Mapping, Highlighting No Fault Found

This may be a faulty sensor or actuator, an incorrect fault isolation process or even an operator policy decision. These removal events can then be classified as ‘Confirmed External’, giving the incorrectly removed product a clean bill of health. For the remaining removal events where no fault is detected during acceptance tests AND no external effects or system level interactions can be observed, the event is classified as Fault Not Found (FNF). This subtle word change attempts to emphasize the point that a fault is present in the system somewhere, although it has not yet been found! This contrasts with the classic NFF definition, which suggests that there is no fault present in the product.

Unlike the failures that result in 'Confirmed Fault' events, the product manufacturer is unlikely to have a direct influence on those aspects of the system that determine the NFF rate. For this reason, only limited mitigating action can be undertaken without the participation of the major system owners, i.e. accessory suppliers, engine manufacturer, airframer and operators. It is hoped that the REMM consortium provides the depth of supplier chain and user expertise to determine effective mitigating action that can be compiled into usable guidance for use with IRIS.

6.0 SERVICE DATA CLASSIFICATION PROCESS

In order to compare the impact and significance of NFF events for each partner company, across product ranges, a concise but robust definition for the classification of service data was required along with a process for categorising the cause of each NFF event.

6.1 *Classification of In-Service Data*

The applicability of the classification system used during REMM, described in section 5.0 was reviewed for use with a wider consortium. In order to meet the broader objectives of REMM2 the existing process would need some refinement. A flowchart was used to develop distinct product removal classifications that could be used by all REMM partners for the purposes of data collection and categorisation. It was agreed that the existing definition for Confirmed Fault, Confirmed External Fault and Fault Not Found defined in section 5, were still applicable, but the following definition for a 'Secondary Fault' category was considered a necessary addition.

The product has failed test but the failure detected is categorically NOT responsible for the reason for removal. This may be confirmed by comparing the reasons for removal with the test failure.

The flowchart used to define the classification of service data is shown in Figure 4.

6.2 Classification of Fault Isolation Failure

Those events categorised as 'Confirmed – External' hold the key to understanding the cause of NFF events. For each of these events, the team must endeavour to answer the following two questions:

- Why the fault occurred in the external equipment, and more importantly
- Why the product under review was removed for this fault

The first question is to be answered by the supplier of the failed external equipment. It is essential that the failure mechanism be defined and recorded to facilitate any future system modelling. The answer to the second question is key to understanding the fault isolation error responsible for the event under review. If the source of this error can be successfully mitigated there will be no further removal events attributable to it. This philosophy underpins the method for determining those failures that are at the root cause of NFF.

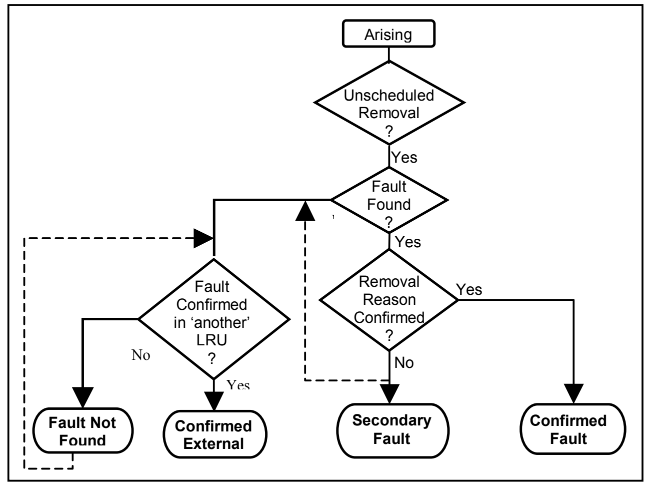

Figure 4: Product Removal Classification Flowchart

During the early stages of REMM, TRW Aeronautical Systems formulated a process to specifically analyse the 'Confirmed – External' element of in-service data with root cause classification (Ref. 10). Application of this process has facilitated an improvement in the rejection rate of their electronic control system products by the order of 50%.

It was however, suggested that the definitions developed by TRW to enable classification of fault isolation failure for their products may not encompass the NFF issues observed by other manufacturers or users of Aerospace technology.

One of the major factors that will determine the success of the activity is the ability of the task team to define and agree a set of categories for fault isolation failure. Although the original root cause classifications served only as a starting point for further discussion within the team, the concepts were thought appropriate. An initial review by the task team has highlighted troubleshooting activity, system design and fault isolation manual as the three main categories of concern, believed to be at the heart of fault isolation failure, shown in figure 5.

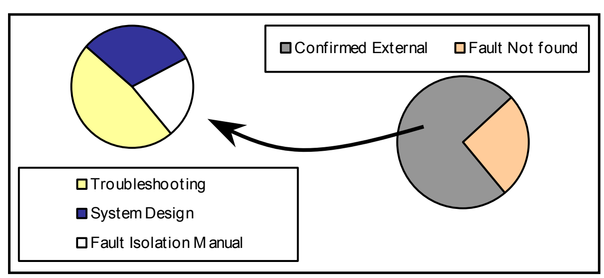

Figure 5: Fault Isolation Failure – Categories of Concern

6.3 *The Root Cause of Fault Isolation Failure*

Poor troubleshooting is often cited as a major cause of NFF removal events. Ultimately, it will always be the act of troubleshooting that results in the removal of a product, but the activity itself is not necessarily the root cause of the fault isolation failure. In addition to the need for well-trained troubleshooters, robust fault isolation also relies on a system design that will correctly detect and annunciate faulty products and a set of user-friendly troubleshooting tools and guides. It will be the responsibility of the team to distinguish between failure in these elements of the fault isolation system to determine which has the most significant effect upon NFF.

Root cause mapping can also be carried out for a subset of the removal data selected by specific criteria. For example, mapping removal data for a particular operator or route structure may indicate distinct fault isolation problems that are characteristic of that operating environment. This analysis therefore has the potential to indicate the significance of each factor upon fault isolation effectiveness, on an individual operator basis. The major classifications of fault isolation failure detailed in figure 5 have been further divided into the more tangible, recognizable features shown in figure 6. The REMM task-team must revisit this sub-classification definition in light of its wider system participation and knowledge base.

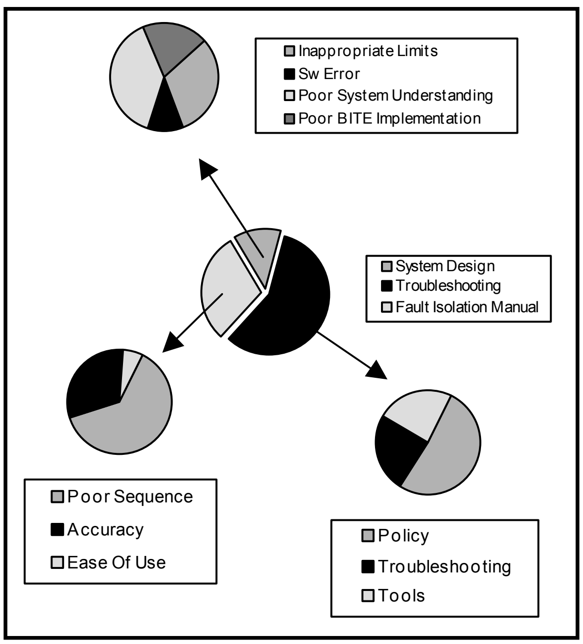

Figure 6: Fault Isolation Failure – Root Cause

6.3.1 *Troubleshooting*

Under the general heading of troubleshooting, a distinct number of potential fault locations can be defined. *Operator Policy* may dictate a product removal to protect an aircraft dispatch schedule where further troubleshooting may have correctly uncovered the faulty product. A *Troubleshooting Manual* is intended to provide the troubleshooter with the most effective sequence of diagnostic activity, utilizing the most applicable techniques and tools; this is not always the case. Given sufficient time, tools and procedures, *Troubleshooting* is still a human activity and as such relies upon the decision making experience of the troubleshooter.

6.3.2 *System Design*

The design of a Built-In-Test-Equipment (BITE) system is not a trivial task and relies upon an in-depth knowledge of all system interactions. There will inevitably be a number of failure mechanisms that will only manifest themselves during a limited envelope of operation. These scenarios may not be recognised during the BITE design due to a *Limited System Understanding*. Even where the designer demonstrates a good system understanding, selection of inappropriate detection and confirmation strategies may result in *Inadequate BITE* design. A recurring failure theme within the requirement capture process is the definition of *Inappropriate Limits* for interfaces operating in a new environment. Finally having designed the system it is also necessary to recognize that *Software Coding Errors* within the BITE are inevitable if the process depends on human judgement for design and validation activities.

6.3.3 *Interconnection*

Poor electrical connection between system interfaces can produce intermittent fault conditions that are extremely difficult to detect. Moreover, breaking into the system during maintenance activity may actually remove the fault. Although 'system design' and 'troubleshooting' activities may be blamed for this situation, the increasing occurrence of this fault type in today's complex airframes does appear to warrant a separate category and associated investigation action. The main elements of the interconnection system are the *Connectors* and the *Harnesses.* The characteristics of the interconnection system *Installation* also appears to have an influence upon its operation.

7.0 *SOFTER ELEMENTS OF NFF*

Of particular interest to the task-team is the situation where a component exhibits a continuous loop of rejection from aircraft followed by NFF classification in the workshop. Those products that appear to repeatedly slip through the net are often referred to as *rogues*. The success, or otherwise, of an aircraft operator to detect and remove these *rogue* components from its operation is an important factor in the management of its fleets' NFF performance (Ref. 11).

The task-team is using soft-system tools (Ref. 12-13) to explore anecdotal evidence regarding the cause of NFF, particularly *rogues*. The data has been collated from various questionnaires, interviews and maintenance base visits. This review has highlighted a high proportion of issues relating to human interaction and behaviour within the aircraft maintenance system. The task team will attempt to develop a model of the human-system at the core of aircraft maintenance to explore the effects of intervention. Elements of this system identified for further study include relationships between flight crew and maintenance engineers, conflicts in performance measures, lack of feedback from investigation and inconsistent fault reporting.

Some operators actively search for *rogue* components and blindly reject them with the assumption that the replacement costs will be fully justified by the reduction in operational disruption caused repeated NFF incidents. It is the intention of the task-team to further develop the philosophy of improving

NFF by reducing *rogue* components, but with a more controlled approach. Modelling the soft systems in which these multiple rejections appear should enable the task team to develop criteria to distinguish between rogue components and rogue processes, and to provide guidance for the reduction of *rogues* by suitable intervention.

8.0 CONCLUSION / FURTHER WORK

At the time of writing, the task-team has been active for approximately one year. While some progress has been made in all three areas of investigation, most effort has been directed at defining the failure classification system to enable industrial partners to compare service data. Now this task is complete, a generic definition for fault isolation failure can be developed, enabling the significance of particular failure types to be assessed.

It is likely that a number of failure classes defined by observation of service data will show a degree of overlap with issues emerging from the parallel investigation activities. For example the service events broadly classified as *operator policy* for the cause of fault isolation failure may form part of the generic NFF generation system review described in section 4, or part of the soft systems analysis on the human elements of aircraft maintenance, described in section 7. In this way the results of all analysis activities can be integrated to provide an understanding of the underlying reasons for the failure types observed using hard classification. The availability of this information will enhance the hard classification system, enabling failure sub-classes to be defined that can relate service events to the likely root cause.

It is the task-teams's objective to develop a definitive classification mechanism that enable users of IRIS to gain an understanding of the reasons for NFF rejection in particular product types operating in diverse operational environments with a selection of maintenance practices. Inclusion of guidance in best practice techniques for the reduction of NFF and integration of hard and soft models with the IRIS system will enable designers, service engineers and aircraft operators to make decisions regarding NFF issues in a far more data literate manner.

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Ian James graduated with first class honours from the Open University in 1998, specialising in systems theory and artificial intelligence. He has worked at Goodrich (formally Lucas Aerospace) for 23 years in the electronic design group. He presently has an engineering consultant role covering reliability, maintainability and performance issues with responsibility for requirements capture and troubleshooting system design for new products. He is a Chartered Engineer and a member of the Royal Aeronautical Society.

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David joined Westland in 1981 as a Technical Apprentice. On completion of training he joined the Mechanical Research department developing advanced transmission system technologies and health monitoring techniques. This activity led to involvement in the modelling of transmission system reliability and has ultimately resulted in David becoming the Westland representative to the Ultra Reliable Aircraft programme. He has extensive experience of participation in collaborative research programmes and is responsible for reliability research and improvements in company data feedback activities.

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John graduated from UCNW Bangor in 1986 having completed his apprenticeship with the Ministry of Defence. John then followed a career with Marconi Defence Systems, Thorn EMI Electronics and BMT Reliability Consultants before joining BAE SYSTEMS in 1999. John is currently Deputy Leader of the Underwater Weapons Division Reliability Group with ARM Programme responsibility for a variety of development and conceptual projects and is the Waterlooville representative to the Aerospace Sector Process for the Insertion of Reliability (ASPIRE) DTI programme.