The impact of no fault found on through-life engineering services

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Abstract

Purpose – The purpose of this paper is to provide a platform for discussion on the problem of no fault found (NFF) events which continues to plague maintenance operations of complex engineering systems.

Design/methodology/approach – The research has been collated from many sources: academic literature, industrial discussions and the authors' experiences. The study defines the NFF problem, its causes, impacts and costs as well as an evaluation of the available scientific research.

Findings – The paper identifies a continuing serious problem with NFF; it is not just a technical problem but also encompasses organisations, culture and behaviours. Focusing only on one of these at a time is no longer enough to solve the NFF problem in modern maintenance operations and solutions will require each category to be addressed as an integrated problem.

Originality/value – The overall value is a detailed picture of the NFF field seen from both an industrial and academic viewpoint. The originality of the paper is that it articulates and organizes the existing knowledge concerning the NFF phenomena, the value of which is to identify gaps in existing research and knowledge.

Keywords Maintenance, Production engineering, Operations management, No fault found, Through-life engineering services, Maintenance quality and effectiveness

Paper type Research paper

Definitions of no fault found (NFF)

In the first place we need to know what is meant by NFF, cannot be duplicated or a re-tested OK (both terms used to mean NFF in the USA). It is the airline industry that has done the most work in this area and has the most information to share. A common definition provided by Cockram and Huby (2009) is:

> A reported fault for which the root cause cannot be found.

This implies that NFF is a diagnostic failure and certainly many NFF incidents can be described in this way. But perhaps it is wider than this? It might also be said that there are examples that are:

> Reported faults for which there never was a root cause.

These could be described merely as misreporting or reporting failures, but nevertheless will cause nugatory maintenance effort.

A well-used definition in the airline industry is defined within the ARINC Report 672 (2008) as:

> Removals of equipment from service for reasons that cannot be verified by the maintenance process (shop or elsewhere).

But it is really even wider than this as it should also cover cases when no fault is found at the aircraft or equipment and as a result it is returned to service with nothing found or replaced. So perhaps we should describe NFF as any reported fault which results in

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nugatory maintenance and logistical efforts, or in other words a maintenance action that is a complete waste of time and effort!?

To achieve diagnostic success is surely what we want though which implies identification of the root cause if there is one, or positive identification that there is no root cause if not. Only in that case will the correct maintenance activity able to be selected and performed or if there was no root cause the equipment being able to be safely returned to service. This all suggests a closed-loop system that can relate the symptoms to the fault and to the correct maintenance action, easier said than done, however.

A brief history of NFF

It is worth looking at some history of costs associated with NFF to ensure we have the correct perspective on the importance of the problem. The level of NFF in the system is certainly one issue that can throw any maintenance policy into disarray. It is something intimately tied up with the monitoring techniques that have been chosen and in particular the whole area of testing with built in test (BIT), built in test equipment (BITE) and the levels of mean time between unscheduled repair (MTBUR) that are achieved in the system. It is an area where millions of pounds can be wasted through high levels of NFF. For example in 1993 a British-based commercial airline operator was extremely concerned at the high cost of removals where nothing could be found wrong and the same fault re-occurring.

They formed a task force, which established that it was not as bad as first suspected, i.e. that 33 per cent of all unscheduled removals were NFF. From the data they captured for the year of 1992, it was in fact 13.8 per cent of all unscheduled removals that could be positively identified as NFF. Nevertheless this was costing £17.6 M per year. The team also found that avionics components made up 80.4 per cent of all registered NFF; these components represented 26.6 per cent of all avionics removals. Albeit the study highlighted older aircraft that suffered the highest rates, Concorde, Tristar and Classic 747; they established that aircraft engineers were removing components for the wrong reason and workshop technicians were failing to repair the reported faults. Whilst it was impossible to accurately allocate, it was estimated to be 60/40 per cent split between the aircraft engineers and the workshop technicians.

The reasons were fairly easy to identify. There was not enough emphasis on diagnostics training. There was also pressure on the quantity of items going through workshops and not on the quality of maintenance or repair. Strangely there was no emphasis put on the history of components by tracking them by serial number. This would have identified what they then called rogue units. Rogue units (Söderholm, 2007) were identified as ones which rotated between aircraft and workshop with alarming regularity. When they investigated they found that 360 identified rogue units resulted in 2,300 removals at the aircraft in the year. To solve this problem, data were clearly a key element. Feedback of data were required to the sub-contractors to track the history of a unit all around the repair loop. Data on repetitive defects needed to be shared between the users and the repair shops and data on the potential rogue units needed to be collected in order to identify and monitor them and then to remove them.

By 1998, a comparative study was once again done to check progress. The study showed that they had improved their MTBUR by 20-30 per cent. They had brought in a system to identify the "rogue units" and they had set various criteria to identify these units:

- the component had to have a history of repeated "short service" periods;
- the component demonstrated repeated, identical system faults;

- the cause of the failure or fault could not be detected by standard bench or overhaul testing procedures; and
- a replacement component of the same type resolved the system fault.

A short service period was at that time defined as 250 flying hours (approximately 25 trips for a 747) but logically each aircraft type might need a different period set, for instance long haul vs short haul. The rogue units are all ones which would and have passed the standard serviceability checks. Rogue units are quarantined and subject to detailed tests and analysis when time allows. If a fault is identified, components exhibiting the same fault are then also examined for the same fault and this has proved very worthwhile. Since adopting the system, 300 items with a value in excess of £2 M have been quarantined. Many subsequently returned to service when a fault had been positively identified.

Another system introduced to reduce the likelihood of NFF occurring in the second line bays is the "subject to aircraft (ac) check" (STAC). This allows licensed engineers to replace a component with a known serviceable item. If the ac then suffers the same fault during its next flight or very soon after, it is very possible the originally removed item is in fact "serviceable". It will therefore be returned to stock as "STAC serviceable". If, however, the ac does not display the same fault the item follows the normal U/s route to second/third/fourth line. In 1998 it was estimated that this procedure alone saved £17 M per year. From 803 units subjected to STAC, 303 were declared serviceable and thus did not go to second line for repair. From these "serviceable" units, there were only 15 that experienced early failure with the same symptoms or fault representing only a 4.95 per cent re-occurrence rate. Of the remaining 500, 50.6 per cent were found to be unserviceable and removed from system, the rest still being NFF. Other airlines have now adopted similar procedures and these changes of procedures are now recognised as best practise.

In 1996, Boeing stated that they believed there was a 40 per cent rate of incorrect parts removal from the airframe. As recently as 2007 *Aviation Week* reported that avionics constitutes 75 per cent of NFF occurrences in the airline industry (Burchell, 2007).

In 1998 the military sector was no different to commercial airlines in relation to NFF. Some 10 per cent all aircraft fault arising's in military aircraft were found to be NFF. That meant on average, 3.5 per cent of all work done at the aircraft (first line) was nugatory. That alone represented 60,000 man-hours per year at first line, costing some £1 M (at 1998 prices). That figure can be doubled probably if second line maintenance was included. Unfortunately operators of military aircraft have so far been unwilling to adopt the same sort of policy changes as within the commercial sector to reduce these costs which are no doubt only the tip of the iceberg, as they are just first line costs.

A comparative study under the direction of the author (Chris Hockley) was carried out to see if there was any discernible difference between analogue and digital systems. The Digital Engine Control Unit (DECU) on the Tornado ADV and its comparable analogue unit the Main Engine Control Unit (MECU) fitted to the Tornado GR3/4 were selected. The results were not unexpected but showed greater number of NFF for the DECU than for the MECU. It did show, however, that in terms of NFF, 37.7 per cent of those operational sorties with some negative effect were NFF. For the MECU it was 23.3 per cent of operational effect missions that were then NFF. Further research on the DECU into the possible reasons gave some interesting results. Operational pressure to get the aircraft back on the line was significant in some operational theatres. For instance when there is very little operational pressure, the NFF arising rate can be around 25-30 per cent. In contrast, however, where there is strong operational pressure and particular patrol times to meet, the NFF rate can be as high as 90-100 per cent, as there just is not time to investigate the root causes. This certainly results in over-manning needed at second line to deal with the extra quantities of DECU to investigate. BITE was assessed as responsible for 30 per cent all DECU fault arisings and for those diagnosed using BITE, at least 26.5 per cent were found to be NFF at second line. NFF at second line and for the units tested using Automated Test Equipment was at least 45 per cent.

From the more detailed investigations of the DECU on the Tornado some general reasons for NFF were established:

(1) Lack of knowledge by user or maintainer:
   - new equipment:
     - early in service life; and
     - discrepancies in procedures.

(2) Poor diagnostic techniques:
   - personnel's experience low and with test equipment.

(3) Poor test equipment (including BITE):
   - design and/or tolerances.

(4) Intermittent faults due to environment and usage.

(5) Software faults.

(6) Pressure to get job done.

(7) Lack of spare parts.

The commercial and military aircraft studies have shown that NFF costs can be generated through the following activities:

- removals for the wrong reasons;
- workshops failing to find and then repair the reported fault; and
- inability to simulate the conditions in which the fault occurred.

The costs of removals due to NFF can therefore be huge where nothing has been found at fault, or the same fault re-occurs in the next or a subsequent mission, risking safety and/or mission success.

Common classes of NFF

So what are the conclusions that can be drawn as to where the NFF problem is most prevalent and to what is it most applicable? Clearly a great deal is applied to avionics, electrical and electro-mechanical, but initial research has shown that software is also becoming an increasing NFF problem. Mechanical and structure are not as common but there are occurrences as it will manifest itself as a maintenance action for any of the non-destructive testing (NDT) inspections which range from simple visual checks to the most sophisticated; a NFF can be caused due to lack of skill, training or just simply incorrectly applying the NDT procedure. The point is that traditionally we think of NFF as simple classes such as an intermittent failure but actually the problem is wider, in that a poorly executed inspection finds no fault, yet there is a fault there which may manifest itself later as a mission failure or worse still result in an accident!

Based on previous studies therefore it is perhaps necessary to review the earlier definition of NFF as a "reported fault for which the root cause cannot be found, in other words a diagnostic failure". This implies that we merely have to achieve diagnostic success, which will "identify the root cause so the right maintenance relates the symptom to the fault and the right maintenance solution". This implies being able to relate the symptoms to the root cause so the correct maintenance action provides the right solution, but it is clear that the NFF causes are much wider than this. In order to assess the problem therefore we must look at all the causes before proposing solutions. In general it has been common to classify NFF into three classes or categories of faults:

Intermittent – this refers to the malfunction of a device or system that only occurs at irregular intervals with normal functionality at all other times. They can be defined as a loss of some function/connection for a limited period of time and can be minute breaks in a connection perhaps caused by flexing under vibration or through corrosion.

Integration – a category that for example includes a component or sub-system that works successfully when tested, but indicates the presence of faults when incorporated with other systems. They occur due to the way the sub-systems have been assembled, or software incompatibilities, rather than due to the integrity of any individual sub-system in the system hierarchy.

Testing – the third common category is with on-board BIT/BITE and testing off-board. These are tests that are incorporated either on board or as part of the BIT/BITE routines where a fault is indicated but the BITE fails to diagnose the root cause and isolate the right component to replace. Similarly tests off-board may fail to diagnose the root cause for any number of reasons.

The existence of three classes or categories probably needs to be challenged, however, and current research which is underway at the EPSRC Centre for Innovative Manufacturing in Through-Life Engineering Services will certainly keep an open mind on this question. The research will evaluate the many and varied causes throughout different industries, many of which are likely to be industry specific. But in general the most popular causes seem to be able to be categorised under poor design, lack of communication, mis-communication, wrong diagnostic methods, poor training, wrong processes applied and operational pressure. They all will produce NFF which can fall into one of the accepted three classes, but more rigorous analysis will be necessary once further research has been conducted as to whether there is a need for any other specific classes or merely some sub-divisions to be identified.

General causes of NFF

In general it would seem that there are several categories that causes can be grouped under: organisational and culture, technical inefficiencies, procedures and rules and finally workforce behaviour.

With organisational and culture, the organisation is often too bureaucratic and cumbersome to be able to change and may not even recognise that it has a problem. There is a need for serious data and evidence on the cost of NFF in order to make management recognise the need to make the change. The costs, however, may not be easy to establish and there may not even be the willingness to establish these costs! As far as procedures and rules are concerned military organisations will necessarily cite the situation that military aircraft are built to safe-life criteria where there is no redundancy, unlike commercial aircraft built to fail-safe standards; this they would maintain preclude many of the new practises adopted by commercial operators such as the STAC approach. But there is another reason with organisations such as the military. There used to be no real incentive to track rogue units and to solve that part of the problem because their own maintenance and supply organisations would cope with the extra repairs required and indeed justified their existence. The organisation was also too big and cumbersome to make the necessary changes easily. There were plenty of people with little focus on actual costs of such nugatory effort. Now, however, there is more pressure on individual fleets to improve efficiency, especially with the contracting out more and more support that is now in force, where the contractor needs to drive out as much waste as possible in order to maximise profit.

Technical inefficiencies are another source and could be anything from the inability to get test equipment and diagnostic routines changed because the problem is not known or not reported effectively, to the inability to track the cost of the problem and establish solutions. In the last category we see workforce behaviour where the reliance on "Norms" is prevalent: "we have always done it this way and it always works". But whilst it does always gets the equipment back on line, it may have involved changing a number of components when only one is truly at fault but now they have generated two NFFs in the system with all the attendant costs in the maintenance and supply chain. It is perhaps worth exploring many of these causes further as it gives greater insight into the need to group them into categories.

Organisational and culture

Time pressures on maintenance operations. In many organisations there is an overriding need to get equipment back into service quickly. Availability of the equipment for service provides an overwhelming pressure on diagnosis and maintenance actions. It means that often a speculative maintenance action is the quickest solution that may involve removing several line replaceable units (LRUs) or components – an activity that causes NFF further down the supply chain but has solved the fault at the original equipment. All too often the pressure to return the equipment to service means that changing the three LRUs will be quicker than doing any detailed diagnostics to determine which of the three is the cause. The result though is that now there is one LRU that has the fault and another two that will show up as NFF when subject to tests at the next level in the repair chain.

Organisational cultures also exist in many industries where there is no cross-functionality, employee empowerment and encouragement to identify the root causes of reported faults. In other words, wrong behaviours have been allowed to grow.

Inadequate training or lack of training tools. Training must be good if complicated diagnosis is required. It is poor maintenance practise that does not provide adequate training or the necessary training tools and will contribute to the overall levels of faults not found.

Poor training and skill levels. This is fairly self-explanatory but often the task is given to someone who has not had sufficient training or experience.

Sharing information. There needs to be a culture and commitment to share knowledge between designers, manufacturers, service providers and operators. This may be easier said than done but it needs a system set up to share appropriate information between all the stakeholders. This might require an organisational investment in resources to enable an effective, speedy transfer of shared information.

Reluctance to change. Solutions that are likely to be disruptive to normal working practises are seen as unnecessary and a challenge to technical skills. Often an organisation will not change and solve the problem perhaps because in their view the organisation is not the problem.

Lack of historical data. It is essential that fault history on the equipment is known. Often the technician does not have the particular equipment's history to look at so the fact that the same fault is re-occurring is not obvious. It may be a fault on the main equipment or a particular bad LRU.

Lack of communication. This often manifests itself as lack of fleet or original equipment manufacturer (OEM) advice. It may be that a particular fault is being seen across the fleet or a procedure is being improved by the OEM and this information, or rather solution, would be relevant and stop some NFF but is not being communicated.

Technical causes

Undefined or limited performance measures. If the performance level is undefined then one person may perceive a fault whilst another person may classify the same level of performance as acceptable.

BIT levels set too low. If the success levels of BIT are set too low, the BIT is likely to indicate a fault when none actually exists, or at least none that would affect successful operation.

BIT/BITE ability to detect a fault. The capability of the BIT/BITE must be such that it will detect the fault. This also assumes the BITE has been designed correctly.

Erroneous repairs. This affects faults which are usually intermittent in nature and are difficult to detect on test which rarely replicates the environment and usage when the fault first occurred. It is the case that at deeper levels of repair, there is usually higher quality test equipment operating at more sensitive tolerances, which may then find other dormant faults that have no relationship to the original fault. They are repaired but the original fault still lies undetected. The item is then returned to service but without the original fault repaired and will cause the same problem, but now on a different main equipment.

Lack of information on operating environment. This may be critical as for example in an aircraft where the fault occurred when in a high-g manoeuvre or it occurred at 45,000 feet and thus – 40°C.

Inability to reproduce operating environment during test or diagnosis. It may be difficult to replicate the environment even with an environmental chamber, but without testing in the correct environmental conditions the fault may be impossible to replicate.

Intermittent failure caused by stress not replicated on test. Such failures will need the exact stresses applied on test in order to replicate the original fault.

Inadequate design suitable for robust testing for all faults. The pure design of the component or integration does not allow easy on-board or off-board test and diagnosis. This is clearly a design consideration and if it has not been considered subsequent tests in service will be a problem.

Inadequate fault models and fault trees for determining root causes. Again this is poor design or perhaps the inability to analyse the true cause of the problem in service, a lack of understanding of the true operating environment or even a lack of systems understanding regarding failure modes.

Lack of understanding of interactions between different integrated systems and software. All industries suffer from NFF to varying degrees but are also clear that it is a multi-dimensional problem with complex relationships between the domains of structure, mechanical, electrical, electronics and software. The inability to accurately describe the interaction mechanics between these differing domains reduce the ability to provide realistic probabilities of failure under varying operating conditions and the accurate localisation of faults.

Reluctance to adopt new technologies. The reluctance may be due to the need to alter system designs or because the data handling/decision-making infrastructures are not available. Health and Usage Monitoring System (HUMS) and the analysis for decision making on board and off board are hugely beneficial but are difficult to add on later once equipment is in service.

Procedural and rules

Supply chain effect. This is when a fault X generally leads to the replacement of LRU Y in say 75 per cent of cases. The root cause, however, in 75 per cent of cases, is in LRU Z. The supply chain, however, sees increased usage of LRU Y and forecasts that an increased stock level is required. This is sometimes known as the phantom supply chain. It is exacerbated as quantity of LRU Y increases, so the speculative replacement also may increase on the erroneous assumption that it is because of a high fault rate.

Discrepancies and faults in test procedures. Such errors in process and procedures might exist but they are not obvious and therefore lie unidentified but nevertheless generate NFF.

Incorrect fault reporting. Effective communication with a common understanding and interpretation of the fault are sometimes just not able to be achieved. People's differing perceptions and interpretations often mean the fault will not be properly diagnosed and found because the interpretation and understanding is incorrect.

Wrong processes applied. This may result from misinterpretation and presumed symptoms or wrong processes may be applied through lack of training.

Incomplete documentation. This cause might be processes that were not comprehensive when first devised.

Poor/incorrect instructions/procedures. The handbook is wrong or badly written, but this fact is not obvious and so the fault will not be identified. This may therefore keep generating NFF until the procedure is corrected.

Behaviour

The causes recognised in an organisation are very similar to those recognised at the individual level and affect individual behaviour.

Lack of communication. Again at the personal level, perhaps between maintenance personnel when changing shift, poor communication might cause the new shift to misdiagnose the problem. Similarly a lack of communication between experts in the organisation might mean vital information is not passed on to those who might then solve a regularly reported fault but on different equipments.

Reluctance to change. At the individual level people are reluctant to admit their behaviour, procedures and culture might be part of the problem.

Finger trouble. This is anything from the fault being mis-reported through communication mix-ups, to incorrect or wrong procedures being applied and are probably best classified under behaviour.

Incomplete and thorough testing. Technicians might take short cuts because they "know best" or they might make assumptions which are incorrect.

What is not in doubt is that all of these will result in increases in cost and wastage of effort and resources. So NFF problems will manifest themselves and will affect the effective and efficient application of Through-Life Engineering Services. So we need to identify how these problems affect stakeholder requirements. What are the problems that most need solving? Are there impacts on system safety? How do these things affect system safety and above all what are the effects on life cycle costs so we can highlight the true cost that needs to be reduced.

Cost of NFF

Cost is clearly a major aspect to identify and initial studies show a reluctance to harvest the necessary data. Perhaps this is understandable as it may provide an unwelcome shock with no immediate solutions. Typical equipment with an in-service life of around 20 years will have its operating and support phase typically accounting for between 60 and 80 per cent of the whole life cost (WLC) of the equipment. The importance of WLC therefore for through-life service support planning has long been recognised and covers three concurrent aspects: cost breakdown structure that defines and organises all cost elements, the boundaries of those cost elements and the uses of those concepts by decision makers. Initial research indicates in various industries the costs generated by not finding faults can be very significant. They also occur at the different levels of support.

First level of support

At the equipment level there will be costs for investigation and diagnosis whether something is removed or not. The costs manifest themselves as:

- No fault is found despite lots of work but nothing is actually replaced or changed and no positive solution identified. The equipment is declared serviceable with a NFF and all tests passed. However, the fault then re-appears subsequently in next mission or soon after and further work is necessary.
- The wrong solution may be applied which means the fault appears fixed but it then re-appears subsequently on the next mission. The cost is then the actual cost of the first maintenance action which was not a genuine fault solution, i.e. the fault was in fact not found.
- A speculative replacement is made which might consist of several maintenance actions performed out of desperation to show some positive maintenance action has been taken. The fault may be fixed at the equipment level but causes one or more NFF at the next level of maintenance in the components that were speculatively removed.

At the second and subsequent levels of support

At subsequent levels of support there will be wasted man-hours in unsuccessful or nugatory maintenance. This might be:

- looking for faults that are not there – because of speculative replacements;
- looking for intermittent faults that cannot be replicated because temperature and vibration caused intermittent faults which are not able to be replicated now on the test being performed; and
- carrying out inappropriate or inadequate tests such as the wrong procedures, or the test parameters are set at a too high a level to find fault.

In the supply chain

Throughout the supply and support chain there will be wasted man-hours and costs:

- stocking more items to keep up with demand because there are significant numbers of items in the repair loop that are not in fact faulty. Due to the number now in the repair loop more items must be purchased; and
- the increased numbers in the repair loop all need transport, handling and storage when actually these items should not be in the repair and maintenance loop at all.

Diagnostic success rates for avionics system repairs

It is perhaps instructive to look at the diagnostic success rates when trying to ascertain the likely costs of the NFF problem. Here we have some information from research done by Copernicus Technology Ltd on the diagnostic success rate for avionics.

Diagnostic success can be relatively low with avionics and it is perhaps barely more than 40 per cent. Figure 1 includes all types of faults within the system, i.e. hard faults and intermittent faults. Diagnostic failures in Figure 1 account for over 50 per cent of all occurrences. The "functional test only" subset covers a common situation where the maintenance staff cannot confirm a fault, but by confirming there is no fault during a functional test, are able to declare the equipment serviceable. The "speculative replacement" portion if Figure 1 covers all the many reasons already described above (Huby and Cockram, 2010).

A very good example of the type of current costs is with the US F-16 aircraft where its Modular Low Power Radio Frequency units were singled out for study because of a high NFF rate, which were in fact caused by various intermittent faults. Until subjected to analysis in an environmental chamber, the study showed the real cost and effect of NFF and speculative replacement. Over a 10-year period of repairs at the depot the study showed the items that were being returned many times. Some were being returned more than ten times and two LRUs were sent for repair 17 times in ten years. The study showed that 21 per cent (360 units) of all returns were found to be NFF at the depot (Huby and Cockram, 2010).

So just to re-emphasise, to mitigate NFF we need to identify the root causes and the origin of the original problem, which will mean we will have achieved diagnostic success, if we are to provide an increase in satisfaction and a saving of money!

Mitigation of NFF

In terms of mitigation there has been much research in the past and some mitigation is in place in some industries but initial research shows it is patchy and there is definitely

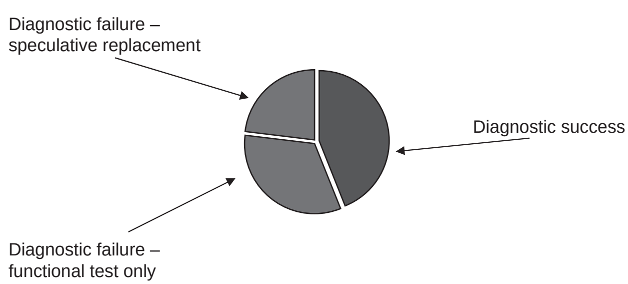

Figure 1.
Diagnostic success rates for avionics system repairs

more to do. The following are some of the key areas which require strong research and development effort for the mitigation of NFF.

In the design and production stages there is a requirement to design more fault-tolerant systems incorporating inbuilt redundancy and the need for a full understanding and modelling of intermittent faults. Understanding intermittency will depend upon being able to accurately describe the interaction mechanics between differing mechanical, software and electronic elements of the system. Modelling of intermittent faults also must include the detection probability of the fault. Accurate fault models, fault/event trees and system understanding, are needed to provide this aid in recognising false BIT alarms caused by such things as a sensor – system synchronisation problems allowing the root causes of BIT deficiencies to be addressed. Also, new systematic tests should be identified in the product design. These tests would aim at allowing multiple testing of stressors, identifying weaknesses and flaws, and the critical contributors to faults before the product is put into service.

Adopting a paradigm shift from a reliability centred maintenance service to a condition-based maintenance service – supported by new technologies such as HUMS and prognostics – will be needed. The use of HUMS and prognostics would enable key operational parameters to be continuously monitored for uncharacteristic deviations. Such technologies would move away from a reactive maintenance concept into more proactive practises, providing vital information on root causes which are unavailable from traditional BIT and also aid in overall maintenance decision making. Incorporating health monitoring, however, is not a straight-forward task and some of the key areas to be considered would include:

- the use of wireless technologies for constant data transmission and adequate data storage, processing and retrieval;
- in built multiple sensor arrays with "data fusion" processing to provide a global view of system health;
- new AI (expert system) processing – combining operational data, models, operator observations, reliability data, costs, risks as well as historical failure and maintenance knowledge; and
- establishing whether it is effective to attempt integrating health monitoring technology onto ageing existing units – or should it be designed in parallel with new units ensuring reliable and robust systems integration.

It should, however, be noted that technology alone will not fully mitigate the NFF problem. As has been highlighted in this paper there are often fundamental problems within the organisational culture and procedures. Any new maintenance technologies or concepts are likely to be disruptive and focus must also therefore be on changes to the management and support aspects (Phillips *et al.*, 2011). These might be:

- improved communication to share information and knowledge between designers, manufacturers, service providers and aircraft operators;
- adoption of procedures which encourage stakeholder-adapted support information which can be transferred across different levels (i.e. organisational level to the maintenance shop level). For example the use of RFID technology to track units within a spare parts pool providing full service histories to the current user (Narsing, 2005); and

- work towards a culture which considers cross-functionality, employee empowerment, training and encouragement to identify root causes.

In addition to these potential mitigations, areas which are of significant importance when trying to understand NFF include:

- the effect that the NFF phenomenon has on specific types of equipment;
- identifying the types of items which NFF frequent; and
- the rate at which NFF re-occur.

It is also important to understand the dependency that NFF events have on repairable items, and how they may change throughout the operational lifecycle of the items (Block *et al.*, 2009). Such questions which can be asked include:

- Do NFF problems become more common after initial repair than after the original delivery?
- Does the number of repairs have any influence?
- Is there any impact of component modification?

Conclusion

This initial research has identified there is still a serious problem with NFF and has shown that organisations, culture and behaviours still need to change if huge costs are to be avoided. An initial conclusion is that by describing the issue as NFF a particular behavioural attitude is encouraged – one of resignation that it was all a waste of time, rather than there is a definite problem that must be solved. Perhaps a re-designation to fault not found is needed! This is at least a positive statement suggesting diagnostic success is required and further action required. The research project though has only just started and will continue for three years with the following objectives:

- to identify procedural, process and behavioural issues that need to be changed, learning from best practise in each industry;
- to develop an *in situ* health monitoring approach at the board level to detect, characterise and locate NFF intermittent failures and deliver a fault localisation mechanism and demonstrator at the board and sub-system level;
- to devise strategies, methodologies and system design rules to mitigate the intermittent NFF failure mechanisms and to demonstrate their effectiveness in reducing the likelihood of NFF occurrences;
- to develop a multi-disciplinary approach at the system level for the effective analysis of the root causes of NFF in order to assist design activity across domains; and
- to develop a handbook and a system design evaluation standard with procedures that will reduce the problem of NFF.

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