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FLEET RECOVERY AND LIFE EXTENSION – SOME LESSONS LEARNED

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Abstract: Extending the life of an existing fleet which still has acceptable operational capability can be enormously attractive in economic terms. Ideally, such extension programs will be planned and managed (via an ASI program), although many are urgent "recovery" programs required when substantial problems are discovered. This paper discusses examples of planned and unplanned programs, highlighting the differences in approach required.

Regulatory systems usually demand that we preserve the prevailing "acceptable level of safety" during fleet life extension, although inevitably, progressive life extension must lead to enhanced risk of unforeseen events which are absent from our structural integrity models. We cannot remove this risk, but we can mitigate it. Paradoxically this requires additional (and potentially unwelcome) investment in broad investigative strategies such as teardowns and damage enhancement test programs. This paper will provide examples of a management program that was successful precisely because it contained such strategies.

The paper argues that we may underestimate the extent to which organisational issues may bring an additional (and perhaps more important) threat to the safety of old aircraft. Two examples are provided in which complacency and a perception that the fleet is nearing end-of-service promoted drawing down of maintenance/safety resourcing, leading to maintenance underperformance, increased risk, accidents, and loss of life. These issues will be particularly evident where we have poor corporate culture, weak organisational structure, progressive deferral of fleet withdrawal dates and increased operational demand. The examples suggest that our structural safety models are in themselves of limited value if these broader system/organisational risks are neglected.

INTRODUCTION

Cost, and the value of Life Extension and Recovery (LEx) programs

The economic impact of replacing a major fleet – even in terms of the relatively small Australian Defence Force this will amount to tens of billions of dollars – is so large that planning to extend the life of current aircraft which are still offering a reasonable level of capability is usually seen as worthwhile. The benefit may not be just economic – usually the new fleet is an aircraft which is still being developed, and deferring an acquisition for a few years is likely to result in the new fleet, when it arrives, to be a more mature and more capable system rather than early production models; this is particularly true in the development of on-board systems which may be at a low level of development in the early models.
The increase in cost of new acquisitions is very substantial; it has been noted [1] that "since the 1950's aircraft payload has increased by a factor of five, performance/range increased by a factor of four, but cost increase is times one thousand, and the main reason is SYSTEMS costs".

Usually, and ideally, the deliberation about whether or not to extend life, and the subsequent decision-making, occurs in a planned environment, and a suitable trade-off between declining capability and cost can be reached. However, more often than not, this process is disrupted by one of two issues:

(i) it is fairly usual to see delays in the "new" fleet's development – this leads to continual rewriting of the Planned Withdrawal date (PWD) for the existing aircraft, each time a further delay is announced.
(ii) there are many cases where the existing fleet experiences an accident, a significant maintenance issue involving unacceptable increases in cost-of-ownership. These life-limiting events usually result in demand for fleet recovery involving desperate efforts to achieve a minimal level of capability with a much reduced fleet. The lead time in any fleet withdrawal and replacement is usually so long that if there is a need to retire a fleet very rapidly, and there is no means of providing the lost capability, there result will be costly short-term purchase (or lease) of alternative aircraft.

This paper discusses two cases – both of which involved *planned* life extensions, but in one case such planning disappeared when there was an accident requiring urgent fleet recovery. Both programs successfully provided economic benefit and preserved capability, but they required very different approaches; the structured example used large-scale testing backed by laboratory-level support, while the recovery program required development of innovative tools "on the run". Interestingly, both led to significant advances in understanding of structural lifing issues.

Maintaining an acceptable level of safety in Life Extension

Given the substantial economic benefits of extending the life of a fleet which can still provide capability, what factors limit this process? In the absence of accidents or major surprises such as discovery of structural problems, individual structural integrity issues do not usually present us with a "hard" limit – even where safe-life presents a "retire by" date, RAAF can usually plan for and implement, transitions to inspection-based approaches. The examples given later outline the need to do this on a "whole-of-aircraft" approach, even though individual structural issues may initially attract attention. The key life-limiting features are usually resolvable by introducing inspections, for example, although such activity will often result in an increase in cost which will need to be sustained throughout the extended life, and it may be more economical (in terms of maintenance and reliability) to introduce a terminating repair or replacement for some issues.

In contrast, there is often a need for systems upgrades to maintain the fleet capability throughout the proposed life extension, and this presents the operator with a major cost step; such a systems upgrade – which is usually extremely costly relative to the structural issues – can become the economic driver for a desired service life limit.

In all of the discussion preparatory to life extension, maintenance of an acceptable level of safety is usually taken to be a "given", and in terms of life extension, our target is usually maintenance of the current level of structural safety. It is worth asking whether these are realistic, and the following sections will attempt to illustrate some of the key issues.

Damage and crack initiators: Take, for simplicity a fleet managed on a safe-life basis. Figure 1, which is discussed in more detail in [2] illustrates the conventional representation of a (log) normal distribution of fleet fatigue lives. In this, cracking will develop readily from small, numerous materials or manufacturing features in any location which has suitably high stress. The initiators are assumed to be numerous throughout the structure, as shown in the notional "inherent" distributions in Fig 2. Fatigue life is dominated by variability in geometry, design and local stressing, and by applying a suitable scatter factor* fatigue life is restricted to a notional safe life which is a fraction of the mean life. That mean life

* In Damage Tolerance, the equivalent would be assuming conservative starter crack sizes and inspection intervals.

is demonstrated by full-scale testing under conditions which are expected to match as closely as possible service conditions. The testing is also expected to reveal unidentified critical locations, an assumption which relies on the test article being fully representative of the fleet. However, it has long been recognised that the promulgated fatigue lives of fleets can be very optimistic. In many cases, this reflects the existence of other features, design oversights, incorrect design/usage data, or damage – perhaps manufacturing features or geometrical anomalies, or unaccounted-for material inhomogeneities – which can generate cracking much earlier in life. What is important here is to recognise that this additional class of damage, here called "rare", some of which carries the likelihood of being in a location with sufficient stress to allow significant growth, may occur in only one or two locations and perhaps in only a few aircraft in the fleet, and we cannot therefore rely on finding it in a full scale test.

It is hard to avoid mention in this context of the "rogue flaw"; the author takes the view that the term has sometimes been used to label an initiator or feature as something which we could not reasonably have been expected to foresee. Unfortunately this might be used to conclude that we cannot be expected to foresee other "rogue flaws". An alternative view would be that such features are usually failures of process, whether that be design, maintenance, or one of the many other facets of a complex systems and its management, and such a view might be more productive in terms of encouraging the broadest possible effort to minimise risk.

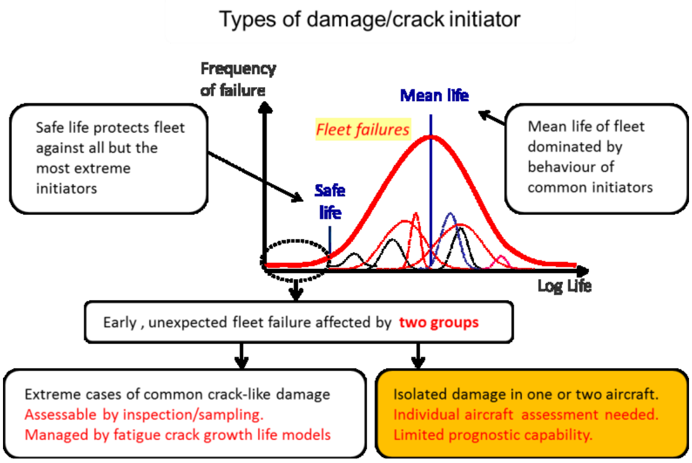


Figure 1. The (log) normal distribution curve usually considered representative of fleet fatigue life reflects the concept that many initiators exist, allowing cracks to develop readily at high stress locations; a scatter factor can be used to protect against all but the most extreme cases in the distribution. However, the same scatter factor also protects against the rare discrete damage which occurs sporadically in some fleet aircraft.

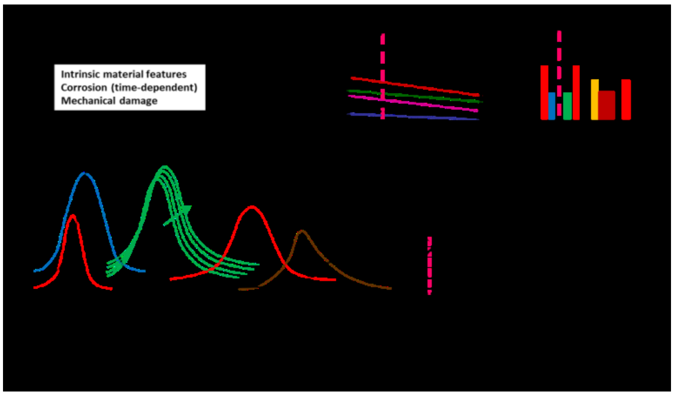


Figure 2. Notional set of crack initiating features (as equivalent crack size) indicating the need to sum the extreme cases (upper tails of distributions) of very numerous initiating sites such as inclusions, and the rare or extreme discrete features such as mechanical damage which may occur only once or twice in a fleet.

Is this additional population of rare damage important? In reality, of course, the scatter factor we adopt for the fleet safe-life also covers the fleet against many of these cases (the “unknown unknowns”) although one issue of concern is that the potential existence of this ‘hidden” population should not be forgotten in situations where there is an attempt to refine the scatter factor based on full scale testing. One obvious reason for the limited discussion of this issue is that it is clearly difficult to introduce any additional, uncertain limits on fleet life service life, based simply on “unknown unknowns”. Such conservatism would need to be justified.

What is clear, though, is that progressive life extension *must* attract an enhanced exposure to risk of unforeseen events – however much we rely on our scatter factors (or inspections) this increased risk will arise from the “unknown unknowns”. Corrosion, for example, can be one such source, causing time-based changes in distributions as illustrated in Fig 2, and corrosion at unexpected locations should feature more highly in a life-extended fleet. Indeed the whole process of breakdown in protective systems –paints, sealants – would be expected to provide many additional problems *only* later in life.

Managing increasing risk from unforeseen events: How can we monitor this enhanced risk and mitigate it? Firstly, we need to observe that aviation accidents are sufficiently rare that simply waiting for accidents (monitoring fleet health on the basis of losses) is not an acceptable approach - risk mitigation requires a pro-active, not a purely reactive approach!

The answer is that there *are* some tools which can be applied;

(i) one obvious one is using the life extension program to introduce enhanced corrosion management, for example by increased scope of inspection, improved broad-area application of corrosion protection and improved maintenance of protection systems; this will help defer the onset of widespread corrosion later in life and will contain fleet whole-of-life costs and minimise the risk of losing capability through surprise discovery of major damage. However, we need to acknowledge that we cannot cover all eventualities by, for example, increasing inspection - some of the areas needing to be examined are simply not readily accessible.

(ii) More aggressive exploratory programs such as additional teardowns – an approach adopted extensively in Australia

(iii) Introduction of damage enhancement testing to promote growth of small cracks already present in the fleet. An example of a damage enhancement test program provided later highlights the value of these proactive programs in mitigating the risk of problems emerging from "unknown unknowns".

Feedback to improved design: An additional benefit flows from the investigations which can be used to support life extension. One such benefit is that access to in-service airframes and systems means that damage enhancement testing, while it cannot guarantee discovery of "rare" fleet damage, *can* identify issues that may be systemic (manufacturing issues, for example). In addition to supporting management of the issue for the in-service fleet, this has the potential to provide valuable feedback to support improved design and manufacturing. Some examples come to mind – experience with SCC in aging aircraft fleets proved clear impetus for the4 development of SCC-resistant materials for new design and manufacture, and also led to the development of innovative methods of restoring SCC-resistance to existing components (eg. Retrogression and Re-Aging). Future teardowns and damage enhancement tests will allow "field" evaluation of approaches currently being used to produce fatigue –resistant holes, and more complex joint designs, and will also provide valuable feedback on the performance of composites and adhesively bonded joints.

Impact on overall LEx planning: A practical, political difficulty is that these approaches involve *additional investment*; damage enhancement testing and teardowns, in particular, are significant cost items, and arguing for such additional investment, particularly in the context of a life extension proposal focussed on economy, can present a challenge. Nevertheless it is vital to mount an effective argument to ensure that such proactive activities are included in programs such as Aging Aircraft Audits to minimise structural integrity "surprises" from the kind of sources described earlier.

INVESTMENT TO MITIGATE THE RISK OF SURPRISES

Case Study: Teardown and damage enhancement: RAAF F-111

The RAAF operated the F-111 fleet until late in 2010, some ten years after the USAF retired its aircraft; to allow this required substantial investment in activities (the Sole Operator Program, SOP) designed to equip Australia with the tools and knowledge which would allow operation to a planned withdrawal date of 2020. This SOP program included developing and using a full structural model allowing loads/stress analysis, undertaking management of stress corrosion cracking in an SCC sensitive fuselage structure, and addressing a number of issues relating to wing reinforcement.

The program also allowed development of innovative rework approaches [3] based on structural optimisation approaches which culminated in reshaping of critical regions in the high strength steel wing structure (Fig 3), reducing stresses dramatically, and extending inspection to much more manageable intervals.

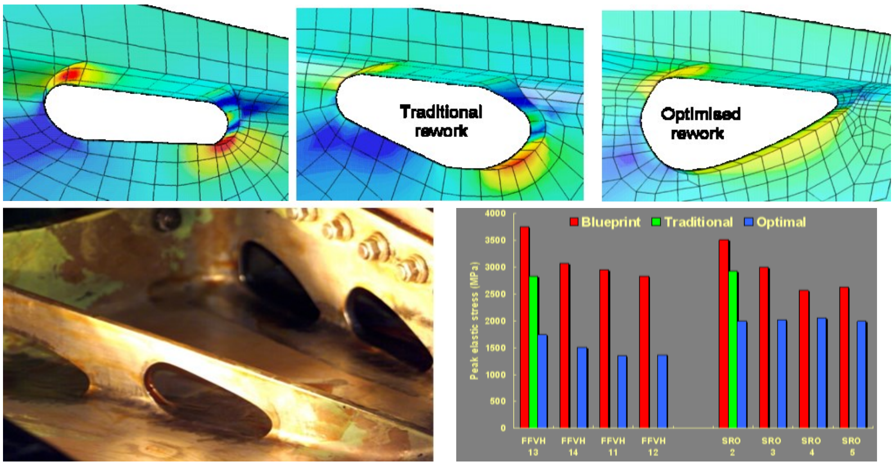


Figure 3. Structural optimisation rework developed and applied to F-111 wing pivot fiting, showing a major reduction in local stress (summarised in [3]).

A key factor in the SOP was the funding of structural teardown of aircraft to identify and document the numerous areas in which corrosion and fatigue degradation might become difficult as the fleet continued in service. More importantly, it transpired, was the conduct of a Wing Damage Enhancement Test (WDET) in which a service wing – which was presumed to contain small cracks that would be difficult to find – was subjected to additional fatigue loading to grow the damage to the stage where a teardown would allow it to be detected, documented and analysed. This test was expected to provide core data for future fatigue evaluations. The test was not a fatigue test which aimed for an exact replication of service conditions, but focussed instead on rapid testing, and the loading was not fully representative of RAAF flight loads.

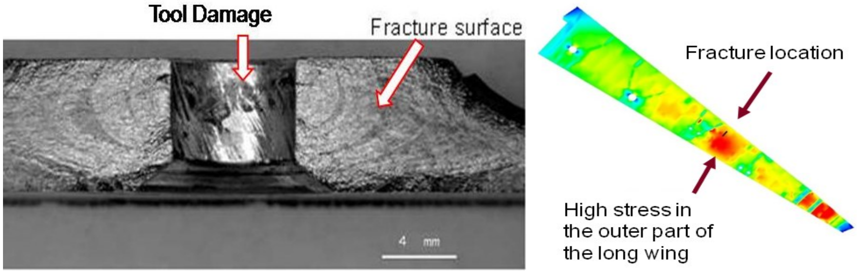


Figure 4. Manufacturing damage leading to fatigue cracking in F-111 wing structure, and a region of high stress in the Australian wing configuration.

In 2002 the test wing failed, revealing numerous sites (Fig 4) with manufacturing damage – damage which had never been revealed or suspected in earlier tests. It also highlighted some high stress regions which showed that the basis for fatigue certification was unreliable - the RAAF wing geometry differed from that in the original test and earlier testing had not addressed this difference. An additional issue complicating fatigue evaluation was that the holes and fasteners relied on achieving a specified level of interference fit, and many lay outside specification.

Recovery from this situation required extensive effort –the older model wings were retired, and when the replacement (used) wings were introduced, and were found to also feature build-quality issues, a two-pronged approach was needed:

(a) a new full scale fatigue test was used to address the overall fatigue life certification of the wing, and
(b) a major NDE development was started to allow examination and inspection-based management of the manufacturing damage issue, based on full inspection to identify anomalies in holes.

It is interesting to note that this two-pronged approach reflects the two sources of failure discussed earlier – dealing with the overall certification issue based on a full scale, representative test (ie. using a test article declared to be as representative as possible), and a program to deal with the variable and scattered manufacturing damage throughout the fleet.

So, how valuable was the investment in the WDET test, and the SOP program? The testing allowed detection of a significant fleet issue which had never been suspected, and which, if the RAAF had continued its fleet operations to 2020, may well have led to loss of aircraft, and an immediate loss of the capability that fleet provided. The same issue may also have become a problem for the USAF, had they decided to extend their fleet life. On a practical level, the Australian result allowed a managed withdrawal of a fleet whose costs were high, and which, as demonstrated, was likely to provide surprises. The proactive testing in this case provides an excellent example of the value of this investigative approach.

The message arising from this is that while extending fleet operations is undoubtedly of economic benefit, the risk of surprise events, and accidents, will rise, and this translates to unreliability in terms of fleet capability. To mitigate this risk requires *additional investment* in the form of damage enhancement testing, or teardown. While such additional investment might be unattractive in terms of life extension focussed on economy, the F-111 case shows that it is vital to argue that such reinvestment is justified as part of a structural integrity management program.

LIFE EXTENSION PROGRAMS, STRUCTURED OR OTHERWISE

A planned Service Life Extension Program: RAAF's P3-C fleet

SLAP Program: The Australian Defence Force (ADF) performs its maritime surveillance role with a fleet of P3-C aircraft; supporting a proposed major avionics update would require extending the PWD to 2015, implying a safe-life extension by approximately 50%. Several limitations were apparent in the basis of the - safe life approach then in use (adopted from the USN); in particular, both the aircraft usage spectrum and key structural elements had changed since the original fatigue test conducted back in 1961. In addition, there were shortfalls in estimating some flight and ground loads and the way they were applied during testing. This led to concern that any inspection program based upon the findings of the original test would not accurately target the critical locations. In addition, the true economic life ie. the point at which generalised cracking became common (whether WFD or not) was not known.

Australia joined a P-3 Service Life Assessment Program (SLAP) proposed by the USN, along with Canada and The Netherlands. The objective of the program was to substantiate the 15,000 hour design life of the structure with an 85th percentile mission profile usage in accordance with USN philosophy [4]. In this program, conducted between 1999 and 2006 [5], Australia performed flight loads measurement, wing teardown and an empennage full scale fatigue test on a retired structure [6]. The wing teardown (Fig. 5) on a high-time fleet wing revealed valuable data on the extent of cracking (relatively little) and corrosion (relatively widespread).

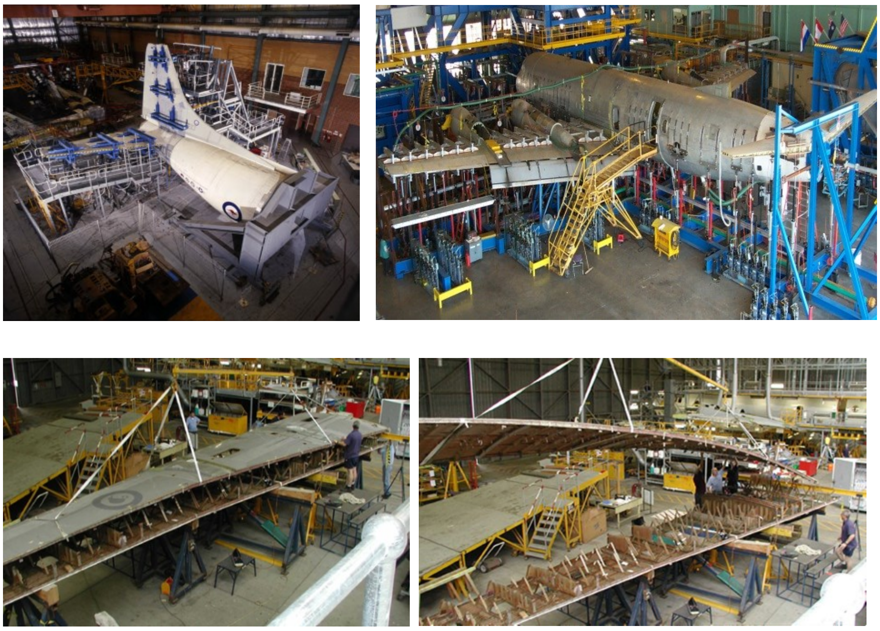


Figure 5. RAAF P-3C Empennage fatigue test. US-based wing test (from [7], and in-service wing teardown.

The P-3C SLAP involved the use of an 85th percentile USN test spectrum to substantiate the 15,000 hour design life of the aircraft [7]. This spectrum was found to be more damaging than the RAAF usage (Fig 6) and so the results from SLAP had to be adjusted so the findings could be applied to the RAAF P-3C fleet.

Research Outcomes: The full-scale empennage fatigue test provided an opportunity for exploration of one issue which affects lightly-loaded aircraft structure, namely the difficulty of running a fatigue test long enough to achieve meaningful results in the low-load (and consequently high-scatter) regime. The test included a phase of augmented loading, which normally would raise the prospect of an unrepresentative fatigue result because of local complex effects involving overload, yielding and retardation; after substantial discussion – essential when such tests involve a major full scale test article – the augmented spectrum was clipped at a level which was able to minimise these potential effects. After two lifetimes of baseline loading (30,000 SFH), a further two lifetimes of augmented loading was applied, the second lifetime of testing including newly-introduced damage (saw-cuts) to provide experimental data to support crack growth calculations. The test successfully revealed the key fatigue critical locations at the base of both the fin and horizontal tail, one location being adjacent to an existing inspection point established analytically under the existing aircraft management regime. The P3 ASI management program that was then in place, therefore, would not have kept the aircraft safe.

Secondly, the results also allowed a comparison of different lifing approaches using the same test data [6, 8]; in particular, it was intended to allow exploration of the UK DEF STAN 00-970 Safe S-N [9] concept of variable scatter factor associated with different structural features. This aspect of the test concluded that inspection thresholds calculated using FAR 25.571 and DEF STAN, while not identical, were fairly close; but, there was a difference in inspection intervals, attributed largely to the different factors called up by the two approaches.

DSTO was responsible for the interpretation, for RAAF, of all the tests results and, translating those results back to ADF usage and proposing a new inspection-based structural management plan for the aircraft. The analysis approach for this interpretation was a generally conventional test interpretation, see Fig 7, incorporating teardown data, as it became available, and from this, presenting options for inspections and structural replacement to the fleet managers.

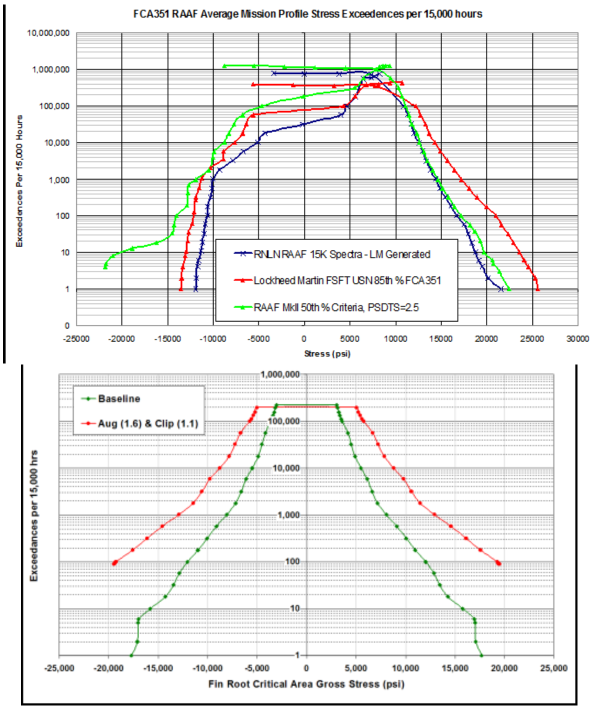


Figure 6. P3 spectra (left) RAAF, Lockheed –Martin wing test and RAAF wing spectra (right) DSTO empennage test baseline and augmented spectra.

The plan also included the determination of more modern elements such as the onset of Widespread Fatigue Damage (WFD) and the Limit of Validity (LOV) of the in-service maintenance program. In this part of the program, RAAF was fortunate to have access to a large quantity of in-service inspection data that had been generated by the USN. With the lead fleet, the USN had begun inspecting their aircraft at the critical locations identified in the fatigue tests and quickly began finding cracks. The data was of sufficient quantity to enable probabilistic assessments to be made to refine the test based inspection thresholds. In this case RAAF, with its relatively younger fleet, was able to take advantage of the time afforded between the conduct of the SLAP and the thresholds for structural inspections and replacements to both plan an orderly and optimised on-going maintenance program and manage the drawdown of aircraft to meet the introduction into service of the replacement capability.

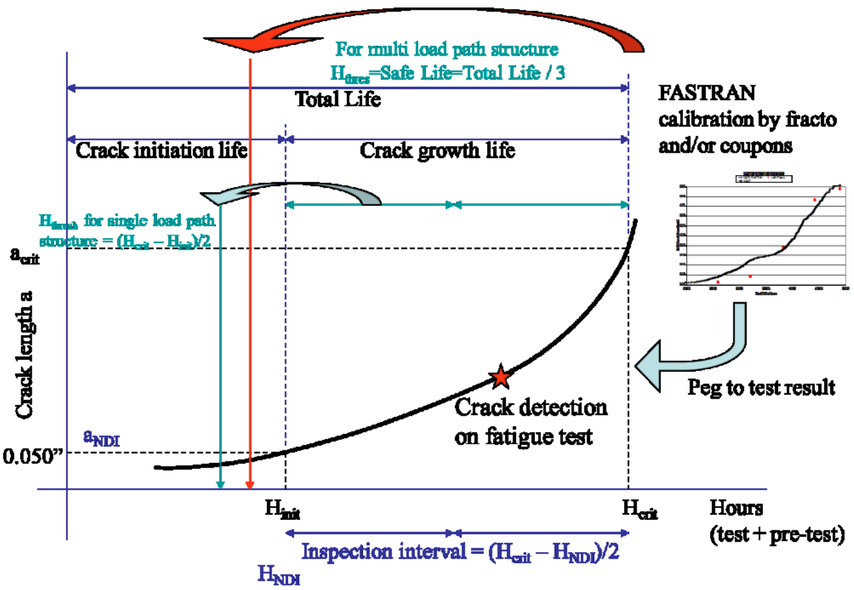


Figure 7. Fleet lifing parameters for RAAF P3-C.

The test concluded that [10] “testing the structure to eventual failure provided a significantly extended structural clearance than did the equivalent conventional test that was halted after a pre-defined service life multiple”. In that sense, the economic penalty of extra testing was offset by the value of increased confidence in structural integrity of the life-extended fleet, in part as a result of use of a carefully thought-out engineering approach to the augmented-load test which allowed test life to be contained.

This program clearly demonstrated the value of collaboration to allow a whole-of-aircraft SLAP, with major fatigue test distributed worldwide, and extensive data sharing, combined analysis and test interpretation providing exceptional robustness for the management strategy.

The results of the full scale testing undertaken by the SLAP participants allowed development of inspection and lifing proposals and individual Aircraft Tracking which would permit RAAF to implement management of the fleet to FAR 25.571.

An unplanned Service Life Extension Program - fleet recovery post-accident

Until 1990 the structural integrity of the RAAF fleet of jet trainer aircraft – the Aermacchi MB326H – had been founded on a "safe life" approach, with aircraft retirement based on achieving a proportion of the life demonstrated in a full-scale fatigue test conducted by Aermacchi in 1974/75 [11] which demonstrated first failure in the lower spar of the centre section, and a second failure location in the wing spars. In the early 1980s, the RAAF conducted a Life-Of-Type EXtension (LOTEX) program to extend the fatigue life of the fleet to 1992. Various modifications were developed by RAAF and carried out by an Australian contractor. Wing spars were replaced, and the original centre sections were replaced by improved centre sections with an (estimated) improved safe life, although, crucially, no fatigue test was undertaken so RAAF had no knowledge of the second most critical fatigue location in the wings.

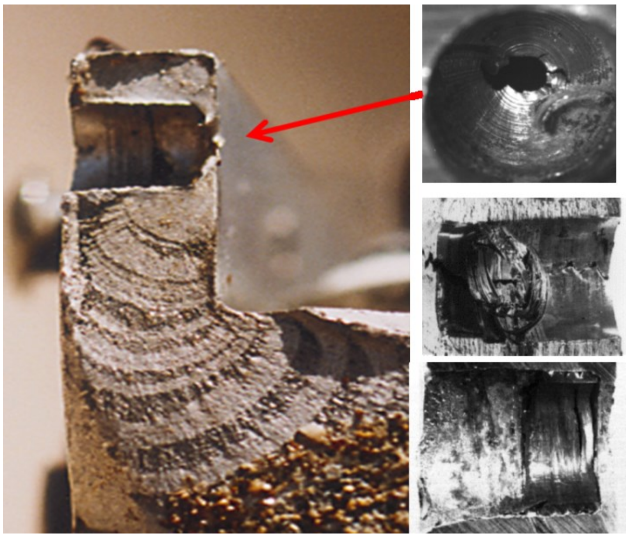


Figure 8 Fracture surface from failed Macchi wing spar, showing manufacturing damage which promoted cracking, and manufaturing damage in other holes.

In the late 1980s the RAAF decided to extend the planned withdrawal date of its MB326H fleet to the year 2000, to align it with the introduction of a new lead-in-fighter fleet. At this stage, the fleet had been managed for many years on a safe-life basis with some locations managed on the basis of safety-by-inspection.

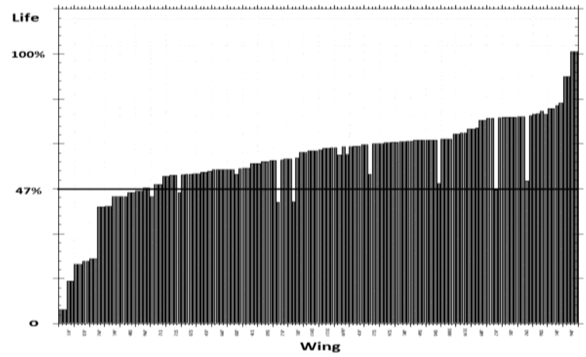
In-flight failure: In 1990, the wing of an aircraft separated during an air combat manoeuvre, at a service life substantially below the safe life currently in force for the fleet. The fleet was immediately grounded, and recovery of parts from the sea identified a severe fatigue cracking problem in the lower wing spar cap (Fig 8) and, after substantial fractographic analysis - complicated by the extensive stable tearing fracture - to determine the crack growth rate, inspection methods were developed to inspect fleet wing spars in this region and to permit the resumption of normal service operations.

Initial Fleet Life Amendment: However, after examining additional recovered parts, many more build quality issues were identified. The situation was made far more complex when significant service cracking was also identified in undamaged holes in the non-failed wing from the accident aircraft. Of course, in a safe-lifed fleet, where the philosophy relies on not allowing the development of significant cracks, such a situation should not arise, and it was discovered that there had been deficiencies in interpreting the results of the original rudimentary fatigue test to develop the service fleet life. The combination of damaged holes and this lifing error required a re-assessment of the safe life of the aircraft, the lifing methodology and fatigue life management tools. This led to a major effort involving the teardown and assessment of five additional high-life wings using fractographic tools, and projection of the lives of these wings. Pooled results from a number of wings led to application [12] of a reduced, conservative, life limit in 1991 which was approximately one-half that originally promulgated. Fig 9(a) shows the fleet usage accumulated at the time, and the impact of this life reduction led to a dramatic reduction in available aircraft – from 69 to 11. This reduced capability meant that the fleet would not reach its planned withdrawal date.

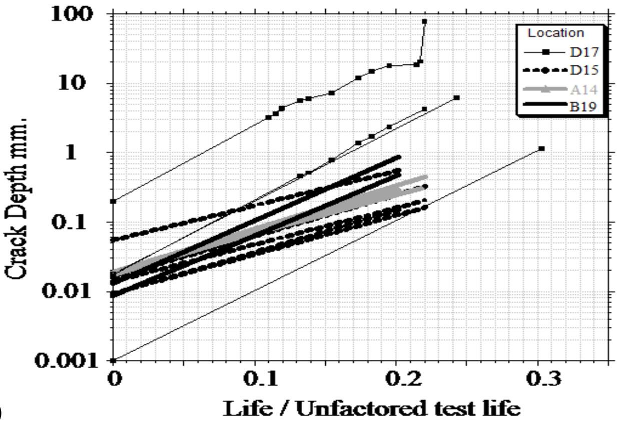
Recovery Actions: The RAAF and DSTO collaborated to find a means of managing the wing spar structural integrity problem, and the first action was to extend the teardown program; soon the database included data on eleven wings, and over 1000 holes of which about 100 had fatigue cracking. The situation was equivalent to a fatigue test in which there is one failure and ten run-outs, and a key issue was how to project the service data to achieve a useful life prediction. The method developed was based on the observations of Goldsmith and others [13-16] who observed that an exponential growth law of the form:

$$a = a_0 e^{\beta N} \qquad (1)$$

where crack length **a** at service **N** (cycles or hours) develops from an initial size $\mathbf{a_0}$ at a rate influenced by loads, material and geometry related factor $\boldsymbol{\beta}$. This provides a remarkably good representation of variable amplitude crack growth in service, as illustrated in Fig 9b, which shows crack depth *vs* service data for several cracks at four different hole locations. Two cracks shown were measured in detail fractographically, and for the rest, crack growth estimates could be made by joining the measured initial and final defect sizes. In this figure, it is interesting to note that four families of curves can be identified, associated with the four hole locations.



(a)



(b)

Figure 9 (a) fleet usage distribution at the time of the accident (b) results of fractographic analysis [12] using log-lin crack growth relationship to develop predicted lives from the observed cracking.

The log-linear formulation is consistent with a model by Frost and Dugdale [17, 18] who developed an earlier representation by Head [19]. This simple relation was used to project forward the observed crack scenarios to allow development of predicted lives for the wings torn down. As a result of the predicted lives, a revised fleet safe-life was developed for the wings, supplemented by an order for new wing sets.

Centre Section Cracking and life: Having determined a suitable wing spar recovery approach, attention was then focussed on other potentially critical areas. The steel booms of the centre section had been managed by inspecting specific bolt holes known to have high stress. However because of changes in boom design at LOTEX, several booms were subjected to component fatigue testing for comparative purposes and to determine whether or not the bolt holes could be cold-worked to extend boom life. Here the lack of a suitable full scale test to identify the second-most-critical area was very evident. The tests revealed a complex set of different failure mechanisms, illustrated in Fig. 10. These modes included manufacturing metallurgical issues, fatigue from corrosion pitting in the bore of the wing attachment lug, crack growth from bolt holes, and also cracking from a complex geometrical region in which small screw holes came close to penetrating the bolt holes. Resolving the issue of criticality order for these different failure modes became paramount, and analysis was based on further development of the log-linear relationship.

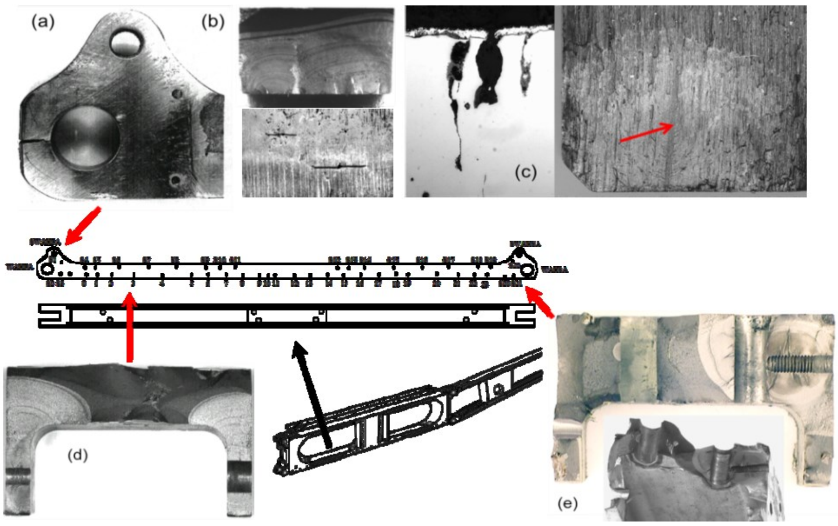


Figure 10 Cracking observed in centre-scetion spar booms (a) lug failure (b) cracking from corrosion pits in lug bore (c) cracking initiating at a forging/intermetallic (d) cracks from flange holes (e) complex crack configurations involving bolt holes and near-intersecting, corroded screw holes.

The exponent parameter beta describes the severity of the "cracking" response of the material and geometry to loading, and this exponent was used to evaluate the criticality of the many holes in the spar, as illustrated in Fig 11, where the beta factor is shown for various locations and configurations along the boom. The results confirmed that bolt holes near the boom ends had a higher beta and were therefore were more prone to cracking. The important result however was that two locations involving screw hole/bolt hole intersection had a high beta value, meaning that there was no prospect of extending the lives of the bolt holes since that would leave these regions vulnerable.

As a result of these anlyses, inspections were introduced (magnetic rubber and eddy current) for the flange bolt holes and lugs. The scerew hole corrosion was removed and protection introduced, and the screw hole/bolt hole intersections were monitored using the same approach, although two of these locations were deemed life-limiting.

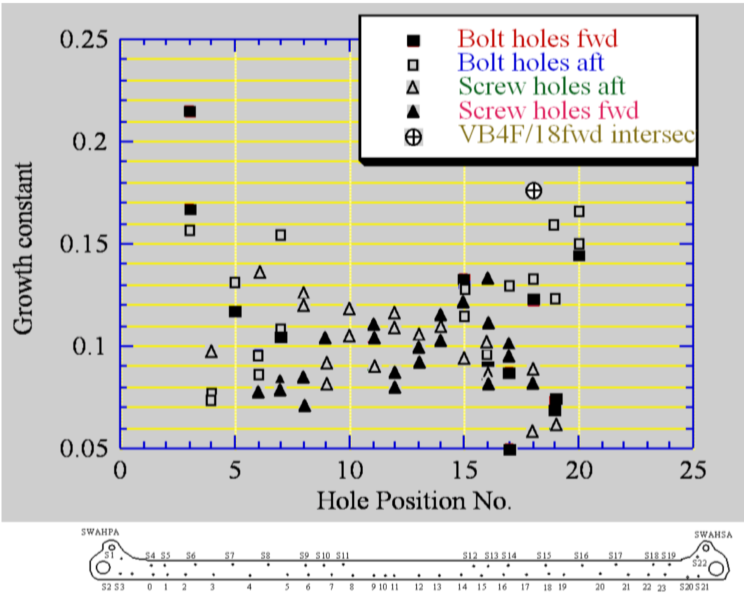


Figure 11 The severity of cracking at various locations and details along the centre-section booms, indicated by the beta growth exponent from the log-linear growth model. The results confirmed the severity of cracks at the end bolt hole region, but also showed the severity of cracking at screw hole/bolt hole intersections. From [12]

This procedure provided the RAAF with a workable, well-substantiated and acceptable centre section structural integrity management strategy

Corrosion Issues: The teardowns, which by now included twelve wings and two fuselages, allowed assessment of the condition of the whole aircraft. Two new corrosion issues were identified:

(a) corrosion of the magnesium alloy centre sections spacer blocks; this was not structurally critical, and could be rectified, and
(b) the discovery of stress-corrosion cracking in primary structure (spars) in the tailplane.

The tailplane SCC illustrated the complexity of dealing with such corrosion damage in structural terms; the SCC often progressed along a cylindrical surface inside the spar as shown in Fig. 12. Detection of this profile of cracking, in unknown locations, presented a major problem, and it was decided that it was prudent to replace the spars with a corrosion-resistant 7xxx alloy. However, the replacement time demanded assessment of whether the spars were safe to fly, and a series of actions was implemented to mitigate risk. These included liberal use of Corrosion Inhibiting Compounds to prevent or limit further development of the cracks, full scale tests on some tailplanes to determine failure loads in bending and torsion. In addition, inspections were introduced insofar as they could be accomplished.

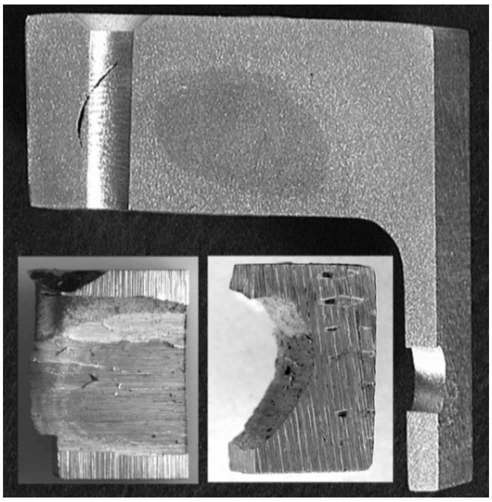


Figure 12: Stress corrosion cracking observed in tailplane spars.

Overall outcome: The program was ultimately successful; training could be continued, and the capability of the Macchi fleet was preserved until the fleet was replaced by a more modern aircraft. Several major lessons were learned:

(i) The fleet service life was based on the results of a full-scale fatigue test which had become increasingly unrepresentative as changes in aircraft configuration were introduced to extend the fleet service life; a full scale fatigue test at LOTEX would have revealed the safe-life problems and probably the build quality issues.
(ii) A teardown program to support the final life extension proposed would have revealed the build quality issues.
(iii) Environmental degradation changed the critical crack location.
(iv) The recovery program ultimately relied on development – and implementation – of new analytical tools, a process which ideally would have been followed in a more structured and robust manner.

The life extension/recovery program, while successful, must be seen as fragile – the program moved from one emerging issue to another, for some five years. At any stage, these emerging problems, which were in fact addressed by innovation and effort, had the potential to derail the whole effort, which would have led to enormous outlay to acquire and alternative training capability.

A BIGGER THREAT TO SAFETY – ORGANISATIONAL ISSUES?

Acceptable level of safety

First we need to note that the concept of an acceptable level of safety, which is, after all, our goal, is itself complex – what is acceptable? And how useful is the concept? Recently the FAA Transport Airplane Directorate published a Risk Methodology Handbook, [20] which included the illustration shown below in Fig 13, showing the current level of risk associated with various activities; in this commercial aviation provides approximately 10^{-8} risk of individual fatality per hour. Is this an "acceptable level" of risk? The same figure shows several other risk levels which greatly exceed this, suggesting that political or economic issues, and perhaps the extent to which those interests deem fatalities sufficiently newsworthy to achieve public prominence, may play a large role. It seems likely that the alleged cause of the losses (eg. terrorism, mechanical failure) are parameters which influence the result. For military aviation, risk of aircraft loss is substantially higher – a few decades ago, Australia lost approximately one-third of a fighter fleet over its service life, representing approximately 10^{-6} losses per hour, although with ejection systems, individual fatality rate is substantially lower than this. The reasons are again complex – the military role is perhaps more complex, more variable, and demanding of equipment and planning.

To illustrate the variable levels of acceptability, it is interesting to note Fig 14 [21-23] which provides another risk representation, in this case associated with an event (not specifically aviation); para. 136 of [22] states "Where societal concerns arise because of the risk of multiple fatalities occurring in one event from a single major industrial activity, HSE[1] proposes that the risk of an accident causing the death of fifty people or more in a single event should be less than one in five thousand per annum". Using these figures suggests an accident involving total loss of a civil transport aircraft would be seen as "intolerable" only if it occurred 10^{-3} times per annum, and we would be successful in achieving a "negligible" risk if such an accident occurred 10^{-6} times per annum – perhaps a worthy goal, but are we anywhere near that?

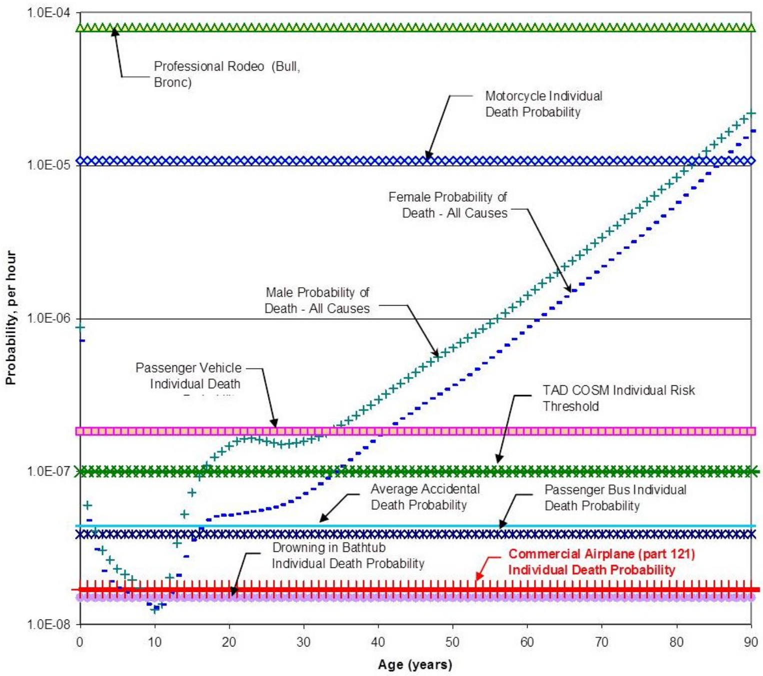


Figure 13. Data (illustrative only) for a range of risks. For aviation, data is from NTSB 2002-6. From [20]

Naturally, such comparisons are made more complex by the different populations of events being assessed, but it is clear that judging public acceptability of risk in aviation is difficult, and we should perhaps avoid assuming that current levels of risk are indeed acceptable – a small number of highly publicised losses could change public perception very dramatically; indeed in the earlier days of aviation, civil aviation safety in Australia was greatly influenced by such losses. One

[1] (the UK Health and Safety Executive)

obvious conclusion is that assuming the current level of losses as acceptable is something we should avoid if we are to avoid complacency.

There are of course many contributors to the overall level of aviation risk, and ASI is only one of them. In an attempt to put that balance into perspective, the last section of the paper raises the issue of non-structural factors affecting safety of old fleets.

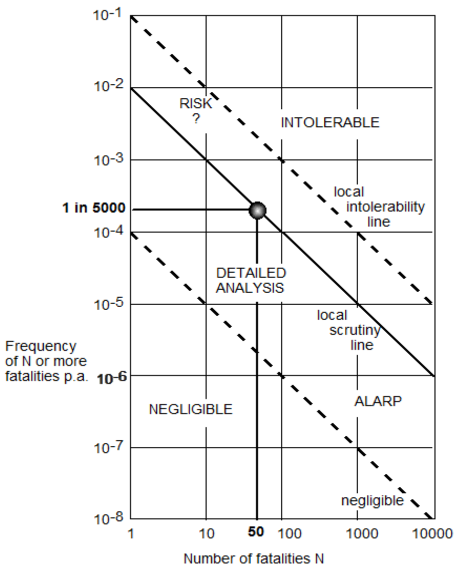


Figure 14. Frequency / number risk diagram, after [23].

System threats to safety of an old fleet

More challenging, however, is another issue – however laudable our focus on managing structural risks through life, we cannot rely solely on this process. The results – fleet safety – are threatened by organisational issues such as financial cutbacks which affect maintenance and cloud the chain of responsibility. *Older* fleets in particular are vulnerable through diversion of resources to other programs, and the possibility of progressive decay of maintenance support systems such as documentation. These issues, particularly when compounded by the uncertainty of progressive deferral of fleet withdrawal dates, and increased operational demand, can, and do, lead to "maintenance debt", accidents, and loss of life. Two examples of this are described briefly below. What is at issue here is that our structural safety models are in themselves of limited value if the system risks are neglected.

Taking the larger view raises the question of prioritisation of effort when safety risks – losses – may be dominated by non-structural issues such as crew or maintenance performance.

Example: Sea King accident 2005

In 2005, a RAN Sea King helicopter crashed in a remote location in Indonesia with the loss of nine lives [24]. The Board of Inquiry report [25] noted that the primary cause of the accident was flight control system failure caused by separation of components; the separation was "the result of a series of errors and non-compliances with Maintenance Regulations which ultimately led to…deficient fitment of the split-pin and nut that secured the pivot bolt". Importantly, the BoI stated that the accident was "not an isolated random event caused by the actions of a few maintenance personnel. Rather it was the result of a complex interaction of individual and systemic failing". Limited staff resources, personnel seeing little future opportunity working on that type, the favouring of newer aircraft types, declining spares resourcing, declining documentation control, and a pervasive culture of maintenance work-around and non-compliance.

One key observation was that the performance of maintenance on this aircraft had already been observed to be deficient – many breakdowns in performance of maintenance had already been observed, but recovery of maintenance performance to a more appropriate level did not occur, in part because of declining interest in the older aircraft, reluctance to invest in facilities, staff and training, and the gradual predominance of a culture of 'work-arounds" to cope with limited resourcing (in terms of staff, facilities, tools, spares, documentation). In this case, the environment – an old aircraft approaching the end of its service life – clearly contributed to organisational issues in an already under-resourced maintenance environment, and was a major factor leading to loss of life. The issues are detailed in ref [25] and have also been summarised using an alternative "AcciMap" approach [26].

Example: Nimrod accident

There are many similarities between the conclusions of the RAN Sea King BoI and those of a review [27] of the safety issues underlying the crash of a RAF Nimrod in 2006. RAF Nimrod XV230 was lost on 2 September 2006 on a mission over Afghanistan; a catastrophic mid-air fire led to the total loss of the aircraft and the death of all 14 service personnel on board. While a 'Safety Case', to identify, assess, and mitigate potentially catastrophic hazards before they could cause an accident, had been mandated for military aircraft and other military platforms by regulations introduced in September 2002, the Review concluded "*the Nimrod Safety Case was a lamentable job from start to finish. It was riddled with errors. It missed the key dangers. Its production is a story of incompetence, complacency, and cynicism"*.

More significantly for the present discussion the Review [25] stated, *"The Nimrod Safety Case process was fatally undermined by a general malaise: a widespread assumption by those involved that the Nimrod was 'safe anyway' (because it had successfully flown for 30 years) and the task of drawing up the Safety Case became essentially a paperwork and 'tickbox' exercise"*.

In this instance, as in the RAN Sea King earlier warning signs of fuel system problems had been ignored by some parts of the safety system. A Nimrod report in 1998 [28] had warned of *"the conflict between ever-reducing resources and ... increasing demands; whether they be operational, financial, legislative, or merely those symptomatic of keeping an old aircraft flying. The pressures…ensue from reducing resources place additional burdens on a 'can do' organisation such as the Nimrod Force and call for highly attentive management, closely attuned to the incipient threat to safe standards, if airworthiness is to be safeguarded."*. The Haddon-Cave [27] review concurred: *"The Nimrod fleet of aircraft was going to require more (not less) care, resources and vigilance and a strengthening (not weakening) of the airworthiness regime and culture if these 'legacy' aircraft were going to continue to operate safely until their extended Out-of-Service date."*

One of the issues discussed earlier as likely to lead to increased risk was repeated changes (ie. deferral) of Planned Withdrawal date. The Review [27] noted in regard to this issue: *"the MR2 Out-of-Service Date was continually being put back led to planning, spares, sourcing and long-term investment problems"*.

In this instance the continual extension of life to match the introduction of new equipment was a clear factor contributing to the fleet problem, and this was compounded by a "muddy" system of airworthiness/safety responsibility.

A similarity exists to the state of the RAAF Boeing 707 fleet in the early 2000's; repeated deferral of the PWD for the fleet meant that the management system for the fleet – particularly any elements of proactive maintenance – was degrading, to the extent that with each PWD deferral, it became harder and harder to restore a functional maintenance program. The fleet was effectively being managed on an individual aircraft basis, day to day, records were becoming progressively less complete, and the retention of a fleet capability was threatened continually by each inspection.

In summary, the tools and procedures we have developed for managing structural integrity are highly effective, but the question remains…as engineers and scientists focussed on safety management, do we do enough to engage with other safety-related issues (such as the maintenance of old fleets) which in the broader picture, may have far more impact on overall fleet safety?

CONCLUSIONS

Overall, fleet life extension has the potential to be extremely cost-effective, by delaying costly fleet replacement. However, several issues demand attention:

- When we consider the nature of the damage or features which can cause failure, we need to include the class of initiators (including damage) which are not widely represented in the fleet, and which are not necessarily present in "representative" test articles. Using the descriptor "rogue flaw" misses the point that such initiators are failures of process, involving complacency, or omission in design, maintenance, and overall systems management.
- The presence of this population of discrete, individually unique, damage suggests that fleet life extension will be accompanied by an increased risk of accident/failure, since our models do not address "unknown unknowns" and these risks inevitably increase with increasing service time.
- There are methods to mitigate these risks; they involve proactive investigative programs such as teardown, coupled with more aggressive programs such as damage enhancement testing, and proactive management of deterioration such as corrosion. Even though such on-going investment in ASIP is of course something that should be part of a "normal" fleet management approach, adding these costly programs will require significant reinvestment in an old fleet. They should be made an integral part of the LEx proposal, and that may require strong argument on safety grounds.
- One example was provided of a successful program in which damage enhancement testing identified, safely, some serious issues with an old fleet in Australian service.
- Innovative risk mitigation programs in a LEx program can provide valuable information to guide future design and manufacturing.
- Life extension programs will naturally function most effectively in a planned environment, and can include significant research and development which will provide improved capability in Structural Integrity.
- An example of a successful life extension program showed that it can provide an opportunity to consider recent improvements to ASIP and on-going airworthiness processes by civil and military authorities; these include limits of validity of maintenance programs (due to limits of underpinning data), initiatives to improve assessments by using probabilistic techniques (eg. by developing distribution functions for crack growth to support further analysis).
- Unfortunately, life extension often occurs in an unplanned manner, as a result of an accident, or other failure. Such extensions can be successful, and can be extremely cost-effective (avoiding the cost of an "emergency"

acquisition of alternative capability) but an example provided shows the difficulties which are encountered in such “reactive” recovery-based programs, and highlights the fragility of the outcomes.

- The concept of an “acceptable” level of risk is complex, because of a strong tendency to equate it to “current” level of risk.
- Finally, the paper has raised the issue of just where our major safety risks lie, noting that there is evidence that progressive deferral of retirement dates for old fleets can lead to declining maintenance effort and effectiveness. The impact of such issues - some recent accidents involving such issues have caused heavy casualties - may be to introduce risks very much greater than those posed by structural integrity matters, and this perhaps places a demand on ASI specialists to contribute to the broader issue of fleet risk.

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