AGEING AIRCRAFT SYSTEMS & COST EFFECTIVE SAFETY

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Abstract

Requirements and regulatory guidance suitable for all aspects of aging systems in military vehicles were reviewed for RAAF combat and trainer aircraft. Desk-top audits, detailed inspections and laboratory analyses address the parallel demands of acceptable levels of safety and long service lives for military aircraft in a cost-sensitive environment.

1 Introduction

Keeping fleets of military aircraft in service for long periods of time requires significant effort to maintain acceptable levels of safe operation under the constraints of limited resources and the demands for high capability. Loss of lives, equipment and fleet capability are some of the possible outcomes of inadequate attention towards safety. There are also risks to culture, reputation and public confidence arising from accidents. Ageing is the degradation of the system (people and equipment) which leads to an increased safety risk [1]. This review considers the important factors in ageing aircraft and identifies how to obtain value from an ageing systems audit that enables continued service.

The Australian Defence Force (ADF) is balancing the introduction of new aircraft fleets with their history of operating legacy fleets for 3-4 decades, see Table 1. The effects of age on these ageing fleets is an issue that demands a mixture of specialist scientific, technical and industrial support to the operators to efficiently meet safety requirements. The recent retirements of the F-111, Boeing 707 and Caribou aircraft by the Royal Australian Air Force (RAAF) are excellent examples of how this can be safely achieved. The adoption of Aircraft Structural Integrity Programs for all RAAF aircraft types in the mid 1990s has enabled an effective means to manage fleet safety. It is notable that since then, there has been no loss of aircraft from in-flight structural failure or engine failure [2]. The dominant cause of aircraft loss has been due to human factors (e.g. controlled flight into terrain) rather than technical causes. However, losses and significant damage have occurred from failures in systems other than engines or structures including: flight controls, fuel pumps, hydraulic lines, wiring, undercarriage and (suspected) in oxygen systems.

Table 1: RAAF aircraft service life [2]

Aircraft Type	Model	Service Dates	Life (yrs)
Fighter	Avon *Sabre*	1954-‘71	26
Fighter	*Mirage III*	1964-‘89	25
Fighter	F/A-18 *Hornet*	1985 -	27+
Trainer	Macchi MB326	1967-‘99	32
Trainer	Pilatus PC-9A	1989 -	23+
Transport	Boeing 707	1979-2011	32
Transport	DHC-4 *Caribou*	1964-2011	47
Strike	EE *Canberra*	1951-‘82	31
Strike	GD *F-111C*	1973-2010	37

To ensure safety of a military aircraft, certification of its design and operation is assessed upon its entry into service. Numerous regulatory means and formal requirements support this process, such as Design Standards [3-9] from the United States of America (USA) and the United Kingdom (UK). As part of the consideration of the full life cycle for a fleet, a key re-assessment is a necessary activity partway through the service life. The current benchmark [24] requires an Ageing Aircraft Audit (AAA) 15 years after the type's declared In Service Date (ISD) and thereafter at 10-yearly intervals. This 15-year mark should be no later than 50% (mid-life point) between the declared ISD and the planned Out of Service Date (OSD) with any audit activity completed within a 3-year period. This assessment can often be undertaken as part of considerations for a 'mid-life' capability upgrade for avionics and weapons systems, either to ensure there is adequate life remaining in the aircraft or to identify upgrades in other systems, especially structures. By this time, there is a greater understanding of the performance and maintenance of the aircraft in its operational environment in terms of the integrity of its constituent systems. These systems include structural, propulsion, mechanical (e.g. safety, fuel, control), avionics (e.g. radar, wiring, communications), payload and potentially, support equipment and personnel. For the US Navy, this typically structures-focussed process is termed a service life assessment program (SLAP) and potentially leads to a service life extension program (SLEP). This intent can also be seen in the AAA process performed on RAAF aircraft, where the assessment is driven by the needs of both the operator and regulator. The RAAF process [10] has been recently revised to go beyond the prior focus on structures, engines and wiring largely based on service experience [11] arising from significant accidents both in the ADF [12] and foreign fleets [13]. The new regulatory process includes guidance for assessment of all systems, which usefully provides both technical and budgetary justification for priority by the operator.

The investigation into the loss of an RAF Nimrod aircraft in 2006 [14] due to an uncontained fire arising from subsystem failure has led to an increased focus on the impact of age on the systems integrity of military vehicles, especially aircraft. The interaction of systems and their co-location can create failure modes that may not be obvious, making accurate risk assessment difficult, particularly on aged vehicles modified since their manufacture.

Based on these observations, a complete AAA for the RAAF's older aircraft, such as the F/A-18 Hornet (with at least 7 years remaining to its planned withdrawal date (PWD) [15]), is significantly enhanced by an Ageing Aircraft Systems Audit (AASysA) and the first step has now been completed with a baseline desktop audit.

System Failure Example

Technical management processes may not adequately account for system interaction. This example focuses on a mechanical component within a combat aircraft leading edge flap control system. The component and its back-up system were certified based on laboratory testing using an assumed usage profile and were located in an area that made it difficult to inspect. Due to the life of type certification and designed redundancy, this component was not classified as a Critical Item, so there were no planned inspections of the component or the backup system. Throughout the life of the aircraft the flight control software had undergone multiple updates affecting the usage rates of the control surfaces. The resulting usage profile of the component exceeded that assumed during the certification process and, with no planned inspection regime in place, the condition of the component and backup system deteriorated, resulting in several Class A Mishaps (aircraft losses).

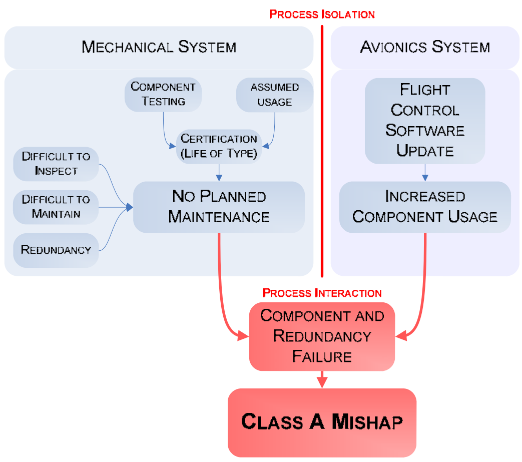

Figure 1 Example of system management process isolation leading to a Class A Mishap

This example highlights two key issues facing the ageing aircraft sustainment community.

1. Critical Items certified for the life of type still need to be inspected, particularly as the aircraft ages. The rate of use and/or degradation of a component may change over time. Without inspections it will not be known if rates are increasing, invalidating the original certification. This highlights the importance of a targeted condition survey during the AASysA and using the 'consequence of failure' method of system targeting[1]. This is important if scheduled inspections are considered too resource intensive and intrusive.
2. The need for reliable backup and emergency systems is also emphasised. A component and therefore, potentially, the management process has already failed if a backup or emergency system is required in flight. The same management process should not be applied to the backup or emergency system as its correct function is of greater criticality.

DSTO approach to AASysA

An audit of any vehicle's system integrity needs to consider all factors that could lead to changes to the operation, maintenance or service life of that vehicle and can be grouped under the four categories of safety, cost, capability and availability. These categories could be considered simultaneously and would likely be given different preferences by each stakeholder in the assessment process. However, without ignoring the impact of the other three categories, safety was given first priority for this DSTO review. In every vehicle there are a range of systems and each can be systematically evaluated to assess what relevant data are available and what analyses can be (or have been) completed, with particular emphasis on inputs and outputs of each system to identify the inter-relationships between them. This high-level preliminary view is shown in Figure 2.

Potential factors are: Failure Mode and Effects Criticality Analysis (FMECA), Zonal Hazard Analysis (ZHA), Durability and Damage Tolerance Analysis (DADTA), Aircraft Structural Integrity Management Plan (ASIMP), Safety by Inspection (SBI), Rate of Effort (ROE) and Maintenance Requirements Determination (MRD). For initial studies, the use of Fault Tree Analysis (FTA) and its 'top-down' approach is likely to be undertaken before FMECA and its 'bottom-up' approach. The use of FTA in conjunction with the criterion of single point of failure criticality provides simple prioritisation tools.

This review of available requirements and other regulatory guidance assessed those that could extend the safety-driven approach to all aspects of aging systems in military aircraft. Related issues involving obsolescence, training and ground-based systems that interface with the airborne element of the aircraft system create a complex picture.

The aim of an ageing aircraft systems audit (AASysA) is to provide assurance to the operator that the risks to aircraft system integrity (ASysI), and hence the airworthiness of its ageing systems, are being managed in accordance with airworthiness regulations. In more generic terms, a system safety program identifies the maintenance of a safety baseline in addition to mishap investigation and correction during the entire utilisation/support stage of a system life cycle[17]. Therefore, an AASysA is an assessment of the performance of the whole business of operating an aircraft fleet[18]. Being an integral part of the AAA, it takes advantage of the routine ASysI activities that help "tell us what the fleet is saying" such as: Cost, Dependability (i.e. Reliability, Availability and Maintainability as well as Supportability) and Obsolescence control.

[1] Targeting components using consequence of failure as a distinguishing factor can be helpful where probability of failure over the life of type is difficult to determine.

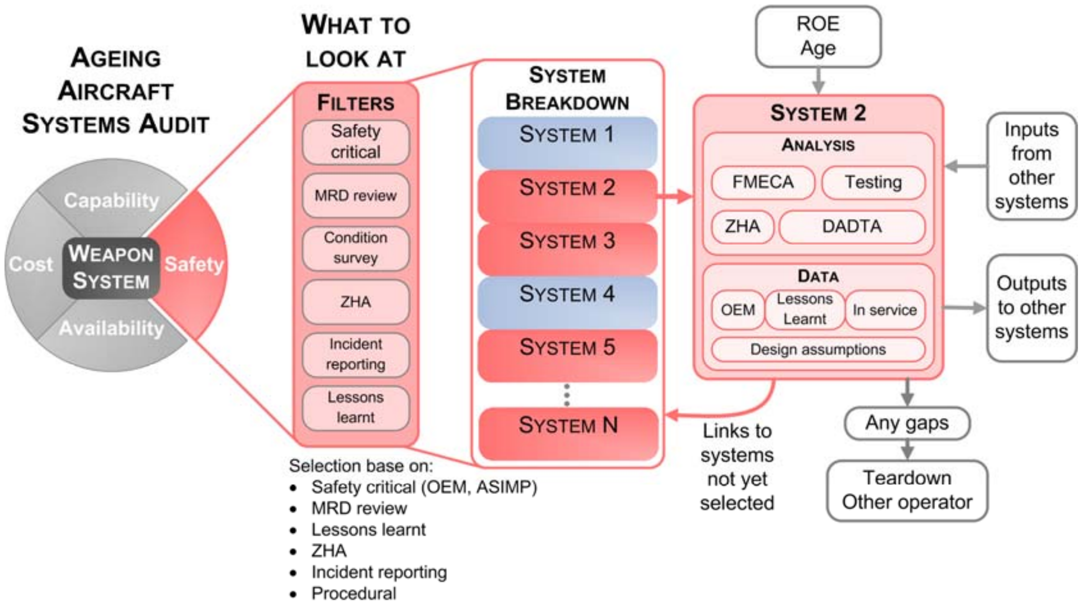

Figure 2: Ageing Aircraft System Audit schematic

The authors' review of the AASysA process highlighted the data items (DIs) in Figure 3 that usefully define the boundaries of what should be initially assessed given typical project constraints of time and resources.

DI-01	Identify all systems that impact safety capability, availability and cost. i.e. *what will be included and excluded?*
DI-02	Identify all fleet systems processes that require data for performance assessment.
DI-03	Identify operating parameters of these systems *As for DI-02*
DI-04	Identify data sources for operating parameters. *As for DI-02*
DI-05	Identify data archives. i.e. *where is the data held and by whom?*
DI-06	Generate baseline data snapshot.
DI-07	Assess data veracity for parameter monitoring.

Figure 3 AASysA Initial Data Requirements

Since this activity seeks trends, not just status, it also supports risk assessments up to PWD, which are often extended under the influence of technical, budgetary and program management reasons.

DSTO currently performs a Technical Risk Assessment (TRA) for major ADF projects (new acquisition, upgrades and PWD extensions). One of the key outcomes of the AASysA is the identification of new risks that may be beyond those found in any previous TRAs for an aircraft, as well as re-assessing known risks. Relevant time points for a risk assessment based on results of AASysA's are: (i) at AASysA conclusion; (ii) 5 years from AASysA conclusion; (iii) PWD; and (iv) possible PWD extensions (authors suggest using 3 year blocks for multiple options i.e. PWD+3yr, PWD+6yr). Strong value from these multiple target dates has been found when repeated reviews or TRAs have been needed to support repeated delays in PWDs. The authors' experience has been that well-planned fleet life extensions were typically 3-5 year intervals.

Stakeholders

One of the first goals in any project [17] is to determine the stakeholders who are involved and it was useful in this circumstance to identify and clarify all parties that could be affected by the possible outcomes of the AASysA. This enables some level of attribution and responsibility so that important issues, such as risk assessments, can be resolved with the assistance of the primary stakeholders. In this case, they were the Systems Program Office (SPO) responsible for ongoing support to the squadrons (SQNs) and DSTO as the subject matter expert (SME). Secondary Stakeholders were the Air Combat Group (ACG) as a higher level 'customer' and Maintenance Contractors and companies that overhaul removable items who also provide ongoing support to SQNs. Other parties of interest were: the SQNs who operate the aircraft, the OEM (or equivalent) as the design authority, and other operators of that aircraft system type. Collaboration with other operators is likely to expand the useful MRD database(s).

Scope

RAAF policy guidance has recently improved for this AASysA issue in terms of what systems need to be considered after the acceptance process has been completed and the aircraft is in service. The RAAF's technical airworthiness management manual [10] provides specific guidance for systems designated as Structures, Engines and Wiring[2], as part of formal assessments during the service life at an estimated mid-life point.

The authors' review also identified a limited number of documents that provide specific relevant guidance[18] and experience [1, 19] on the AASysA process rather than a more general approach [9, 16, 20-24] to managing vehicle systems. Hence, when planning the details of the AASysA with stakeholders, consideration should be given to, but not limited to, addressing the following elements[1]:

1. Qualification and certification evidence, particularly for systems affected by upgrades typically undertaken around the mid-life stage[3].
2. TLMP and ASysI Strategy review.
3. Adequacy of maintenance policies and procedures related to all aircraft systems.
4. Configuration process, including all usage history, life consumption, modifications, repairs and concessions.
5. Changes in operational role and environment.
6. Life Extension Programme evidence.
7. Hazard Log/Risk Register entries.
8. Review procedure for items 1 to 7 above.

The scope needs to specifically confirm which systems are to be included and excluded under the AASysA. The systems include those that become airborne as well as those that do not, and systems that include (or are) a human component and should incorporate results from relevant work that meets the same intent. For a combat aircraft, such as the Hornet Weapon System (HWS) the following breakdown (omitting the commonly well-managed airframe structural and engine systems) is useful but its order does not suggest any level of importance:

Mechanical systems: flight control, fuel, hydraulic, cooling, pneumatic, landing gear, environmental control, air services, ice and rain protection, oxygen, nitrogen, arrester, ejection, personal survival gear, equipment and furnishings, gearboxes.

Avionic systems: radars, data buses, electro-optics, photographic, defensive aids, navigation aids, communications, data links, electronic warfare, identification, air traffic management aids, electrical power generation and distribution, weapon control and release, air data, displays, prognostics and health management, mission planning, flight control, data recorders, all wiring (including interconnections and connectors.

Weapons/Munitions/Stores systems: aircraft guns and ammunition, countermeasure stores, free-fall and guided bombs, guided missiles, auxiliary fuel tanks, mission pods, launchers/racks and carry-on-board personal weapons/munitions.

Ground-Based Test & Support Equipment.

Personnel.

The last two listed categories may be considered at a high organisational level, for

[2] Condition assessment via visual inspections of aircraft wiring has been completed on the ADF fleets of C-130H & J, F-111, AP-3C, DH-4, C-17, PC-9A, F/A-18A/B and Hawk 127 aircraft as well as Tiger, AS350BA, 206B, SH-50K, S-70A & B and CH-47 helicopters.

[3] Both RAAF fleets of F-111 and F/A-18 aircraft completed significant avionics systems upgrades.

instance in annual airworthiness board assessments of age-related degradation of ADF aircraft. However, at lower organisational levels within the SPO, it is not clear by what means concerns about any ASysI shortfalls in these categories can be fully integrated with the other categories to take advantage of the potential impact from deficiencies in one category upon another. For instance, while maintenance-induced damage may be a visible example of a deficiency, the extension of maintenance intervals is at risk of masking less obvious failure modes [25]. It is notable that recommendations from UK MoD experience in several AASysAs identify skills, training and inspection [19], emphasising the significant effect of the human element on system safety. DSTO considers here that emphasis should also be placed on education in terms of exposure to the possible consequences of inadequate maintenance practices. Although human factors are yet to be considered in more detail for this AASysA, it is not considered benign and should be included as part of any fleet viability review.

System Priority

Based on safety criteria, each system could possibly be prioritised for attention under the AASysA. However, this requires a risk assessment based on an appropriate level of information about each system (operation and failure modes) and, crucially, its interaction with other systems. Not all RAAF aircraft types have a defined Hazard Analysis or FMECA, which prevents this step being straightforward. In particular, the effect of cascading failures between systems in the same zone (e.g. a fuselage bay or wing bay) may not be readily apparent [14]. The HWS is undergoing a step towards this level of knowledge to identify zonal inspection methods (excluding maintenance managed items, MMIs). It is a significant challenge to rigorously prioritise systems for an AASysA fully on the basis of safety. A measure of likelihood of individual system and/or component defects and/or failures should be obtainable from MRD records for the HWS or on other aircraft. However, in practice these records have been found by DSTO to be intermittently incomplete or holding conflicting data.

A simple process to prioritise AASysA effort based on safety could consider a single level of failure that could lead to catastrophic outcomes [1]. Hence, an assessment of the causes of fatal accidents and/or hull loss can provide a measure of relative importance for accident cause(s) between technical and non-technical and also the breakdown within technical causes. This can provide a measure of relative criticality to inform a risk assessment. The UK MoD experience [1] with 316 accidents over the past 3 decades suggested that technical reasons were a significant cause (29%) of aircraft accidents and that failures of propulsion (12%) and systems (15%) are more prevalent than structural causes (2%). With a relatively small fleet, the ADF accident history (67 over 30 years [26]) is more sparse but a review by the authors indicates similar conclusions with technical reasons being a significant cause (34%) of aircraft accidents due to failures of propulsion (13%), systems (15%) and structures (6%). For a civil aircraft perspective, a review [27] of commercial jet accidents[4] showed there were 89 accidents with fatalities in the decade 2000-2009, of which 9 were due to technical causes such as system/component failure or malfunction (6), fuel (1) or fire/smoke (2). These data suggest that all systems should be considered in an AAA, going beyond the traditional focus on engines, structures and wiring.

There are two caveats with this hull loss approach: firstly, if it is applied to combat and trainer aircraft, the consequences do not usually include fatalities to crew due to the availability of personal egress options such as ejection seats. The second is that it simply implies that complete loss of an individual aircraft is the defining criteria, when operators are also faced with providing a fleet service (e.g. Combat Air Patrol or Regular Passenger Transport service). Since hull loss is more commonly caused by unsatisfactory human decision making, the

[4] The fatal accident rate for US and Canadian operators has reduced only gradually since 1990 to stabilise at approximately 0.2 per million departures, albeit from a high point of 40 in 1959.

direct immediate impact is more likely to be on individual aircraft safety, in contrast to technical causes (i.e. engine, system or structural integrity-driven concern) that may lead to fleet grounding and hence total loss of fleet capability.

The steps outlined in Figure 5 show the direction of this process, that were defined in Figure 4, as directed to the HWS in the near future [27].

1)	Identify zones for complete HWS hazard assessment.
2)	Perform hazard analysis suitable for critical HWS prioritisation.
3)	Update Baseline Desktop Audit and additional system audit areas as above in Step 1.
4)	Highlight areas for recommended future detailed inspection and teardown activities.
5)	Update TRA for PWD projections.
6)	Repeat and revise each 3-5 years.

Figure 5 AASysA Future Phase for HWS

Summary

The development and application of consistent processes to address age-driven safety concerns has the potential to be directed to all ADF vehicles. This DSTO review of the Ageing Aircraft Systems Audit focused on RAAF combat aircraft and warrants further development. This work can urgently address all fleets that are already more than 15 years old and support planning for those more than 10 years old. In a perfect world, these actions would not be required if design, manufacture and maintenance were sufficient to prevent critical problems arising in service. However, complexities arising from human involvement in any system at any stage introduce a risk of degradation over time that may lead to catastrophic consequences for vehicle fleets. The Ageing Aircraft Systems Audit is intended to be a rigorous process to identify any corrective action needed to remedy the effects of degradation in a timely manner. It could be usefully applied to other vehicles, such as ships, submarines, helicopters, tanks and trucks.

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