Material Selection and Design Handbook – A Compendium of Technical Challenges, Solutions, and Lessons Learned

Karl A. Hart
Senior Engineer, Alion Science & Technology
ASC/XRS
1970 Monahan Way
Wright Patterson AFB, OH 45433

karl.hart@wpafb.af.mil

Jeffrey Guthrie
Science Advisor, Advanced Materials, Manufacturing,
& Testing Information Analysis Center, Alion Science & Technology
201 Mill Street, Rome, NY 13440

jguthrie@alionscience.com

Christopher Fink
Assistant Manufacturing Engineer, Advanced Materials, Manufacturing,
& Testing Information Analysis Center, Alion Science & Technology
201 Mill Street, Rome NY 13440

cfink@alionscience.com

Abstract:

As our older weapon systems continue to age and newer systems coming online continue to become more complex, system availability (broken out by time spent in available status vs. not available status at the unit or depot) is becoming more of a challenge to maintain much less improve. Maintainers and weapon system managers need tools to assist them with this challenge. For instance, while the overall availability rate of the total US Air Force (USAF) aircraft fleet has been steady for the last few years, breaking out the elements within the availability rate tells a different story. The good news is that the not mission capable due to supply rate is decreasing, most likely due to increased depot level reparable (DLR) funding. However, the bad news is that the non-mission capable due to maintenance rate has been increasing steadily for years, except for sharp decline due to deferred maintenance during major Afghanistan and Iraq wartime missions. Therefore, to improve aircraft availability in the case of the USAF, further examination of maintenance non-availability issues and their solutions is warranted.

One such attempt at examining weapon system availability is the development of a US Department of Defense (DoD) level guide which a) explains the root causes of materials and manufacturing issues that impact system availability and performance and b) compiles and presents the remediation of such issues through lessons learned, best practices, success stories, and technical solutions.

The handbook will be focused on the weapon system acquisition community, in particular the program engineers and designers, to improve availability of follow-on systems, modifications, upgrades, and resets. The handbook will be based upon trend analysis of maintenance data (obtained from military services' databases, major commands, non-geographic specific commands, field units, and maintenance depots) that correlate failures to specific materials, manufacturing, and testing factors and upon success stories where adverse availability trends indicated by these analyses were mitigated. Collected data includes non-availability drivers and respective root causes, system age and usage (i.e., flight hours for aircraft), and operational environments (dry, salt, wet, sand, etc.) in the areas of field and depot level maintenance, parts supply, and logistics. In addition, the investigation is cross-cutting in nature in that it is capturing unique issues across services (Army, Navy, Air Force), across weapon system types (air, sea, land), across weapon systems (F-16, C-130, F-18, CV-63, UH-1, M-1, etc.), and across components (active, guard, reserves). Completion of the handbook will be mid-2008.

This paper will review weapon system availability rates, non-availability drivers and respective root causes, and various technological and/or process oriented initiatives that weapon system program managers have undertaken and proved successful at overcoming adverse availability trends. The following topic areas are discussed:

(1) Critical reviews of military SVS lifing and reliability methodologies and tools for protecting safety and enhancing availability/reliability.

(7) Identification of key system elements for managing aging-failure phenomena, based on SVS operational impact, support cost, and reliability.

1.0 INTRODUCTION

As our older weapon systems continue to age and newer systems continue to become more complex, system availability (broken out by time spent in available status vs. not available status at the unit or depot) is becoming more of a challenge to maintain much less improve. Maintainers and weapon system managers need tools to assist them with this challenge.

While the overall availability rate of the total US Air Force (USAF) aircraft fleet has been steady for the last few years, breaking out the elements within the availability rate tells a different story. The good news is that the "not mission capable due to supply rate" is decreasing, most likely due to increased depot level reparable (DLR) funding. However, the bad news is that the "not mission capable due to maintenance rate" has been increasing steadily for years. Therefore, to improve aircraft availability, further examination of maintenance non-availability issues and their solutions is warranted.

One such attempt at examining weapon system availability is the development of a US Department of Defense (DoD) level guide which a) explains the root causes of materials and manufacturing issues that impact system availability and performance and b) compiles and presents the mitigation of such issues through lessons learned, best practices, success stories, and technical solutions. This "readiness" handbook has been developed by the Advanced Materials, Manufacturing, and Testing Information Analysis Center (AMMTIAC), Rome NY, and was funded by the Defense Technical Information Center (DTIC) under the technical direction of Dr. Lewis Sloter from the Office of the Deputy Undersecretary of Defense for Science Technology/Weapon Systems.

This paper presents the results of the development of the handbook.

1.1 Background

In 1990, the Air Force aircraft inventory average age was almost 17 years. In 2007, it was nearly 24 years. See figure 1. Its KC-135 fleet of over 500 aircraft has an average age of 46.5 years. Its B-52 fleet of over 90 aircraft has an average age of 45.8 years. Almost a third of the aircraft in the AF fleet is over 30 years old and one fifth is over 40 years old!

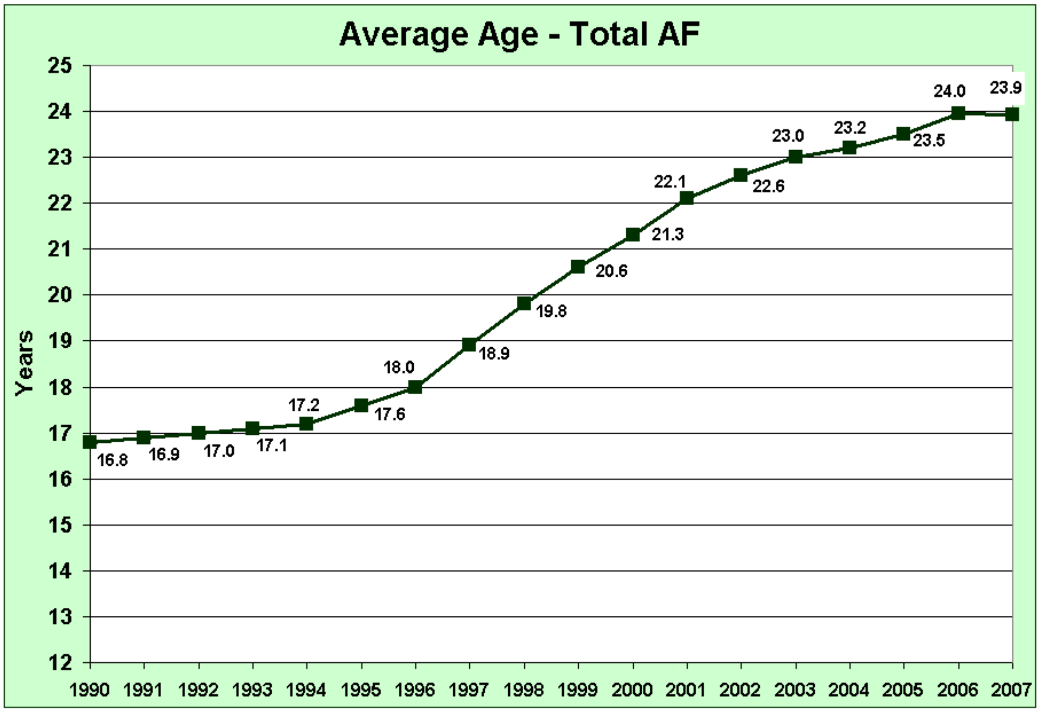


Figure 1: Average Age, Total AF

Overall, AF total fleet availability trends have declined throughout the 1990s (from 77% to 65%) and have been level throughout this decade (68%). See figure 2. However, age doesn't appear to be the sole factor for the behavior of the availability rates. While the AF is retiring old aircraft and adding new aircraft to its inventory (2007 saw no growth in fleet average age for the first time since the early 1990s), some of the newer aircraft (e.g., B-2 and F-22) are more complex resulting in availability rates lower than the AF fleet average. See figure 3.

As our older weapon systems continue to age and new replacement systems coming online continue to become more complex, maintainers must overcome difficult and multifaceted issues to sustain and improve availability.

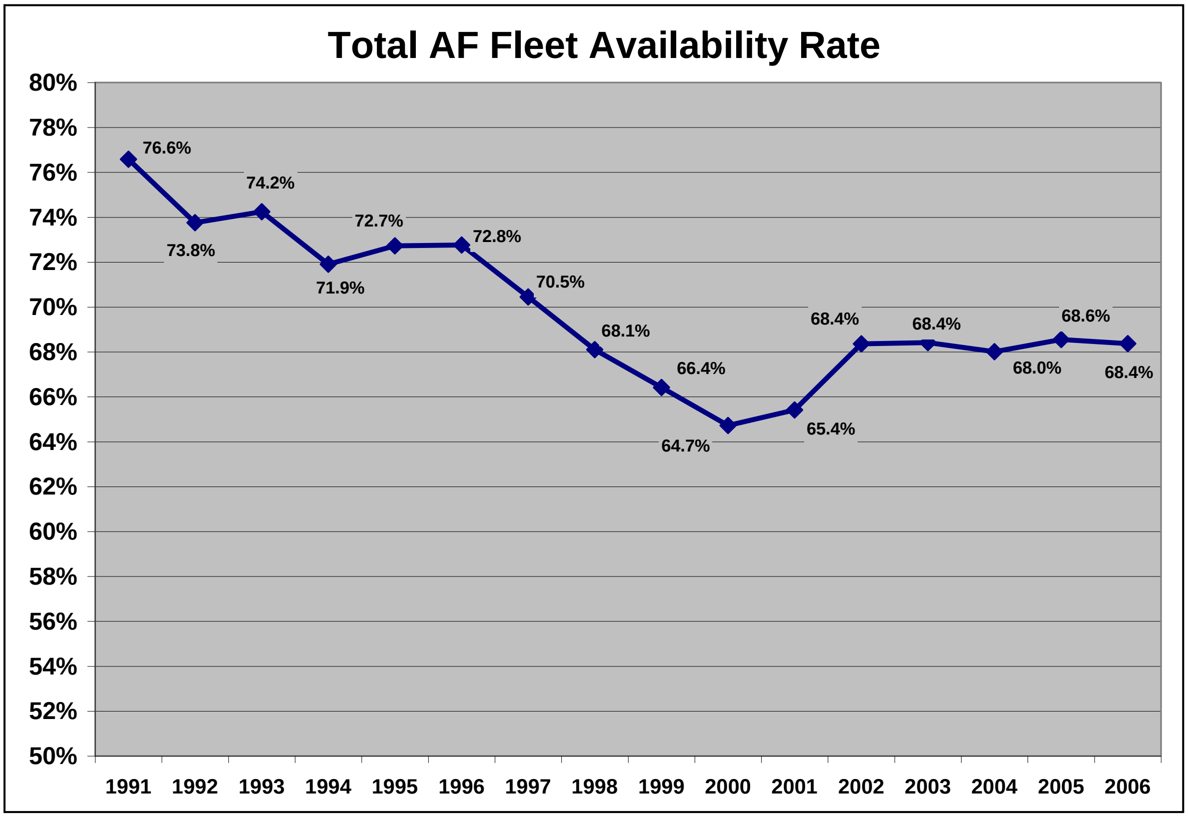
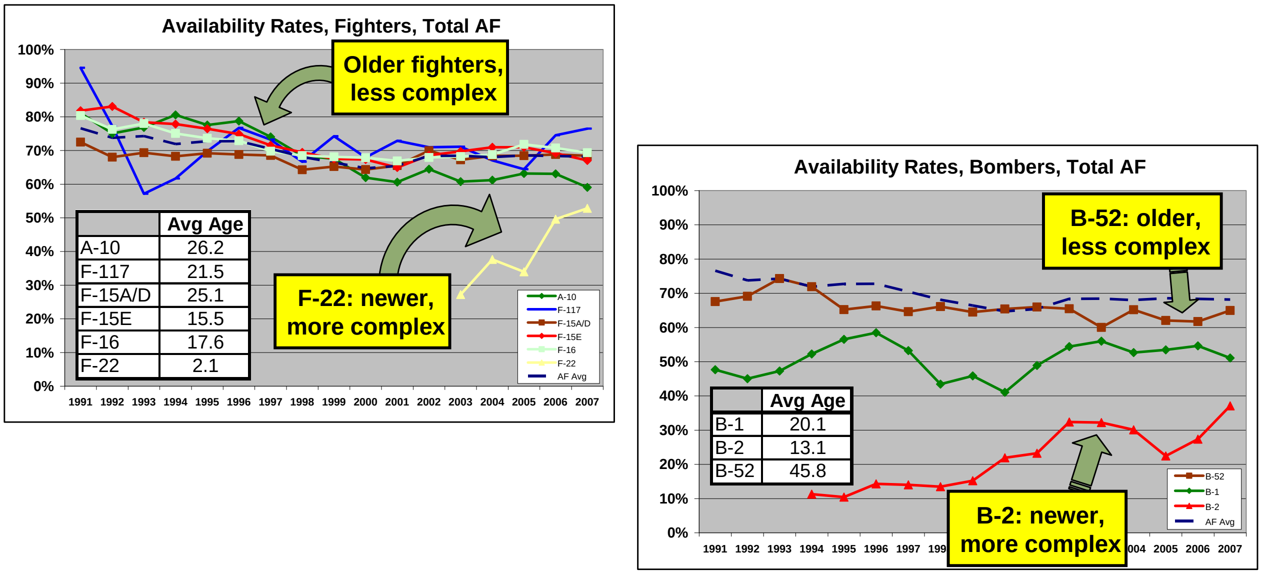


Figure 2: Total AF Fleet Availability Rate



	Avg Age
A-10	26.2
F-117	21.5
F-15A/D	25.1
F-15E	15.5
F-16	17.6
F-22	2.1

	Avg Age
B-1	20.1
B-2	13.1
B-52	45.8

Figure 3: Availability Rates, Fighters & Bombers

1.2 Approach for Completion Of Handbook

The following approach was taken in completing the handbook:

- Collected and analyzed maintenance and operational data using the following databases: Aircraft Maintenance Production/Compression Report System (AMREP), Air Force Total Ownership Costs (AFTOC), Global Combat Support System – Air Force (GCSS-AF) Data Services, Maintenance Requirements Review Board (MRRB), Multi-Echelon Resource and Logistics Information Network (MERLIN).
- Conducted site visits/communications/discussions with weapon system maintainers and program managers at Major Commands, Defense Supply Centers, and organic depots/logistics centers.
- Performed literature searches at Government Accountability Office (GAO, formerly General Accounting Office), Congressional Budget Office (CBO), Scientific and Technical Information Network (STINET), Defense Technical Information Center (DTIC), and Air Force Institute of Technology/Air Force Research Lab (AFIT/AFRL).
- Attended conferences. Department of Defense Maintenance Symposium and Exhibition, AF Corrosion Conference. Joint NASA/FAA/DOD Conference on Aging Aircraft.

2.0 METRICS: CATEGORIES, DEFINITIONS, AND COLLECTION PROCESS

2.1 Metrics Categories

Good metrics analysis starts with a good understanding of the metrics. One way to gain this understanding is to know why they are collected, how they can be used to improve performance, and how they are organized. The following subsections present different categories that metrics have been classified depending on the performance goals set for their collection.

2.1.1 Leading/Lagging Indicators.

Two key categories of metrics maintenance and flying units have employed are leading and lagging indicators.

- Leading indicators directly impact the maintainers' capability to provide resources to execute the mission. These will show problems first.[1] Examples of leading indicators include Abort Rate, Break Rate, Deferred/Delayed Discrepancy Rate, Dropped Object Rate (DOP), Fix Rate, Logistics Departure Reliability (LDR), Maintenance Scheduling Effectiveness (MSE), Repeat/Recur Rate, Re-Test OK, Total Repair Cycle Time, and Usage Rate (USE).
- Lagging indicators show firmly established trends and will follow the leading indicators.[2] Examples of lagging indicators include Cannibalization (CANN) Rate, Customer Wait Time, Issue Effectiveness Rate, Mission Capable (MC) Rate, Mission Capable (MICAP) Hours/Incidents, Not Mission Capable Due To Maintenance (NMCM) Rate, Not Mission Capable Due To Supply (NMCS) Rate, and Stockage Effectiveness Rate.

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[1] Metrics Handbook for Mobility Air Forces, 2nd Edition, Dec 03

[2] Ibid

2.1.2 Sustainment/Operational Metrics

Aircraft metrics have also been organized by the operations and sustainment communities and fall within the following four broad categories. A few specific examples within each of these categories include (note: some are also leading and lagging indicators and are repeated here for illustration):

- Flying and maintenance. Generally, active aircraft will be possessed either by an operational unit or by the depot. Sample metrics of unit possessed aircraft include Abort Rate, Break Rate, Fix Rate, Repair Cycle Time, Maintenance Manhours (MMH), Mean Time Between Failure (MTBF), MICAP Rate, CANN Rate, and Weapon System Availability (MC, NMC, NMCM, NMCS, and Unit Possessed Not Reported Rates). Sample metrics of depot possessed aircraft include Aircraft Production Rate, Engineering Dispositions, Programmed Depot Maintenance (PDM) Cycle Time, PDM Manhours, Unscheduled Depot Level Maintenance (UDLM), and Weapon System Availability (Depot Possessed Rate).
- Cost. Sample operations and maintenance (O&M) costs include Aircraft Depot Maintenance, Depot Level Reparable (DLR), Sustaining Engineering, etc.
- Risk to Flight Safety. Sample metrics used to determine the safety of an aircraft fleet include Flight Restrictions, Hazard Risk Index (HRI), and Mishap Rate.
- Mission Effectiveness. Sample metrics used to determine the effectiveness of a mission include Airmen Mobilized, Bombs on Target, Enemies Targeted, Fuel/Cargo Delivered, Intelligence Collected, Rescues Accomplished, Threats Detected, etc.

2.2 Metrics Definitions

The Weapon System Availability metrics require further explanation to better appreciate their composition and significance.

2.2.1 Weapon System Availability

Simply stated, weapon system availability is an assessment of the weapon system’s unrestricted time to perform its mission(s). It is measured through possession – which unit possesses the weapon system, where is it possessed, and for how long is it possessed. Each weapon system spends its time in one of the following possession status types:

- Available hours (also known as mission capable hours)
- Not mission capable hours (aircraft cannot do any assigned missions while possessed by the unit)
- Unit possessed – not reportable hours (e.g., battle, crash, birdstrike, or weather damage; aircraft is under major maintenance awaiting parts; or, owning unit is performing depot level maintenance)
- Depot possessed hours (organic/contractor depot or at the unit but maintained by a depot field team)

The addition of the hours spent in each of the above four status types over a given period constitutes total possessed hours which is also the amount of time a weapon system is in the inventory. Available (also called mission capable or MC) hours plus not mission capable (NMC) hours equals unit possessed hours. The MC rate is defined as the ratio of available (MC) hours to unit possessed hours whereas availability rate is defined as the ratio of available hours to total possessed hours. While the unit commander is accountable for what he controls (MC rates), there is a move (at least at the MAJCOM, Air Force, and DoD levels) to transition from analyzing MC rates to analyzing availability rates. Trends in the latter present a more holistic representation of the weapon system’s limitations on performing its mission(s).

2.2.2 NMC Rate Breakdown

The MC rate and the NMC rate are related as follows:

$$MC = 1 - NMC \tag{1}$$

NMC is when the aircraft cannot do any assigned missions. The NMC rate is calculated as:

$$NMC = NMCA + NMCB + NMCM + NMCS \tag{2}$$

Thus, it can be stated that:

$$MC = \boldsymbol{f}(NMCA, NMCB, NMCM, NMCS) \tag{3}$$

where NMCA is NMC Airworthy (aircraft fly and is not restricted from use), NMCB is NMC Both (maintenance and supply).[3]

2.3 AF Aircraft Maintenance Data Collection Process

Maintenance data collection (and subsequent analysis) was accomplished solely on the AF inventory. It has the largest fleet among the military services which provided a good sample size for analysis. While the Army, Navy, and Marines certainly have unique issues, for the sake of expediency, the authors believed analysis on the AF data was sufficient to build a strong story showing how maintenance drivers impact aircraft availability. The resulting trends among AF aircraft should be quite comparable to the other services' fleets.

The analyses of AF aircraft in the handbook were conducted using data from the aircraft depicted in table 1.

A-10	C-5	C-22	C-40	E-8	F-22	KC-10	T-6
A-37	C-9	C-25	C-130	EC-130	F-4	KC-135	T-37
A-7	C-12	C-26	C-135	F-111	H-1	MC-130	T-38
AC-130	C-17	C-27	C-137	F-117	H-53	MH-53	T-39
B-1	C-18	C-32	C-141	F-15A/D	H-60	OC-135	T-43
B-2	C-20	C-37	E-3	F-15E	HC-130	RC-135	U-2
B-52	C-21	C-38	E-4	F-16	HH-60	T-1	WC-130

Table 1: AF Aircraft Used in Analyses

Several minor aircraft fleets within the AF inventory were not included in the analyses due to suspect data. These fleets had availability rates of either 100% or nearly 0% and included gliders, unmanned air vehicles (UAV), and a few special mission aircraft.

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[3] Air Force Instruction (AFI) 21-103, "Equipment Inventory, Status And Utilization Reporting," 14 Dec 05, Attachment 2, "Maintenance Status Codes and Condition Status Codes"

3.0 OBSERVATIONS OF COLLECTED AND ANALYZED DATA

Significant analyses were conducted on the collected metrics to determine notable trends, establish broad observations, and formulate global conclusions with the intent of focusing attention on opportunities where improvements can be realized and on areas were improvements have already been realized.

3.1 Summary of Observations

- The combined MC rate of the AF active and reserves continually improved throughout the 1980s (except for 1989) from 61% to 85%, declined through the 1990s to 76%, increased somewhat between FY00-02 to 80%, and has been steady at around 80% since then.
- The combined NMC rate for the AF active, reserves, and guard has been fairly level at around 19% since FY02 (except for a small decrease in FY05) while the depot possessed rate has been fairly constant between 9% and 10% since FY03.
- The NMCS and NMCB rates have peaked (FY98-01) and have been declining or stayed level since then. This is most likely due to DLR funding and the NMCS rate appearing to be inversely related. When DLR funding increased, the NMCS rate stopped increasing. When the DLR funding decreased, the NMCS rate stopped decreasing.
- The NMCM rate continues to increase, almost doubling from 7.2% in FY91 to 13.4% in FY07. The top six drivers in FY07 were inspections (phase and special), engines, fuel system, airframe, flight controls, and landing gear. These top drivers accounted for more than two-thirds of the AF’s unit possessed total downtime and inspections alone comprised of almost one-fifth of the total downtime. Unfortunately, maintenance did not experience the same inverse relationship between funding and NMCM rate as funding has with the NMCS rate.
- Inspection requirements do not appear to be directly related to where the fleets are in their life cycle. On an aircraft size basis, it appears that the smaller aircraft (e.g., fighters, trainers) require more downtime to inspect. And, inspections are not a function of aircraft complexity.
- No overall trends were found in the flight hours, age, and availability rates data that showed an apparent “by aircraft tail number” retirement methodology for the retired C-141, H-53, and F-117 fleets. In fact, there was a noticeable increase in availability rates during their final years before retirement.
- The AF fleet’s availability trends are not necessarily a function of age. The analysis suggests that older, simpler aircraft seem to have much higher availability rates than newer, more complex aircraft (i.e., F-22, B-2, and B-1) indicating that complexity is a strong factor in the lack of aircraft availability.
- Maintenance funding does not appear to be directly related to where the fleets are in their life cycle but it does appear to be heavily influenced by aircraft complexity countering the often held notion that maintenance costs are increasing due to aging aircraft.

3.2 Challenge to Root Cause Analyses

Finding trends in the root causes of system and component failures proved to be a significant challenge that was difficult if not impossible to overcome. Analysis showed that maintainers do not code the entire maintenance job with the malfunction (how mal) code of the reason for the maintenance. Instead, they applied various how mal codes for the tasks within the job. While some of the actual repair tasks received the true codes of the overall job, many associated subtasks either received codes describing generic, ancillary maintenance causes or types of maintenance, or they received “no defect” type codes. In other instances, many maintainers often entered five digit work unit codes (WUC) that describe the aircraft component receiving maintenance at the two digit level with three zeroes instead of the actual five digits of the specific aircraft component. The result was that, in many cases, the true cause for the aircraft downtime could not be properly evaluated at the component level.

3.3 Opportunities to Increase Availability

In light of the observations and challenges described above, opportunities where availability improvements can be realized in the field and at the depot are presented here to highlight the most significant problems currently facing aircraft maintainers.

- Scheduled inspections (e.g., phase, special, isochronal, home station check, major/minor, and periodic) process. Review scheduled inspections for:
    - Out-of-date requirements. E.g., inspections may no longer be needed because their original reasons were resolved by structural improvements over time but the weapon system management did not remove the inspection requirements).
    - Frequency. Data may support reducing the inspection frequency (e.g., conduct inspections every 800 flight hours instead of 400 flight hours).
    - Concurrency. Different inspections may be able to be performed at the same time.
    - Availability of technological improvements. E.g., enhanced NDI equipment that examines substructure from the aircraft’s exterior reduces the amount of time needed for structural component disassembly/reassembly and engine/LRU removals/reinstallation to gain access to the substructure and internal subsystems. Additional benefits include being able to perform the NDI more quickly and reliably with fewer personnel, reducing the number of false positives and missed positives, and reducing the amount of personnel fatigue).
- Integral and bladder fuel tank leaks. Implement improved trouble shooting and repair techniques. Implement improved technologies for sealant removal. Design more durable bladders and sealants.
- Doors and panels. Design for maintainability of internal subsystems with enhanced opening/closing features.
- Paint. Incorporate improved depaint and repaint processes and equipment, and procure paint with improved life and functionality.
- Structural composites. Reduce delaminations by designing them to be more ruggedized and durable.
- Landing gear components. Design more durable landing gear tires, brakes, and strut seals.
- Low observable (LO) materials. Design LO materials to be more durable and faster to repair when removing to facilitate other maintenance FOM.

- Corrosion prevention.
  - Develop more effective primers and paints that will assist in preventing or mitigating corrosion initiation and growth while being in compliance with environmental regulations.
  - Design structural joints to avoid galvanic coupling.
  - Incorporate improved drainage systems in structural components.
  - Implement more effective manufacturing and repair techniques (e.g., install coated fasteners, ensure mated surfaces in structural joints are properly coated, etc.)
- Improve maintenance data quality.
  - Reduce maintainer data entry workload by having upgrading maintenance database software with capability to more easily, accurately, and definitively enter maintenance codes (e.g., pull down menus, predictive word suggestions in text box, etc.)
  - Increase usability of maintenance data through reduced allowance of general WUC entries and by connecting the primary Hal Mal code to all maintenance tasks within a maintenance job as identified by the job control number (JCN).
  - Implement barcoding to track maintenance actions.

4.0 LESSONS LEARNED

Several common themes that affect aircraft readiness became evident when conducting literature searches, data analysis, and site surveys of AF and Navy service depots. These common themes were turned into lessons learned which have been divided into the following four categories: global rules of thumb, maintenance best practices, design recommendations, and depot success stories. Due to limitations of this paper, only a few examples within each category are provided. A more exhaustive list of lessons learned is provided in the readiness handbook.

4.1 Global Rules of Thumb

Global rules of thumb capture overarching sustainment and design considerations that affect availability and are presented in the areas of better communication and aircraft complexity.

4.1.1 Better Communication and Sharing of Data is Needed

- AF helicopters share lessons learned in the helicopter weapon systems through the Corrosion Prevention Advisory Board (CPAB) to reduce corrosion problems at Robins AFB GA. This has reduced training needs and improved retention of corporate knowledge.
- Training O-level personnel at North Island Fleet Readiness Center FRC. This has produced better trained personnel in the field and increased manpower at the depot.
- Electronic manuals has resulted in share technical data and reduced report time at Jacksonville FRC, Elizabeth City, C-5 ASIP, and JSTARS.
- Conferences such as Air Force Corrosion Prevention, Aging Aircraft, etc., facilitate multiple discussions including strategy sessions and maintenance burden resolutions.

4.1.2 Aircraft Complexity vs. Maintenance Burden

As the aircraft systems have become significantly more advanced over the last few decades, the advancements have increased the aircraft complexity substantially. This has made maintaining the aircraft more time and labor intensive resulting in lower availability rates as figure 3 suggests. Therefore, as the aircraft technologies advance, the sustainment (inspection and repair) methods need to advance also. The following examples illustrate the affects that added complexity from LO materials has had on the maintainability of aircraft.

- B-2 forward deployment – need for shelters. During the design phase of the B-2, on March 1998, the AF sent B-2A's to Andersen AFB, Guam, to test its performance when deployed. While at Andersen, issues with maintenance of the LO materials were a major problem due to the environmental conditions in the South Pacific Ocean. In addition, the lack of shelters prohibited any significant repairs to the LO materials. As a result of these shortfalls, operational requirements for deployment of the B-2 were not met. As a result, programs to develop both permanent and temporary shelters for the B-2 were initiated.[4]

Figure 4: B-2 Inside Shelter

- B-2 LO coating repair – leads to depot time reduction. Every time work is performed on surface panels of the B-2, specialized caulks and tapes had to be completely removed and re-applied before the plane could be returned to mission capable status. These caulks and tapes required excessive down times, as long as 72 hours, to properly cure.

  To alleviate the additional delay of curing, a joint effort between maintainers in the B-2 Systems Group and Northrop Grumman developed a new coating and application system called Alternate High-Frequency Material (AHFM). AHFM is applied by four independently controlled robots that expose gaps and fasteners for easy removal of surface panels. In addition, AHFM eliminates the need for over 3000 ft of radar absorbing tape that would be traditionally used to cover gaps, further reducing downtime and labor. As an example, it normally took several days to repair a failed flight-control component because of the cure time for the special tapes and radar absorbing coating on the

Figure 5: Northrop Grumman robotic facility in Palmdale CA applying AHFM material on B-2 parts

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[4] "Defense Acquisitions: Achieving B-2A Bomber Operational Requirements", United States General Accounting Office, GAO/NSIAD-99-97, June 1999

aircraft. An AHFM-configured aircraft demonstrated a repair in less than 2 hours and the B-2 flew on another mission that same evening."[5]

4.2 Maintenance Best Practices

Maintenance best practices are processes or procedures that improve aircraft availability in the field (operational level) and are presented in the areas of corrosion prevention and bonded composite patches.

4.2.1 Corrosion Prevention

Since corrosion is a significant driver of life cycle costs, costing the military $20 billion annually for prevention and mitigation efforts[6], major initiatives have been undertaken to reduce the effect of corrosion. Below are examples of mitigation and prevention techniques and processes that have shown tangible results

- Dehumidification to mitigate corrosion. A Navy report stated that corrosion increases at relative humidity (RH) levels above 60% and the corrosion process virtually ceases at RH levels below 45%. According to Sandia National Laboratories, the MTBF of electronics is greatly reduced when humidity levels are below 50%. Therefore, as another means to reduce corrosion, the concept of dehumidifying aircraft is gaining popularity with the fleets in the military and the US Coast Guard (USCG). Currently, the USCG is implementing the use of dehumidifiers on its C-130, HH-60, HH-65, and HU-25 aircraft to reduce the relative humidity (RH, moisture) in the airframe. Their requirements for the deployment of dehumidifiers are:
    - Ease of use – the dehumidifiers must be connected to and disconnected from the aircraft in 5 minutes or less
    - Quick RH reduction – the relative humidity must be reduced to 40% RH or below in 1 hour
    - Hangar/ramp operations – the dehumidifiers must operate in a hangar or ramp

Figure 6: Dehumidification on Coast Guard C-130

Figure 7: Dehumidification on Coast Guard HH-60

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[5] http://www.af.mil/news/story_print.asp?id=123025201

[6] GAO-04-640, "Defense Management: Opportunities Exist to Improve Implementation of DOD's Long-Term Corrosion Strategy", 4 June 2004.

The Coast Guard expects increased aircraft availability through greatly reduced corrosion repair maintenance.

In addition, the AF and Navy are now investing in dehumidification technology for their aircraft and aircraft ground equipment (AGE). For example, the Air National Guard (ANG) has developed AGE dehumidification procedures for the KC-135 and F-15. The ANG has also developed a portable dehumidification system for the F-15 which allows the aircraft to be repaired while simultaneously being dehumidified.

- The Marines have employed the following best practices to reduce corrosion:
    - End-of-day engine washes – AV-8B demineralized water, C-130J soap/water
    - Alodine pens in field on exposed aluminum surfaces – AV-8B, EA-6B, UH-1
    - CPC change for desert deployment to avoid sand entrapment
    - Daily alcohol wipe down of greased areas – UH-1, H-46
    - High gloss touchup paint to reduce mildew – C-130J, H-46, H-53
    - Teflon tape for high wear surfaces
    - Field inspection to clear drains – UH-1
- High pressure equipment wash. In most common operating environments, washing is a fairly effective corrosion prevention method. However in arid, salty climates, like those found in Iraq and Afghanistan, equipment washing can be a challenging task. It can actually be detrimental to deployed aircraft in these climates because poor water quality and electrolytic sand is more likely to promote corrosion than prevent it. As a result of these factors, the Air Force Corrosion Prevention and Control Office (AFCPCO) suggested that all permanently stationed support equipment be washed on a 90-day cycle to minimize wash impact on acceleration of corrosion using a clean water source.[7]

4.2.2 Bonded Composite Patch Repair Confidence

Over the years, the AF has applied bonded repairs on various aircraft including the H-3 main rotor, the B-1 shoulder longeron, the F-111 wing carry-through structure, the F-16 wing fuel vent holes, and the C-141 lower wing skin fuel tank integral risers (weepholes), to name a few. The benefits of bonded repairs include a lack of additional stress raisers (i.e., not drilling additional holes in the damaged structure to fasten the doubler), ease of application (e.g., "gluing" a composite patch onto the damaged structure), and repair patch tailorability (e.g., stiffness and strength directionality). However, up to now, bonded repairs to safety of flight structure were only permitted if the unrepaired structure could withstand the design limit and the repaired structure could be inspected using a schedule based on the unrepaired structure – in essence removing the benefit of the repair. AF structural technical leaders levied these requirements due to a lack of confidence in: the bond line integrity and durability, the ability to repair complex geometries, and the available repair design and analysis tools.

The AF has recently concluded an evaluation to assess the residual strength of bonded repairs on C-141 aircraft that experienced over a decade of operational service. This evaluation used 156 patches from 52 structural specimens from retired C-141 aircraft located at the Aerospace Maintenance and Regeneration Center (AMARC), Davis-Monthan AFB, Tucson, Arizona. The evaluation revealed:

- No discernable crack growth occurred in service
- No evidence of environmental degradation to critical metal-primer interface was detected
- No specimens failed below the design ultimate stress (1.5 times the design limit stress, the highest stress encountered during service life of the aircraft)

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[7] 2007 Air Force Corrosion Program Conference Proceedings

Based on these positive results, the AF is revising its bonded repair policy. The inspection burden is being reduced and credit is being given for bonded repairs allowing the AF to take full advantage of their benefits.

Thus, the bonded composite repair materials and processes that will serve as the baseline for all future USAF bonded repairs include:

- Boron-epoxy repair patches – pre-cured and inspected Textron/Specialty Materials 5521
- Standard installation procedures – grit-blast silane surface prep, pre-cured BR127 epoxy primer, 250°F curing epoxy film adhesive, and controlled heater blankets and vacuum bagging[8]

4.3 Design Recommendations

In many cases, the aircraft design can be the root cause of failures that result in decreased availability. Information collected from depot level maintainers and repair database queries has helped identify areas where availability is affected because of design oversights. The most common areas include inspection, repair and access, corrosion prevention, and material reliability.

4.3.1 Design for Inspection

As discussed section 3, the current top NMCM rate driver is inspections. Therefore, great effort must be initially placed in designing the aircraft to be easily inspected, especially in areas with difficult access, high probability of failure, and/or large consequence of failure.

Figure 8: E-2/C-2 Arresting Hook

- E-2/C-2 arresting truss assemblies. The arresting truss assemblies on the E-2C/C-2A are a vital component of the tail hook where a single failure can result in catastrophic damage to the aircraft and potential death for the crew. However, previous inspection specifications for the arresting truss required no physical inspection of the inner diameter (ID) of the truss leg because the entire assembly was dipped in an anti-corrosion bath and the leg ID is extremely small. Even though no failures had occurred it was deemed necessary to consider new corrosion inspection techniques for the truss assembly. Consequently, upon inspection of the truss leg ID with a borescope, severe pitting corrosion was discovered. The reason was determined to be caused by the yoke design which is susceptible to the pooling of salt solutions. These results caused changes to be made: 1) New inspection specifications were instituted that required physical inspection of the truss leg ID with either a borescope or videoscope; 2) Sodium hydroxide was found to be ineffective at preventing corrosion in this case. It was replaced with an alternative corrosion prevention compound. While a solution was found for the current design, recommendation is to design future yolks to readily inspect strut IDs thereby reducing or eliminating the need for time-consuming videoscope and borescope inspections which would result in shorter inspection times and increased availability.

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[8] "Residual Strength of Bonded Repairs After 10 Years of Service," 2007 Aircraft Structural Integrity Program Conference, Lt Col Butkus, 30 Nov 06

4.3.2 Design for Repair and Access

Repair and access considerations must be incorporated into the weapon system designs to greatly reduce the effects of the requirement for disassembling and reassembling the aircraft structure to perform the repair. For instance, in addition to the airframe being a huge driver because of fatigue cracks and corrosion, it is a significant driver because it is in the way – the lack of accessibility adds a lot of maintenance time since various panels and structural components must be removed and replaced or disassembled and reassembled to facilitate other maintenance (i.e., removing wing/fuselage panels, separating the wing from the fuselage, etc.).

- F-18 integral fuel tanks. The fuel tank on the F-18 Hornet is integrated into the wing structure. This design is exceptionally difficult to access for inspections (and repairs). To gain access to the tank, the entire flap system and wing structure has to be dismantled. The result is a large cost and time burden – there have been instances where it was more cost effective to scrap the entire aircraft.

4.3.3 Design for Corrosion Prevention

The corrosion related maintenance burden (compared to the total AF MMH) is 5.4%. This burden includes cleaning, inspections, surface preparation, surface treatments, and repairs which add to weapon system downtime. If corrosion can be prevented or at least its growth can be retarded, the corrosion burden can be minimized and aircraft availability increased. Thus, various design considerations should be incorporated to greatly reduce the effects of corrosion:

- Use of AVDEC™ polyurethane seals and gaskets. Using these seals and gaskets, the US Coast Guard has dramatically reduced trapped moisture on the HH-60 swimmer’s deck and forward antenna system. Also, the U.S. Navy has begun using AVDEC™ gaskets and sealants on and around its F-18 antennas to mitigate corrosion. The result was a reduction in the amount of time required to remove the antenna from 45 minutes to 4 minutes. Therefore, AVDEC™ has reduced replacement costs, maintenance hours, and damage due to removal of current sealants, and has increased the maintenance intervals for these antennas.
- Reduced galvanic contact between composite and metallic components. As of January 2007, the F-22 identified 318 cases of galvanic corrosion. The F-18E/F solved this by insulating all metal to composite connections.
- Clog-free drainage ports.
    - Frequent and thorough inspection of all drainage ports is extremely important to rotorcraft because of the ramifications of corrosion and debris-related failures. For example, while performing an inspection of a UH-1 at Fleet Readiness Center East (FRCE) – Cherry Point, serious clogging of a drain hole was discovered. This clogging had pushed water and debris back into the turbo pump. This backup severely corroded the pump and could very easily had led to its failure and resulted in a crash.
    - In some occurrences, rotorcraft systems lack proper drainage altogether making the need for frequent inspection even more imperative. For example, the pump/bilge area on the H-53 has no drainage system. The crew at FRCE – Cherry Point drains the bilge by removing a screw and then mopping/vacuuming out the water and debris thereby affecting the aircraft’s availability. Due to the potentially catastrophic failures from corrosion and built-up debris, frequent inspections are necessary to prevent rotorcraft from needing extensive depot repairs that reduce availability even more.

- Improved fuel cell foam drainage. The rigid polyurethane foam used to support the fuel cell structure in the F-18 Hornet has been trapping moisture. This combined with the rubbing that occurs between the Kevlar coating on the tank and the foam has led to corrosion. In the future, to help reduce the opportunities for corrosion to develop, aircraft fuel tanks should be designed so that opportunities for rubbing or moisture entrapment are minimized.
- Wet installation of fasteners – C-130 rear sloping longerons take a long time to remove

4.3.4 Design for Material Reliability

- Metallic Materials Properties Development and Standardization handbook (MMPDS, formerly MIL-HDBK-5). MMPDS is the preeminent source for aerospace component design allowable properties used in the design and repair of metallic commercial and military aircraft structures and mechanically fastened joints. The MMPDS contains material allowables, mechanical properties, fatigue data, and fastener joint allowables data. Use of the MMPDS ensures the best materials are selected during the weapon system design phase.

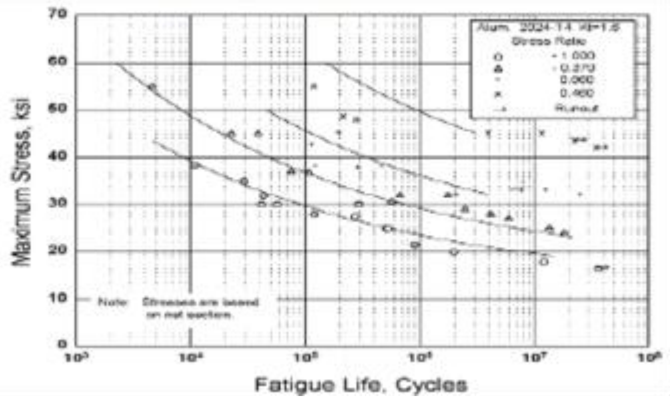

Figure 9: MMPDS Fatigue Curves

- CH-47 cargo hook redesign. The cargo hooks in the fore and aft positions of the CH-47 Chinook helicopter are experiencing mechanical failure while under load. A latch assembly in the cargo hook that is comprised of a one-piece roller and a two-piece body has been found to be the most susceptible to excessive damage and in most cases requires replacement. The latch assembly has several legacy components, which amplifies the effects of failure because legacy components are expensive and incur long lead times for delivery. Inability to obtain replacement components in an efficient manner has significantly hindered the ability of a CH-47 to perform large cargo transport, which is one of its primary functions. The inability to make repairs to the latch assembly lead to a complete materials and structural redesign. The redesigned assembly exhibited improved wear characteristics as a result of a combination of hardening the base material for the roller and pin but the inner and outer surfaces of the components through induction hardening and applying an Electroless Nickel coating. In addition to hardening the material, a separate roller and press-fit pin design was developed, eliminating the need to disassemble the latch body to replace the

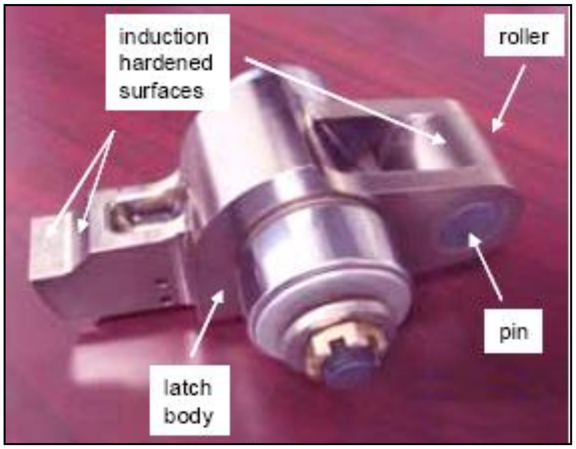

Figure 10: CH-47 Cargo Hook Latch

roller or pin. These improvements assisted in eliminating long lead times and reducing maintenance costs for the cargo hook, allowing the CH-47 to perform all its intended functions.[9]

4.4 Depot Success Stories

Depot success stories correspond to the longer-term solutions employed at depots, logistic centers, and supply centers which remediate issues that adversely affect availability and are presented in the areas of inspection and rework intervals, anticipating maintenance needs, maintenance cycle time reduction, and bringing the depot to the customer.

4.4.1 Inspection and Rework Intervals Tailored to Appropriate Metric

- C-2 fatigue inspection around nacelle has been pushed to a 74 month cycle.
- Extended landing gear barrel nut inspection interval (inspection was causing premature corrosion).
- F-18E/F is investigating the modeling of strength loss in exfoliated parts using laser metrology.
- Landing gear maintenance for all systems may benefit from using the number of landings as a basis instead of flight hours.

4.4.2 Anticipate Maintenance Needs

The following represent changes to practices and design that dramatically reduced the time at depot:

- KC-135 engine strut risk analysis (IAW MIL-STD-882D). From 1982 to 1990, TF33 engine struts obtained from retired commercial 707 aircraft were installed on KC-135s. These installations were intended to be interim pending KC-135R re-engining. However, subsequent exposure to moisture, soot, vibration and heat took their toll.

  In Aug 02, an AFRL strut teardown analysis concluded that corrosion on some struts was worse than estimated and degradation will continue at an accelerated rate. Nov 02 Boeing stress analysis indicated the engine struts were unable to carry some loads expected from authorized ground and flight use. The KC-135 program office then performed a hazard risk assessment in accordance with MIL-STD-882D. They determined that the probability of occurrence of a critical vertical or side load was remote (between 10^{-3} and 10^{-6}) within the next 2 years but the probability worsened to occasional (between 10^{-2} and 10^{-3}) after 2 years with prolonged continuing degradation of the struts. The consequence of strut failure was considered catastrophic in that it could have caused a dropped engine and strut scenario possibly resulting in loss of aircraft/crew and/or damage to objects on the ground. This hazard risk assessment strongly conveyed the justification for developing the risk mitigation action plan and the time frame for which to execute it and included operational parameters (flight restrictions), interim repairs, and ultimately, overhaul and/or replacement. These actions were designed to maintain the aircraft availability as high as possible by pre-empting the potentially catastrophic effects due to the inevitable onset of failures.

  While the KC-135 program office was able to successfully use MIL-STD-882D for their specific situation, the engineering community within the Aeronautical Systems Center (ASC) believes this standard is somewhat broad in nature in that it provides a means for evaluating identified mishap risks for diverse situations and a wide variety of systems, subsystems, equipment types, and facilities. The use of MIL-STD-882 to continually resolve air vehicle life cycle airworthiness issues has proven difficult. For aeronautical applications, the result has been an inconsistent set of criteria that is platform dependent and provides no specific traceability to the originating basis for airworthiness. To adapt MIL-STD-882D to air vehicles, ASC/EN published Airworthiness Certification Circular #5,

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[9] "Damage Investigation and Redesign of the Latch Assembly for the CH-47 Chinook Cargo Hook", G. Dicks, W. Sequeira, M. Jensen, E. Peterson, and S. Thieman. 2008 Aging Aircraft Conference.

"Airworthiness Certification Risk Evaluation and Acceptance," to provide guidance in determining the specific risk of aircraft loss. The guidance in this circular is designed to provide that traceability and linkage.

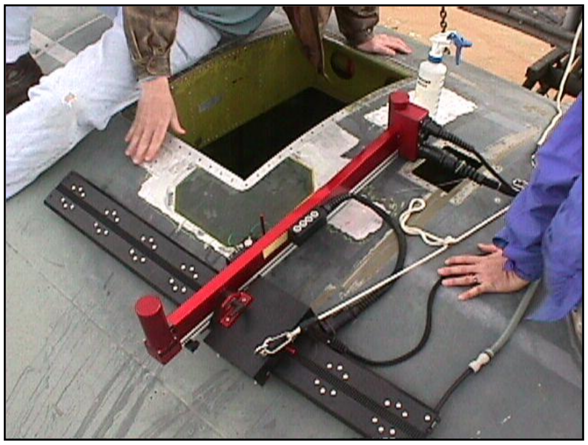

Figure 11: B-52 NDI

- B-52 NDI and repair development through structural teardowns. The Aerospace Maintenance and Regeneration Center (AMARC) at Davis-Monthan AFB, Tucson, Arizona, is used for storage of retired aircraft. Among the many services they provide is the ability to use retired aircraft to assist aircraft managers with identifying potentially hidden problems from teardown inspections and developing new non-destructive inspection (NDI) and repair techniques. For example, AMARC and B-52 personnel discovered severe corrosion in the cockpit structure of a B-52G as a result of teardown inspections. This discovery lead to an inspection and repair of fielded B-52H aircraft. This averted a catastrophic incident and grounding of the aircraft. In another example, inspection of the bearings in flight control assemblies on the B-52G led to all flight control bearings on the B-52H being replaced due to the amount of degradation found when the sealed systems were opened.

4.4.3 Depot Maintenance Cycle Time Reduction

4.4.3.1 Inspections

Figure 12: MAUS V

- Detection of cracks, corrosion, and repair integrity. The MAUS®V system is a portable c-scan inspection system that integrates several traditional inspection techniques into a single package. Its capabilities include raster, rotational A-scan, B-scan, and C-scan scanning modes; pulse-echo, thru-transmission, shear wave, and phased array ultrasonic methods; resonance, pitch/catch, and mechanical bond test methods; and, single and double frequency and transient eddy current methods.

  This system is effective in a variety of production manufacturing and aircraft maintenance environments for process quality inspections, damage assessment, aging structure evaluation, and repair validation programs. Unique features of the MAUS®V system include equipment portability, ease of setup, inspection versatility, very fast inspection rates, and advanced imaging and data analysis for enhanced inspection data interpretation. Inspection applications include metals, monolithic composites, hybrid composite-metals, and bonded structures. MAUS®V can be used to detect delaminations in composite structures, bond-line integrity in composite patch repairs, hidden corrosion in substructure, and fastener hole cracks without fastener removal.

- C-141 and B-1 inspections of fastener hole fatigue cracks in complex and/or hidden structure. The UltraImage NDI system resolved difficult inspection requirements for the C-141 lower wing skin fuel tank integral risers and the B-1 wing pivot clevis joints.

  The C-141 inspection of 7,000 lower wing fasteners would have taken 9,500 manhours per aircraft with wing entry and using eddy current every 120 days. The UltraImage system reduced the labor to 450 manhours per aircraft every 5 years by eliminating fastener removal and wing entry. The reduction therefore equates to going from 142,500 to 450 manhours in a 5 year period per aircraft.

  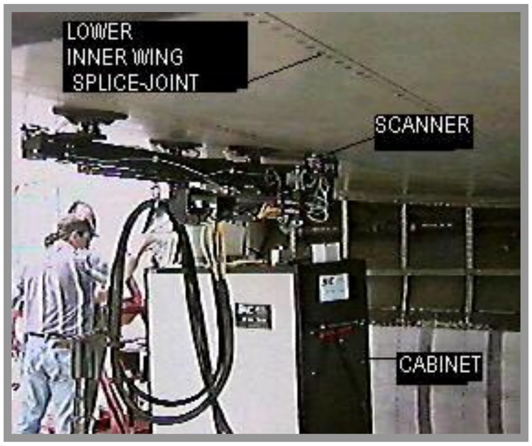

  Figure 13: C-141 Spanwise Splice NDI

  The B-1 inspection of the tapered bolt holes in the aluminum/titanium clevis joint of the wing pivot would have taken 480 hours per aircraft for fastener removal/replacement and hole inspection alone plus additional hours to repair the scored holes from the fastener removal process. The UltraImage system reduced the labor by 85% to 68 manhours per aircraft through the elimination of the requirement for fastener removal to inspect the hole.

  The UltraImage system, using ultrasonic C-scan imagery, has improved 2nd layer fatigue crack detection using neural network logic to enhance scanning ultrasound techniques. The system also can employ a couplant recovery process that allows for scanning over button head fasteners.

- Thermography to test for water ingestion. Water ingestion is a relevant problem that often arises in bonded structures, and has a particular importance when it happens on aircraft mobile parts. Thermography has been identified as a potential nondestructive inspection (NDI) technique for these bonded structures because it has a high inspection speed, easy documentation of the results, no coupling mediums, and no exposure to dangerous radiations. Higher inspection speed, radiation free inspection, and uncomplicated result documentation make Thermography an economically advantageous and a valid alternative to traditional NDI techniques.[10]

4.4.3.2 *Corrosion Prevention*

- Corrosion prevention compound (CPC) primer application. Obtaining a proper coating thickness for primer is a vital factor in the application of CPCs. However, achieving the correct thickness is a very difficult task, especially for large aircraft (such as a cargo plane). Aircraft painters at Warner-Robbins AFB GA have developed a process of color-coding the primer coats to properly obtain correct coating thickness. When a certain shade of coating is obtained, the painters know they have applied the correct amount of powder coat primer over the entire plane. This shading process has greatly improved the accuracy of the primer thicknesses and reduced the overall time required for the coating process.

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[10] "Water Detection in Honeycomb Structures by Use of Thermography," Lt. Col. G. Trivisonno, Maj. E. Dati, 01 APR 2005

4.4.3.3 *Lean Initiatives*

Figure 14: F-18A-D Center Fuselage Barrels

- F-18A-D and F-18E/F center fuselage barrels. The fuselages of the F-18A-D and, to a greater degree due to its higher weight, the F-18E/F undergo a significant amount of stress from hard carrier landings that cause the titanium bulkheads in the center barrel to crack. Since these bulkheads are difficult to repair, maintainers and engineers at Fleet Readiness Center South West (FRCSW)[11] developed a procedure to just replace each center barrel section as the plane comes in for repair instead of repairing individual cracked bulkheads. This new center barrel replacement procedure significantly reduced the time required for center-barrel-related repairs. As a result, F-18's were returned to the fleet in less time resulting in increased aircraft availability.
- E-2/C-2 depot cycle leaned out. This Lean Program employs:
  - Single piece flow
  - Cell-based work environment (e.g., a problem board for each aircraft)
  - Pull system based on fleet flight line requirements
  - Vending machine self-checkout tooling
  - Artisans are allowed to build own tooling

  The result has been a reduction in the average time in depot from 6 to 3 ½ months.
- Maintenance cycle time reduction. One of the most effective ways to reduce the effect of aircraft in depot on overall availability is to reduce the length of time required for each maintenance procedure. There are two approaches to make these cycle time reductions: a depot-wide logistics and process optimization effort and weapon-system specific process optimization. In both efforts, processes, procedures, and resources for several aircraft maintenance tasks are standardized, and logistics, maintenance, and support functions are streamlined. The only difference between the two approaches is the scale with which they are implemented. Depot level efforts are more difficult to undertake due to the large size of the facility and the number of weapon systems that any changes would affect, whereas system specific efforts are on a smaller, more concentrated scale.

  Over the past two decades, all four services have adopted and applied six sigma and lean manufacturing principles to their depots and weapon systems in order to optimize maintenance processes. Lean and six-sigma focus on the elimination of waste (both physical and procedural), standardization of work, process and product repeatability, and increased quality.

  Below are several case studies of the use of lean/six sigma and other optimization efforts to improve maintenance processes and help increase availability.

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[11] http://www.frcsw.navy.mil/frcsw/docs/fa-18_brochure.pdf

- Fleet Readiness Center Southwest lean/six sigma. Employing AIR*Speed* lean/six sigma techniques, maintainers and engineering staff at FRCSW have made several maintenance procedures more efficient, providing better quality repairs in a shorter period of time. One of the first weapon systems to have its maintenance lines undergo this transformation was the E-2 Hawkeye/C-2 Greyhound. The new maintenance line consists of several consolidated maintenance and sustainment processes and employs a synchronized pull system to achieve one piece flow based on the current needs of the fleet. As a result, a C-2A was able to return to the fleet after undergoing the Structural Life Extension Program (SLEP) in a record 287 days.
- Warner Robins Air Logistics Center lean principles. A project to implement Lean manufacturing principles across several depot repair tasks at Warner Robins Air Logistics Center (WR-ALC)[12] has greatly improved aircraft availability by reducing time in depot. Lean manufacturing has produced remarkable improvements in productivity for maintenance, repair, and overhaul on F-15 and C-5A/B. The on-time completion rate for the F-15 Wing Shop from 0% to 95% in the span of 6 months. In addition, production of the F-15 horizontal stabilizer was doubled in just 6 weeks while the flow days for the process were decreased from 61 to 36 days. For the C-5A/B, cellular flow reduced the flow days for engine pylons from 63 to 35 and increased production of floorboards by 470 %. The success of lean implementation has lead to an effort for the Army Material Command to implement lean manufacturing principles in all its repair depots.

Figure 15: C-5 Depot Maintenance Cycle Time Reduction

- Redesign of large aircraft paint/de-paint facility.[13] De-painting large aircraft like the C-5, C-130 and KC-135 is an arduous, time consuming process that poses several problems related to aircraft part accessibility. Due to the large size of the existing stripping equipment, a fixed aerial system was needed for spraying the aircraft. A joint effort between the Manufacturing Technology Division of the Air Force Research Laboratory's Materials and Manufacturing Directorate (AFRL/RXM) and U.S. Technology Corporation developed an innovative and highly efficient aerial-based, semi-automated system to perform maintenance, repair & overhaul called the Aerial Multi-Axis Platform (AMP).[14]

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[12] https://www.dodmantech.com/successes/AirForce/04-08/LDR.pdf
[13] https://www.dodmantech.com/successes/AirForce/04-08/AMP.pdf
[14] Technical Paper for the Aging Aircraft Conference 2008 on Aerial Multi-axis Platform (AMP)

Figure 16: Aerial Multi-Axis Platform

The AMP system eliminates the need for ground-based scaffolding and hoses in addition to improving positional accuracy, spray efficiency, and worker safety. To ensure adequate coverage to all areas of the aircraft, AMP employs a Stewart Platform (figures 16 & 17) that is suspended over the aircraft for automated spraying processes. For manual processes, a manned basket is suspended from a cable system attached to the existing hangar structure. In addition to improved accuracy, AMP reduces occupational hazards by eliminating exposure to chemicals and medium pressure jets. AMP also reduces blasting time and overall aircraft flow time because the operator no longer has to maneuver around in difficult spaces around dangerous scaffolding. These improvements lead to an estimated four-day reduction in flow time for the C-5 platform in addition to reducing overall cost by 20% or potentially $8 million per year.

Figure 17: Diagram of AMP Stewart Platform

4.4.3.4 Bring the Depot to the Customer.

- Mobile Composite Repair Facility. The ability to make composite repairs in the field can reduce the need for aircraft to enter depot for certain types of structural repairs and avoiding lengthy downtime. To help make this a possibility and due to the ease of application and structural advantages of composite patches (e.g., no requirement to drill stress raising fastener holes for fasteners to secure patch to structure), a mobile, go-anywhere-at-anytime composite repair facility has been developed by WR-ALC. Dubbed the "war-wagon," this 37-foot long, tractor-trailer based at the 402nd Commodities Maintenance Group, Robins AFB, GA, can be loaded onto a cargo aircraft and sent anywhere in the world with a traveling repairman. The trailer contains all the necessary equipment and supplies to handle repair sizes up to five square feet.

Figure 18: Mobile Composite Repair Facility, aka "War Wagon"

5.0 SUMMARY

In 1990, the Air Force (AF) aircraft inventory average age was almost 17 years. By 2007, it was nearly 24 years with almost a third of the aircraft inventory over 30 years of age and one fifth over 40 years of age! Overall, the AF total inventory availability rate trend has declined throughout the 1990s (from 77% to 65%) and has been level throughout this decade (68%). However, age doesn't appear to be the sole factor for the trend behavior of the availability rates. While the AF is retiring old aircraft and adding new aircraft to its inventory (2007 saw no growth in fleet average age for the first time since the early 1990s), some of the newer aircraft (e.g., B-2 and F-22) are more complex resulting in their respective fleet availability rates being lower than the AF fleet average. With the dual occurrence of the legacy weapon systems continuing to age and new replacement systems coming online continuing to become more complex, maintainers must overcome difficult and multifaceted issues to sustain and improve availability.

To assist these maintainers, further examination of non-availability issues and their solutions is warranted. One such attempt has been the development of a US Department of Defense (DoD) level guide which a) reveals the drivers that impact weapon system availability and performance and b) compiles and presents recommendations for reducing the burden of such issues through lessons learned, best practices, success stories, and technical solutions. This "readiness" handbook is based upon trend analyses of maintenance data that correlate availability issues to specific factors and upon success stories where adverse availability trends were mitigated. Most of this information was obtained from the AF's (and some from the Navy's) databases, major commands, field units, and maintenance depots.

5.1 Conclusions

Notable observations of the maintenance trend analyses include:

- The AF NMCS and NMCB rates have peaked (FY98-01) and have been declining or stayed level since then. This is most likely due to the inverse relationship between DLR funding and the NMCS rate. When DLR funding increased, the NMCS rate stopped increasing. When the DLR funding decreased, the NMCS rate stopped decreasing.

- The NMCM rate continues to increase, almost doubling from 7.2% in FY91 to 13.4% in FY07. The top six drivers in FY07 were inspections (phase and special), engines, fuel system, airframe, flight controls, and landing gear. These top drivers accounted for more than two-thirds of the AF's unit possessed total downtime and inspections alone comprised of almost one-fifth of the total downtime. Unfortunately, maintenance did not experience the same inverse relationship between funding and NMCM rate as funding has with the NMCS rate.

- Inspection requirements do not appear to be directly related to where the fleets are in their life cycle. On an aircraft size basis, it appears that the smaller aircraft (e.g., fighters, trainers) require more downtime to inspect. And, inspections are not a function of aircraft complexity.

- Complexity appears to play a strong role in the AF fleet's availability trends and maintenance funding whereas age does not. The analysis suggested that older, simpler aircraft seem to have much higher availability rates than newer, more complex aircraft (i.e., F-22, B-2, and B-1). And, analysis suggested that maintenance funding does appear to be heavily influenced by aircraft complexity countering the often held notion that maintenance costs are increasing due to aging aircraft.

In light of the observations and challenges described in this paper, opportunities where availability improvements can be realized in the field and at the depot and their respective recommendations to lessen their impacts were presented. These included: scheduled inspection processes (review for out-of-date requirements, reduced frequency, possible concurrency, and new technologies), integral and bladder fuel tank leaks (develop improved trouble shooting and repair techniques, improved technologies for sealant removal, durable bladders and sealants), doors and panels (design for maintainability of internal subsystems with enhanced opening/closing features), paint (incorporate improved depaint and repaint processes and equipment, and procure paint with improved life and functionality), structural composites (design to be more ruggedized and durable), landing gear components (design more durable tires, brakes, and strut seals), LO materials (design to be more durable and faster to repair when removing to FOM), corrosion prevention (improved mitigation of corrosion initiation and growth that are in compliance with environmental regulations, avoidance of galvanic coupling in structural joints, incorporation of improved drainage in structural components, implementation of more effective manufacturing and repair techniques), maintenance data quality (reduced maintainer data entry workload, reduced allowance of general WUC entries, connection of the primary Hal Mal code to all respective maintenance tasks within a maintenance job), and barcoded maintenance (improved tracking of maintenance actions).

Several common themes that affect aircraft readiness became evident when conducting literature searches, data analysis, and site surveys of AF and Navy service depots. These common themes were turned into lessons learned and divided into four categories:

- Global Rules of Thumb. These captured the overarching sustainment and design considerations that affect availability. The two examples presented were better communication and aircraft complexity.
- Maintenance Best Practices. These are processes or procedures that improve aircraft availability in the field (operational level). The two examples presented were corrosion prevention and bonded composite patches.
- Design Recommendations. In many cases, the aircraft design can be the root cause of failures that result in decreased availability. The examples presented were inspection, repair and access, corrosion prevention, and material reliability.
- Depot Success Stories. These correspond to the longer-term solutions employed at depots, logistic centers, and supply centers which minimize issues that adversely affect availability. The examples presented were inspection and rework intervals, anticipating maintenance needs, maintenance cycle time reduction, and bringing the depot to the customer.

5.2 Recommendations

To improve the handbook’s ability to assist weapon system managers and maintainers, future spirals should involve the following activities:

- Discovery or development of a methodology to more quickly derive root causes of availability drivers with respect to manufacturing and maintenance processes, aircraft materials, structural and component designs, and data quality and analysis.

- Broader examination of cross-cutting and unique availability issues, best practices, and “up and coming” technologies from all branches of the US military (i.e., AF, Army, Marines, Navy), other U.S. government departments (e.g., Homeland Security – Coast Guard), diverse vehicle environments (i.e., air, sea, land), foreign militaries, various vehicle types (e.g., fixed wing aircraft, rotary wing aircraft, trucks, cars, ground support and test equipment, missiles, ships, etc.) and components (i.e., active, guard, reserves).