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## **USAF Strategy for Aging Aircraft Structures Research and Development**

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### **SUMMARY**

Many nations are now keeping aircraft in their inventories longer than ever before. In many cases, aircraft are left in the inventory longer because they are still operationally effective; however, in most cases, they remain in the inventory because the money is not available to replace them. Aircraft, which are seeing the effects of aging through corrosion and fatigue cracking, are causing their operators to bear a significant economic burden to keep them operational with the potential for degradation of flight safety of aging aircraft if they are not maintained properly.

The United States Air Force (USAF) has maintained safety of their aircraft for the last thirty years through the application of damage tolerance principles to determine inspection intervals. This approach has on occasion been modified because of the onset of widespread fatigue damage (WFD) or the loss of material because of corrosion. In the case of WFD, the USAF has developed a modification program to alleviate the problem. In the event of corrosion damage, both modification and reduced inspection intervals have been used.

The USAF has developed a strategy for the sustainment of their aircraft starting with the identification of user needs requiring research and development efforts. The strategy is based on identifying research and development opportunities that will have a favorable return on the investment through cost savings or cost avoidance and increased aircraft availability. This has presented problems since it is difficult to determine the cost of maintaining aircraft in enough detail to determine the return on the investment accurately. To date, identified activities include improvements in nondestructive inspection capability, corrosion tracking and prevention techniques, and advances in repair of metallic structures through composite patching. In addition, improved materials for substitution and environmentally compliant coatings have been identified. The purpose of this paper is to provide a discussion of the aging concerns found in the structure of USAF aircraft and the approach the USAF is pursuing to alleviate these concerns.

### **BACKGROUND**

The dawn of the aging aircraft program for the USAF began on 13 March 1958 with the structural fatigue failure of the wing of the B-47 aircraft [1]. Those events led directly to the initiation of the USAF Aircraft Structural Integrity Program (ASIP) [2]. The ASIP defines all of the structurally related activities on an aircraft from initial development until retirement; therefore, it can be considered an aging aircraft program. This program was significantly changed as a result of the failure of an F-111 on 22 December 1969, which ushered in the era of damage tolerance in the USAF [3], changing the technology basis of the program from fatigue to fracture. This change in approach prompted considerable research and development in area of fracture mechanics. In addition, since the damage tolerance approach forced the designer to better understand the stresses in the structure, emphasis was placed on the emerging finite element analysis methods.

In the early nineties, the then Wright Laboratory recognized the growing need for further research and development for aging aircraft and on 28 April 1993, they initiated the Aging Aircraft Structures Steering Group. This activity was designed to work hand-in-hand with both the Federal

Aviation Administration (FAA) and the National Aeronautics and Space Administration (NASA). Both the FAA and NASA had ongoing aging aircraft programs as a result of the Boeing 737 failure on 28 April 1988 [4]. The Wright Laboratory activity identified many research and development activities, but the lack of sufficient funding prevented some of these initiatives from reaching fruition.

The climate changed on 1 June 1995 when the commander of the Air Mobility Command (AMC), growing concerned about the future of his aging aircraft fleet, initiated an Aging Aircraft Process Action Team (PAT) to identify actions needed to alleviate the impending crisis. Because of this action, on 26 February 1996 the commander of the Air Force Materiel Command (AFMC) established the Aging Aircraft Program Office in the Aeronautical Systems Center (ASC) to facilitate the transition of technologies from the laboratory to the USAF Air Logistics Centers.

On 28 June 1996 the Air Force Research Laboratory (AFRL) commander, because of concerns about the direction of his aging aircraft research and development program and potential for duplication across other agencies, initiated a National Research Council (NRC) study on this subject. The NRC report [5] was released in September of 1997 and identified 49 research and development activities along with recommendations for some organizational changes to facilitate these recommendations. On 31 March 1998 the AFMC commander approved the formation of the Aging Aircraft Technologies Team (AATT) in response to the NRC report. The AATT consists of representatives from AFRL, ASC Engineering Directorate and the Aging Aircraft Program Office and its purpose is to orchestrate the Aging Aircraft Structures activities from research and development through transition into implementation.

Finally, on 25 January 2001, the Aging Aircraft SPO was formed out of the Aging Aircraft Program Office to further increase the awareness and importance of solving these aging aircraft issues within the USAF.

The problems with aging aircraft are not new and for many years have had a significant influence on the USAF research and development programs and have been a major driving influence on the elements of the USAF Aircraft Structural Integrity Program. The forty-year history of the development of this program provides insight on the how the USAF reacted to the problems with aging aircraft.

#### STRATEGY FOR AGING AIRCRAFT

The damage tolerance approach [6] has led to a greatly improved understanding of aircraft structures and their performance. It, when properly applied, will essentially eliminate fatigue cracking as a threat to structural integrity. Therefore, damage tolerance should be the foundation on which the structural maintenance program should rest. During the 1970's and 1980's, the USAF performed an assessment on every major weapon system using the damage tolerance approach to develop appropriate inspection/modification programs to maintain operational safety [7]. As a result, the USAF has maintained an excellent structural failure safety record despite the ever increasing age of its' fleets.

As the aircraft grow older, the potential for fatigue cracking and corrosion increases. Many of the aging aircraft in the USAF inventory are experiencing increased maintenance costs because one or more of these problems are present [8]. To determine the research and development actions that could be pursued relating to these problems, the USAF formed the AATT. At the outset, the AATT decided they would operate under the following guiding principles:

- Research and development:
  - ◆ Must be directed towards needs of USAF aircraft
  - ◆ Must be oriented towards flight safety, maintenance cost reduction, and/or enhanced availability

- ◆ Must be output-oriented and cost-focused
  - Researcher and customer must communicate on expectations from research
  - Researcher must be able to define cost and schedule for activity
- Develop technology that can be transitioned
- Augment highest level of capability in industry or government
- The USAF laboratories must maintain organic competencies in key areas related to aging aircraft

The most difficult challenge for the AATT was to determine the return on the research and development investment for aircraft. Although the USAF has usable cost information on total cost for depot or field operations, they do not know the cost in sufficient detail to judge whether an effort on a certain component of the aircraft is justified. For example, a wing section may be subject to corrosion, but without cost data on this component, it is difficult to determine if the USAF should replace this component using a more corrosion resistant material or keep repairing the corrosion damage.

The strategy for identifying research and development programs to reduce maintenance costs can be described by six steps. These steps are

- Conduct surveys to determine problems
- Identify and prioritize solutions requiring research and development
- Establish research and development roadmaps
- Obtain management and customer approval
- Execute research and development efforts
- Transition technology to the operator

The first three steps are designed to identify the problems and develop a plan for their solution. The final three steps engage management to implement the plans and carry the research and development through to technology transition.

The first step is to conduct surveys on aging aircraft in the inventory to identify their problems in as much detail as possible. This effort includes interviews with engineers and maintenance personnel that are directly responsible for the continuing integrity of the aircraft. In addition, the AATT discussed the aging aircraft issues with the operators of the aircraft. Identification of problem areas generally requires multiple meetings with these individuals in order to get a complete understanding of the problems that may have a solution through research and development. For example, for the USAF, surveys by the AATT of approximately thirty aircraft have taken place annually four times. In most cases, the reviews required approximately one day to complete. In some cases, however, there was interest in the review by the operator because of the potential for significant funds to be expended by them for modernization of the aircraft. In these cases, the reviews required two to three days to complete. The surveys, whenever possible included laboratory personnel so that they could see the nature of the problems for themselves. In addition, the surveys included the original equipment manufacturer (OEM) since their knowledge of the aircraft is essential for a clear definition of the problem. The relationship between the USAF and the OEM for maintaining the integrity of aging aircraft has been outstanding.

The second step is to determine the potential solutions to the aging problems. The AATT makes an initial screening of the problems and makes a preliminary determination of those problems that may have potential for a research and development solution. These problems are then given the widest dissemination possible to solicit possible solutions. The potential solutions are then categorized as basic research, exploratory development, and advanced development. The last category is for technology that is ready for transition. Usually, solutions categorized as basic research require development times that are extremely long for the technology to reach maturity. However, this area cannot be overlooked since it may, in time, have significant return on the investment.

The third step is to develop "roadmaps" for the maturation of the technology for use in the aircraft. The roadmap identifies the problem, the technology to be used to solve the problem, the tasks to be performed for the solution, the schedule for completion of each of the tasks and the funding required for completion of each task. This step requires close adherence to the AATT guiding principles.

The fourth step, which is management approval, is likely the most important in that the success of the entire program rests on the agreement of the technologists and managers that the research and development program has the greatest return on the investment. This, of course, means that the manager has an understanding of the scope of the effort required to reach the desired goals. With this step the process changes from bottom up to top down. The first three steps could be identified as "bottoms up" activity. These steps started with identification of the problems and ended with a strategy for solution.

The fifth step is execution. The strategy is not complete, however, without the implementation step. This step is "top down" in that management charges the researchers to perform to the aging aircraft roadmaps. Essential to this step is the acceptance of the technology by the logistics managers and the operators. They must demonstrate willingness to implement the technology developed to reduce their maintenance burden.

The final or sixth step is technology transition. Actually, technology transition starts with the second step since there is no solution unless the technology can be transitioned to the logistics centers. Another name for this effort that is at times more descriptive is "industrialization of the process." The first requirement for technology transition is adequate funding. The second requirement is that logistics personnel understand and are trained in the execution of the process. The final requirement is that logistics personnel are convinced that the new technology will enable them to do the job better than they are doing with existing technology.

### AGING AIRCRAFT ISSUES

#### Funding

Funding for aging aircraft research and development activities is likely the number one problem faced by the manager. Funding of aging aircraft requirements is usually inadequate due to ever-increasing structural modification programs, safety issues, sustaining engineering needs, and responding to ever changing retirement dates. It is difficult, if not impossible, to support all identified technology areas. Consequently, there is a need to establish priorities.

In addition, justification is typically difficult for non-safety related problems since the available funding is usually consumed by safety related problems affecting the force. Care should be taken in the maintenance of non-safety related problems in that they may become safety issues through improper maintenance. An example of this is the use of inferior bonding techniques to repair honeycomb structures. Improper techniques can lead to moisture intrusion and an accelerated degradation that has the potential for loss of integrity of the component. Future funding requirements need a better understanding of return on the investment (ROI) where the ROI includes cost and availability in order to compete competitively with all the other identified requirements. Improved cost data collection procedures are needed in order to accomplish this

In many cases, the budgets have not allowed the modernization of maintenance facilities or the upgrading of their information management systems. This has led to maintenance practices that are not state-of-the-art in that the use of information management has not become ingrained in the work force. This inadequacy is compounded by inaccurate and often-inadequate maintenance databases that lead to a misunderstanding of logistics requirements that raises costs and reduces aircraft availability. Retention of maintenance records for structural repair needs to be made a priority.

## Fleet/ Depot Planning/Procedures

Another issue is the lack of support from operators for tail number tracking used to determine damage and sources of damage. Too often, since the recorder for flight loads is not flight essential equipment, the operator fails to adequately download data or service the recorder. This has led to many cases where the operators were not aware that some of their practices were causing damage to aircraft that could have been avoided. The logistics community needs to communicate with operators to find operational techniques to reduce damage.

There is a concern that inadequate manning levels in both the field and at depots are causing lack of compliance with technical orders. In addition, the experience level of maintenance personnel has been steadily reducing for both the civilian and military population due to workforce downsizing. These problems are compounded by diminishing engineering resources in the manufacturing base result in increases in flow days and costs since the parts must often be fabricated through reverse engineering.

There are also many depot maintenance procedures/planning issues that cause increased costs. The maintenance planners should look at the frequency of depot maintenance visits, especially for aircraft experiencing moderate to high levels of corrosion. In some cases, the depot intervals are so long that many problems are discovered too late, resulting in more expensive and complex repairs that could have been caught earlier and remedied much easier with more depot visits. To make matters worse, many times within the same depot, there will be inconsistent maintenance practices being used from one product line to the next.

Finally, although experience shows that there are many surprises found in the maintenance of aging aircraft, there is usually a lack of planning and budgeting for these events. This leads to increased costs and a further lack of availability.

One of the most important aspects of an aging aircraft program is the quantification of the economic burden of systems in future years. This activity is necessary to support planning for retirement of existing aircraft and procurement new aircraft in the future. Without this information, the visibility is lacking to make sound judgements for aging aircraft. The process for doing this is well established for fatigue cracking. Unfortunately, for corrosion it is not as well understood.

## FATIGUE CRACKING AND CORROSION

The USAF identified that the root causes for most aging related structural issues are fatigue cracking and corrosion. For each of these causes, the solutions could be obtained in one or more of the categories: nondestructive inspection (NDI), repair, modification, prevention, analysis, health, or information technology. Usually, the ultimate solution will be a combination of these categories. The discussion below covers the main efforts for both fatigue cracking and corrosion.

### FATIGUE CRACKING

The introduction of damage tolerance principles by the USAF in their structural inspection program in the early seventies virtually eliminated fatigue as a safety problem in their aircraft. However, fatigue cracking of operational aircraft in the USAF is still a significant economic problem. The USAF estimates that this problem cost approximately \$250 million in 1997. The USAF attributes much of this burden to operational usage being more severe than the usage assumed for design. This occurs because as the aircraft is fielded, the operators find unique and unanticipated ways to take full advantage of the capabilities of the aircraft. This often results in more severe usage due to weight growth for new capabilities or new operational mission profiles.

Based on design processes used today, fatigue cracking in an airframe should not be a significant factor for an aircraft whose operational usage is approximately the same as its design usage. However, many of the older aging aircraft in use today were designed at a time when the effects of

repeated loading was not a design consideration. Consequently, fatigue cracking is surely an economic problem and in most cases is a potential safety problem. Fatigue cracking found by inspections based on damage tolerance principles had resulted in many repairs on operational aircraft. In many cases, the cracks are repaired when found. The USAF has found that historically this is the most economical approach and consequently, this approach is most often used until it becomes evident that the structure needs to be modified.

The certification basis on which the structure was qualified also plays a critical role in the research and development for aging aircraft. The USAF guidance for structural certification [9] includes both slow crack growth and fail-safe structures. Although, the slow crack growth approach is most often used today, the USAF strongly advocates the use of fail-safe designs whenever practical. Designs that are fail-safe can tolerate the failure of a structural member and still maintain adequate residual strength until the failed member is discovered through inspections.

#### Widespread Fatigue Damage

The certification basis for many aircraft is fail-safety because it provides a good overall approach to achieve both safe and economic operation. However, when the structure develops WFD, it can cause a loss of the fail-safe capability in the airframe and drastic action is needed to restore it. Perhaps, the most famous incident of WFD is the 1988 operational failure of a Boeing 737. This event provided the motivation for the considerable emphasis by the FAA on the structural issues associated with aging aircraft. This event occurred on Boeing 737 (N73711) on 28 April 1988. On this date, cracks in the fuselage lap-splices coalesced resulting in loss of the upper fuselage from just aft of the pilot's cockpit to the wing leading edge. For the FAA, the aging aircraft program started on that day.

The Aloha incident was not the only operational failure caused by WFD. Another one in Japan was much more serious, but did not receive the notoriety in the United States that the dramatic Aloha incident received. WFD resulting from a faulty repair of the aft pressure bulkhead of a Japan Air Lines (JAL) 747 caused the failure of JAL Flight 123 from Tokyo to Osaka. The total casualties resulting from this accident was 520.

The effect of WFD on flight safety has long been a concern of many researchers. Most of the older USAF aircraft designs did not comply with the modern guidance for damage tolerance assessment (DTA) [9]. Consequently, there is a potential for the crack population to be so large in the structure that the application of the deterministic damage tolerance process may not protect safety. Large crack populations could also exist in monolithic structures such as the T-38 aircraft, which the USAF analyzed using probabilistic methods [10]. The USAF refers to cracking as found in the T-38 aircraft as generalized cracking rather than WFD. The occurrence of WFD can significantly degrade the fail-safety of the structure. This problem has been evident on the KC-135, C-5A, G-141 [11] and the E-8 aircraft. The USAF subjected these aircraft to teardown inspections. They incorporated the results of these inspections in a risk assessment to quantify the time when the probability of failure, conditioned by the fact there had been discrete source damage, becomes unacceptable.

#### Probabilistic Methods

For safety of flight structure, many of the problems, such as WFD need to be terminated by modification of the affected structure. There are other cases; however, where safety is not a concern, but there are significant economic implications that need considerable attention aimed at finding solutions for them. In some situations, cracking may occur at some point in the life of an aircraft where it may not be readily apparent whether a repair or a modification is the answer to a problem in fatigue cracking. In these cases, a probabilistic assessment may be useful to determine whether it is more economical to repair the aircraft when cracks are found or to perform a modification for the entire population at a certain time in their life [12].

One approach for accomplishing this is to determine an estimate of the expected number of future repairs from existing evidence of repairs made on the population. This requires that a probabilistic analysis be made to determine the distribution of fatigue cracking in the fleet. The essential element for performing this type of analysis is an accurate database of the cracking incidents. With this information, the analysts can use the powerful tools derived for the well-known distributions such as the Weibull and the Lognormal. With information derived from these analyses, the operator is able to make an informed decision on whether to keep repairing the structure or to make a modification to correct the problem.

#### Nondestructive Testing

The need for nondestructive inspection technology to enable the DTA driven inspections has been a major thrust of the USAF for many years. However, the AATT found inadequate NDI methods was a major concern with the ALC engineers. They stated that existing methods were too slow and sometimes unreliable. It was difficult for them to find cracks in fastener holes in multiple layered structure. In addition, the implementation times are too long for new techniques. There are two reasons for this. The first is that the budgeting process has built into it long delays in getting funding for new technology. The second is that the problem with transitioning the technology. The approach for transitioning newly discovered methods it is not well understood and consequently many techniques that hold promise are never used. There is also a need for more efficient and reliable methods for depot and field level inspections. For many of the inspections, there is a lack of established limits for damage so that it may be repaired and replaced efficiently and economically.

For all aircraft, there is a need to develop crack detection in second layer for cracks approximately 1.25 millimeters in aluminum, titanium, and steel. In some cases, where there is a faying surface seal between the structural layers this capability could be obtained with ultrasonic methods. For other structures, this is much more difficult task, although low frequency eddy has enjoyed some success.

For fail-safe aircraft, there is a need to develop crack detection of 0.75 millimeters in fastener holes in fuselage splices that could degrade fail-safe capability of the structure. Because of the safety implications, it is important to be able to detect cracks that could be significant for determination of the onset of WFD. There is a need to make an estimate of this onset based on probabilistic assessment of cracking data derived from the teardown inspection of fatigue test articles or operational aircraft. It must be recognized, however, that this is only an estimate. The actual time may be either somewhat earlier or later than this estimate. It is important, therefore to be able to validate this prediction with nondestructive evaluation. This task is made difficult by the fact that the size of defect to be found is quite small. The experimental evidence to date indicates that cracks of the order of two millimeters can significantly lower the fail safety capability of certain structural configurations.

The reliability problems with some of the NDI techniques make it desirable to make the structure safe in the event of rapid fracture in a component. Fail-safe structure greatly simplifies the NDI problem in an aging aircraft. Consequently, there is a need to develop methods for enhancing fail-safety of all structures with safety of flight implications. One of the more promising approaches is the use of bonded composite straps.

#### Repairs/ Material Substitution

In the past, repairs placed on aircraft have been designed based only on static strength considerations only. One reason for this is there is no need to know the loads on the aircraft. However, on aging aircraft, the repairs to flight safety critical structure need to be assessed for their damage tolerance capability. This means that the stresses in the structure must be known. This knowledge is typically only known to the OEM; however, in many cases, the USAF has worked with the OEM to use their knowledge of the loads without violating their proprietary rights. In other cases, the USAF has contracted for the development of the loads by a source

independent of the OEM. For new aircraft, the USAF has funded the effort for the OEM to design the standard repairs to be damage tolerant. This effort was a logical activity subsequent to the DTAs that were made for the intact structure.

There are numerous applications currently of composite repairs in the USAF, in addition to the applications in Australia and Canada and the United Kingdom. The USAF applications include the C-130, C-141, KC-135, and the B-1. The success of these applications has motivated the USAF to spend the resources to further exploit this technology. The procedures have been established for successfully preparing the surface for the bonding operation. Further research is needed to include other targets for composite repair, such as thick structures that are inherent in many bulkhead designs.

For composite repairs of metallic aircraft on safety of flight locations, it is essential to be able to determine the bond-line integrity of composite patches. Because of the limitations of NDI to determine the strength of the bond, the use of "smart patches" appears to be a viable alternative.

Metallic repairs to metallic structures will remain important for the aging aircraft problem. It is not uncommon to find hundreds of metallic repairs on a single aging aircraft. Many of them are on safety of flight structure. There is a need to develop the guidance for these repairs to ensure that they are damage tolerant and do not degrade the fail-safe capability of the structure.

Material substitution is an attractive approach for aging aircraft since it eliminates the mistakes in material selection made before the threats to their structural integrity were understood. Guidelines and criteria are needed for material substitution to enable this to be accomplished. These substitutions may include alternate product forms for obsolete forgings and extrusions.

The use of interference fit pins in fastener holes or fastener hole cold expansions are important for extending the life of aging aircraft. There is a need to determine stress intensities for interference fit and cold expanded hole locations so that fracture mechanics calculations are possible for these applications.

There are some problems associated with the dynamic response in aging aircraft from buffeting due to flow separation. In most cases, the technology to predict these problems is not well developed and likely will not be developed in the near term. Therefore, the researcher must rely on flight test data. Since these problems were not adequately solved in the design development phase, they become problems that usually never find a solution. The use of passive damping techniques has been successfully used and needs to be further evaluated for control of these problems. In the case of the F-15 vertical tail response to buffet, a partial solution was found by the use of composite patching to the surface of the vertical tail. This solution required that the dynamic response of the tail be extensively modeled.

## CORROSION

Corrosion and fatigue separately have both led to serious safety as well as economic problems. Corrosion alone, in forms such as uniform corrosion (thinning) or exfoliation, may reduce the strength of aircraft and lead to failure. Both of these forms of corrosion may lead also to expensive component repair or replacement. There are many cases where corrosion alone is not significant from a safety consideration, but is a very significant economic problem. In the case of corrosion alone, one must judge the seriousness of this problem on an individual basis. Nondestructive inspections have found fatigue problems where there is essentially no influence from corrosion. Researchers have documented many cases over the years where the consequences were catastrophic. The results of fatigue cracking have caused many expensive repairs and modifications to the structure including component replacement. Fatigue often combines synergistically with corrosion. In these cases, the term corrosion fatigue is more appropriate. In most cases, corrosion, fatigue, or corrosion fatigue becomes a safety consideration only when either maintenance is not performed properly or the maintenance program is inappropriate. Experience derived from diligent maintenance has repeatedly shown that the operator need not

compromise safety resulting from these problems. The purpose of this section is to describe some experiences with corrosion, fatigue, and corrosion and fatigue and to review some of the relative literature on this subject.

#### Economic Impact of Corrosion

There is considerable evidence that corrosion is a major economic problem with both military and commercial aircraft. The USAF sponsored a contract in 1997 to determine the cost of corrosion in USAF aircraft and found in this study as in a previous study performed in 1990 that the cost of corrosion prevention and repair is significant. They found that the total cost from corrosion in 1997 was approximately \$795 million dollars. This was an increase of 4% over the 1990 costs although the USAF reduced the force structure by 28%. The C-5, KC-135, and the C-141 account for 50% of all direct corrosion maintenance costs. Of the \$795 million spent, painting the aircraft cost \$136 million. The USAF spent approximately \$425 million of the \$795 million specifically on corrosion repairs. The survey highlighted the A-10 as a success story in defeating a serious corrosion problem.

Many of the older military aircraft that are currently operating were constructed with corrosion prone materials and essentially no corrosion protection. One aircraft in this category is the KC-135 that initially used 7178-T6 for the lower wing skins. This material was selected rather than the 2024-T3 material used in the Boeing 707 to provide structural efficiency. That material exhibited low fracture toughness, poor crack growth rates, susceptibility to corrosion, and low resistance to stress corrosion cracking. To make matters worse, the USAF elected to save money by omitting corrosion protection of the material by faying surface sealing or wet-installation of fasteners. The result was that the USAF had to replace the lower wing skins at 8,500 flight hours [13]. Corrosion fatigue likely played an important role in the early cracking of this structure.

This same material, 7178-T6, is used in the upper wing skins of the KC-135. It is now causing a significant problem in that there is considerable exfoliation corrosion around the fastener holes. A process that may be able to find these problems is called search peening. In the performance of this process, maintenance personnel shotpeen the upper wing skins with glass beads that cause corroded areas to reveal themselves through local deformation around fastener holes. In some cases, the exfoliation is severe enough to cause panel replacement. When the Oklahoma Air Logistics Center (OC-ALC) replaces upper wing panels, they select a replacement material that is much more resistant to corrosion than the original material. The troublesome part of this problem is that the USAF does not have a solution that would preclude further replacements in the future. The use of peening; however, for new structure does appear to extend their lives. There is evidence of beneficial effects of shotpeening from the B-52H upper wing. These wings, which had their upper surface shotpeened at the time of fabrication, are showing only minor corrosion damage although they have been in service for many years. Another technology that appears to have application to corrosion inhibition is laser peening.

The AGARD Corrosion Handbook [14] discusses the problems found on these aircraft and many others through case studies. This document places the cost of corrosion in the United States alone in 1978 at \$70 billion overall. The USAF can account for approximately one of those billions for their airplanes. The case studies in this handbook show the results of corrosion that remained undiscovered by maintenance personnel until it was a significant economic or safety problem.

These problems include both military and commercial aircraft. As evidenced by the currently documented cost of the major maintenance visits by large category transport aircraft, the cost of corrosion is a major factor in commercial maintenance budgets. However, the use of corrosion prevention compounds in commercial aircraft has significantly reduced the burden. It is encouraging that the airframe manufacturers are doing a much better job of applying corrosion protection during fabrication. One would anticipate that these improvements would relieve some of the maintenance cost burden when the operators bring these aircraft into the inventories.

## Potential Safety Impacts of Corrosion

The fail-safe design augmented by DTA derived inspections is largely responsible for preventing the combined effects of corrosion and fatigue from becoming a major problem on large category transport aircraft. For the USAF, the inspection program derived from DTAs is certainly the primary means of maintaining safety from corrosion fatigue. The USAF also uses another inspection process called the Analytical Condition Inspection (ACI) to augment the DTA derived inspections. The USAF initiated the ACI program many years ago to help the maintenance personnel discover distressed areas of the aircraft not identified by the design analyses or testing. For this process, the USAF selects a small sample of aircraft from the inventory and inspects the entire aircraft thoroughly. To gain better access to concealed areas they remove fasteners and panels to interrogate the structure. This is done as completely as possible nondestructively to ensure that the structure is not experiencing corrosion or fatigue cracking that could jeopardize continued flight safety or economic operation. When they find an area that does not correlate with design experience, they make appropriate changes to the Force Structural Maintenance Plan (FSMP) [15] which is an integral part of the ASIP. The FSMP tells the maintenance personnel how, when and where to inspect the structure to maintain its safe operation.

A paper written in 1997 describes the forms of corrosion that could compromise flight safety. The authors of this paper list pitting corrosion, intergranular corrosion, exfoliation corrosion, stress corrosion cracking, corrosion fatigue and uniform corrosion as safety issues. In this document, they suggest a number of research and development activities that should enhance the state of knowledge about the effects of corrosion. They suggest many activities including teardown inspections of ex-service aircraft and scheduling of maintenance on a time basis as well as a usage basis.

The USAF Aircraft Structural Integrity Program makes an assumption about the effects of some of the forms of corrosion listed above. It presupposes that corrosion damage will not raise the stress sufficiently to change the inspection program to ensure flight safety. This infers that the maintenance program is able to control corrosion damage through inspections and preventative measures. Experience has shown that this assumption has not led to serious consequences. The USAF maintenance program is outstanding. One reason for its success is the advice given to them by the resident ASIP Managers and other engineers at the Air Logistics Centers. The USAF cannot attribute any catastrophic failure since the early seventies to corrosion or corrosion related phenomena. There have been; however, numerous local failures from corrosion, particularly stress corrosion cracking. This has been a chronic problem in many landing gear systems and in large bulkhead forgings.

Even though the USAF maintenance program is outstanding, many corrosion findings are surprises. Corrosion is difficult to predict, especially stress corrosion cracking. It is difficult to quantify the impact of corrosion on a specific aircraft because of maintenance variability within the population. The uncertainty in corrosion predictions appears to be large. Laboratory tests are difficult to correlate with operational experience. In addition to a lack of corrosion tracking and modeling, the corrosion database is immature.

The applications of the 1975 version of ASIP addressed corrosion fatigue by modifying the crack growth rates in an attempt to account for the corrosion environment such as moisture, salt or sump tank water as appropriate. The validity of these corrections is subject to question because of such factors as loading frequency, temperature and the use of crack growth rate data from constant amplitude testing. However, the USAF has found few errors in the DTAs that they can directly attribute to the manner in which they accounted for the effects of the environment. Most often, the increase in crack growth rates in critical locations in the structure is associated with operational usage spectra that are more severe than the design spectrum of loading. The USAF accounts for these differences through individual aircraft tracking for loads.

Despite the USAF's excellent track record, there are serious concerns about the impact of corrosion on structural integrity. The first and most obvious is the effect of lapses in proper

maintenance that have led to significant loss of structural strength. The structure must be maintained in such a manner as to maintain the static margins at no less than zero. Thinning of the structure may increase the stress in the structure such that the structure inspection intervals required for flight safety will need to be decreased.

There is limited nondestructive inspection capability to accurately quantify the amount of material loss due to corrosion. Technology is needed to detect corrosion thinning at a level of three percent in multiple layers. A much easier task is to interrogate the structure for the existence of corrosion. Consequently, at this time, the safest approach is to remove corrosion indications when found. As the capability for nondestructive inspection is improved, then the opportunity for corrosion management is improved. Further, it is essential that those areas that are damage tolerance critical be an integral part of the corrosion detection program. In addition, those areas that are damage tolerance critical and the NDI demonstrates that the stresses have increased because of thinning of the structure, then suitable changes must be made to the FSMP.

The NDI methods for detection of hidden corrosion in the form of pitting, intergranular, exfoliation, and stress corrosion cracking are too slow and sometimes unreliable. As for NDI for fatigue cracking, the implementation times too long. There is a need for more efficient and reliable methods for depot and field level inspections since searching for corrosion is a major cost factor. There is a need for a NDI capability to reliably find corrosion pits with cross-sectional area of 0.04 square millimeters and pitting depth of approximately 0.125 millimeters.

Hidden corrosion is also a major concern for continuing structural integrity. It is essential that the maintenance personnel have a clear understanding where they may find corrosion in the structure so that they may use appropriate inspection procedures to find it when it is present. It is also incumbent on the laboratory to develop the inspection equipment to improve the likelihood of detecting corrosion. Since corrosion damage appears to reoccur in the same locations in a population of airplanes, the use of teardown inspections is helpful for locating potential damage. The OC-ALC performed a teardown inspection on a KC-135 on an aircraft retired to Davis Monthan Air Force Base in 1991.

This aircraft, delivered to the USAF in 1962, had spent twenty-nine years at Mildenhall Air Base in the UK. Therefore, the aircraft saw a severe corrosion environment during its life. The inspection interrogated the structure for cracking as well as corrosion. The USAF found little cracking since the aircraft had only 16,521 flight hours and 2,942 flights. They cleaned the parts and etched them approximately thirty micrometers to enhance corrosion and crack detection. The USAF, for this study, classified corrosion as light if it was less than 25 micrometers, moderate if it was between 25 and 250 micrometers, and severe if it was greater than 250 micrometers.

For the fuselage, there was extensive light corrosion in the skin and doubler faying surfaces. They found limited moderate and severe corrosion below the cargo door, lower bilge, and at the spotwelds. None of the fuselage corrosion was severe enough to affect flight safety. For the wing, there was extensive moderate and severe pitting at the steel fasteners in the upper surface. Most of these had not progressed to exfoliation and none was severe enough to affect safety of flight. There were several areas of severe corrosion at the upper wing skin and spar interface. The center section of the horizontal tail suffered from severe exfoliation on the lower spar caps. They also found stress corrosion cracking in the horizontal tail. This inspection is significant in that it provided considerable insight on the extent of corrosion. It also served as an excellent representative aircraft for identifying areas of hidden corrosion that the USAF did not address in previous depot maintenance activities. In addition, it assessed the ability of available nondestructive inspection procedures to locate corrosion. The goal is three percent for the detection of thinning in a structure. Even this detection capability may not be adequate to maintain zero or positive static margins in the structure.

Another major concern is that pitting corrosion may accelerate the onset of WFD. This could be a serious safety concern unless the operators take proper care to use teardown inspections and nondestructive inspections to reveal the problem. The damage tolerance initial flaws as adopted

by the USAF in the early seventies are well in excess of the size of defects associated with pitting corrosion. The criterion used by the USAF for damage tolerance design of new aircraft is that the initial flaw will not grow to critical in two design lifetimes. Further, the damage tolerance guidance emphasizes the selection of ductile materials that are tolerant to defects. As a further safety measure, the USAF guidance to the contractor is to design the structure such that it is inspectable. This is an advantage, not only for crack detection, but also for corrosion detection. The effects of pitting corrosion; however, could affect the safety of older aircraft that were not designed to the current damage tolerance guidance. Therefore, for these aircraft it is likely that cracks derived from pitting corrosion will need to be found by the inspection program.

The other concern with pitting corrosion is that it could result in a significant degradation of the durability of the structure and hence shorten its useful life in service. Experiments with specimens exhibiting pitting corrosion show that cracks appear much sooner than otherwise expected. These cracks could degrade the fail-safe capability of the aircraft and consequently precipitate the need for structural modifications. A teardown inspection of a high time Boeing 707 wing revealed many significant cracks [16]. These cracks appeared to be predominantly in holes where the manufacturer used steel fasteners. The steel was not protected from the aluminum wing skins and stringers. Consequently, it is likely that pitting corrosion did contribute to the cracking found in this structure.

Another concern about the effect of corrosion on structural integrity is the effect of corrosion products on stresses in structural joints. Mostly, maintenance personnel will find evidence of this problem in the longitudinal lap splices in the fuselage. The corrosion products are much less dense than the original material and consequently the trapped powder causes the joint to expand. The stresses derived from this expansion are significant. At the lower limit of NDI detection capability of joint thinning, the stresses may reach yield. There have been many cases found where the stresses are sufficiently high to cause cracking in the skins. There is no known case where this problem has caused a catastrophic failure or the onset of WFD. However, the potential is there for the cracks to turn into fatigue cracks and propagate. There is also the possibility that even without cracking the stresses may degrade the fail-safe capability of the structure. There is a need to investigate this problem. In addition, NDI needs development that can detect cracks from pillowing that are approximately 2.5 millimeters in length.

The potential for stress corrosion cracking to become a fatigue problem is another concern. This seldom happens, but the result can be serious if the maintenance does not find the crack. There is no known case where a stress corrosion crack in an airframe has resulted in a catastrophic failure. The use of 7079-T6, 7178-T6 and 7075-T6 in aircraft designed in the sixties and seventies has led to numerous cases of stress corrosion cracking. In the USAF the C-130, C-141, C-5A and the T-38 are aircraft where stress corrosion cracking is a significant economic burden. The Materials Information Analysis Center performed a study [17] in 1996 and found that 70 out of 115 or 60.9% of the corrosion failures (problems) in C-130 airplanes were attributed to stress corrosion. NDI needs development that can detect stress corrosion cracks that are approximately 2.5 millimeters in length.

A paper given by a member of the AFRL of the USAF [18] begged the question on when a predictive model would be available for corrosion. Since then, AFRL has started research programs aimed at answering that question. Today, unfortunately, no one appears to possess such a tool. Fortunately, the results of these on-going AFRL research efforts will be available within the next few years and should go a long way toward answering that question.

#### Corrosion Prevention/Repair

One of the most effective corrosion inhibitors available today is the so-called corrosion preventative compound (CPC). However, the use of them is inconsistent among the aircraft in the USAF inventory. One of the reasons for this is that maintenance becomes more difficult after these chemicals are applied to the structure. Another reason is that there is inadequate research and development funding given to their development so that the benefits are clearly defined. They

must be developed to provide protection of lap splices and interior surfaces. It would be desirable for them to suppress corrosion and stress corrosion cracking and have no significant impact on fatigue capability. Lastly, they should have no significant impact on maintenance practices

In addition, there is a need to develop coatings that have a long life and are environmentally compliant. They should provide corrosion protection for their entire life. In conjunction with this effort is the development of NDI tools that will be able to inspect without paint removal. There is no real benefit from a long life coating that will require removal at the depot every four or five years to enable the performance of an inspection.

The repair of corrosion damage is a problem in that the repair technology is immature. For example, the USAF has had poor experience in the purchase of older aircraft from the commercial market. Some of these were so badly corroded that they could not be economically repaired. The USAF believes the decision by the owners to sell the aircraft exacerbated the extent of corrosion damage in these aircraft. After they made that decision, the aircraft evidently received very little maintenance until the owners could sell them. Under these conditions, it did not take long before the damage from corrosion was so extensive that the USAF had to condemn the aircraft immediately after they were purchased. If the USAF had used the current nondestructive inspection capability at the time of purchase, they would not have purchased these aircraft. Examples such as this highlight the diligence needed in a maintenance program. The owners of these aircraft, up to few years before they sold them, maintained them properly and they were flying in an airworthy condition.

### CONCLUSIONS

The USAF research and development program for aging aircraft have provided the technology base for safe and economic operation of military aircraft. As an indicator of this success, the failure rate for all systems designed to and/or maintained to the current policy, is one aircraft lost due to structural reasons in more than ten million flight hours. This is significantly less than the overall aircraft loss rate from all causes by two orders of magnitude. This success, however, should not be used to indicate that there is no need for continued research on aging aircraft. The dangers from corrosion, fatigue or corrosion fatigue are ever present in operational aircraft. Presently, the largest danger by a considerable margin is economic rather than flight safety. All of the collective experience from both military and commercial operations indicates this to be true. No one can foretell with any degree of accuracy what to expect as both military and commercial aircraft push further into the uncharted waters of aging. It is incumbent; however, for the researcher, the engineer and the maintenance personnel to maintain a diligent approach to the problem. They must use all available techniques such as DTA scheduled inspections, ACIs, and assessments for the onset of WFD to help ensure that they maintain the safety of future aircraft operations. Diligent use of CPC's and research into better means of corrosion detection and prevention appear to be the most promising ways to reduce the economic burden of these problems in the future. The priority for corrosion research and development needs to be given to corrosion detection and the inhibition of corrosion when found.

One of the major problems found in operations with aging aircraft is the cost associated with corrosion damage. Unfortunately, the progress made in the recent past in the control of this problem does not bode well for the future. This is especially true when one considers the impact of new environmental laws that remove many of the corrosion fighting chemicals that are currently used. Continued emphasis on research in the area of corrosion control is certainly one area that could have significant benefit.

Another major problem is WFD in primary structural elements. There will be costs incurred to establish an estimate of the time of onset of this problem. This will need to be done through the analysis of data derived from teardown inspections of fatigue test articles and/or of operational aircraft. These estimates will need to be corroborated through the use of detail inspections of suspect structural elements. Once this onset time has been reached, then there will be costs incurred by the modification of the aircraft to remove this problem.

The severity of both of these problems is made worse today because of a lack of adequate nondestructive evaluation techniques to look for corrosion damage in structural joints and to find the small cracks that would be the indicator of the onset of WFD. It appears that the current efforts in research in nondestructive evaluation will produce the technology for these problems. It remains to be seen if there is an economic motivation to transition this technology from the laboratory to inspections of operational aircraft.

Many of the aging military aircraft problems find an exact parallel in aging commercial aircraft. It is prudent, therefore, that these problems be worked through the combined talents and resources of the cognizant organizations. Efforts to date indicate that this approach will be successful and most efficient in solving these complex problems.

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