4.0 An Air Force of Aging Systems

4.1 An Aging Fleet

Continuing trends toward reduced procurement of new aircraft is forcing the USAF to extend the operational life of its current weapons systems. This trend is expected to continue for the foreseeable future (see Table 4.1).

Table 4.1 Fleet Life Extension

Aircraft Type	Number of Aircraft	Average Age	Projected Retirement
C/KC-135	**638**	**33**	**2040**
B-52	**94**	**34**	**2030**
C-5A	**77**	**25**	**2021**
C-141	**248**	**29**	**2010**
C-130 (20 years or older)	**439**	**30**	**2030**
F-15	**940**	**12**	**2020**
F-16	**1727**	**7**	**2020**

This unanticipated extension is placing ever greater emphasis on the ability to find, characterize, and ameliorate the deleterious effects of fleet operations. In addition, most systems are being asked to operate with changed mission requirements that were not envisioned when they were originally procured. In the future, radical improvement in the life management of the aging fleet will be fully dependent upon the ability to identify and characterize changes in materials and structures throughout their lifetimes.

One is immediately struck both by the broad variation in ages and by the distribution of ages of weapon systems in the current inventory. It is important to note that the length of service of an aircraft is not the only indicator of its “age.” Both time-dependent and time-independent deteriorating processes are at work on the fleet. An example of a time-dependent process would be corrosion, where environmental conditions would have to operate over a period of time to have a significant effect, whereas a time-independent process such as stress corrosion cracking is directly related to the imposition of structural stress on the material. Time-dependent processes such as corrosion can be affected by design practices such as the use of corrosion prevention coatings, whereas time-independent processes can only be affected by changes in systems use. Design practices for each weapon system are commonly dependent upon the specifications in place at the time of manufacture.

The operators of older systems such as the KC-135 are generally confronted with corrosion as it affects the economic life of the aircraft. Another important consideration with an aging fleet, is that multiple problems will occur with increasing frequency. To highlight how broadly based problems with the aging fleet are, current systems considering or conducting serious structural modifications, due to the affects of aging, range from the C-130 Special Operations Force aircraft wing/fuselage structural elements to the F-16 fuselage structural frames, and to the B-1B horizontal stabilizer internal spars.

Whereas most components in an airframe are not removed and replaced on a regular basis, most turbine engines are routinely disassembled during programmed depot maintenance (PDM) cycles. This offers the opportunity to carefully inspect critical components. In an effort to extend the useful life of the F100 turbine engine, the Air Force developed and has implemented the Retirement For Cause (RFC) program for this engine's disks and other flight-critical high cost components. The advantages and disadvantages associated with this effort are currently being weighed as they might be applied to other turbine engines. Given the large numbers, the high costs, and the extremely critical nature of most of the components, the Air Force is attempting to significantly enhance its understanding of the behavior of critical components in fleet aeropropulsion systems. Given earlier successes in low cycle fatigue life prediction, behavior and life prediction methodologies are now being addressed.

On a total system basis, retrofits, replacements, and upgrades are critical elements in all efforts to extend the life of the aging fleet. This is a particularly effective strategy for onboard electrical, electronic, and electro-optical systems, since these tend to be replaceable on a unit or modular basis. Electronic, optical and magnetic materials technology is the enabler for this concept of life extension. As an example, the F-15 will have at least two complete avionics suite replacements before the airframe is finally retired.

4.2 Materials and Structural Integrity

Careful, detailed understanding of the behavior of materials subject to structural loads is at the heart of the Airframe Structural Integrity Program (ASIP) used by the Air Force to manage the flying fleet. In the 1994 SAB Summer Study on Life Extension and Mission Enhancement for Air Force Aircraft, the Materials Degradation Panel discussed the main focus of the ASIP as being to ensure that aircraft are being operated in the most economical manner possible. The ASIP has evolved over the years, primarily through the efforts of the Aeronautical Systems Center, into a process that develops aircraft that are tolerant to both manufacturing and service-induced damage throughout their design life and usage.

Experience has shown that it is rare for an Air Force aircraft to be retired because of structural degradation due to fatigue cracking. This type of degradation normally occurs on a single component of the aircraft rather than the entire aircraft. The damage tolerance approach is directed towards repair, modification, or retirement of a component only when in-service inspections require that one of these actions be taken.

There have been many cases of structural modification to preclude retirement of the aircraft. It is believed the damage tolerance approach incorporated in the integrity process in the 1970s is still the cornerstone for protecting the safety of aging aircraft. The operational usage of

Air Force aircraft is almost always found to be considerably different from that assumed in design. This is primarily the result of increased weight and more aggressive mission profiles. Many aircraft, such as the C-130 and F-15E, are flying in low-level environments where the damage from cyclic loading is many times worse than for high-altitude missions.

As a weapon system ages, it is exposed to multiple threats to its integrity. Threats to integrity can take on many forms. Metallic structures may be compromised through the initiation and propagation of cracks while composite structures frequently suffer from environmentally driven weakened adhesive bonds and matrix degradation. Electronic component life is greatly influenced by the robustness of the device with respect to the environment. The Air Force must maintain the fundamental capability to understand the chemistry and physics of failure of materials in order to provide quick, responsive solutions to failures that occur in the aging fleet. Given the success of the ASIP program, the Air Force has expanded its structural integrity efforts to include both turbine engines and mechanical systems, annotated as ENSIP and MechSIP, respectively.

4.3 Characterization

Behavior and Life Prediction

Destructive characterization of materials behavior plays a vital role in the development of new materials and in understanding the behaviors of materials currently in service. Current applications make increasingly more aggressive use of demonstrated materials properties. In addition, new applications will require a better understanding of materials response over the lifetime of the system. This includes being able to correlate changes in microstructural features with the eventual changes in the materials system that result in changes in the overall structure. For some applications this is called understanding the “effects of defects.” The current need for this technology is best exemplified by the problems in the fleet caused by the F100 fan blade failures attributed to high cycle fatigue. In this situation, several different failure mechanisms are being investigated. The fundamental characterization of the failure mechanisms of emerging materials becomes an essential part of their transition. Current modeling technology does not permit failure prediction and current lab level testing capabilities are not yet able to duplicate all of the critical dynamic modes felt to be contributors to the failures.

Deterministic Prediction of Damage - Modeling Combined Corrosion and Fatigue

The aging aircraft community should move to the development of deterministic models for the nucleation and growth of damage. No reliable empirical method exists for even qualitatively predicting the nucleation of damage. The nucleation process involves a large number of variables that are almost always very poorly defined and characterized. The number of degrees of freedom in this problem is such that a purely empirical description of the nucleation process is unrealistic. Our contention is that deterministic models are required to provide a framework within which the seemingly disparate observations can be rationalized, and which might then be used as the basis for the prediction of nucleation times.

Deterministic methods for predicting the nucleation and growth of damage are now beginning to emerge from corrosion science. However, for the prediction of damage, complete determinism is currently excluded because of limitations in our knowledge of the basic laws and because of the complexity of the systems. On a more practical level is the lack of fundamental data, requiring that even the most deterministic algorithms be calibrated against a few known, well-controlled cases. However, even this is much more efficient than the empirical methods, which require huge data bases to capture all of the constitutive relationships.

The technical community that deals with aircraft problems has never had a strong representation in electrochemistry and corrosion science, so that damage and failures have tended to be addressed in terms of purely mechanical phenomena. There is a critical need for engineers to recognize environmental effects in the development of damage. The basis of damage tolerance analysis (DTA) needs to be expanded to include environment effects on the development of damage in a much more realistic and effective manner. Current materials qualification test protocols do not capture all the of the environments in which weapons systems currently operate. The panel strongly recommends that handbook data for new aircraft stress levels and fatigue lives be based on fracture mechanics parameters developed for corrosive environments. Along with the expansion of the DTA methodology, the SAB Materials Degradation Panel report of the 1994 SAB Summer Study recommended that the Air Force develop deterministic corrosion damage prediction technology based on damage function analysis (DFA). It was also predicted that DFA, as a stand-alone damage prediction technology, would eventually supersede DTA as the understanding of corrosion mechanisms became more complete. Further, the panel recommended the continued education of key personnel to enhance their understanding regarding the effects of corrosion on the acceleration of fatigue crack growth rates, and therefore on the availability of aircraft now and in the future.

Nondestructive Inspection/Evaluation

Crack detection. Current Air Force efforts in crack detection address the recently identified problem of multiple subcritical cracks in aircraft that can link up to compromise structural integrity. The current focus is on the rapid detection of first layer and second-layer cracks under fasteners. The detection of small second-layer cracks with conventional low-frequency eddy current methods is generally limited by the presence of structural features near the fastener hole. These features create eddy current signals that can mask crack indications. Responses due to probe tilt, off-centering, and fastener-related responses can also hinder crack detection. Current methods include principally hand-held probes, with a limited number of semi-automated systems. In the future, robotic handling of electromagnetically based inspection systems will allow automated scanning over large areas. The focus will be on the ability to identify small, subcritical, widespread cracks that could interact in a catastrophic manner.

Corrosion detection. Most corrosion is found visually, both in military and commercial aircraft. Therefore, corrosion that does not produce any visual indications may be missed. Current efforts have shown that some locations in the aircraft have hidden and inaccessible corrosion that do not produce visual indications. It must be concluded that some aircraft corrosion could go undetected, be missed, be hidden from view, or that aircraft disassembly would be required to uncover the inaccessible corrosion. Further, it must be concluded that in these hidden and/or inaccessible areas, the corrosion will continue to grow until it causes or produces some visually observable indications that someone detects, or misses, or it continues to grow until the material is degraded to the point that cracks nucleate under normal operating loads and grow to a detectable length.

Corrosion detection in hidden and inaccessible structures is a key USAF Air Logistics Center need. The Air Force has several ongoing efforts to develop corrosion sensing technology. This technology will be evaluated on KC-135 components before disposition to flight test aircraft. In addition, multiple exploratory development new start efforts are underway with follow-on advanced development, culminating with initial availability in fleet in the late 1990s. In the near future, methods will be available to verify materials losses of between one percent and five percent due to corrosion. This will allow changing the maintenance philosophy of removing corrosion whenever it is found to monitoring corrosion loss until maintenance economics necessitate remedial action. This will be one of the cornerstones in allowing the Air Force to utilize condition-based maintenance (CBM) instead of the current approach of PDM. In the more distant future, methods will be available to detect nascent corrosion. These may involve a combination of very small, wireless imbedded sensors and indicator systems such as thin film, bimetallic, galvanic sensors. The identification of areas for tracking or immediate remediation will further improve CBM and further reduce costs due to corrosion.

High resolution digital radioscopy. X-ray inspection is moving from analog (film) data acquisition to digital data acquisition. Recent advances in high resolution x-ray detectors; high fidelity, low light-level camera systems; image enhancement techniques; and robotic inspections have been spurred by the development of new fiber-optic scintillating face-plate technology for x-ray detection that can be used in conjunction with a high resolution, low noise, wide dynamic range, cooled charge-coupled device (CCD) for imaging. This capability allows x-ray data acquisition with film resolution, 10 to 20 line pairs per millimeter, along with much higher dynamic range, 4000 vs. 200 to 500. This means that data for both thick and thin structural components can be acquired in the same data set.

Current methods have shown the feasibility in identifying tight fatigue and corrosion induced cracks. The development of digital radioscopy is directly tied to improvements coming in the fields of image processing and computer data storage, both of which will continue rapid growth for the foreseeable future. The digital data set has the advantage of allowing sophisticated processing methods to be employed to identify potential defects and the disadvantage of a massive amount of information that must be archived for subsequent use over the life of the system. Development of advanced particle accelerators for medical use will benefit neutron radioscopic inspection processes. New accelerator designs are producing neutron fluxes comparable to reactor fluxes and are capable of being transportable. In the near future, advances in x-ray detection system development will be used in all the active depots. This will lead to the use of image processing and computerized accept/reject criteria as more is learned about defect signatures.

The ability to do multilayer, in-depth inspection will reduce the costly downtime associated with current radiographic methods. Rapid, robotic inspection will reduce the maintenance downtime caused by the need to clear the hangar. The overall result will be improved defect sensitivity, enhanced speed (factors of 3 to 10 are possible because of scanning techniques and wide dynamic range), and reduced inspection materials costs (no film or processing chemical expenses). In addition, the ability to inspect directly through the paint will reduce the need to remove the paint to allow inspection, certainly an important corollary effort to the “Paint for Life” philosophy being pursued by the Air Force.

In the more distant future, advancements will come in the imaging devices, resulting in much more compact, lighter weight detection heads. Automated quantification and recognition of features will further enhance accept/reject methodologies. Portable neutron sources will allow both neutron and x-ray inspection modalities to be conducted with the same detector package, further enhancing the ability to discriminate corrosion and cracking in the structure. Absolute alignment of the detectors will allow image processing equipment to do subtraction to show the locations subjected to the combined effects of corrosion and fatigue.

Massive amounts of data. One of the problems presented by accurate large area, high resolution crack and corrosion detection in the future is that massive amounts of presumably digital data will be generated. This data will most likely be stored on either magnetic or optical media. The requirements for long term storage of inspection data means that archiving of the data will have to be addressed aggressively. Advancements in computer processing and storage capabilities should provide the needed technology base for the Air Force.

Automation. Because NDE inspections are completed during scheduled maintenance periods, the amount of time available for these inspections is limited. Manual inspections introduce potential avenues for inspection errors, including operator fatigue, data evaluation, data translation, and reproducibility. Automation of ultrasonic and eddy current methods can improve flaw detection resolution, reduce inspection times, and reduce errors inherent in the manual process, with results available in a fraction of the time required to complete a manual inspection. Automated probe positioning relieves the operator of the tedious task of moving the probe and improves data repeatability. Recently a portable, semi-automated scanner and related electronics package (for acquiring and imaging data) has been demonstrated that will enable maintenance personnel to perform inspections of large metallic and fiber-reinforced composite surfaces in a fraction of the time required by current off-the-shelf equipment. This scanner provides production quality C-scan (two lateral dimensions) presentations in a portable package and can be adapted for ultrasonic or eddy current evaluation methodologies. Future efforts in automated NDE are critical for the affordable operation of the aging fleet. This would include all NDE modalities, with near term emphasis on eddy current, ultrasonic, and x-ray methods.

Remote inspection. In many cases, components may develop structural defects in inaccessible portions of the structure, necessitating significant disassembly to perform the required inspection to validate the defect. A recent problem with cracking on one of the spar caps inside the wing of the F-15 forced removal of the wing skins to allow eddy current validation. Recent cracking problems in one of the fuselage bulkheads in the F-16 made for very difficult access for inspection validation. With the increased use of composite structural elements, it is likely that there will be a need for inspection to validate a potential delamination deep in the heart of the wing or fuselage structure. The use of active optical inspection methods such as laser generated ultrasound through flexible fiber optics and MEMS offers the opportunity for future inspection of internal structures without requiring disassembly. This would be accomplished via a “design for inspection” approach that would provide small access ports similar to those that are currently provided for conventional optical borescope access. Given this design feature, the active fiber optic system would thread itself through the structure, conducting inspections or materials characterizations at key points throughout the structure. The end result will be verification of structural anomalies without the high cost of current disassembly methods.

4.4 Life Extension via Retrofits and Upgrades

A critical consideration in extending the life of existing platforms is the replacement, retrofit and/or upgrade of onboard systems and subsystems. These can lead not only to life extension, but also to increased capability, concurrently with increased maintainability, reduced life-cycle cost and in some cases, pollution prevention. This is a particularly effective strategy for electrical, electronic and electro-optic systems, and these are enabled by the related materials technologies. Examples include high-performance and/or low cost transparency materials, frequency conversion materials (second order nonlinear optical materials) for infrared countermeasure systems, and high-performance magnetic materials, which are enabling for high-performance aircraft on shaft starter/generators, which in turn would eliminate the need for hydrazine and a large amount of ground support equipment.

Future aircraft platform concepts need to encourage “plug-in” upgrades and retrofits, in a concept similar to the “universal bus” concept for spacecraft. This will enable higher performance Air Force systems by allowing for more rapid transition of new technology to existing systems.

4.5 Coatings and Inhibitors

Aircraft coatings and corrosion inhibitors offer significant challenges. Coatings are multifunctional, providing air vehicles with three main attributes: 1) survivability, 2) corrosion protection, and 3) cosmetic appearance. Current coatings for aluminum-skinned aircraft consist of a chromated surface pretreatment, a chromated paint primer layer and paint topcoats, each of which performs several crucial functions. Here, the term “coatings” refers to the aircraft coating structure as a system and includes all the individual elements of the system from the surface treatment to the topcoat paint. The term “paint” refers to a single organic coating comprised of a binder, solvent, pigment, and additives. The surface pretreatment provides passivation of the metal surface, incorporates corrosion inhibitors, and creates a surface topography for maximum primer coating adhesion. The organic primer coating also incorporates corrosion inhibitors and serves as an adhesive layer between the metal substrate and the topcoat layers. At mechanically stressed or damaged areas such as fasteners, rivets, expansion joints, and scratches, the surface pretreatment/primer system provides active corrosion protection from exposure to environmental factors (e.g., water, acids, and solvents). The paint topcoat layers provide signature control and protection against erosion and mechanical abrasion, in addition to providing acceptable cosmetic appearance. The surface treatment/primer coatings are intended to remain intact throughout the PDM cycle. Mission-related topcoat layers are intended to be applied and removed as needed, based on the mission. However, current actual practices have aircraft being repainted, primer as well as topcoats, well ahead of the PDM cycle because of poor appearance due to degradation.

Current materials and processing technology for organic coatings is based on a formulation chemistry involving extensive utilization of volatile organic compounds (VOCs) and hazardous air pollutants (HAPs). Current Air Force corrosion inhibitor paint chemistry relies on the heavy use of metal chromates (Cr [VI]) in the form of strontium chromate which are incorporated into both the surface pretreatment and the primers as highly effective corrosion inhibitor additives. Environmental regulations are forcing paint materials and processing technology to move away from the use of formulation chemistries involving VOCs, HAPs, and chromates. These ingredients will soon be substantially reduced or eliminated from the paint tech base. Estimates indicate that aircraft painting/stripping/ repainting and handling the hazardous waste associated with these materials and processes costs the Air Force in excess of $150M per year, and the hazardous waste costs are rapidly increasing. Corrosion-related problems are the number one maintenance cost to the Air Force (estimated $700M per year but suspected to be much higher, because of the way “corrosion” is defined) and paint-related corrosion consumes about 15 percent of this cost. Currently, there are no known high-performance coatings with extended durability, and little is understood about paint degradation phenomena. Presently, there are no known alternatives to dichromates as corrosion inhibitors. None of the materials currently under investigation seem to work as well as chromates.

The Air Force has established goals for coating systems from now to beyond the year 2003 which call for: 1) life extension of coatings to a permanent foundation layer, and 2) chromate-free corrosion prevention. To meet these Air Force requirements, establishment of a revolutionary new coating materials and processing technology base is required. The future tech base must be founded on a knowledge base created by basic research. A chromate-free foundation layer coating would require invention of a new corrosion inhibitor chemistry utilizing elements having atomic weight less than zinc and would utilize a high solids paint chemistry involving no VOCs. Improved coating materials would utilize formulation concepts such as pigmented polymeric beads and ultraviolet light resistant binders to achieve cleanability, durability and extended life. Application techniques for such a coating would involve processes such as high velocity thermal spray and include tight process controls based on robotic control and qualitative process algorithm (QPA). Concepts such as self-healing, optical detection of corrosion, microencapsulated inhibitors, and corrosion-activated inhibitors will be actively pursued and will require new polymers to be designed with such end requirements in mind. Mission coatings would still need to be applied and removed as needed, but these coatings would also undergo tremendous changes, including self-healing and tailored, on-demand low observability.

4.6 Structural Repair

Repair of cracked and corroded structures has always been challenging. Not infrequently, conventional mechanically fastened patches are not practical. Since the early 1960s, high modulus, high strength fiber-reinforced composites have been used to repair metallic structures. The patches are designed for the specific application and either cocured or secondary bonded to the surface. The high modulus patch dramatically reduces the stress in the vicinity of the crack, effectively extending the life of the component. For thin fuselage structures, the use of multilayer metal/composite patches offers advantages in providing a closer match with the thermal coefficient of expansion of the structural element being patched. In the future, as systems continue to be forced to operate beyond their original design, expanded use of patch repairs will allow the managed reduction of strain in structural “hot spots” that would otherwise begin to fail before the rest of the structure. Careful consideration will have to be given in the design of the patch to prevent forcing excessive strains into the surrounding structural elements. Given the excellent fatigue performance of fiber-reinforced composites, it is conceivable that very significant extensions in the structural life are possible.

4.7 Direct Fabrication of Replacement Components

Replacement of damaged components is never easy or inexpensive, especially for aging systems for which there may be no digital data that would allow fabrication via modern automated methods. Digital metrology via methods such as x-ray computed tomography allows the direct fabrication of components via a variety of approaches that have flowed from stereolithography. The end result is that in the future the maintenance of older systems will be greatly enhanced if enough work is done to continue to develop the combined opportunities of digital metrology, CAD/CAM engineering, and process modeling. The resulting novel processes with computer process development and control will allow fabrication of custom parts directly in the depot at very low cost.

An ancillary activity to direct fabrication of complete replacement components is replacement of only that portion of the component that has been damaged, referred to as refurbishment technology (REFTECH). In many cases, this would allow retention of the majority of the economic cost of the component while restoring it to useful performance. An excellent example of the opportunity possible is the turbine engine disks that are removed due to low cycle fatigue exposure. In many cases, these very expensive components may only have damage in very limited areas. If this material could be removed and replaced via a process such as vapor deposition, plating, or even the insertion of a thin layer of new material, the cost savings would be enormous. This is not a particularly new concept, but one which must be explored as the Air Force strives to extend the economic life of its weapons systems. One of the key limitations in the past has been the inability to inspect beyond the boundary of the old and new materials, thereby preventing normal in-service nondestructive inspection to validate structural integrity. Implementation of REFTECH will require extensive coordinated programs for design, structural testing, advanced materials and process development, and advanced inspection technologies to realize the savings possible.