CORROSION DAMAGE TOLERANCE METHODOLOGY FOR C/KC-135 FUSELAGE STRUCTURE

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ABSTRACT

The purpose of this paper is to describe a corrosion damage tolerance procedure for assessing hidden corrosion damage in C/KC-135 fuselage skins and lap joints. Corrosion damage tolerance analysis parallels traditional fatigue crack damage tolerance analysis based on fracture mechanics. There are three fundamental elements of corrosion damage tolerance analysis. First, appropriate non-destructive inspection (NDI) procedures are required to assess the hidden corrosion damage condition in the airframe. Eddy current NDI systems can be calibrated to measure thickness loss in fuselage skin doublers and the faying surface of the lap joints. The resolution, threshold, precision and bias for measurement of corrosion thickness loss have been estimated for the MAUS IV eddy current system. Second, the corrosion damage growth rate must be known so that the future corrosion damage condition can be predicted. The rate of C/KC-135 corrosion growth at several geographic locations has been measured based on simulated fuselage lap joint coupons exposed to the corrosive environments where aircraft are commonly stationed. Finally, the critical corrosion damage condition must be known so airframe flight safety and reliability can be predicted. In contrast to traditional damage tolerance analysis where failure is by crack propagation and crack length is a well-defined measure of fatigue damage, three possible corrosion failure mechanisms for C/KC-135 fuselage structure are discussed. First, localized deep pitting that penetrates all the way through the skin has been observed in a few C/KC 135 lap joints during programmed depot maintenance (PDM). Loss of cabin pressurization could result from this type of localized corrosion damage. Second, it is possible for static yielding due to heavy corrosion damage in the lap joints to cause the skin to deflect into the airstream, resulting in loss of fuselage skin sections similar to the Aloha airlines incident of 1988. Finally, multiple site damage (MSD) in the fuselage lap joints (identified as a fundamental cause of the Aloha airlines incident) could develop in the future as fatigue cycles continue to accumulate and corrosion continues to grow. More research is needed to characterize the interactions between corrosion, MSD and fatigue cycles. This paper describes a systematic approach for assessing hidden corrosion damage in C/KC-135 fuselage skins and lap joints as a function of the environment where they are stationed.

INTRODUCTION

Structural members whose service loads are periodic experience cycle-dependent fatigue failure at stresses significantly lower than the ultimate strength. For aircraft structures, significant periodic loading occurs during take-off and landing. Other sources of fatigue cycles include cabin pressurization-depressurization, pilot-induced maneuvers and encounters with gusts. The fatigue life of an aircraft is based on the number of cycles accumulated during these cyclic loads. As fatigue cycles accumulate, damage is done to the structure by cracking in the high stress components. Modern fracture mechanics provides accurate predictions of the crack growth as a function of fatigue cycles as well as the decrease in failure stress in cracked structure. The ability of an aircraft structure to maintain adequate residual strength in a damaged condition is called damage tolerance. Durability and damage tolerance analysis (DADTA) is the process of evaluating the effect of fatigue damage on structural integrity. DADTA is invaluable in assessing the useful service life of aging aircraft.

While aircraft fatigue damage is based on the number of loading cycles, corrosion damage in aging aircraft depends on the time spent in the corrosive environment. Corrosion damage in aluminum alloys can occur by several electrochemical processes (Foley, 1986). Basic definitions of six types of corrosion were described by Wallace, et.al. (1985). Uniform corrosion refers to a localized electrolytic attack occurring consistently and evenly over the surface. Galvanic corrosion occurs when metals of different electrochemical potential are in contact in a corrosive medium. Pitting is a strongly localized attack that leads to the formation of deep and narrow cavities. Pitting is commonly observed in C/KC-135 lap joints and between skin doublers. Crevice corrosion occurs when a corrosive liquid gains access to crevices in or between components. Intergranular corrosion is a highly localized form of dissolution that affects the grain boundary regions in a polycrystalline metal. Exfoliation is a form of intergranular corrosion that attacks elongated grains in rolled material such as 7xxx series aluminum. Filiform corrosion is similar to pitting and intergranular corrosion. It starts from a corrosion pit but instead of penetrating deep into the thickness of the metal it spreads out sideways to form threadlike lines of corrosion near the surface. Filiform corrosion is often found in aluminum alloys where the initial pit will penetrate the cladding and then will be diverted by the underlying grains to run parallel with the surface in numerous meandering filaments. Filiform corrosion sometimes occurs under the paint in C/KC-135 fuselage skins. These various forms of possible corrosion damage pose a substantial challenge for NDI systems used to measure corrosion damage in the maintenance environment, especially when combined with fatigue damage.

Fatigue cracking that occurs simultaneous with corrosion is known as corrosion fatigue. Many mechanical, environmental and metallurgical variables have an effect on corrosion fatigue susceptibility (Bayoumi, 1993). The interaction between corrosion and crack growth depends on the environment where the aircraft operates and the way loading cycles are accumulated (Goswami and Hoeppner, 1995), (Mehdizadeh, et.al., 1966). Corrosion damage may be coupled with fatigue crack growth, causing complicated failure mechanisms (Brooks, et.al., 1999). During corrosion, the aluminum structural material transforms to a mixture of amorphous aluminum hydroxide [AL $(OH)_3$] and trihydrated aluminum oxide ($AL_2O_33H_2O$) (Rebbapragada, et.al., 1999). This corrosion by-product material increases volume by approximately 6.5 times the original uncorroded aluminum (Bellinger, et.al, 1994). When these corrosion by-products build up between two layers of skin, the volume increase deforms the skin structure between the rivet rows leading to a phenomenon known as skin pillowing. Skin pillowing increases the damage corrosion does to the airframe by substantially increasing the stress in the lap joint (Bellinger and Komorowski, 1999).

Early research recognized the different character of fatigue damage in the presence of corrosion. Gough (1932) defined corrosion fatigue as the formation of pits by electrochemical attack and then the spread of cracks from those pits. Numerous deep corrosion pits have been associated with crack initiation in those pits. The cracks then link up between the pits to form larger cracks. Fatigue damage is commonly modeled by the relationship between crack length and critical crack length, and sometimes by a reduction in the fatigue limit (Gough, 1932). Corrosion pits are usually assumed to be stress concentration sites and therefore crack initiation sites (Lindley, et.al., 1982). Kondo (1989) suggested three stages of corrosion fatigue in steel: pit growth, crack formation at the pit and crack propagation. He concluded that pit initiation is the dominant factor for crack initiation. Corrosion fatigue crack initiation can be characterized as a random, poorly characterized process that tends to occur at discontinuities and corrosion pits. There is synergism between corrosion and fatigue for a high-usage aircraft in a corrosive environment (Du, et.al., 1995).

The most critical component for structural integrity assessment is a validated method for the prediction of damage accumulation (Harlow, et.al., 1999). The critical issue in corrosion quantification is to identity the most probable behavior of the structure in actual service under realistic corrosion fatigue conditions (Schutz, 1995). Development of accurate and reliable corrosion damage metrics remains a fertile area of research (Brooks and Simpson, 1998), Komorowski et.al. (1998). The most difficult challenge is the requirement that corrosion damage be quantified by NDI suitable for the maintenance environment. Material thinning is the most common corrosion damage metric since it can be related directly to reduced residual strength and accelerated crack growth. Material thinning has also been applied to exfoliation in 7178-T6 aluminum (Chubb, et.al., 1995). Thickness reduction by pitting at the constituent particle sites is the most basic corrosion damage mechanism for 2024-T3 aluminum fuselage skin material (Johnson, W. K., 1971), (Chaudhuri et.al., 1992), (Chaudhuri et.al., 1994), (Burynski, et.al., 1995), (Goswami and Hoeppner, 1995), (Harlow and Wei, 1995), (Harlow and Wei, 1998), (Piascik and Willard, 1994), (Schmidt, et.al., 1995), (Richardson and Wood, 1970). Pits form in the grain structure in regions where metallurgical and environmental conditions are most favorable (Cawley and Harlow, 1996), (Laycock, et.al., 1990).

Wei and Harlow (1997) identified pitting in aluminum as a dominant mechanism for corrosion growth in an environment of 0.5M NaCl. Cathodic constituent particles (Al, Cu, Fe and Mn) dissolve the matrix while anodic particles (Al, Cu and Mg) dissolve leading to intergranular corrosion (Chen, et.al., 1996), (Burleigh, 1991). There are approximately three times more anodic particles than cathodic particles in 2024-T3 aluminum (Cawley and Harlow, 1996). The pits form in clusters because that is the way the constituent particles form. Therefore pitting does not always occur as isolated pits but frequently as clusters spread over a significant area (Chen, et. al., 1996). Aluminum pitting usually leads to thinning spread over a significant area with occasional deep pits, depending on the electrochemistry (Hoar, 1967), (Nilsen and Bardal, 1977), (Baumgartner and Kaesche, 1990).

The selection of appropriate corrosion damage metrics will be critical to the quantification of the affect of corrosion on reliability. Fracture mechanics analysis has always been required in damage tolerance analysis because airframe durability is known to be controlled by crack growth. The presence of corrosion significantly complicates fatigue damage mechanisms. Fatigue cracks may initiate from corrosion pits, and a particular size pit may form a significant risk of cracking in some alloys but not others (Hoeppner, et.al., 1995). In a description of the disassembly and inspection of a retired C/KC-135 aircraft, Groner and Nieser (1996) reported that no significant fatigue cracks were found at the corroded fuselage lap joints. Therefore, crack growth does not seem to be a suitable corrosion damage metric for the C/KC-135 airframe. Walton, et.al. (1953) reported that corrosion in aluminum alloys is more likely to spread over the surface than to penetrate deep into the thickness. Therefore, material thinning is a more relevant quantification of the effect of corrosion in C/KC-135 fuselage lap joints because it can be directly related to a stress increase in the skin. Since naturally occurring corrosion is not uniform and occurs randomly, two corrosion damage metrics are suggested for quantification of C/KC-135 fuselage lap joints. In addition to material thinning, the area affected by corrosion should be a corrosion metric. Both metrics can be measured using NDI appropriate for the maintenance environment.

The objective of this paper is to describe a corrosion damage tolerance analysis procedure for C/KC-135 fuselage structure. Corrosion damage tolerance analysis consists of three elements: (1) the hidden corrosion damage condition must be measured using appropriate NDI, (2) corrosion damage growth rate must be known and can be used to predict the future corrosion damage condition (3) the most probable critical corrosion damage conditions must be determined (Wei and Harlow, 1997), (Nieser, 2000). The MAUS IV eddy current system has been selected as the NDI procedure for fuselage hidden corrosion detection between fuselage lap joints and spot-welded doubler skins (Nieser, 2000). Therefore, the MAUS IV was used to collect the data reported in this paper. The resolution, threshold, precision and bias were determined for the MAUS IV system in order to quantify the accuracy of the measurements. Thickness loss is the assumed corrosion damage mechanism, leading to higher stress levels in the lap joints. Corrosion growth as a function of exposure time was measured in simulated lap joint coupons exposed to the corrosive environments where C/KC-135 aircraft are stationed. It is possible to predict future corrosion damage condition based on those measurements.

Three damage mechanisms are considered in this paper. First, localized deep pitting that penetrates all the way through the skin has been observed in some C/KC-135 during PDM. Loss of cabin pressurization could result from this type of damage rendering the aircraft unable to perform its mission. This kind of damage can be measured using conventional eddy current NDI procedures. Second, loss of residual strength due to heavy corrosion damage could allow static yielding to occur in the lap joints, causing the skin to deflect into the airstream. This kind of damage is more complicated than localized deep pitting because corrosion may be spread over a significant area. However, the MAUS IV system includes software tools that permit calculation of thickness loss and area of corrosion. Resultant loss of fuselage skin sections caused by corrosion spread over a significant area could jeopardize flight safety. This kind of heavy corrosion damage has been observed in C/KC-135 fuselage lap joints during PDM. The third potential corrosion damage mechanism is crack growth accelerated by material thinning and multiple site damage. C/KC-135 usage is much lower than many aging aircraft fleets, currently at approximately 20% of the design service life (Nieser, 2000). According to Brooks et.al. (2000), corrosion can have a much greater influence than crack growth in the early fatigue life of structural components. Although significant fatigue cracks are not expected until much later in the service life of the fleet, corrosion accelerated crack growth could occur much earlier than expected, increasing maintenance costs and jeopardizing flight safety. Accelerated crack growth combined synergistically with MSD and corrosion damage similar to the Aloha airlines incident of 1988 must be evaluated, but is beyond the scope of this paper.

CORROSION DAMAGE TOLERANCE

Conventional damage tolerance analysis is based on crack length predictions as a function of fatigue cycles with structural inspection intervals and maintenance actions programmed accordingly. The length of the longest crack is assumed to be just below the threshold of the inspection system, then crack growth at the next scheduled inspection is predicted based on the airframe loading cycles. Appropriate NDI is applied to the airframe at inspection intervals programmed for half the cycles necessary to grow from the minimum detectable crack length to the known critical crack length. Corrosion damage tolerance analysis parallels this process with suitable NDI used to estimate corrosion damage in the airframe at some future inspection time. Several different corrosion mechanisms occur in aircraft structure and they lead to quite different damage effects on the structure. It will be very important to analyze the structural effects of these corrosion damage mechanisms, similar to the way different crack growth mechanisms are treated in different structural members and materials. Structural assessment and NDI should complement each other for effective damage tolerance analysis (Chang, 1995). The effect of corrosion on residual strength and crack growth must be assessed in support of corrosion damage tolerance analysis (Achenbach and Thompson, 1991).

According to Goranson (1993), damage tolerance analysis is used to achieve aircraft structural operating safety based on timely damage detection. The damage detection period can be significantly reduced in the presence of corrosion, and the random nature of corrosion makes it impossible to establish typical damage growth patterns (Goranson, 1993). There are three distinct elements of equal importance for achieving the desired level of safety: allowable damage as specified by the residual strength, damage accumulation by crack growth and damage detection through an inspection program (Goranson, 1993). Accurate assessment of residual strength and crack growth based on fracture mechanics has always been critical for achieving flight safety. It will be just as critical to evaluate the residual strength and crack growth of corrosion damaged structure. This section includes detailed discussions of the three elements of corrosion damage tolerance analysis: assessment of corrosion damage by NDI, corrosion damage growth modeling and critical corrosion damage condition.

Assessment of Corrosion Damage by Non-destructive Inspection

There are a number of NDI systems available for detecting hidden corrosion and cracks in aircraft structure. The best choice of NDI system depends on the kind of structure being inspected and the type of damage expected (Kollgaard, et.al., 1999). Single frequency eddy current techniques have been used for many years to detect corrosion in single or top layer aircraft skins (O'Keefe, et.al., 1995). Multiple-frequency-mixing techniques have been explored to suppress the effects of air gaps or corrosion by-products without significantly affecting the ability to measure corrosion damage (Chevalier, 1993). Pulsed eddy current systems are being developed for multi-layered applications (Ricci, 1999), (Smith and Hugo, 2000). For C/KC-135 aircraft in programmed depot maintenance (PDM), the requirement is rapid inspection of fuselage skins and lap joints from the exterior of the aircraft and eddy current systems are best suited for that application (Howard, et.al., 1995). The MAUS IV eddy current system fulfills the requirement and will be used for C/KC-135 fuselage lap joint NDI during PDM at the Oklahoma City Air Logistics Center (Nieser, 2000).

The frequency response of eddy current probes is fundamental to accurate assessment of corrosion damage. The excitation frequency of the probe must be consistent with the thickness of the part to be inspected since the depth of penetration is proportional to inverse square root of excitation frequency. Figure 1 shows the frequency response curves of three identical probes, differing only in the serial number. All three were labeled as appropriate for frequencies between

1 and 20 kHz. Using the half power points as the common designation for bandwidth yields a frequency range of 3-12 kHz in Figure 1. This example illustrates the need for standardization of the frequency response specifications among probe manufacturers, since appropriate choice of excitation frequency is required for corrosion damage assessment.

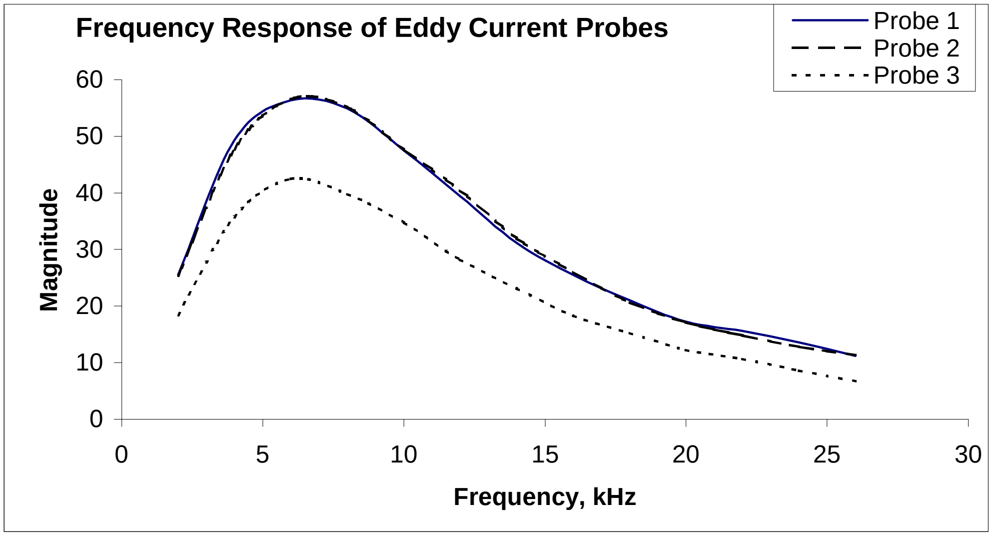
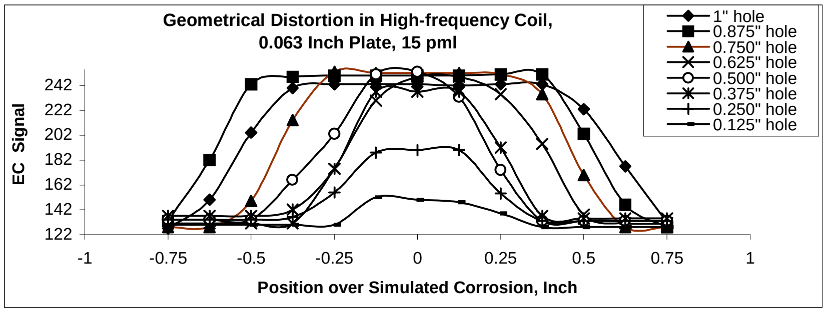


Figure 1. Frequency Response Curves of Three Eddy Current Probes Labeled as Identical by the Manufacturer

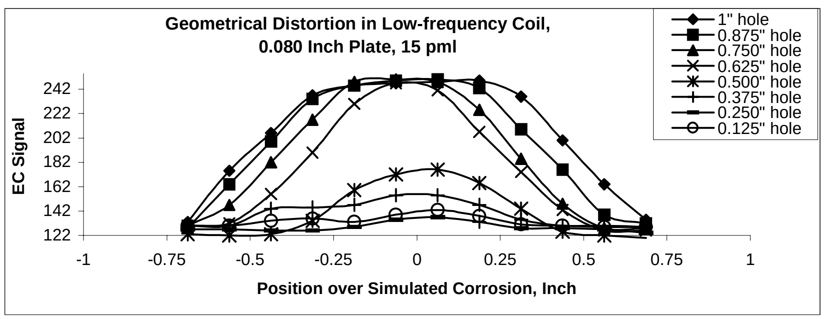
Calibration experiments on two typical eddy current probes were conducted to investigate their spatial resolution. Corrosion damage was simulated by flat bottom holes machined on the backside of aluminum plates, the same diameter but different depth. Figure 2 is a plot of signal strength as a function of position over the simulated corrosion. Both probes give an approximately trapezoidal response because they are sensitive to the volume of material in the footprint giving an average thickness loss under the footprint. The high-frequency probe in Figure 2a is smaller and therefore follows the geometry change better than the low-frequency probe. Figure 2 shows that the spatial resolution is approximately equal to the probe cross-sectional area and that the probe diameter should be small compared to the corrosion damage. However, smaller probes operating at higher frequencies are unable to penetrate as deep into the material. This is a design trade-off between the operating frequency of the probe and the desired spatial resolution.

The experiments illustrated in Figure 2 were for uniform simulated corrosion. In the field, corrosion in fuselage skin doublers and lap joints is not uniform. Corrosion between spot-welded skin doublers is most likely in smaller spots where the protective clad layer has been disturbed. This means that an isolated corrosion pit could grow all the way through the skin in some cases. Figure 2 shows that when the area of corrosion damage is smaller than the probe cross-sectional area, the response of the probe is significantly attenuated. In that case, the calibration is invalid, making it impossible to quantify the depth of small corrosion pits. Hagemaier, et.al. (1985) report that high-frequency (100-300 kHz) eddy current pencil-point probes can be used to detect very small areas of corrosion.

A series of very small holes were drilled into a 2024-T3 aluminum plate 0.040 inch thick, simulating the effect of isolated, deep corrosion pits. Figure 3 shows the results of a MAUS IV eddy current scan of the plate using the same two probes used in Figure 2. The bottom holes in each pattern were drilled all the way through the plate. The high frequency probe in Figure 3b produces a clearer scan because the probe is smaller and therefore more sensitive to smaller defects. The isolated small holes have a distinctive concentric ring pattern, with the holes all the way through the plate giving a stronger signal. When the hole diameter is less than approximately half the plate thickness, the holes cannot be detected by the eddy current system. Figure 3 demonstrates the pattern recognition capability of the MAUS IV system. Although pits smaller than the probe cross-section can not be quantified, they can be recognized by the concentric ring pattern.



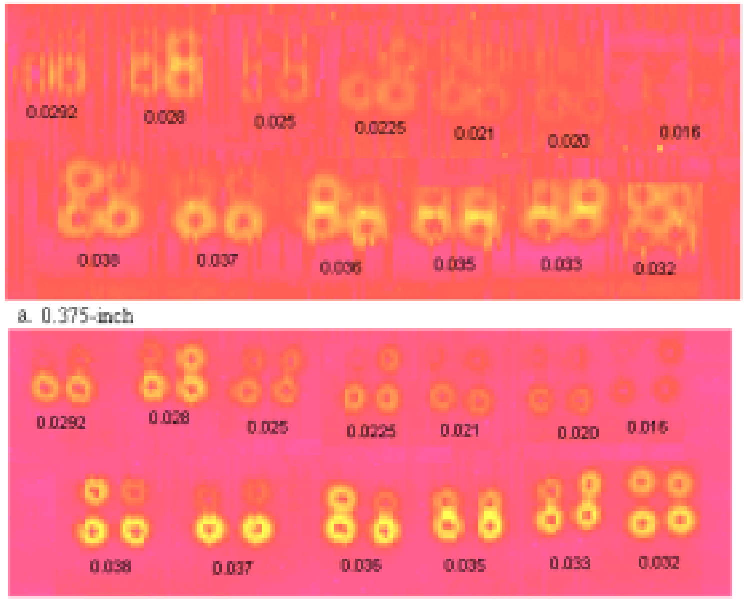
a. 0.25-inch Diameter Probe



b. 0.375-inch Diameter Probe

Figure 2. Geometric Distortion of two Eddy Current Probes. a. High-frequency Probe, 0.25-inch Diameter, b. Low-frequency Probe, 0.375-inch Diameter

It will also be necessary to quantify corrosion damage in terms of thickness loss and area of corrosion. Six measurement characteristics are commonly used to describe instrumentation systems: resolution, threshold, sensitivity, accuracy, precision and bias. When the input is slowly increased from some arbitrary nonzero value, the output will not change until a certain minimum increment, the resolution, is exceeded. When the input is gradually increased from zero, there is a minimum value below which no output change can be detected. This minimum value is the threshold. The sensitivity is the amount of output increment due to a specific input increment. The accuracy is the deviation of a particular measured quantity from the true quantity. Since the true quantity can never be known exactly in all real systems, the accuracy is usually expressed in statistical terms. The precision error is usually defined as the range over which the reading might be expected to vary with a particular predefined probability. The bias error is systematic. It is a deviation from the "true" value that is present in all the readings.



b. 0.25-inch

Figure 3. Eddy Current Scan of Corrosion Pit Simulation by Very Small Holes Drilled in a Sheet of 2024-T3(4) Aluminum, 0.040 inch Thick. a. Low-frequency Probe, 0.375-inch Diameter b. High-frequency Probe, 0.25-inch Diameter

The threshold, bias, precision and accuracy are critical measurement characteristics for estimating corrosion damage. The threshold is important because it identifies the level of corrosion that could be left in the aircraft after PDM. The bias and precision are important because they represent the statistical uncertainty of the corrosion quantification process. These measurement characteristics of the MAUS IV eddy current system have been estimated, as summarized in Table 1.

Table 1. Measurement Characteristics of Typical High-frequency Probe

Standard	Peak	Resolution	threshold	Bias error	Precision error	Statistical error
1	65.55%	0.31%	8.53%	0.98%	1.58%	0.18%
2	58.15%	0.26%	10.04%	1.12%	1.60%	0.18%
3	60.83%	0.31%	9.02%	1.84%	1.82%	0.21%
4	63.98%	0.36%	6.04%	1.88%	3.80%	0.44%
5	56.26%	0.29%	9.25%	0.59%	3.56%	0.41%
6	57.22%	0.27%	11.80%	1.30%	6.30%	0.73%
7	42.46%	0.19%	10.72%	0.94%	2.93%	0.34%
8	69.85%	0.40%	3.81%	0.97%	1.96%	0.23%
9	51.61%	0.26%	9.18%	0.62%	4.34%	0.50%

Table 1 shows the results of thirty MAUS IV eddy current scans completed on nine calibration standards. The statistical error is approximately an order of magnitude lower than the precision error in Table 1. The peak value is listed because it reflects the gain setting in the MAUS IV calibration procedure. The average threshold of all nine calibration standards is approximately nine percent. For this particular gain setting, corrosion less than approximately nine percent could not be detected. However, since the calibration is linear changing the gain so that the peak value is approximately 15 percent will reduce that threshold to about two percent. There is a bias error because of the uncertainty in the null reading. The precision error is the variation between readings. The data summarized in Table 1 can be used to identify the threshold and error bars for MAUS IV eddy current thickness loss measurements.

Since the measurement characteristics depend on the gain setting of the MAUS IV, it will be very important to set the gain appropriate to the corrosion damage expected. Figure 4 shows a simulated lap joint coupon scanned with two different gain settings. Figure 4b shows a large saturation region (areas in black), indicating the probe gain is too high. Reducing the gain setting produces the image in Figure 4a, suitable for quantitative analysis of thickness loss. In a realistic application, it may be required to scan more than one time with different gain settings in order to produce accurate results. The recommended application is to set the gain so the MAUS scan detects just those corrosion damage conditions known to be critical to the airframe. Those locations can then be scanned with modified gain settings for more accurate quantification.

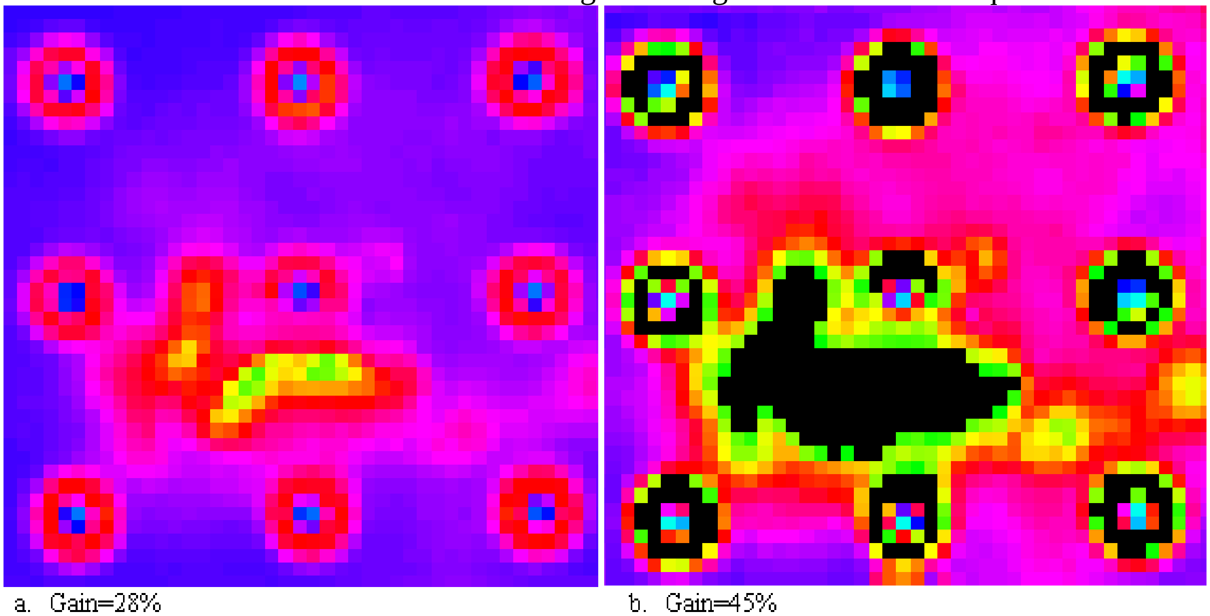


Figure 4. MAUS IV Eddy Current Scan of a Simulated Lap Joint Coupon Showing the Effect of Gain Setting

To summarize, it will be very important to select the most appropriate eddy current probe for NDI of fuselage skins and lap joints. Smaller probes reduce geometric distortion but do not penetrate as deep into the fuselage skin. For inspection of several layers, engineering judgement is required in a trade-off between required penetration depth and acceptable geometric distortion. The frequency response of eddy current probes must be known in order to select the best probe for each application. The threshold, bias, precision and accuracy of the MAUS IV eddy current NDI system were estimated so that corrosion damage can be quantified. Presently, material thinning and area affected by corrosion are the best corrosion damage metrics for C/KC-135 fuselage structure. Evaluation of these two metrics is currently underway. Better corrosion damage metrics will require better NDI procedures and both remain the subject of significant ongoing research. Corrosion damage growth modeling is the next corrosion damage tolerance element to be described, given in the next section.

Corrosion Damage Growth Modeling

Natural corrosion occurring in service is difficult to reproduce in the laboratory (Shutz, 1995). Therefore, simulated C/KC-135 fuselage lap joint coupons have been exposed to the corrosive environment where the aircraft are commonly stationed as part of a research project to determine the environment-dependent corrosion growth rate (Nieser, 2000). The final result of that ongoing research project will not be available for several more years, but preliminary results are described here. Corrosion grows at a rate that depends primarily on the environment where the aircraft are stationed, while crack growth depends primarily on the airframe load history. Corrosion damage growth rate in the aircraft operational environment must be identified in order to predict corrosion damage in the future.

Proper evaluation of the data collected from the corroded lap joint coupons requires knowledge of the basic physics of corrosion growth. Corrosion growth depends on the electrochemistry of the environment and the metallurgical properties of the aircraft structural material. A power law mathematical model for corrosion growth in aluminum alloys has been used by several researchers (Aziz and Godard, 1952), (Godard, 1960), (Johnson, 1971), (Rowe, 1976), (Hoeppner, 1979), (Harlow and Wei, 1995). The power coefficient ranges between 0.3 and 0.5 (Kawai and Kasai, 1985), (Turnbull, 1993). The pitting current has been related to the pit radius for stainless steels, with a power law exponent of 0.5 (Rosenfeld and Danilov, 1967). The equation for thickness loss as a function of exposure time is:

$$h = A\left(t - t_{in}\right)^q, \qquad t > t_{in} \qquad (1)$$
$$0 \text{ otherwise}$$

The thickness loss is h, A and q are parameters determined by power law regression analysis and t_{in} is the induction period. An induction period is frequently observed in natural corrosion growth processes (Gough, 1932), (Godard, 1960), (Dallek and Foley, 1978), (Sato, 1982b). During this induction period no corrosion is observed to grow, perhaps due to an oxide film or clad layer that must be penetrated on the surface of the alloy (Nguyen and Foley, 1979) or because the potential is below the critical pitting potential (Sato, 1982a). The induction time has been quantified as the time required to produce an appreciable anodic current at a given anodic potential (Hoeppner and Chandrasekaran, 1998). Most metals will form a very thin surface oxide film at low humidity (Wallace, et.al., 1985). This oxide film is usually protective and significant corrosion will not occur until a critical level of humidity (about 60% relative humidity) is reached. The time of wetness is significant because it represents the time during which exposed non-conducting surfaces are sufficiently wet to allow the passage of an electric current.

There is experimental evidence to show that 7075 aluminum follows the cube-root rule when pitting is controlled by the concentration of halide ions (Dallek and Foley, 1978). Atmospheric exposure of aluminum alloys shows results that are consistent with a power low growth model (Walton and King, 1955), (Carter, 1968), (McGeary, et.al., 1968). There is mechanistic evidence to support the cube root growth model (Wei and Harlow, 1993). Harmsworth (1961) investigated the effect of corrosion pitting on fatigue lives of rotating beam 2024-T4 aluminum specimens exposed to a salt solution. He measured the depth of the deepest pit on the fracture surface and showed pit depth as a function of exposure time. His data are plotted in Figure 5 along with a cube-root-time curve fit. Confidence intervals can be established using statistical analysis procedures described in any good undergraduate probability and statistics textbook (Walpole, et.al., 1998). Ninety- percent confidence intervals are shown in Figure 5 based on a linear regression of $\sqrt[3]{\text{time}}$. The power law regression curve and confidence intervals are consistent with the data.

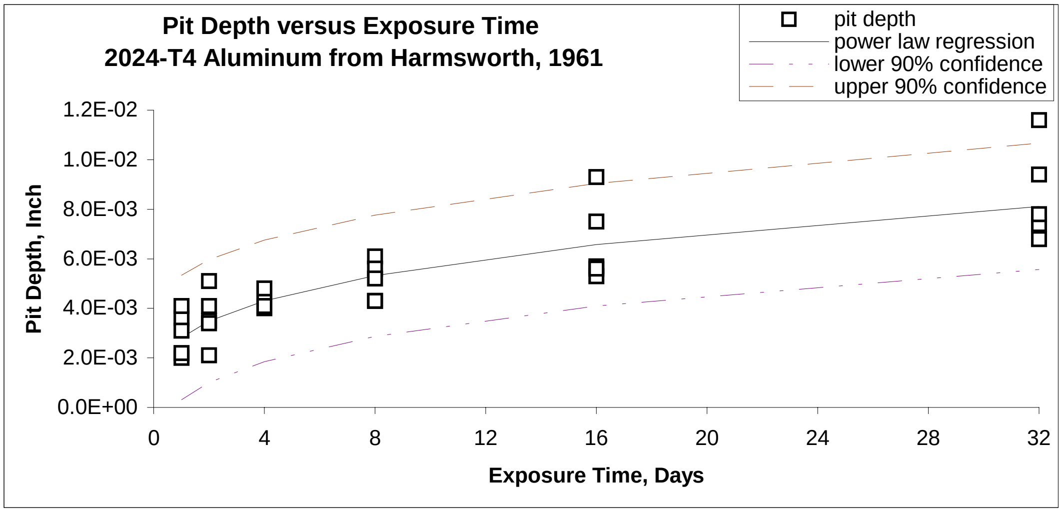


Figure 5. Pit growth in 2024-T4 Aluminum versus Exposure Time in 20 percent NaCl Solution at 95 F. Data from Harmsworth (1961).

Accelerated laboratory corrosion experiments in a salt solution, illustrated in Figure 5, have been conducted by numerous researchers because they are a valuable way to identify the corrosion growth model. However, corrosion damage tolerance analysis requires knowledge of natural corrosion in the environment where the aircraft are stationed.

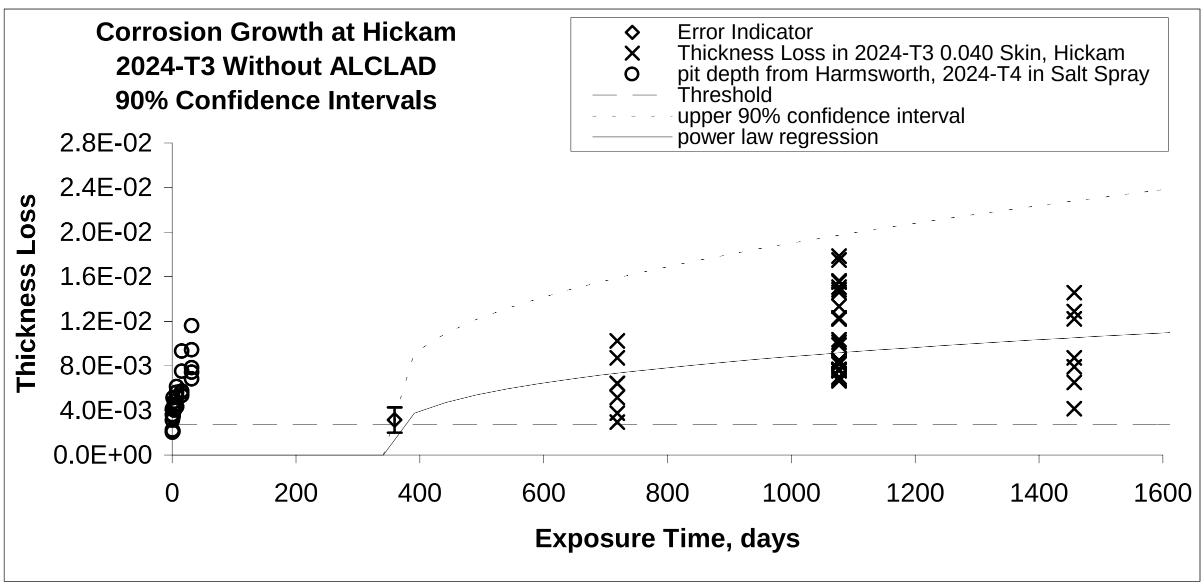


Figure 6. Corrosion Thickness Loss in 2024-T4 Aluminum (Harmsworth, 1961) and 2024-T3 Aluminum Fuselage Lap Joint Coupons at Hickam AFB Hawaii, Protective ALCLAD Layer Removed versus Exposure Time

Figure 6 shows some preliminary results of 2024-T3 aluminum simulated fuselage lap joints with the ALCLAD layer removed, exposed to the environment near the runway at Hickam AFB, Hawaii. Thickness loss was measured using MAUS IV eddy current scans. The MAUS IV histogram tools were used to calculate the hidden thickness loss at selected points on the coupons, with the results plotted in Figure 6. Figure 6 also shows Harmsworth's (1961) laboratory corrosion data superimposed with the natural corrosion growth results, validating the value of accelerated laboratory corrosion studies and showing that the MAUS IV eddy current measurements are reasonable. Although Harmsworth (1961) experimented with 2024-T4 aluminum, the composition is identical to 2024-T3. The difference between the two alloys is the heat treatment. Figure 6 is also consistent with corrosion growth results reported by Ailor (1968). Figure 6 shows the upper 90% confidence interval along with threshold and error estimates of the MAUS IV eddy current system. An induction time between 300 and 360 days is indicated in Figure 6. Coupons exposed for one year show negligible evidence of corrosion, providing experimental verification for the induction time. Future research will measure the corrosion by independent means and validate the MAUS IV results of Figure 6.

The power law regression in Figure 6 depends on the induction time. More data are required to identify the exponent of the power law relationship. There is significant scatter in the data, suggesting a probabilistic analysis of corrosion growth. The accelerated corrosion growth illustrated in Figure 6 shows how corrosion would grow in C/KC-135 lap joints after the protective ALCLAD layer has been penetrated. Given the estimated corrosion damage condition after PDM (NDI detection threshold) and the expected corrosion growth rates in the operational environment, the corrosion damage condition in the future can be predicted. The last element of corrosion damage tolerance analysis is the critical corrosion damage condition, discussed in the next section.

Critical Corrosion Damage Condition

The critical corrosion damage condition is the level of corrosion damage to the airframe such that either the aircraft is no longer able to accomplish its mission or flight safety is jeopardized. Three possible critical corrosion damage conditions for C/KC-135 fuselage structure are proposed in this paper. Two of the three have been observed in C/KC-135 during PDM. First, cabin pressurization could be lost due to localized deep pits that penetrate all the way through the skin. Second, widespread corrosion damage could be severe enough so that lap joints fail by static yielding and cause the skin to deform into the airstream. Such an event could result in portions of the fuselage skin being torn off in flight, similar to the Aloha airlines incident of 1988. This level of corrosion severity in the lap joints has been observed in some C/KC-135 aircraft during PDM. Finally, material thinning over a large area could cause accelerated crack growth. Since the C/KC-135 fleet is currently at about 20% of the design fatigue cycles, this damage condition has not been observed in C/KC-135 aircraft. It may occur in the future as more fatigue cycles accumulate, influenced by corrosion. Engineering judgement is required to decide which of these critical damage conditions is most likely depending on the location of the corrosion on the airframe, accumulated fatigue cycles on the airframe, aircraft usage and the severity of the corrosive environment where the aircraft are stationed.

In some cases, corrosion damage in the C/KC-135 has been severe enough to penetrate all the way through the skin thickness (Nieser, 2000). Using the corrosion damage growth data of Figure 6 as an example, the predicted time to penetrate all the way through fuselage skin 0.040 inch thick should be based on the upper confidence interval of the corrosion growth. Since the 90% confidence intervals are used, the predicted time to failure is interpreted as the time such that 10% of the pits would be expected to penetrate through a 0.040-inch skin.

$$t_f = \left(\frac{h - h_{th}}{A} \right)^{1/q} + t_{in} \qquad (2)$$

Equation 2 is the inverse of equation 1. Undetected corrosion below the threshold of the NDI equipment is assumed initially. The estimated time to failure is t_f and the threshold of the NDI system is h_{th}. The remaining parameters h, A, q and t_{in} are the same as in equation 1. Table 2 shows a comparison of three possible values of the power parameter, q.

Table 2. Evaluation of Corrosion Growth Models Based on Data for 2024-T3 Aluminum

q	A	t_{in}	t_f (days)
0.333	1.019E-03	341.2	5,191
0.448	4.648E-04	300.0	3,500
0.500	3.223E-04	271.0	3,171

Since the induction time is not known, three reasonable values have been estimated in Table 2. Each different induction time gives different regression parameters, A and q. The cube root form of the hemispherical pit growth function is intuitively pleasing since the pit depth would be proportional to cube root of volume and the volume is proportional to exposure time (Johnson, 1971). Dallek and Foley (1978) offered experimental evidence for hemispherical pits in 7075 aluminum. Table 2 illustrates how corrosion damage tolerance could be used to predict pit penetration through the skin leading to loss of cabin pressurization. Assuming the CLAD layer has been penetrated, between 3171 and 5191 days at Hickam would be expected to cause ten percent of the pit population to penetrate through the skin.

There is a significant variation in the predictions of critical thickness loss for the three different induction time estimates, although all of them are a good curve fit to the data in Figure 6. It will be very important to collect enough corrosion growth data covering sufficiently long exposure time to estimate the corrosion growth model parameters. Long exposure times are usually required in atmospheric exposure tests (Lifka and Sprowls, 1974). Figure 6 shows corrosion growth in lap joint coupons with the protective ALCLAD layer removed to permit accelerated growth data. The C/KC-135 fuselage skins were originally made from 2024-T3 aluminum sheet with ALCLAD. For ALCLAD-covered specimens, it takes a long time for the corrosion to penetrate the ALCLAD layer. This is to be expected, since the purpose of the ALCLAD layer is to prevent corrosion. Most of the ALCLAD specimens evaluated so far show negligible evidence of corrosion up to four years of exposure. Therefore, it will take several years to get enough data from the corrosion growth test sites around the world to estimate corrosion growth as the aircraft experiences it (Nieser, 2000).

The thickness of the ALCLAD layer is below the threshold of the MAUS IV eddy current NDI system in many cases. Therefore, it is possible for a small pit that has penetrated the ALCLAD layer to be undetected during PDM. The calculations in Table 2 illustrate a reasonable engineering estimate of the time required for a pit that has penetrated the ALCLAD layer to grow through the skin in C/KC-135 aircraft stationed at Hickam AFB, Hawaii.

The growth of isolated pits is a basic critical damage condition that can be analyzed using knowledge already available. Widespread corrosion damage causing reduction of residual strength requires additional analysis, currently ongoing. Isolated deep pits only require one corrosion damage metric, thickness loss. Widespread corrosion damage in the lap joints will require two corrosion damage metrics, thickness loss, and area of corrosion. Residual strength data on simulated C/KC-135 fuselage lap joint coupons will yield valuable information to validate the corrosion metrics and identify failure modes with heavily corroded parts. However, additional analysis is required to investigate the effects of pillowing and widespread corrosion. When corrosion occurs as an isolated deep pit, the residual strength of the lap joint is probably not significantly impacted although decompression could occur. When corrosion causes a significant thickness loss spread over a large area, widespread corrosion damage is indicated and loss of residual strength is more likely. More research is needed to complete the analysis of this critical corrosion damage condition.

Material thinning in the C/KC-135 fuselage skins and lap joints could synergistically impact accelerated crack growth and multiple site damage (Swift, 1993). Although accelerated crack propagation because of corrosion damage in C/KC-135 fuselage structure is not expected soon, it may occur sooner than expected. Accumulated fatigue cycles in the C/KC-135 fleet are currently only about 20% of design service life (Nieser, 2000). Steadman, et.al. (1999) report that fleet inspection for MSD may be necessary as early as 50% design service goal. There is also a significantly reduced interval between the detection and critical condition of MSD cracks. If corrosion damage synergistically accelerates crack growth, crack growth may become a critical corrosion damage condition before the C/KC-135 fleet is retired.

Corrosion damage tolerance analysis has the potential to reduce maintenance costs and improve flight safety in the C/KC-135 fleet by reducing missed corrosion after PDM and improving accuracy of hidden corrosion indicators. MAUS IV eddy current inspection of fuselage lap joints along with an appropriate corrosion quantification post processor will identify hidden corrosion and quantify its severity. Appropriate quantification of corrosion damage will give engineers information they can use to decide whether corrosion is bad enough to require skin replacement. In some cases, when the corrosion growth rate is known to be low, it may be best to leave the corrosion in place as long as it does not challenge the structural integrity of the aircraft. There are a number of technical challenges that must be addressed in order to transfer corrosion damage tolerance into practice, described in the next section.

TECHNICAL CHALLENGES AND PLANNED RESEARCH

Three essential technologies must be developed to formulate a corrosion damage tolerance methodology for C/KC-135 fuselage structure. The MAUS IV eddy current system can be used to quantify thickness loss and area of corrosion damage. However, thickness loss and area of corrosion alone are inadequate corrosion metrics. The influence of corrosion damage on structural durability must be determined. The first essential technology that must be developed is to fully characterize the effect of corrosion damage on structural durability. Second, corrosion growth as a function of geographical location must be fully developed in ALCLAD specimens and in all of the six geographical locations. Preliminary results on bare 2024-T3 aluminum are encouraging, but longer exposure times on ALCLAD specimens are needed to approximate the C/KC-135 fuselage skin structure. Finally, more research is needed to accurately predict when corrosion will increase the danger of MSD. Table 3 summarizes planned and in-progress tasks by OC-ALC in support of corrosion damage tolerance development.

Table 3 does not include research to identify appropriate corrosion damage metrics. Corrosion damage metrics remains the subject of significant on-going research. Although thickness loss and area of corrosion are the most common metrics, other effects will be important. Brooks and Simpson (1998) and Brooks et.al. (1998) have investigated several possible corrosion damage metrics, including general thickness loss, accelerated crack growth, stress corrosion cracking, pitting and pillowing. Natural corrosion causes a non-uniform thickness loss, so stress concentration is expected. For small areas of corrosion, flaw volume has been suggested as a better corrosion metric (Howard and Mitchell, 1995). Koch (1995) developed a geometric model of corrosion assuming that corrosion can be treated as a combination of a general thickness reduction and a local stress concentration. Doerfler et.al. (1994) suggested that corrosion damage could be quantified by thickness loss and stress concentration from pitting, and modeled the deepest pit as an equivalent initial flaw for crack growth purposes. Scheuring and Grandt (1999) proposed a two-parameter corrosion damage metric. They assumed that the stress raiser causes crack initiation sites at the deepest pits. They used the equivalent initial flaw size (EIFS) to model this effect. The concept of EIFS is based on characterization of statistics of defects in rivet holes that are too small to be detected by NDI. There are two problems with EIFS as a corrosion damage metric for the C/KC-135 fleet. It can not be measured using NDI suitable in the maintenance environment and the effect of corrosion on EIFS is not known. It will be very important to evaluate future corrosion damage metrics against C/KC-135 PDM requirements.

Table 3. Research Projects Needed to Fully Develop Corrosion Damage Tolerance Analysis for C/KC-135 Fuselage Structure

Project	Status	Contribution
Chemical analysis of corrosion by-products and atmospheric data at geographic locations	Ongoing	Correlate damage analysis in fuselage lap joint coupons with atmospheric corrosivity variables
Corrosion damage growth rate as a function of geographic location	Ongoing	Thickness loss vs. exposure time in geographic locations where C/KC-135 are commonly stationed
MAUS IV eddy current corrosion damage quantification post-processor	Completion summer 2001	Measure hidden corrosion thickness loss in C/KC-135 fuselage lap joints
Residual strength correlation to thickness loss	In planning	Estimate residual strength in C/KC-135 fuselage lap joints with hidden corrosion damage
Crack Growth correlation to thickness loss	Recommended by the author	Estimate crack growth in C/KC-135 corrosion damaged fuselage lap joints

The most critical component for structural integrity assessment is a validated method for the prediction of damage accumulation (Harlow, et.al., 1999). It has been known for a long time that even slight corrosion simultaneous with fatigue significantly decreases fatigue life (McAdam, 1928). The number of fatigue cycles required for crack initiation decreases by a factor of two or three when corrosion pits are present (Pao, et.al., 1999). The threshold stress intensity also decreases by about fifty percent in the presence of corrosion pits. Severe corrosion regions may tunnel into the matrix of the material beneath the surface leading to significantly more complicated damage than simple thinning (Rowe, 1976). Finally, corrosion pillowing is known to significantly increase the stress in fuselage lap joints (Bellinger and Komorowski, 1996).

Most researchers assume that crack growth is the corrosion fatigue damage mechanism and that cracks grow from some corrosion-induced flaw (Koch, 1995), (Brooks, et.al, 1999). In the presence of corrosion, small cracks may grow much faster than large cracks (Dolley and Wei, 1999). In addition, the effect of corrosion on widespread fatigue damage (WFD) is not known. WFD is a very dangerous condition in aging aircraft characterized by multiple cracking that decreases the airframe residual strength below the damage tolerant requirement. Swift (1993) described two types of WFD. First, multiple site damage (MSD) is characterized by simultaneous cracks in the same structural element. Second, the presence of fatigue cracks in adjacent structural elements is called multiple element damage. Multiple site damage is characteristic of fuselage structures and multiple element damage is characteristic of wing structures.

MSD coupled with material thickness reduction by corrosion leads to a dangerous scenario (Chen, et.al, 1999). The critical crack length with MSD decreases and the crack growth rate also increases (Schmidt, et.al, 1999). MSD might reduce residual strength and critical crack length substantially (Goranson, 1997). The nature of corrosion damage accumulation in fuselage lap joints suggests a fundamentally different character of the crack population. Traditional deterministic damage tolerance analysis is based on a single crack, usually assumed the largest crack. Corrosion damage accumulation occurs randomly. Since corrosion pits are a site for crack initiation, corroded materials with many corrosion pits would likely have many cracks initiating (Pao, et.al., 1999). Some of the corrosion pits or cracks may link up to form larger damage regions (Harlow, et.al., 1999).

MSD influenced by corrosion damage may occur in the C/KC-135 fuselage lap joints as the airframes continue to accumulate fatigue cycles (Schmidt and Brandecker, 1992). The possibility of MSD is a significant technical challenge to NDI systems. MSD could occur with very small cracks under rivet countersinks in lap joints (Piascik and Willard, 1997). This will require NDI systems to detect much smaller cracks in the presence of corrosion and under the rivet heads in lap joints. NDI equipment needs to have significantly higher probability of detection an order of magnitude smaller than current practice. Furthermore, NDI equipment needs to provide information on size, location and geometry of damage. Cracks on the order of one or two mm (0.040 to 0.080 inch) might degrade the fail-safe capability of the airframe (Lincoln, 1997). Therefore, NDI systems must be capable of detecting very small cracks in the presence of corrosion for airframes that have accumulated a lot of fatigue cycles (Hagemaier, et.al., 1997), (Hagemaier and Kark, 1997).

CONCLUSIONS

The three parts of corrosion damage tolerance for C/KC-135 fuselage structure have been described. The MAUS IV eddy current system has been selected by the Air Force as the NDI tool for detecting hidden corrosion during programmed depot maintenance. Thickness loss and area of corrosion in the lap joint can be measured, but more work is needed to relate those measurements to structural durability assessment. Corrosion damage growth rate is being measured at six locations where C/KC-135 are commonly stationed. Once these measurements are completed, it will be possible to predict the corrosion damage condition in the future. It will be critical to keep this research project funded for several more years so that sufficient data can be collected to accurately predict future corrosion damage growth. Finally, the most probable critical corrosion damage condition must be known.

Three possible critical damage conditions have been suggested in this paper. Localized deep pit growth that penetrates all the way through the fuselage skin has been observed in some C/KC-135 aircraft during PDM. This kind of corrosion damage could cause loss of cabin pressurization. Static yielding in the fuselage lap joints due to widespread corrosion damage could occur, causing the skin to deflect into the airstream. Resultant loss of fuselage skin sections could jeopardize flight safety. Such widespread corrosion damage has been observed in some C/KC-135 aircraft during PDM. Finally, accelerated crack propagation caused by material thinning could cause multiple site damage later in the service life of the C/KC-135 fleet. The synergy between corrosion damage, fatigue cycles and multiple site damage must be understood. Thickness loss and area of corrosion are the corrosion metrics currently supportable by NDI. More work is needed to develop additional corrosion metrics and corresponding NDI systems.

Acquiring realistic corrosion fatigue specimens quickly and in sufficient quantities to support fatigue and residual strength testing is a severe limitation. Accelerated corrosion grown in the laboratory can supply large quantities of specimens, but they may not replicate the natural corrosion that occurs in the aircraft. Natural corrosion in specimens exposed to environments where the aircraft must operate replicates the natural corrosion that occurs in the aircraft, but several years are required to produce significant corrosion intensity and insufficient specimen quantities are produced. Future research is needed to develop techniques capable of producing large quantities of accelerated corrosion specimens that replicate the corrosion patterns observed in the aircraft.

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REFERENCES

Achenbach, J. D. and D. O. Thompson, “Towards Quantitative Non-destructive Evaluation of Aging Aircraft,” Structural Integrity of Aging Aircraft, Proceedings of Structural Integrity of Aging Airplanes, Atlanta, 20-22 March 1990, Atluri, S. N., S. G. Sampath and P. Tong (Eds.), Springer Verlag, Berlin 1991, pp. 263-273.

Ailor, W. H., Jr., “Performance of Aluminum Alloys at Other Test Sites,” *Metal Corrosion in the Atmosphere*, ASTM STP 435, American Society for Testing and Materials, pp. 285-307, 1968.

Aziz, P. M. and H. P. Godard, “Pitting Corrosion Characteristics of Aluminum,” *Industrial and Engineering Chemistry*, Vol. 44, No. 8, 1952, pp. 1791-1795.

Baumgartner, M. and H. Kaesche, “Aluminum Pitting in Chloride Solutions: Morphology and Pit Growth Kinetics,” *Corrosion Science*, Vol. 31, 1990, pp. 231-236.

Bayoumi, M. R., “Fatigue Behaviour of a Commercial Aluminum Alloy in Sea Water at Different Temperatures,” *Engineering Fracture Mechanics*, Vol. 45, No. 3, pp.297-307, 1993.

Bellinger, N. C. and J. P. Komorowski, “Environmentally Assisted Cracks in 2024-T3 Fuselage Lap Joints,” The Third Joint FAA/DoD/NASA Conference on Aging Aircraft, 20-23 September 1999, Albuquerque NM.

Bellinger, N. C. and J. P. Komorowski, “Implications of Corrosion Pillowing on the Structural Integrity of Fuselage Lap Joints,” Proceedings of the FAA-NASA Symposium on the

Continued Airworthiness of Aircraft Structures, Report no. DOT/FAA/AR-97/2, II, 28-30 August 1996, Atlanta, GA.

Bellinger, N. C., S. Krishnakumar and J. P. Komorowski, “Modeling of Pillowing Due to Corrosion in Fuselage Lap Joints,” *Canadian Aeronautics and Space Journal*, Vol. 40, No. 3, pp. 125-130, September 1994.

Brooks, C. L., K. Honeycutt and S. Prost-Domsky, “Case Studies for Life Assessments with Age Degradation,” Fourth Joint DoD/FAA/NASA Conference on Aging Aircraft, May 2000, St. Louis Mo.

Brooks, C. L, D. Peeler, K. T. Honeycutt and S. Prost-Domasky, “Predictive Modeling for Corrosion Management: Modeling Fundamentals,” Proceedings of the Third Joint FAA/DoD/NASA Conference on Aging Aircraft, 20-23 September 1999, Albuquerque NM.

Brooks, C. L. and D. Simpson, “Integrating Real Time Age Degradation Into the Structural Integrity Process,” Proceedings, NATO RTO’s Workshop 2 on Fatigue in the Presence of Corrosion, Corfu, Greece, October 1998.

Brooks, C. L., S. Prost-Domasky and K. Honeykutt, “Corrosion is a Structural and Economic Problem: Transforming Metrics to a Life Prediction Method,” Proceedings, NATO RTO’s Workshop 2 on Fatigue in the Presence of Corrosion, Corfu, Greece, October 1998.

Burleigh, T. D., “The Postulated Mechanisms for Stress-Corrosion Cracking of Aluminum Alloys – A Review of the Literature 1980-1989,” *Corrosion*, Vol. 47, No. 2, February 1991, p.89.

Burynski, R. M., Jr., G.-S. Chen and R. P. Wei, “Evolution of Pitting Corrosion in a 2024-T3 Aluminum Alloy," ASME AD-Vol. 47, Structural Integrity in Aging Aircraft, Proceedings of ASME Winter Annual Meeting, San Francisco, CA, 1995.

Carter, V. E., “Atmospheric Corrosion of Aluminum and Its Alloys: Results of Six-Year Exposure Tests,” *Metal Corrosion in the Atmosphere*, ASTM STP 435, American Society for Testing and Materials, pp. 257-270.

Cawley, N. R. and D. G. Harlow, “Spatial Statistics of Particles and Corrosion Pits in 2024-T3 Aluminum Alloy,” *Journal of Material Science*, Vol. 31, pp. 5127-5134, 1996.

Chang, J. C. I., “Aging Aircraft Science and Technology Issues and Challenges and USAF Aging Aircraft Program,” ASME AD-Vol. 47, Structural Integrity in Aging Aircraft, Proceedings of ASME Winter Annual Meeting, San Francisco, CA, 1995.

Chaudhuri, J., Y. M. Tan, V. Gondhalekar and K. M. Patni, “Comparison of Corrosion-Fatigue Properties of Precorroded 6013 Bare and 2024 Bare Aluminum Alloy Sheet Materials,” *Journal of Materials Engineering Performance*, Vol. 3, pp. 371-377, 1994.

Chaudhuri, J., Y. M. Tan, K. M. Patni and A. Eftekhari, “Comparison of Corrosion-Fatigue Properties of 6013 Bare, Alclad 2024 and 2024 Bare Aluminum Alloy Sheet Materials,” *Journal of Materials Engineering Performance*, Vol. 1, pp. 91-96, 1992.

Chen, C.-S., P. A. Wawrzynek and A. R. Ingraffea, “Residual Strength Prediction in KC-135 Fuselages and Curvilinear Crack Growth Analysis in Narrow Body Fuselages,” The Third Joint FAA/DoD/NASA Conference on Aging Aircraft, 20-23 September 1999, Albuquerque NM.

Chen, G.-S., M. Gao and R. P. Wei, “MicroConstituent Induced Pitting Corrosion in a 2024-T3 Aluminum Alloy,” *Corrosion*, Vol. 52, pp. 8-15, 1996.

Cherry, M. C., S. Mall, M. B. Heinimann and A. F. Grandt, Jr., "Residual Strength of Unstiffened Aluminum Panels with Multiple Site Damage," *Engineering Fracture Mechanics*, Vol. 57, No. 6, pp. 701-713, 1997.

Chevalier, W. D., "Dual Frequency Eddy Current Testing for Second Layer Corrosion," presented to the 1993 ATA NDT Forum, Scottsdale Plaza Resort.

Chubb, J. P., T. A. Morad, B. S. Hockenhull and J. W. Bristow, "The Effect of Exfoliation Corrosion on the Fracture and Fatigue Behavior of 7178-T6 Aluminum," *International Journal of Fatigue*, Vol. 17, No. 1, pp. 49-54, 1995.

Cope, D., "Corrosion Damage Assessment Framework," Corrosion/ Fatigue Effects on Structural Integrity, USAF Contract No. F9603-97-C-0349, Subcontract NCI-USAF-9128-001, August 1998.

Dallek, S. and R. T. Foley, "Propagation of Pitting on Aluminum Alloys," *Journal of the Electrochemical Society*, Vol. 125, No. 5, 1978, pp. 731-733.

Dawicke, D. S., J. C. Newman, Jr., J. H. Starnes, Jr., C. A. Rose and R. D. Young, "Residual Strength Analysis Methodology: Laboratory Coupons to Structural Components," The Third Joint FAA/DoD/NASA Conference on Aging Aircraft, 20-23 September 1999, Albuquerque NM.

Doerfler, M. T., A. F. Grandt, Jr., R. J. Bucci and M. Kulak, "A Fracture Mechanics Based Approach for Quantifying Corrosion Damage," Proceedings of the 1994 Tri-Service Conference On Corrosion, Orlando, Florida, 1994, p. 433.

Dolley, E. J. and R. P. Wei, "The Effect of Frequency on Chemically Short-Crack Behavior and its Impact on Fatigue Life," The Third Joint FAA/DoD/NASA Conference on Aging Aircraft, 20-23 September 1999, Albuquerque NM.

Du, M. L., F. P. Chiang, S. V. Kagwade and C. R. Clayton, "Synergism Between Corrosion and Fatigue of AL2024-T3 Alloy," ASME AD-Vol. 47, Structural Integrity in Aging Aircraft, Proceedings of ASME Winter Annual Meeting, San Francisco, CA, 1995.

Foley, R. T., "Localized Corrosion of Aluminum Alloys – A Review," *Corrosion*, Vol. 42, pp.277-288, 1986.

Godard, H. P., "The Corrosion Behavior of Aluminum in Natural Waters," *Canadian Journal of Chemical Engineering*, Vol. 38, p. 167, Oct. 1960.

Goranson, U. G., "Structural Airworthiness Initiatives," Plenary Session on Industry and Government Perspectives," 1st Joint DoD/FAA/NASA Conference on Aging Aircraft, Ogden, UT, July 1997.

Goranson, U. G., "Damage Tolerance – Facts and Fiction," *Durability and Structural Integrity of Airframes*, Vol. I, Proceedings, 17th Symposium of the International Committee on Aeronautical Fatigue, A. F. Blom, Ed., Stockholm, Sweden, pp. 3-105, June 1993.

Goswami, T. K. and D. W. Hoeppner, "Pitting Corrosion Fatigue of Structural Materials," ASME AD-VOL. 47, Structural Integrity in Aging Aircraft, Proceedings of ASME Winter Annual Meeting, San Francisco, CA, 1995.

Gough, H. J., "Corrosion Fatigue of Metals," *Journal of the Institute of Metals*, Vol. 49, No. 2, pp. 17-92, 1932.

Gruff, J. J. and J. G. Hutcheson, "Effects of Corrosive Environments on Fatigue Life of Aluminum Alloys under Maneuver Spectrum Loading," AFFDL TR 70-144, Proceedings of the Air Force Conference on Fatigue and Fracture of Aircraft Structures and Materials, Miami Beach, Florida, 15-18 December 1969.

Hagemaier, D., B. Jappe, D. Wilson and N. Wood, “Improved NDI Techniques for Aircraft Inspection,” Proceedings of the First Joint DoD/FAA/NASA Conference on Aging Aircraft, 8-10 July 1997, Ogden, Utah.

Hagemaier, D., and G. Kark, “Eddy Current Detection of Short Cracks Under Installed Fasteners,” *Materials Evaluation*, January 1997.

Hagemaier, D. J., A. H. Wendelbo and Y. Bar-Cohen, “Aircraft Corrosion and Detection Methods,” *Materials Evaluation*, Vol. 43, pp. 426-437, 1985.

Harlow, D. G., L. D. Domanowski, E. J. Dolley and R. P. Wei, “Probability Modeling and Analysis of J-STARS Tear-Down Data From Two B707 Aircraft,” The Third Joint FAA/DoD/NASA Conference on Aging Aircraft, 20-23 September 1999, Albuquerque NM.

Harlow, D. G. and R. P. Wei, “A Probability Model for the Growth of Corrosion Pits in Aluminum Alloys Induced by Constituent Particles,” *Engineering Fracture Materials*, Vol. 59, No. 3, 1998, pp.305-325.

Harlow, D. G. and R. P. Wei, “Probability Modeling for the Growth of Corrosion Pits,” ASME AD-VOL. 47, Structural Integrity in Aging Aircraft, Proceedings of ASME Winter Annual Meeting, San Francisco, CA, 1995.

Harmsworth, C. L., “Effect of Corrosion on the Fatigue Behavior of 2024T4 Aluminum Alloy,” ASD Technical Report 61-121, July 1961.

Hoar, T. P., “The Production and Breakdown of the Passivity of Metals,” *Corrosion Science*, Vol. 7, 1967, pp. 341-355.

Hoeppner, D. W., V. Chandrasekaran and A. M. H. Taylor, “Review of Pitting Corrosion Fatigue Models,” International Committee on Aeronautical Fatigue, July 1999.

Hoeppner, D. W. and V. Chandrasekaran, “Corrosion and Corrosion Fatigue Predictive Modeling State of the Art Review,” FASIDE report to NCI Information Systems, Inc., Fairborn OH, January 15, 1998.

Hoeppner, D. W., L. Grimes, A. Hoeppner, J. Ledesma, T. Mills and A. Shah, "Corrosion and Fretting as Critical Aviation Safety Issues," ICAF 95, Estimation, Enhancement and Control of Aircraft Fatigue Performance, Vol. 1, J. M. Grandage and G. S. Jost (eds.), Proceedings of the 18th Symposium on the International Committee of Aeronautical Fatigue, 3-5 May, 1995, Melbourne, Australia, EMAS, Warley, West Midlands, U.K., 1995, pp. 87-106.

Hoeppner, D. W., “Model for Prediction of Fatigue Lives Based Upon a Pitting Corrosion Fatigue Process,” Fatigue Mechanisms, Proceedings of an ASTM-NSB-NSF symposium, Kansas City, Mo., May 1978, J. T. Fong, Ed., ASTM STP 675, American Society for Testing and Materials, 1979, pp. 841-870

Howard, M. A. and G. O. Mitchell, “Nondestructive Inspection for Hidden Corrosion in U. S. Air Force Aircraft Lap Joints: Test and Evaluation of Inspection Procedures,” ASME AD-Vol. 47, Structural Integrity in Aging Aircraft, Proceedings of ASME Winter Annual Meeting, San Francisco, CA, 1995.

Howard, M., G. Mitchell and H. Tietz, “Development of Procedures for Using Non-destructive Inspection Equipment to Detect Hidden Corrosion on USAF Aircraft,” page 3-35, Annapolis, MD, ARINC, Contract Report F41608-93-D0649, 1995.

Jeong, D. Y. and J. C. Brewer, “On the Linkup of Multiple Cracks,” *Engineering Fracture Mechanics*, Vol. 51, No. 2, pp. 233-238, 1995.

Johnson, W. K., “Recent Developments in Pitting Corrosion of Aluminum,” *British Corrosion Journal*, Vol. 6, pp.200-204, 1971.

Kawai, S. and K. Kasai, "Considerations of Allowable Stress of Corrosion Fatigue (Focused on the Influence of Pitting)," *Fatigue and Fracture of Engineering Materials and Structures*, Vol. 8, No. 2, 1985, pp. 115-127.

Koch, G. H., "On the Mechanisms of Interaction Between Corrosion and Fatigue Cracking in Aircraft Aluminum Alloys," ASME AD-Vol. 47, Structural Integrity in Aging Aircraft, Proceedings of ASME Winter Annual Meeting, San Francisco, CA, 1995.

Koch, G. H., "Effect of Preexisting Corrosion on Fatigue of High Strength Aluminum Alloys," *Durability of Metal Aircraft Structures*, Proceedings of the International Workshop on Structural Integrity of Aging Airplanes, S. N. Atluri, C. E. Harris, A. Hoggard, N. Miller and S. G. Sampath (eds.), Atlanta Technology Publications, Atlanta, GA., pp.2-27, 1992.

Kollgaard, J., B. Motzer and E. Linstrom, "Inspection Methods for Faying Surface (Bending Mode) Cracks," The Third Joint FAA/DoD/NASA Conference on Aging Aircraft, 20-23 September 1999, Albuquerque NM.

Komorowski, J. P., D. S. Forsyth, D. L., Simpson and R. W. Gould, "Corrosion Detection in Aircraft – Approach to Development of Probability of Detection Data," NATO Research and Technology Organization Conference Proceedings MP-1, 1998.

Kondo, Y., "Prediction of Fatigue Crack Initiation Life Based on Pit Growth," *Corrosion*, Vol. 45, pp.7-11, 1989.

Laycock, P. J., R. A. Cottis and P. A. Scarf, "Extrapolation of Extreme Pit Depths in Space and Time," *Journal of the Electrochemical Society*, Vol. 137, pp. 64-69, 1990.

Lifka, B. W. and D. O. Sprowls, "Relationship of Accelerated Test Methods for Exfoliation Resistance in 7XXX Series Aluminum Alloys with Exposure to a Seacoast Atmosphere," *Corrosion in Natural Environments*, ASTM STP 558, American Society for Testing and Materials, 1974, pp. 306-333.

Lincoln, J. W., "Risk Assessment of Aging Aircraft," Proceedings of the First Joint DoD/FAA/NASA Conference on Aging Aircraft, 8-10 July 1997.

Lindley, T. C., P. McIntyre and P. J. Trant, "Fatigue Crack Initiation at Corrosion Pits," *Metals Technology*, Vol. 9, 1982, pp. 135-142.

Luzar, J., "Corroded Material Crack Growth Rate Test Results," Proceedings of the First Joint DoD/FAA/NASA Conference on Aging Aircraft, 8-10 July 1997, Ogden, Utah.

Mal, A., J. Lee and O. Salmassy, "Multiple Corrosion Defect Considerations in the Life Prediction of Aging Aircraft Structures," Proceedings of the First Joint DoD/FAA/NASA Conference on Aging Aircraft, 8-10 July 1997, Ogden, Utah.

McAdam, D. J., "Corrosion of Metals as Affected by Time and by Cyclic Stress " *Transactions of the American Institute of Mining and Metallurgical Engineering*, Vol. 69, pp. 571-607, 1928.

McGeary, F. L., T. L. Summerson and W. H. Ailor, "Atmospheric Exposure of Nonferrous Metals and Alloys – Aluminum: Seven-year Data," *Metal Corrosion in the Atmosphere*, ASTM STP 435, American Society for Testing and Materials, 1968, pp. 141-174.

Mehdizadeh, P., R. L. McGlasson and J. E. Landers, "Corrosion Fatigue Performance of a Carbon Steel in Brine Containing Air, H_2S and CO_2," *Corrosion*, Vol. 22, pp. 325-335. 1966.

Moukawsher, E. J., M. B. Heinimann and A. F. Grandt, Jr., "Residual Strength of Panels with Multiple Site Damage," *Journal of Aircraft*, Vol. 33, No. 5, 1996.

Nieser, D. E., “Effects of Corrosion on C/KC-135 Structural Life and Flight Safety to 2040,” Proceedings of the Fourth Joint DoD/FAA/NASA Conference on Aging Aircraft, St. Louis, MO, 15-18 May 2000.

Nilsen, N. and E. Bardal, “Short Duration Tests and a New Criterion for Characterization of Pitting Resistance of Al Alloys,” *Corrosion Science*, Vol. 17, 1977, pp. 635-646.

Nguyen, T. H. and R. T. Foley, “On the Mechanisms of Pitting of Aluminum,” *Journal of the Electrochemical Society*, Vol. 126, No. 11, 1979, pp. 1855-1860.

O’Keefe, C., D. Mayton, J. Alcott, K. Dougan and M. Howard, “Results of Evaluation of Non-destructive Inspection Equipment for Long-Term use to Detect Hidden Corrosion on Aging Aircraft Systems,” Annapolis, MD, ARINC, Contract Report F41608-90-D-0544-SD01-04, 1995.

Pao, P. S., S. J. Gill and J. C. R. Feng, “Fatigue Crack Initiation from Corrosion Pits in Aluminum Alloys,” The Third Joint FAA/DoD/NASA Conference on Aging Aircraft, 20-23 September 1999, Albuquerque NM.

Park, J. H., R. Singh, C. R. Pyo and S. N. Atluri, “Integrity of Aircraft Structural Elements with Multi-Site Damage,” *Engineering Fracture Mechanics*, Vol. 51, No. 3, pp.361-380, 1995.

Piascik, R. S. and S. A. Willard, “The Characteristics of Multi-Site Fatigue Damage in the Fuselage Riveted Lap Splice Joint,” Proceedings of the First Joint DoD/FAA/NASA Conference on Aging Aircraft, 8-10 July 1997.

Piascik, R. S. and S. A. Willard, “The Growth of Small Corrosion Fatigue Cracks in Alloy 2024,” *Fatigue & Fracture of Engineering Materials & Structures*, Vol. 17, No. 11, pp.1247-1259, 1994.

Rebbapragda, S., M. J. Palakal and R. M. Pidaparti, “Corrosion Detection and Quantification Using Image Processing for Aging Aircraft Panels,” The Third Joint FAA/DoD/NASA Conference on Aging Aircraft, 20-23 September 1999, Albuquerque NM.

Ricci, R. J., “Enhanced Pulsed Eddy-current Method for Detection of Subsurface Corrosion and Cracks in Multi-layered Structures,” The Third Joint FAA/DoD/NASA Conference on Aging Aircraft, 20-23 September 1999, Albuquerque NM.

Richardson, J. A. and G. C. Wood, “A Study of the Pitting Corrosion of Al by Scanning Electron Microscopy,” *Corrosion Science*, Vol. 10, 1970, pp. 313-323.

Rosenfeld, I. L. and I. S. Danilov, “Electrochemical Aspects of Pitting Corrosion “ *Corrosion Science*, Vol. 7, pp. 129-142, 1967.

Rowe, L. C., “Measurement and Evaluation of Pitting Corrosion,” *Galvanic and Pitting Corrosion - Field and Laboratory Studies, ASTM STP 576*, American Society for Testing and Materials, 1976, pp. 203-216.

Sato, N., “Anodic Breakdown of Passive Films on Metals,” *Journal of the Electrochemical Society*, Vol. 129, No. 2, 1982. pp. 255-260.

Sato, N., “The Stability of Pitting Dissolution of Metals in Aqueous Solution,” *Journal of the Electrochemical Society*, Vol. 129, No. 2, 1982. pp. 260-264.

Scheuring, J. N. and A. F. Grandt, “Quantification of Corrosion Damage Utilizing a Fracture Mechanics Based Methodology,” The Third Joint FAA/DoD/NASA Conference on Aging Aircraft, 20-23 September 1999, Albuquerque NM.

Schmidt, H.-J. and B. Brandecker, “Results of the AAWG Industry Committee on Widespread Fatigue Damage,” *Durability of Metal Aircraft Structures*, Proceedings of the International Workshop on Structural Integrity of Aging Airplanes, S. N. Atluri, C. E. Harris, A. Hoggard,

N. Miller and S. G. Sampath (eds.), Atlanta Technology Publications, Atlanta, GA., pp.279-295, 1992.

Schmidt, H.-J., B. Schmidt-Brandecker and H. Trey, "Airbus A300 Fuselage Program for Life Extension and Widespread Fatigue Damage Evaluation," The Third Joint FAA/DoD/NASA Conference on Aging Aircraft, 20-23 September 1999, Albuquerque NM.

Schmidt, C. G., C. H. Kanazwa, D. A. Shockey and T. H. Flournoy, "Corrosion-Fatigue Crack Nucleation in the Alclad Layer of 2024-T3 Commercial Aircraft Skin," ASME AD-Vol. 47, Structural Integrity in Aging Aircraft, Proceedings of ASME Winter Annual Meeting, San Francisco, CA, 1995.

Schutz, W., "Corrosion Fatigue – The Forgotten Factor in Assessing Durability," 15th Plantema Memorial Lecture, ICAF 95, Estimation, Enhancement and Control of Aircraft Fatigue Performance, Vol. 1, J. M. Grandage and G. S. Jost (eds.), Proceedings of the 18th Symposium on the International Committee of Aeronautical Fatigue, 3-5 May, 1995, Melbourne, Australia, EMAS, Warley, West Midlands, U.K., 1995, pp. 1-51.

Smith, R. A. and G. R. Hugo, "Transient Eddy-Current NDE for Aging Aircraft, Capabilities and Limitations," Proceedings, Fourth Joint DoD/FAA/NASA Conference on Aging Aircraft, 15-18 May 2000, St. Louis MO.

Steadman, D., A. Carter and R. Ramakrishnan, "Characterization of MSD in an In-service Fuselage Lap Joint," The Third Joint FAA/DoD/NASA Conference on Aging Aircraft, 20-23 September 1999, Albuquerque NM.

Swift, T., "Widespread Fatigue Damage Monitoring Issues and Concerns," Proceedings of The 5th International Conference on Structural Airworthiness of New and Aging Aircraft, Hamburg, Germany, June 1993.

Turnbull, A., "Review of Modeling of Pit Propagation Kinetics," *British Corrosion Journal*, Vol. 28, pp. 297-308, 1993.

Wallace, W., D. Hoeppner, P. V. Kandachar, "Aircraft Corrosion: Causes and Case Histories," *AGARD Corrosion Handbook*, AGARD-AG-278-Vol. 1, 1985.

Walpole, R. E., R. H. Myers and S. L. Myers, *Probability and Statistics for Engineers and Scientists*, Prentice Hall, 1998, Chapter 11.

Walton, C. J., D. O. Sprowls and J. A. Nock, Jr., "Resistance of Aluminum Alloys to Weathering," *Corrosion*, Vol. 9, No. 10, October 1953, pp. 345-358.

Walton, C. J. and W. King, "Resistance of Aluminum-base Alloys to 20-year Atmospheric Exposure," *Atmospheric Corrosion of Non-Ferrous Metals*, ASTM STP 175, American Society for Testing and Materials, pp. 21-46, 1955.

Wei, R. P. and D. G. Harlow, "Aging of Airframe Materials: From Pitting to Cracking," Proceedings of the First Joint DoD/FAA/NASA Conference on Aging Aircraft, 8-10 July 1997, Ogden, Utah.

Wei, R. P. and D. G. Harlow, "A Mechanistically Based Probability Approach for Predicting Corrosion and Corrosion Fatigue Life," *Durability and Structural Integrity of Airframes*, Vol. I, Proceedings, 17th Symposium of the International Committee on Aeronautical Fatigue, A. F. Blom, Ed., Stockholm, Sweden, pp. 347-366, June 1993.

Whaley, P. W. and S. N. Gurney, "Static Strength Properties of Naturally Corroded and Uncorroded Aged Aircraft Skin Materials," The Third Joint FAA/DoD/NASA Conference on Aging Aircraft, 20-23 September 1999, Albuquerque NM.