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Corrosion Management – A Statistical Approach

Robert Bell and Don Shelton

Lockheed Martin Aeronautics Company
86 South Cobb Drive
D 6ESM, GA 30063-0569
United States

Mike Falugi

AFRL/VA
Building 45, 2130 8th Street, Suite 1
Wright Patterson AFB, OH 45433-7542
United States

SUMMARY

One of the major cost drivers for any aging aircraft is the mitigation of corrosion damage. This problem has been exacerbated as aircraft are being kept in service beyond their original design service life in terms of both flight hours and calendar years. As this trend continues, the need to understand the impact corrosion has on reliability, maintainability, and the cost to maintain an aircraft becomes increasingly important. This paper will focus on these issues and the proposed methodologies by which they can be addressed in the Aircraft Structural Integrity Program (ASIP) today.

BACKGROUND

Table 1 below provides a brief summary of the average age of some United States Air Force weapons systems.

Table 1. Average age of USAF Aging Fleets

Aircraft	Average Fleet Age (years)
C-141	35
KC-135	38
C-5A	30
C-130	36
B-52	39

Corrosion maintenance cost were found to be the highest for the heaviest aircraft. Table 2 summarizes the annual maintenance cost due to corrosion per aircraft for each fleet. This data was obtained from an NCI Information Systems report [1].

Table 2. 1997 Annual Corrosion Cost per Aircraft

Aircraft	\$ Cost Per Aircraft
C-141	\$341,258
KC-135	\$324,425
C-5A	\$806,500
C-130	\$63,338
B-52	\$363,739

Again, these dollar amounts reflect maintenance cost for corrosion. They do not include the lost revenue for the aircraft due to unscheduled downtime caused by corrosion. All of this is mentioned to emphasize the significant impact corrosion has on the overall cost of ownership for an aging aircraft. For the purposes of this paper the C-141 will be discussed and used as an example.

The need for a different approach exists in regards to corrosion maintenance for an aging fleet. The current ASIP methodology is "Find it Fix it". While this does address the issue, it leaves much to be desired. Ideally, it would be beneficial to manage the fleet for corrosion much in the same way it is for fatigue. The current methodologies in ASIP for fatigue are as follows:

- Where to inspect (FSMP)
- When to inspect (FSMP, Individual Aircraft Tracking)
- How to Inspect (FSMP, NDE)
- What to Look for (FSMP, NDE)
- Inspection results (Repair Databases; i.e. G081, CARR, OSCAR, 202's)
- What to do next; inspect?, repair?, replace? (FSMP)
- Cost to inspect, repair, or replace (needed)
- Individual Aircraft Tracking

These same issues are relevant to corrosion. Therefore, corrosion maintenance methodologies could be incorporated into the existing ASIP framework including the Force Structural Maintenance Plan (FSMP), Individual Aircraft Tracking, Repair databases, and Non-Destructive Evaluation (NDE) requirements. Some of the proposed corrosion methodologies that could be incorporated right now to improve reliability, maintainability, and cost of maintenance for corrosion related problems are as follows:

Reliability can be improved by reviewing maintenance data on aircraft. Costs analysis can be performed using data gathered from planners at Warner Robins Air Logistic Center (ALC). Dollar amounts would be associated with each maintenance option (repair, replace, leave as is and inspect, apply CPC's). The result would be improved maintainability for the aircraft. Our approach will be to statistically analyze the maintenance data related to corrosion at the Air Force depots and determine the probability of occurrence. Cost data is available for the C-141 and KC-135 in the Crevice Corrosion computer program[2] developed under prior Air Force contracts. Using this data a matrix of maintenance options can be developed and the probabilities of experiencing different costs obtained. This will allow maintenance managers to manage their aircraft in the most efficient manner. Obviously, it is essential to maintain safety of flight while reviewing any maintenance options. Programs such as "Environmental & Cyclic Life Interaction Prediction Software" (ECLIPSE)[3,4] can provide inspection intervals to be used in the final cost benefit determination. The Corrosion Maintenance Improvement (CMI) program is also developing data which can be used in assessing options such as the use of corrosion preventive compounds (CPCs), optimum finishes, etc. Another ongoing program,

"Corrosion Fatigue Structural Demonstration", like the CMI program, is studying the effect corrosion has on aircraft structures. As these programs and others like them come to a conclusion, any significant findings and technologies provided by them could potentially be incorporated into the existing ASIP framework as deemed appropriate by the aircraft ASIP manager. This would provide additional corrosion management tools for the aircraft maintainer. These programs and any subsequent technologies are mentioned only as potential future additions to the aircraft management framework.

This paper will focus primarily on statistical methodologies for corrosion maintenance that could be incorporated into ASIP now. The first part of this paper is dedicated to discussing the assessment of the aircraft structure. Below is an outline of the Statistical Methodology for the structure to be presented in this paper followed by a detailed description of the process. The second part of the paper will address the cost issue. Obviously, the key to success for the statistical approach discussed in this paper is the amount, and accuracy, of data that is available for an aircraft. Because of this criteria, the C-141 aircraft was chosen to demonstrate the proposed methodology.

STRUCTURAL ASSESSMENT METHODOLOGY

1. Calculate corrosion growth rate per wetted month
 - a) Review historical data for reported corrosion maintenance actions
 - b) Generate a Normal, Log-Normal, and Weibull plot to determine the corrosion growth rate probabilities per wetted month
 - c) Determine which plot to use
2. Calculate corrosion growth by tail number for the period from when corrosion was found to the prior paint date
 - a) Determine time of wetness over this time period
 - b) Use corrosion growth rate from Weibull and Log-Normal plots
3. Determine the mean and standard deviation for the allowable grind-out limits
4. Calculate the probability that corrosion growth will exceed the mean allowable grind-out depth for the specified time period
 - a) Perform a interaction analysis using the grind-out limits and the projected corrosion growth
 - b) Calculate the probability that one corrosion finding in the area of interest will exceed the mean allowable grind-out depth thus necessitating the need for a major repair

Calculate Corrosion Growth Rate per Wetted Month

The first step is to calculate a corrosion growth rate per wetted month. In order to do this maintenance records for twenty-six C-141 aircraft were reviewed. From these records fifty-nine maintenance actions for corrosion were found. The depth of corrosion for each instance was determined by measuring the depth of the grind-out. Next, the Time of Wetness (TOW) [5] in months was calculated for the time span from when the corrosion was found till the immediately preceding aircraft repaint at Program Depot Maintenance (PDM). The TOW is based on ISO 9223, "Corrosivity Classification". A brief description can be found on the world wide web at <http://www.physics.odu.edu/~cmmp/corrosion/ISO.html>. The depth of corrosion was then divided by the corresponding time of wetness for all fifty-nine corrosion entries. Log-Normal, Weibull, and Normal plots were made to determine the corrosion growth rate probabilities per wetted month. These plots are shown in Figures 1, 2, and 3 respectively.

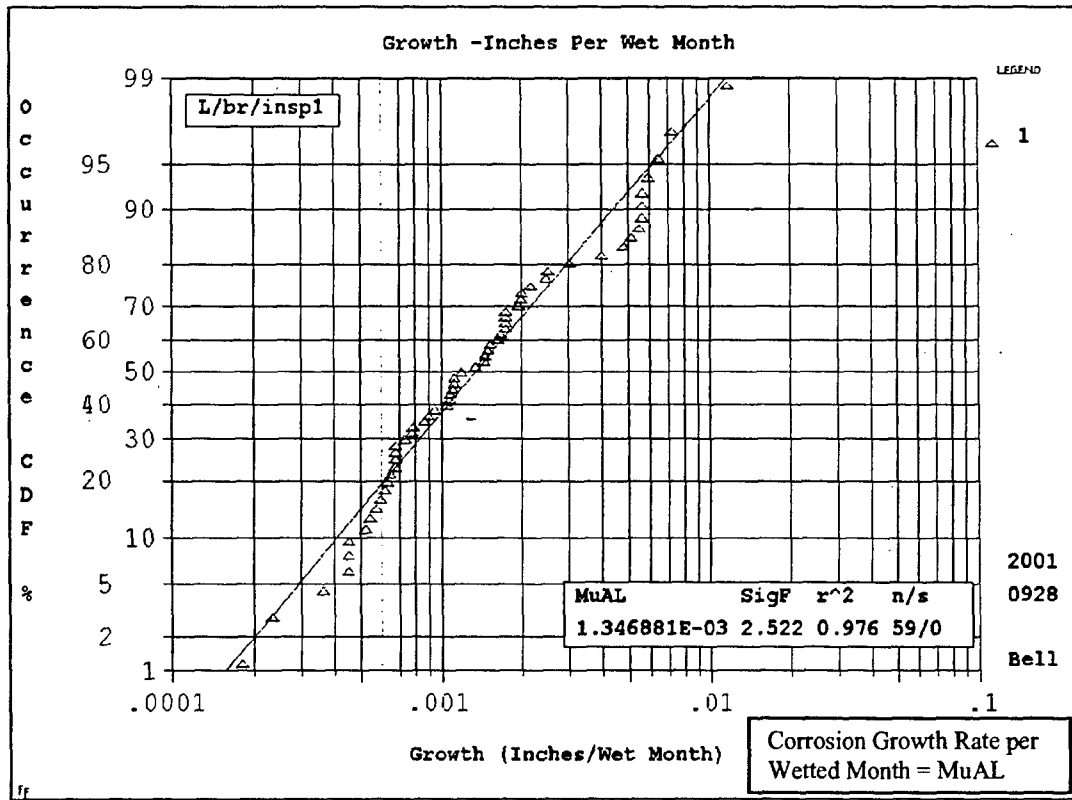


Figure 1. Log-Normal Plot of Corrosion Depth/TOW for 59 Corrosion Records

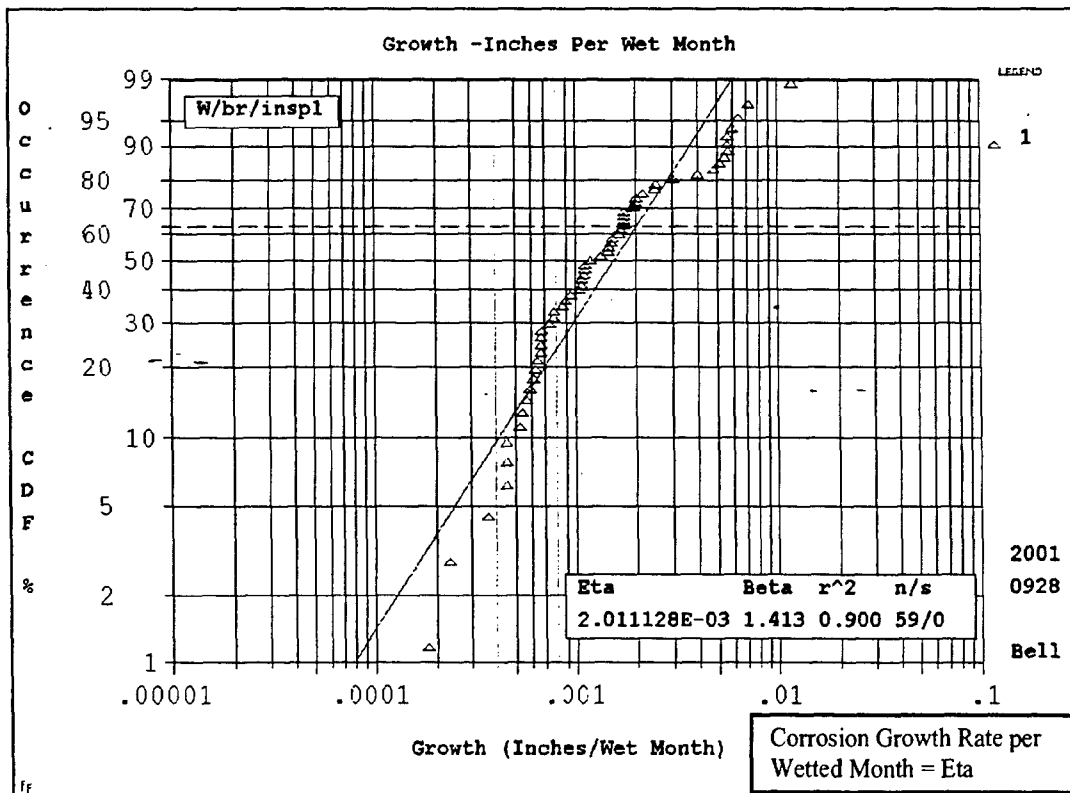


Figure 2. Weibull Plot of Corrosion Depth/TOW for 59 Corrosion Records

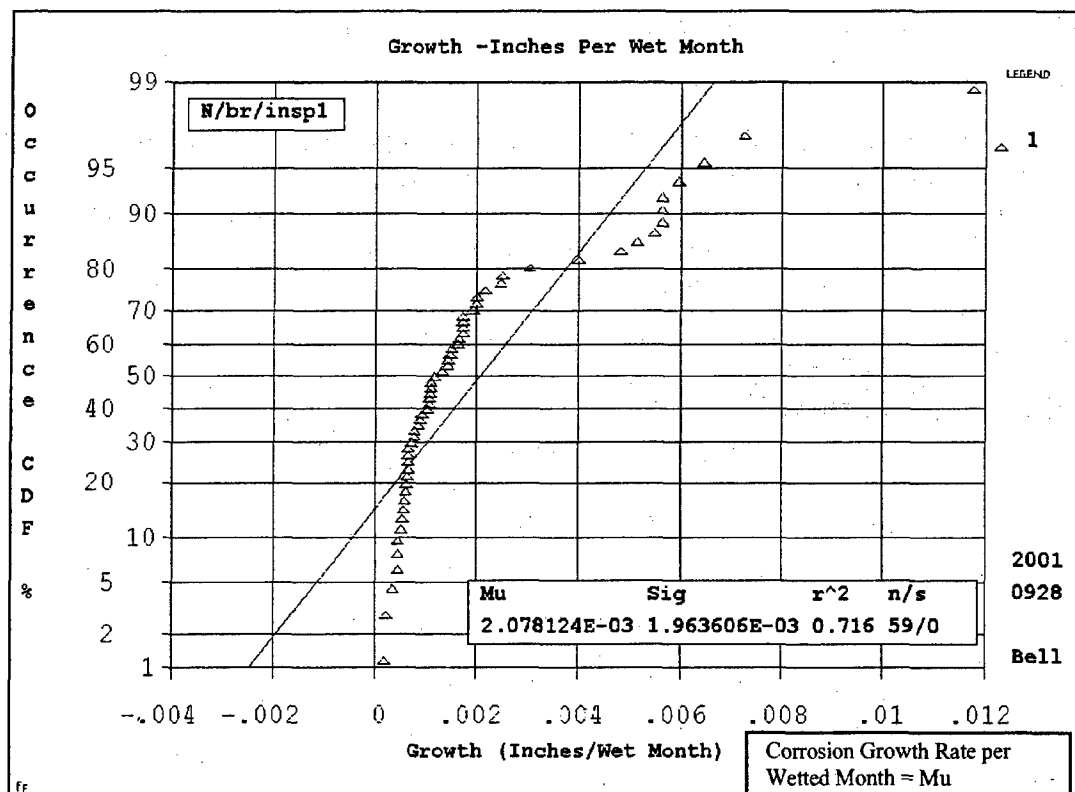


Figure 3. Normal Plot of Corrosion Depth/TOW for 59 Corrosion Records

From the plots it appears the Log-Normal Distribution had the best fit. The Weibull plot had the second best fit. However, due to the limited number of data points it is recommended to use the results from the Weibull plot. Another observation made is that it appears that Corrosion is not a random process according to the Variance from the Normal Distribution plot. Using the results from the Weibull plot the following mean corrosion growth rate was obtained.

Mean corrosion growth rate per wetted month = $\text{Eta} = 2.011128\text{E-}03$ inches/wetted month

It should be noted that the fifty-nine (59) data points used are from various locations on the aircraft. Some are from the fuselage, inner wing, outer wing, center wing, vertical stabilizer, and horizontal stabilizer. Therefore, the corrosion growth rate derived is a generic one encompassing the entire aircraft. Ideally, it would have been preferred to derive a corrosion growth rate per wetted month for each separate component of the aircraft (i.e. one for the fuselage, one for the inner wing, one for the outer wing, etc.). However, at the present time this was not possible. There were approximately sixteen thousand Air Force repair records documented on paper 202's to review. These records span the years from 1989 to 1997. Out of these 16,000, about eight hundred of them were found to be related to corrosion. Compilation of an electronic database detailing the findings from these 800 records has begun. Unfortunately, due to time constraints it was not possible to input all of the available records prior to completion of this paper. At the point in time when all of this data has been input into the electronic database, a mean corrosion growth rate per wetted month will be calculated for each component of the aircraft to determine how much, if any, variation exists. All of this is mentioned to reference where the data came from and why a single mean corrosion growth rate that encompasses the entire aircraft structure was used for the purposes of this paper.

Calculate Corrosion Growth for Individual Aircraft (by Tail Number)

Aircraft 640619, 660151, and 640646 were chosen for this demonstration. Using the Mean Corrosion Growth Rate per wetted month from the Weibull plot, calculate the corrosion growth (depth of corrosion) for each of the three aircraft above. In order to do this we need to calculate the time of wetness for each individual aircraft for the time period from when the corrosion was reported to the PDM paint date prior to when the corrosion was found. The calculated TOW for each aircraft is shown in Figures 4, 5, and 6.

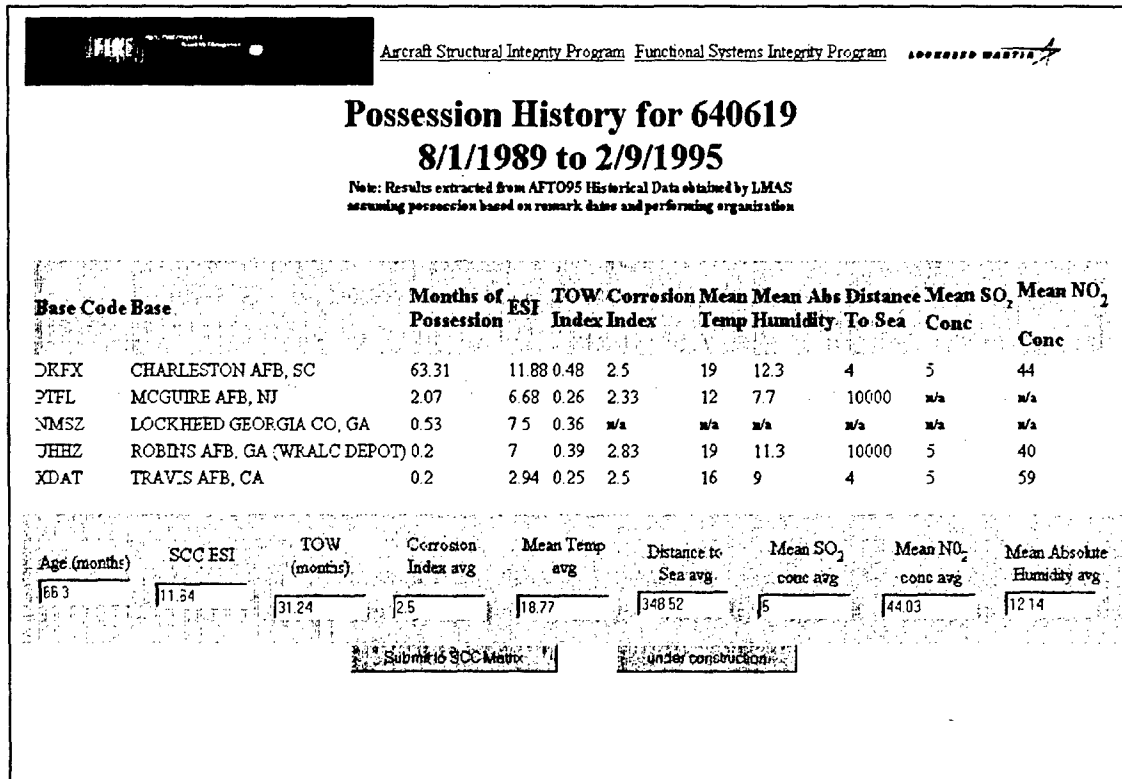


Figure 4. Calculated corrosion growth for aircraft 640619 from 8/1/1989 to 2/9/1995

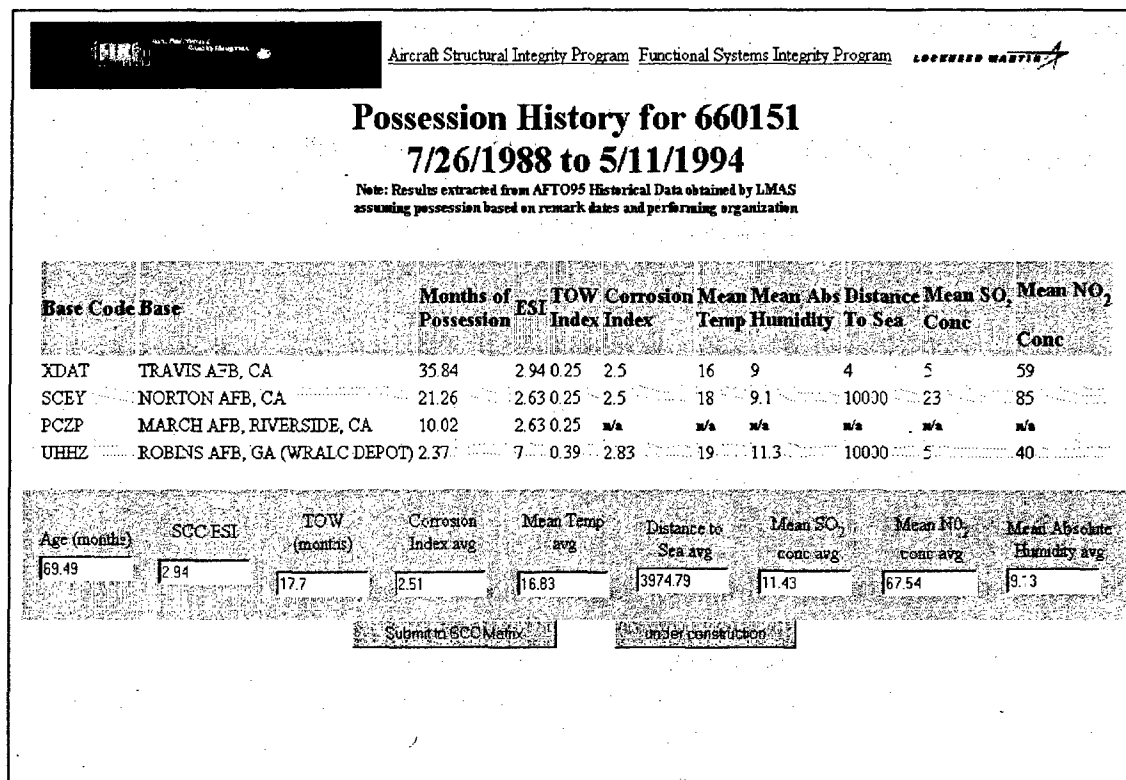


Figure 5. Calculated corrosion growth for aircraft 660151 from 7/26/1988 to 5/11/1994

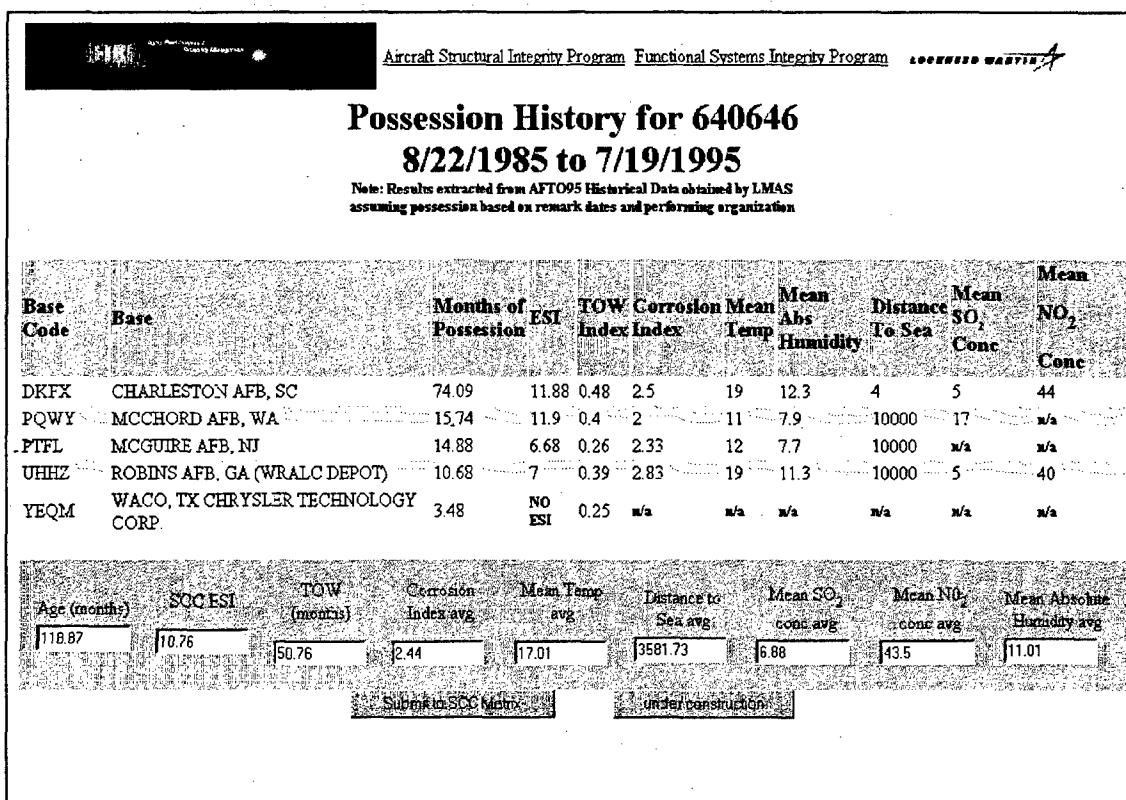


Figure 6. Calculated corrosion growth for aircraft 640646 from 8/22/1985 to 7/19/1995

Table 3 summarizes the TOW for the three aircraft along with their respective calculated Corrosion growth.

Table 3. Summary of Calculated Corrosion Growth for Three C-141 Aircraft

Tail Number	TOW (wetted months)	Eta (Weibull) (inches/wetted month)	Corrosion Growth (TOW x Eta) (inches)
640619	31.24	2.011128E-03	.0628
660151	17.7	2.011128E-03	.0356
640646	50.76	2.011128E-03	.1021

With this information in hand we want to determine the probability that the projected corrosion growth will exceed the mean allowable grind-out limit for the fuselage skins for each of these aircraft. In order to do this the mean and standard deviation must be determined for the fuselage skin allowable grind-out limits.

Determine the Mean Allowable Grind-out Limit for the Fuselage Skins

The allowable corrosion grind-out depths for all of the fuselage skins from T.O. 1C-141B-23 were reviewed. In all, there were one hundred and eight (108) locations with varying grind-out depths allowed. A Log-Normal distribution plot of the 108 allowable grind-out depths was generated. This plot is shown in Figure 7.

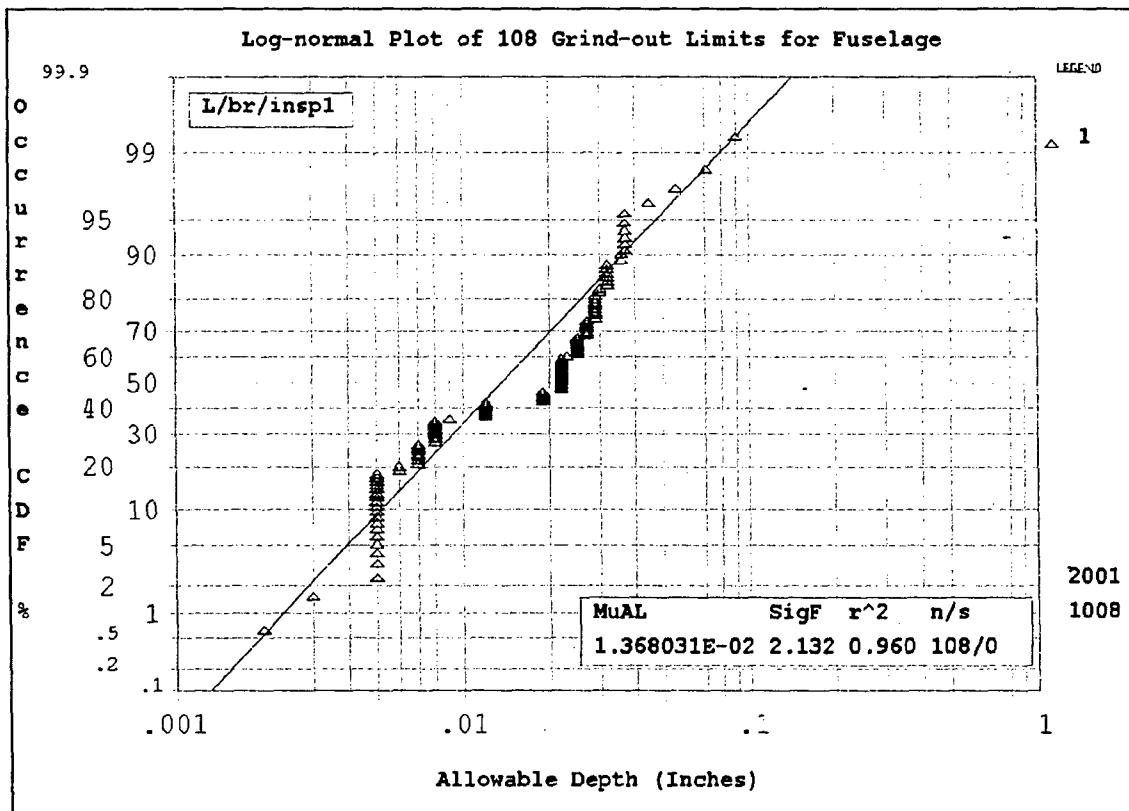


Figure 7. Log-Normal Plot of Allowable Fuselage Skin Grind-out Depths

As can be seen from the plot, the data correlated fairly well. With this in mind, the mean allowable grind-out depth of $\text{MuAL} = 1.368031\text{E-}02$ inches, and the standard deviation of 0.00733 will be used for the interaction analysis discussed below.

Interaction Analysis

With the mean allowable fuselage grind-out depth (MuAL), the corresponding standard deviation, and the calculated Weibull corrosion growths shown in Table 3, an interaction analysis using WinSMITH [6] can be performed. This will calculate the probability for each of the three C-141 aircraft that the anticipated corrosion growth for the fuselage skins will exceed the Mean Allowable fuselage skin grind-out depth. The results of the Interaction analysis are shown in Table 4.

Table 4. Summary of WinSmith Interaction Analysis for Three C-141 Aircraft

Tail Number	Grind-out Mean & Standard Deviation	Calculated Corrosion Growth & Weibull Slope	Probability (calculated corrosion growth > Mean allowable grind-out)
640619	.01368, 0.00733	.0628, 1.413	84.20%
660151	.01368, 0.00733	.0356, 1.413	71.05%
640646	.01368, 0.00733	.1021, 1.413	91.20%

The next step is to calculate the probability that a found corrosion spot would exceed the mean allowable grind-out depth. This will be obtained by using the results from the interaction analysis.

Probability that a found corrosion spot would exceed the mean allowable grind-out depth

Recall that the area of interest for each of the three aircraft was the fuselage skins. In order to calculate the probability that a found corrosion spot would exceed the mean allowable grind-out depth, the effect of each individual zone on the fuselage skins must be included. During the Structural and Systems Assessment Program (SSAP) for the C-141, the fuselage skins were divided into one thousand and seventy (1070) zones. Each zone represents an area twenty inches by twenty inches (20"x20"). The calculated probability is also dependent on the number of corrosion hits found. For demonstration purposes we will assume one corrosion spot was found on aircraft 640619. Therefore, the probability that this one corrosion finding on the fuselage skins will exceed the mean allowable grind-out depth is:

Probability = "# of corrosion hits" x "the inverse of the number of zones on the fuselage skins" x "the probability the Log-normal corrosion growth > mean grind-out limit for the fuselage skins".

Probability = $1 \times (1/1070) \times 0.8281 = 7.739 \times 10\text{E-}04$ (probability one corrosion hit on the fuselage skins of 640619 will exceed the mean allowable grind-out depth)

From this assessment it appears that the effects of corrosion based on the calculated corrosion growth rate for tail number 640619 reduces the structural integrity of the aircraft. However, keep in mind the purpose of this paper was to demonstrate a proposed corrosion maintenance methodology. Not to determine structural integrity. The calculation was done simply to show

that corrosion growth may have an impact on the structural integrity of the airframe. Therefore, the simplified approach shown above was deemed appropriate for the intended purposes of this paper. A much more detailed strength assessment, one that is outside of the scope of this paper, would need to be conducted before any conclusions could be drawn regarding the true impact of corrosion on the fuselage skins.

This concludes the structural portion of the proposed statistical approach to corrosion maintenance. In the following section, the cost issue will be discussed.

COST ASSESSMENT

The first step in determining the cost assessment is to plot the time of wetness (TOW) verses the number of corrosion hits on the fuselage skins by aircraft tail number. The time of wetness was calculated for the time span from when the corrosion was reported to the prior aircraft repaint at PDM. This in essence was the time between consecutive repaints at PDM. The electronic database documenting some of the eight hundred corrosion records mentioned above were reviewed and three aircraft were selected. They were C-141 tail numbers 660151, 640619, and 640646. It should be noted that none of the corrosion records from these three aircraft were included when calculating the generic corrosion growth rate per wetted month discussed at the beginning of this paper (refer to Figures 1, 2, and 3). This was done intentionally.

Table 5 summarizes the findings for aircraft 640619, 660151, and 640646. Included in the Table is the aircraft tail number, associated number of corrosion hits found on the fuselage skins, date the corrosion was found, date of the aircraft repaint preceding the corrosion being found, and the calculated TOW. The time of wetness was calculated using the time from when the corrosion was reported to the prior PDM repaint, and the corresponding base of assignment for the aircraft during that time period.

Table 5. Summary of TOW verses Number of Corrosion Hits on Fuselage Skins

Tail Number	TOW	# of Corrosion Hits on Fuselage Skins	Date Corrosion Reported (at Repaint)	Prior PDM Repaint
640619	31.24	4	2/9/1995	8/1/1989
660151	17.7	2	5/11/1994	7/26/1988
640646	50.76	12	7/19/1995	8/22/1985

From the limited data shown in Table 5 it appears there is some correlation between the time of wetness and the number of reported corrosion findings for these three aircraft. These results represent the first step in validating the statistical approach to corrosion maintenance discussed in this paper. In order to continue the validation of this method more aircraft tail numbers need to be included. Then an accurate "TOW" vs. "number of reported corrosion hits on fuselage skins" could be generated and used. That is providing a correlation analysis was performed that showed good results. However, this was not feasible at the time of this paper due to the amount of time and effort required to process and input all of the accumulated eight hundred corrosion maintenance records into an electronic database. Therefore, only the corrosion data for the three aircraft shown in Table 5 was used at this time.

Once a "TOW" vs. "number of corrosion hits on the fuselage skins" plot is created from existing data and validated, the plot could be used to forecast the anticipated number of corrosion

findings by tail number at the aircraft's next scheduled PDM repaint. This will be illustrated using aircraft 640619. The last PDM repaint for this aircraft was February 2nd, 1995. The next scheduled repaint is July 16th, 2001. With these two dates and the base of assignment data for the aforementioned timeframe, the TOW can be calculated. In this instance, the TOW for aircraft 640619 from February 2nd, 1995 to July 16th, 2001 was 19.97 wetted months. Then using a TOW = 19.97 and the "TOW" vs. "number of reported corrosion hits on fuselage skins" plot mentioned above, an anticipated number of corrosion findings on the fuselage skins at the next scheduled PDM repaint can be obtained. Recalling that this plot was not generated because of the limited amount of data that had been processed, a different approach was taken for this illustration. Since the calculated TOW = 19.97 was relatively close to the TOW = 17.7 shown in Table 5, it was assumed that the same number of corrosion hits would be found for either one. In this case, two. With this in mind, it is now possible to estimate the corrosion maintenance cost for the fuselage skins on aircraft 640619 when it arrives at PDM for repaint on July 16th, 2001.

Calculate Estimated Corrosion Maintenance Costs for Fuselage Skins

In order to calculate the estimated corrosion maintenance costs, an average cost at PDM for a major repair due to corrosion on the fuselage skins was needed. It was assumed that a major repair would be a panel segment replacement. This would be done when the grind-out depth due to corrosion exceeds the allowable grind-out depth for the fuselage skin shown in T.O. 1C-141B-23 manual, and the damage could not be repaired using a flush "dime" and "dollar" repair because of size limitations. Based strictly on manpower hours and a billing rate it was estimated that a fuselage skin panel segment replacement costs \$50,000. Again, this amount is only for labor.

Now, to calculate estimated corrosion maintenance cost for the fuselage skins on aircraft 640619 at the next scheduled PDM repaint multiply the estimated panel segment replacement cost by the estimated number of corrosion hits at the next scheduled PDM repaint and by the probability that the Log-Normal corrosion growth will exceed the mean allowable grind-out (refer to Table 4.). The probability that the Log-Normal corrosion growth will exceed the mean allowable grind-out is included because this is the probability that a major repair (i.e. panel segment replacement) would be required. Therefore, the estimated corrosion maintenance cost for the fuselage skins on aircraft 640619 at the next scheduled PDM repaint is:

Estimated corrosion cost for 640619 fuselage skins = \$50,000 x 2 x .8281 = \$82,810
at next scheduled PDM repaint on July 16th, 2001

CONCLUSIONS

From the preliminary findings documented in this paper it appears the proposed statistical methodology shows promise for forecasting corrosion damage and corrosion cost. Again, this approach hinges on the amount of corrosion data that is available for a particular weapons system, as well as its accuracy. Following is a list of some of the other conclusions that were drawn.

- Mitigation of corrosion is a major cost driver for an aging aircraft
- For most weapons systems the approach taken for corrosion maintenance is reactive, such as "Find it" "Fix it". It is desired to have a proactive approach for corrosion maintenance similar to that used for fatigue.

- The proposed Statistical Methodology could be incorporated into the existing ASIP framework with minimal effort.
- From the variance for the Normal distribution plot shown in Figure 3, it appears that corrosion is not a random process.
- Corrosion locations for same material type appear to be a random process
- More data needs to be processed before determining if the number of corrosion occurrences based on material type is a random process.
- From the calculated corrosion growth rates shown in Table 3, and the interaction analysis, it appears the effects of corrosion may reduce the structural integrity of the aircraft. However, a much more detailed strength assessment would need to be conducted before any conclusions could be drawn regarding the impact corrosion has on the structural integrity of an aircraft.
- Cost of corrosion damage can be calculated as long as accurate cost data is supplied by the maintenance provider.
- The statistical corrosion maintenance methodology presented in this paper was demonstrated on the C-141 but is applicable to any weapons system provided the historical data exists documenting the base of assignment and repair records for each tail number.

RECOMMENDATIONS

The following are recommendations for further areas of study for the proposed corrosion maintenance methodology.

- Continue to analyze and compile an electronic database containing all of the available historical PDM corrosion data to verify and modify the growth rates as required.
- After a sufficient amount of data has been entered into the electronic database, calculate a corrosion growth rate for each separate component of the aircraft (i.e. one for the fuselage, inner wing, outer wing, etc.) and determine how much, if any, variation exists. If variations do exist, use a growth rate for each component as opposed to one that encompasses the entire aircraft structure.
- Calculate a more accurate probability for a major repair being required by using improved methods to obtain an assessment of the structural strength.
- Break out the repair severity probabilities to determine more accurate costs. This would be done in lieu of using an average cost for a repair as was done for this paper.

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