TRI-SERVICE CORROSION CONFERENCE 2007
ARMY • NAVY • AIR FORCE • MARINES • COAST GUARD • NASA

SURVIVAL ANALYSIS MODELING
OF CENSORED AND CONFOUNDING
COAST GUARD CORROSION FAILURE DATA

Samuel Benavides
U.S. Coast Guard
Weeksville Road
Elizabeth City, North Carolina 27909

Thomas A. Mazzuchi, D.Sc.
The George Washington University
2121 I Street, N.W.
Washington, D.C. 20052

Shahram Sarkani, Ph.D., P.E.
The George Washington University
2121 I Street, N,W.
Washington, D.C. 20052

ABSTRACT

As commercial and military aircraft fleets age the time-dependent effects of corrosion threaten their structure. Traditional predictive algorithms for determining the remaining structural life of aging aircraft are based on corrosion modeling. The multifarious variables involved in these models have proven convoluted, complex and interacting for the development of precise time-to-failure algorithms. An advance statistical method to analyze the probability of failure should account for the disparate confounding variables that influence corrosion. This paper introduced the novel use of survival analysis techniques to investigate the time-to-failure of airframe structure on aging aircraft. The objective of this work is to develop corrosion-specific failure rate functions, also known as survival or hazardous functions, for the Coast Guard's fleet of search-and-rescue HH-65 helicopters assigned to environmentally severe geographic locations. Exploring the influence of historical maintenance data, this work is determining how confounding and interacting variables are impacting the corrosion failure rate. This effort is improving the understanding of aging aircraft corrosion failure while demonstrating the successful broadening of survival analysis to corrosion engineering.

Keywords: survival analysis, aging aircraft, modeling, structural failure, censored data

INTRODUCTION

FIGURE 1. Aloha flight 243 after corrosion and metal fatigue compromised the integrity of the cabin

Commercial and military aircraft fleets are aging. Aircraft designers and manufacturers never suspected some of their air vehicles would be flying beyond their designed life. As aircraft become older, they are subject to the deleterious effects of structural corrosion. This was brought to light by Aloha Airline's flight 243 which suffered an explosive decompression in 1988 as a result of metal fatigue exacerbated by corrosion. This watershed event, in which an airline attendant was swept from the cabin at 24,000 feet, established the FAA and DoD programs of aging aircraft.[1] Although corrosion inspections on the Aloha Airlines class of 737's had been proposed by a Boeing alert service bulletin, no one predicted the apocalyptic damage from accelerated corrosion that would result from operating in the severe Hawaiian environment.[2] Since this mishap, the aviation community has struggled to accurately predict the onset of corrosion or the extent of structural damage it induces. Despite advances in corrosion algorithms, computation material research, simulation and maintenance data analysis, a reliable model for predicting corrosion on airframe structure has yet to be forthcoming. This work is narrowing the gap by introducing survival analysis as a statistical framework to further the understanding of corrosion failure rates on aging aircraft.

CLASSIC CORROSION MODELING

Traditional corrosion modeling of aviation structure has been based on electro-chemical mechanisms that drive materials to a lower energy state – that is, the material corrodes. This classical representation is strictly physical and countless laboratory and field experiments have strived to produce empirical functions to account for the complex physical phenomena that occurs as a result of corrosion. Many models include interacting variables to capture elements of realism, such as Miyata, et al. whose extended function includes corrosion as a result from dew, rain, relative humidity, temperature and sea salt particles.[3] Models based on a wide variety of conditions, geometry, alloys and mechanisms for various types of corrosion growth mechanisms in aluminum aircraft structure have also been developed.

$$c = At^B$$ General Corrosion Equation

$$c = Af_1(m)f_2(T)f_3(C) + Bf_4(r)f_2(T)f_5(C)$$ Miyata, et al.

---

[1] Chris Seher, "Managing the Aging Aircraft Problem," in *The AVT Symposium on Aging Mechanishms and Control the Specialist Meeting on Life Management Techniques for Aging Air Vehicles* (Manchester, England).

[2] NTSB, "Aloha Airlines, Flight 243, Boeing 737-200, N737311, near Maui, Hawaii," ed. National Transportation Safety Board (1988).

[3] R.E. Melchers, "Transition from Marine Immersion to Coastal Atmospheric Corrosion for Structural Steels," *The Journal of Science and Engineering Corrosion* 63, no. 6 (2007).

CORROSION IN THE DEPARTMENT OF DEFENSE

Corrosion, a $20 billion annual expense for the Department of Defense affects the military service's 15,000 aircraft and helicopters. Corrosion involves 700,000 military and DoD civilian personnel in addition to several thousand commercial firms.[4] Corrosion impacts aircraft readiness, availability, armament, hangar facilities and, most importantly, the safety of the aircraft.

The Government Accounting Office (GOA) cited the Department of Defense as lacking reliable corrosion data to develop an effective prevention and mitigation strategy.[5] While the GOA recognizes that the Department of Defense operates in high-salt and wet environments that accelerates corrosion, this federal entity lacks reliable data, mechanisms or methodologies to accurately quantify corrosion. The databases that exist are often incomplete as not all corrosion-related damage is reported.[6] Recently, Congress enacted the National Defense Authorization Act of Fiscal Year 2006 to examine the effectiveness of DoD corrosion programs.

TABLE 1
Aircraft age of U.S. Air Force aviation assets

Aircraft	**Quantity**	**Average Age, years**
B-52	94	44
RC-135	22	42
E-8	17	38
EC-130	14	33
E-4	4	31
A-10	356	25
U-2S	28	26
E-3	33	27
F-115 A-D/E	496/224	22 / 15
F-117	55	21
F-16	1331	14
B-1	67	19
B-2	21	11
MQ-1 Predator	67	2
RQ-4 Global Hawk	5	4
MQ-9 Predator B	8	2
F22 A	47	1.5
Average Age		**21.18**

Understanding the impact of corrosion is a primary concern to the Air Force where the average age of its fleet is 21.2 years[7]. Many of these aircraft suffer from corrosion and other age-related problems to such a degree that policy decisions regarding repairing or replacing a fleet are often debated. An example is the corrosion on engine struts that led to the grounding of twenty-nine KC-135 refueling-tankers. The decision to repair or replace these air assets still continues in the Air Force and U.S.

---

[4] GAO, "Opportunites to Reduce Costs and Increase Readiness," ed. United States Government Accounting Office (2003).

[5] ———, "Report to Congressional Committees, High-Level Leadership Commitment and Actions Are Needed to Address Corrosion Issues," ed. United States Government Accounting Office (Washington, DC: 2007).

[6] ———, "Status of Department of Defense (Dod) Corrosion Prevention and Mitigation Efforts (Preliminary Observations)," ed. United States Government Accounting Office (2002).

[7] Colonel Robert Garcia, "Air Combat Command Sustainment Focus," (paper presented at the US Air Force Corrosion Conference, Macon, GA, 2006)

Congress. Another example is the nearly 50 year-old B-52 bombers that are scheduled to fly beyond 2030. Finally, there is the cost of corrosion. In 1991, the Air Force estimated corrosion to cost $700 million; in 2001 the cost had increase to over $1 billion[8]. Although the effects of corrosion impacts cost, readiness and safety, the Air Force does not have a corrosion model to accurately predict long-term corrosion of its aircraft in real-world conditions.[9]

Abbott et al. has examined local corrosion rates on Air Force airframes such as C-141, C-130, F-15, F-16 and KC-135. Abbott has successfully developed an algorithm to predict local geographic corrosion rates based on chloride and other environmental factors.[10] The corrosion growth rates from Abbott provides data to the Air Force's structural analysis software tool that predicts the crack growth on aircraft structure and uses corrosion data to determine the compounding affects of corrosion on the crack.[11] Correlating these and other efforts, Ullett et al. developed growth rate predictions in longitudinal transverse and short transverse grain directions in legacy aircraft alloys.[12]

The U.S. Army maintains the largest fleet of aircraft among the Department of Defense. The average age of these aviation assets continues to increase along with increasing corrosion discrepancies. Major General James Pillsbury, commander of the United State's Army Aviation Command, recently expressed his concerns of the challenges to his Army's aging fleet. In a keynote speech, the General shared his concern on the adverse effects of corrosion on aging aircraft and the Army's ability to fulfill their missions. One solution the General offered was the use of Condition Based Maintenance (CBM) in which data is used to optimize, predict and schedule maintenance resources. A key enabler for the success of Condition Based Maintenance is the ability to "…predict remaining component life".[13] To date, the U.S. Army does not have a predictive model that incorporates real maintenance data to determine the remaining life of aircraft corroded structure.

The Navy's 3,880 aircraft, averaging 18 years in age, are currently the oldest aviation fleet in its history. Like the other armed services, the Navy faces corrosion and age-related challenges in extending the life span of many of its aircraft into the middle of the 21st century. An example is the in-flight refueling tankers and the maritime surveillance aircraft that share an average age of 29 years.[14] Keeping these older aircraft flying is becoming increasingly more costly. Recently the Navy spend $408.6 million to upgrade rotor and engine drive trains on CH-46 helicopters. To address these issues, the Navy is focusing on collecting and analyzing data to forecast incipient component failures.

The U.S. Coast Guard's fleet of aging aircraft operates in extremely corrosive environments. Many of these aircraft are flying beyond their designed life where corrosion has become not only a structural integrity challenge but a major cost of operation. In order to continue meeting the challenges placed upon aviation assets, it has become imperative that the Coast Guard use effective decision support tools to enhance operational availability, extend service life, reduce cost and ensure safety.

---

[8] Government Accounting GAO, "Opportunites to Reduce Costs and Increase Readiness."

[9] Matthew C. Dixon, "The Costs of Aging Aircraft: Insights from Commercial Aviation" (Dissertation, Pardee RAND Graduate School, 2006).

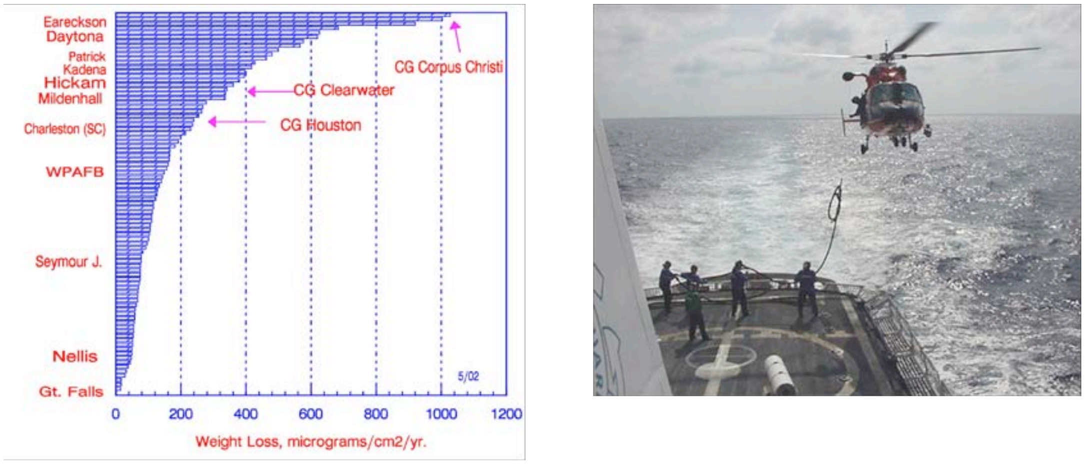
[10] William H. Abbott and Richard Kinzie, "Corrosion Monitoring on Operational Aircraft Status of Recent Work" (paper presented at the Joint NASA/FAA/DoD Conference on Aging Aircraft Conference, New Orleans, LA, 2003).

[11] J. Harter, *Afgrow Users Guide and Technical Manual* (AFRL-VA-WP-TR-2004-XXX).

[12] J.S. Ullett, "Prediction of Corrosion Growth Rates in Legacy Alloys" (paper presented at the U.S. Air Force Corrosion Conference, Macon, GA, 6-8 March, 2007).

[13] Major General James Pillsbury, "Aging Aircraft: An Army Perspective" (paper presented at the 10th Joint Dod/NASA/FAA Conference on Aging Aircraft, Palms Spring, CA, 2007).

[14] John Milliman, "The War on Aging Aircraft: One Battle Down, Many to Go," *Naval Aviation News*, July-August, 2002.



(a) (b)

FIGURE 2. *(a) U.S. Air Force environmental severity rates (b) U.S. Coast Guard HH-65 Helicopter Operating in a Severe Environment*

CORROSION IN CIVILIAN TRANSPORT AIRCRAFT

The civilian commercial airline industry is not immune to the effects of corrosion where the average cost of corrosion can be 10% of total aircraft maintenance costs. In 1996, the annual cost of corrosion was estimated to be $2.225 billion[15]. The commercial industry's databases on age information suggest that maintenance costs increases with age. Boeing maintains a maturity curve to describe corrosion cost as a function of age.[16] The following empirical equation is used by Boeing to calculate annual corrosion maintenance cost:

$$\text{Corrosion Maintenance Cost} = R + NR + P\&C$$

where R is routine maintenance, NR is non-routine maintenance and P&C are parts and consumable costs. Given a technician's hourly rate as HR, the values for a 747-B airplane are: Routine Maintenance (4,500 hours x HR), Non-Routine Maintenance (3,000 hours x HR) and Parts and Consumables $4,500.[17]

Corrosion greatly affects the first generation of jet transports that were designed to a fail-safe strength criterion with little or no attention incorporated into corrosion protection. These aircraft include early models such as the 747-B, 737-B, DC-10 and DC-8, to name a few. In the 1970s and 1980s, damage tolerance was incorporated into the design of the second generation of commercial passenger aircraft. By then, it was realized that corrosion in aircraft was becoming an economic burden and could

---

[15] Gerhardus H. Kock et al., "Corrosion Cost and Prevention Strategies in the United States," (Dublin, OH: CC Technologies Laboratory, NACE International, 2001).

[16] Dixon, "The Costs of Aging Aircraft: Insights from Commercial Aviation".

[17] Kock et al., "Corrosion Cost and Prevention Strategies in the United States."

TABLE 2

Airline Annual Cost of Corrosion[18]

Corrosion Catogory	**Cost, in billions**
Corrosion Maintenance	$ 1.7
Downtime due to Corrosion	$ 0.3
Design & Manufacturing for Corrosion	$ 0.225
Total	$ 2.225

possibly become detrimental to the structural integrity of the airplane. Accordingly, the Federal Aviation Administration issued an Airworthiness Directive related to corrosion control in design and maintenance. The third generation incorporates significant improvements in corrosion prevention in their design.

CARRIER	NUMBER	AGE	CARRIER	NUMBER	AGE	CARRIER	NUMBER	AGE
ALASKA			**DELTA (cont.)**			**UNITED**		
B-737	31	6.9	L-1011	53	17.7	A-319*		
MD-80	44	7.7	MD-11	12	4.0	A-320	35	2.1
Total	**75**	**7.4**	MD-80	119	6.4	B-727	74	17.7
AMERICA WEST			MD-90	12	1.4	B-737	225	11.9
A-320	25	5.6	**Total**	**538**	**11.7**	B-747	56	14.1
B-737	61	12.0	**FEDERAL EXPRESS**			B-757	92	4.8
B-757	14	10.0	A-300-600	19	1.5	B-767	42	8.8
Total	**100**	**10.1**	A-310	29	12.7	B-777	16	1.4
AMERICAN			B-727	159	22.5	DC-10	52	21.4
A-300-600	35	7.2	B-747	2	19.6	**Total**	**592**	**11.5**
B-727	81	19.7	DC-10	34	17.1	**UNITED PARCEL SERVICE**		
B-757	90	4.7	MD-11	21	3.6	B-727	53	27.8
B-767	71	7.9	**Total**	**264**	**17.7**	B-747	16	24.1
DC-10	35	22.2	**NORTHWEST**			B-757	57	4.5
F-100	75	3.8	A-320	50	5.1	B-767	9	0.7
MD-11	16	4.4	A-330			DC-8	9	28.0
MD-80	260	8.6	B-727	46	17.8	**Total**	**144**	**16.5**
Total	**663**	**9.4**	B-747	43	15.5	**U.S. AIR**		
CONTINENTAL			B-757	48	7.2	B-737	203	10.4
A-300	4	16.2	DC-9	180	26.3	B-757	34	6.2
B-727	30	20.5	DC-10	37	22.5	B-767	11	7.5
B-737	132	11.5	MD-80	8	15.1	BAE-146	4	11.3
B-757	71	1.8	**Total**	**412**	**18.9**	DC-9	72	23.7
B-777*			**TWA**			F-100	40	5.8
DC-9	28	24.3	A-330*			F-28	13	12.1
DC-10	18	20.1	B-727	47	24.1	MD-80	31	14.7
MD-80	67	11.9	B-747	15	25.8	**Total**	**408**	**12.3**
Total	**350**	**11.9**	B-757	1	0.3	**SOUTHWEST**		
DELTA			B-767	14	12.4	B-737	241	8.1
B-727	129	19.7	DC-9	58	25.6	**Total**	**241**	**8.1**
B-737	67	11.8	L-1011	13	22.6			
B-757	88	7.9	MD-80	52	9.7			
B-767	58	8.3	**Total**	**200**	**19.9**			

Source: GKMG Consulting Services, Inc.

**Data not available.*

FIGURE 3. Aircraft age, in years, of commercial passenger aircraft

---

[18] Ibid.

SURVIVAL ANALYSIS

Introduction

Survival analysis is a well-grounded biostatistical branch of reliability that involves modeling data until an event occurs. Considering survival analysis originates from the biomedical arena, its no surprise the event is usually associated with death, the onset of a disease, relapse or recovery. For engineering applications, we can replace “death” with “failure” or substitute “the onset of disease” with “the onset of corrosion” (Table 3). For example, R.H. Stillman used survival analysis to model electrical overhead distribution systems, Wang et al. examined fatigue cracking of pavement and Pelletier et al. analyzed municipal infrastructure water pipe failures using this technique.[19,20,21] Similarly, this work is extending the application of survival analysis to the corrosion failure of aircraft structure. Survival is the antithesis of failure; for the engineering community survival analysis may be more appropriately considered in the context of “failure” analysis.

TABLE 3

Application of Survival Analysis to Corrosion

Event	Time
The onset of corrosion on aircraft	Time to onset, months
Failure due to corrosion	Time to failure, months
Aircraft life	Time until retirement due to corrosion, years
Repaired structure	Time until re-occurrence, weeks
Avionic failures due to corrosion	Time to fail, hours

Censored Data

Guedes, et al proposed a three-phase model to describe the stages of corrosion.[22] The first phase, τ_c, is defined by the endurance of the protection systems that prevents the initiation of corrosion. In other words, for a period of time there will be no corrosion in the aircraft. When the protection systems eventually wear, the second phase, τ_c , begins and the airframe structure corrodes. The discreet time this occurs is unknown. Corrosion will then proceed at a non-linear rate eventually reaching a steady asymptotic rate in phase three. In aircraft, the existence of corrosion is often discovered by maintenance personnel only after it has existed for a period of time in phase two or phase three. As in any reliability study, the exact time the corrosion failure occurs is desired, but in survival analysis it is not necessary. Survival analysis handles these unknown occurrences through censoring. Unlike other reliability models, the ability to work with censored data is one of the strong benefits of survival analysis.

---

[19] R.H. Stillman, "Modeling Failure Data of Overhead Distribution Systems," *IEEE Transactions on Power Delivery* 15, no. 4 (2000).

[20] Yuhong Wang, Kamyar C. Mahboub, and Donn E. Hancher, "Survival Analysis of Fatigue Cracking for Flexible Pavements Based on Long-Term Pavement Perfromance Data," *Journal of Transportation Engineering* 131, no. 8 (2005).

[21] Genevieve Pelletier, Alain Maihot, and Jean-Pierre Villenueve, "Modeling Water Pipe Breaks - Three Case Studies," *Journal of Water Resources Planning and Management* 129, no. 2 (2003).

[22] Guedes, Soares, and Garbatov, "Reliability of Corrosion Protected and Maintained Ship Hulls Subjected to Corroson and Fatigue,," *Journal of Ship Research* 43, no. 2 (1999).

Right-censoring is when the event (failure) has not occurred by the end of the observation period. For example, during aircraft depot maintenance a specific structural component is determined to have not failed. Given enough time, T, components eventually succumb to corrosion, but at the time of maintenance, t, the condition observed is that the component has survived, that is, not failed. When the true failure time T is greater then the observed time t, T> t, the data point is classified as a right-censored data point. A left censored data point would occur when the true survival time is less than the time at which the observation is made. Other censoring such as left and right truncation can also be handled by survival analysis. Customary designation for data is to label a known failed time as "Failed= 1" and "Censored = 0."

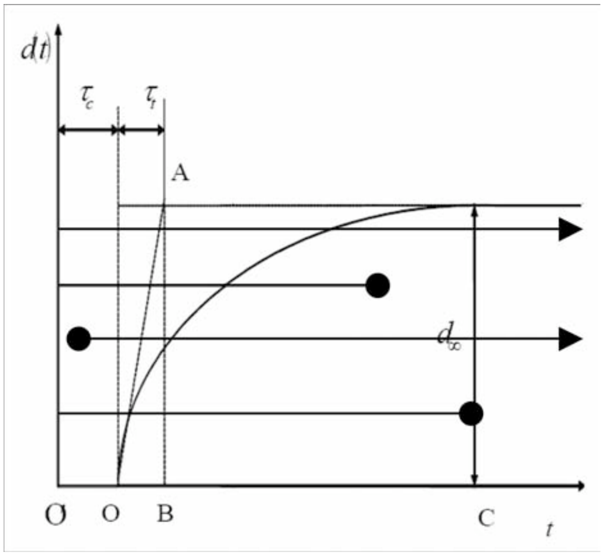


FIGURE 4. The Guedes three-phase model of corrosion. An arrow represents a right-censored data point; a circle is a discreet time. If the event occurred before time C, the data point is left censored.

The Survival Function

The cornerstone of survival analysis is the time-to-event (failure) phenomena described by the survivor function, S(t). The survivor function describes the probability of surviving beyond a specified time, t. It analyzes not only the known failure times but takes into consideration those components that may not have failed at the observed time. This is significant because these un-failed censored data points provide valuable information about the survivability of components up to the observed time, t. The survivor function benefits corrosion engineering in that the exact time that corrosion initiated is not necessary. The survivor function is described as,

$$S(t) = \Pr(T > t)$$

At time t = 0, the probability of surviving is 100%. As t approaches infinity, failure will eventually occur and the probability of surviving becomes 0%.

The survivor function is the complement of the cumulative distribution function:

$$S(t) = 1- F(t), \text{ where}$$

$$F(t) = \Pr (T \leq t)$$

By definition, the survival function then becomes the integral of the probability density function:

$$S(t) = \Pr (T> t) = \int_{x}^{\infty} f (t)\, dt$$ [23]

Survival models are constructed by determining the survival distribution. Common distributions include the exponential, the Weibull and the lognormal.

STATEMENT OF THE PROBLEM

The aviation industry has struggled to develop accurate corrosion probabilistic models because the variables that influence corrosion are convoluted and complex. While classical time-dependent corrosion algorithms are often implemented, they lack realism as they are limited to the bounding conditions of their laboratory source data. An advance statistical method that considers the effects of interacting variables while evaluating real-world censored data is needed as a framework for the analysis of structural airframe corrosion failure. This work is addressing these issues by proposing the novel use of survival analysis techniques to develop time-to-failure probability survival functions for aging aircraft.

EXPERIMENTAL PROCEDURES

Collection of Data

The U.S. Coast Guard maintains a robust depot corrosion mapping program at the Aircraft Supply and Repair Center (AR&SC) in Elizabeth City, North Carolina. This facility performs depot maintenance on C-130, HU-25, HH-60 and HH-65 aircraft. During the overhaul process, corrosion on rotary wing aircraft is documented and charted on a Coast Guard corrosion mapping program. The data is used to identify corrosion “hot spots,” track corrosion mitigation efforts and provide structural reports of the aircraft. Currently, an excess of 15,000 instances of corrosion are captured in the database.

---

[23] Moeschberger, Melvin L. *Survival Analysis*, Secaucus, NJ, USA: Springer-Verlag New York, Incorporated, 1997. p 21.

The corrosion maintenance data residing in the mapping program offers an opportunity to analyze and predict the failure probability of HH-65 search-and-rescue helicopters. Explanatory variables such as geography, corrosion severity, time-of-wetness or diurnal data can be considered in the survival analysis probability plots. The occurance of a corrosion failure prior to the depot is accounted for as censored data.

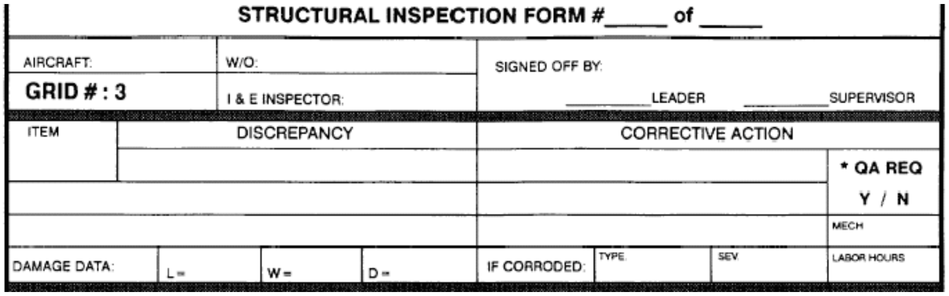
TABLE 4
US Coast Guard HH-65 Corrosion Mapping Program
Instances of Corrosion

Zone	Light	Moderate	Severe	Total
Cockpit	2,162	579	489	3,230
Cabin	2,066	228	414	2,708
Transition	1,824	120	494	2,438
Belly	2,078	1,640	2,725	6,443
Tailcone/Fenstron	99	203	369	671
Total	8,229	2,770	4,491	15,490

TABLE 5
US Coast Guard HH-65 Depot Corrosion Mapping Program
Man Hours to Repair Corrosion

Zone	Light	Moderate	Severe	Total
Cockpit	4,390	1,761	1,856	8,007
Cabin	2,472	952	2,300	5,724
Transition	4,019	488	2,478	6,985
Belly	5,521	8,585	19,206	33,312
Tailcone/Fenstron	2,283	912	1,604	4,799
Total	18,695	12,698	27,444	58,827

Corrosion mapping divides the HH-65 into five zones. Each zone contains individual grid cards illustrating the structure within that zone. Depot personnel document the corrosion discrepancies, the damage data, the corrective action, the corrosion type, the corrosion severity and the number of man-hours to affect the repair. In addition, the corrosion discrepancies are graphically “mapped” on the grid. Once the discrepancies for the entire aircraft have been captured, the cards are scanned and the data is enrolled into the corrosion mapping program.

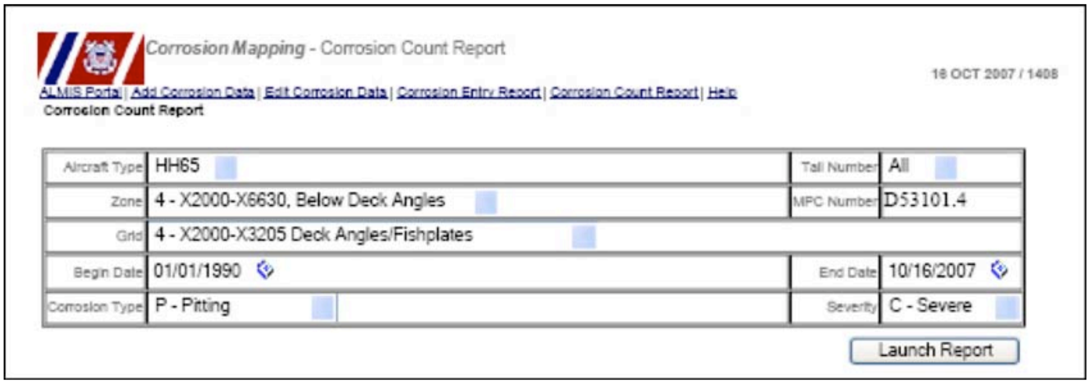


STRUCTURAL INSPECTION FORM #_____ of _____

AIRCRAFT:		W/O:		SIGNED OFF BY:			
GRID # : 3		I & E INSPECTOR:		________LEADER		________SUPERVISOR	
ITEM	DISCREPANCY			CORRECTIVE ACTION			
							* QA REQ Y / N
							MECH
DAMAGE DATA:	L =	W =	D =	IF CORRODED:	TYPE:	SEV:	LABOR HOURS

FIGURE 5. Discrepancy card used to capture corrosion data

Corrosion mapping reports are available in two formats. One is a frequency pictorial grid report that allows the selection of a number of variables. These variables include the aircraft zone, the specific grid, the aircraft tail number, the depot date, the corrosion type and the severity. A multi-dimensional online analytical cube allows for data mining of the corrosion mapping database. The program allows manipulation of all corrosion variables and provides various summary corrosion data reports.



Corrosion Mapping - Corrosion Count Report

16 OCT 2007 / 1408

ALMIS Portal | Add Corrosion Data | Edit Corrosion Data | Corrosion Entry Report | Corrosion Count Report | Help

Corrosion Count Report

Aircraft Type: HH65

Tail Number: All

Zone: 4 - X2000-X6630, Below Deck Angles

MPC Number: D53101.4

Grid: 4 - X2000-X3205 Deck Angles/Fishplates

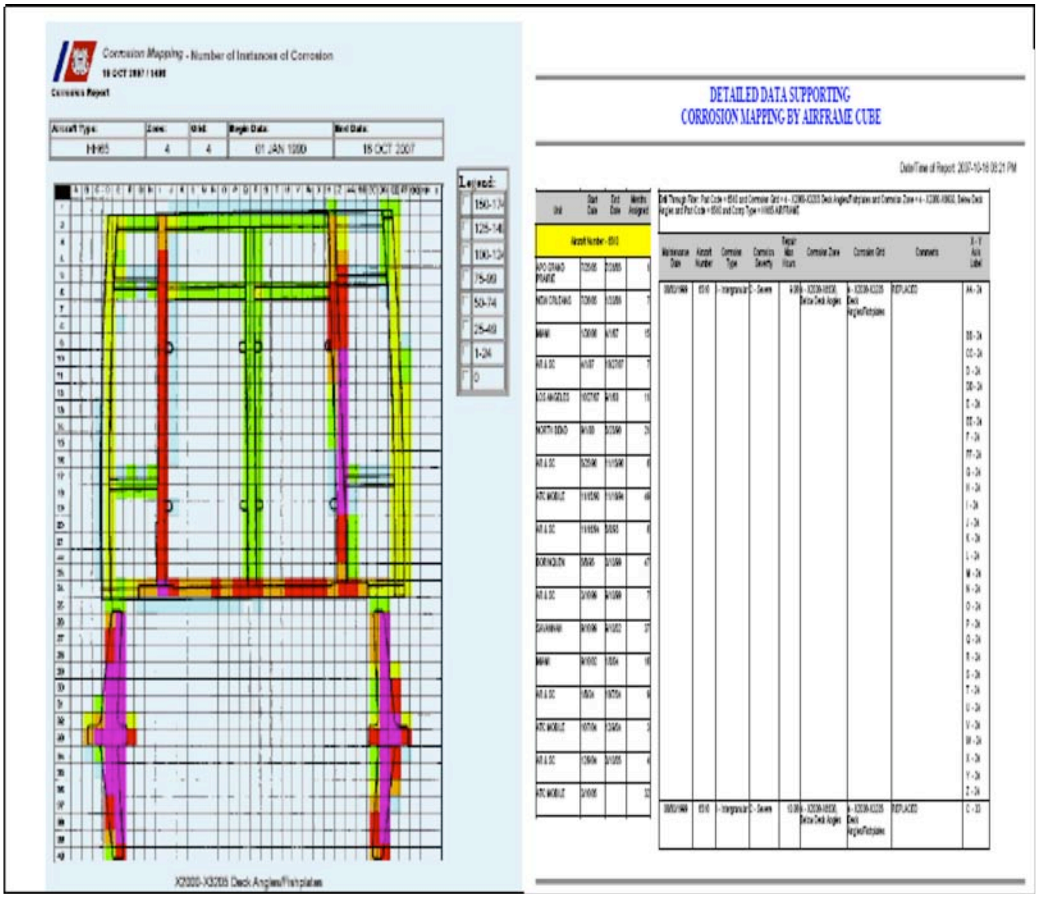
Begin Date: 01/01/1990

End Date: 10/16/2007

Corrosion Type: P - Pitting

Severity: C - Severe

FIGURE 6. Corrosion Mapping Program. Numerous variables can be used to generate corrosion mapping reports



Corrosion Mapping - Number of Instances of Corrosion

Corrosion Report

Aircraft Type:	Zone:	Unit:	Begin Date:	End Date:
HH65	4	4	01 JAN 1990	18 OCT 2007

Legend:

- ☐ 150-17
- ☐ 125-14
- ☐ 100-12
- ☐ 75-99
- ☐ 50-74
- ☐ 25-49
- ☐ 1-24
- ☐ 0

X2000-X3205 Deck Angles/Fishplates

DETAILED DATA SUPPORTING
CORROSION MAPPING BY AIRFRAME CUBE

Date/Time of Report: 2007-10-18 08:21 PM

FIGURE 7. Corrosion mapping reports

EXPERIMENT

Aircraft from six Coast Guard air stations were selected to develop probability survival curves. The air stations were categorized as mild or severe depending on their boldly exposed weight loss corrosion rates. HH-65 corrosion mapping reports of Zone 4 indicate the structure below the floorboard as highly corrosive. Further data mining identifies Grid 4 as highly susceptible to corrosion failure. Data for a small sample size of this area was simulated to develop survival curves.

Table 6 outlines the data layout for the analysis. Failure due to corrosion is designated as a “1”. If the structure survived at observation time t, the data point is censored and assigned a “0”. Explanatory variables such as the air station severity, is designated “1” for severe and “0” for mild. The statistical software used was Stata. A survival analysis curve was generated for Zone 4, Grid 4 comparing the probability of failure for aircraft assigned to mild or severe environmentally corrosive locations

TABLE 6

Basic Data Layout for Computation

Air Station ID	Aircraft Tail Number	Time, months	Corrosion 1 = Failure 0 = Censored	Severity 1 = Severe 0 = Mild
1	6540	56	0	1
2	6553	39	0	0
3	6561	60	1	0
4	6502	36	1	1
5	6527	37	1	1
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
n	$\text{aircraft}_{(id)}$	$t_{(n)}$	δ	X

Results

Figure 8 is a Kaplan-Meier probability plot comparing the corrosion survival curves for aircraft assigned to a mild or severe environment. The two curves do not converge, suggesting the effects of corrosion are greater the longer an aircraft remains in a high corrosive climate.

Given the simulated data for these helicopters, this experiment demonstrates the application of survival analysis to the field of corrosion engineering. The analysis accounts for influencing variables and censored data. It provides statistical framework for structural life assessment and the management of aircraft to minimize the effects from damage environmental locations. Further research applying the statistical techniques of survival analysis to the corrosion of aging aircraft is warranted.

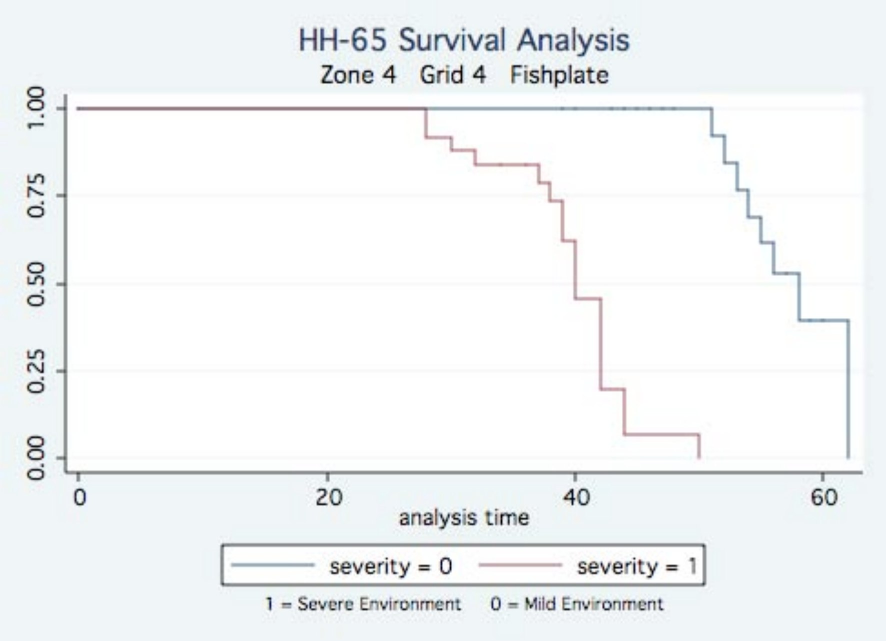


FIGURE 8. Kaplan-Meier survival analysis probability plot

CONCLUSIONS

This work is demonstrating the successful broadening of survival analysis to corrosion engineering by providing an innovative framework of aging aircraft probability corrosion failure. This work is to improving the understanding of failure rates, thereby providing a novel statistical framework for structural life assessments and management of corrosion mitigating based on real-world data.

BIBLIOGRAPHY

Abbott, William H., and Richard Kinzie. "Corrosion Monitoring on Operational Aircraft Status of Recent Work." Paper presented at the Joint NASA/FAA/DoD Conference on Aging Aircraft Conference, New Orleans, LA 2003.

Clark, T.G., M.J. Bradburn, S.B. Love, and D.G. Altman. "Survival Analysis Part I: Basic Concepts and First Analyses." *British Journal of Cancer* 89 (2003): 232-38.

———. "Survival Analysis Part Ii: Multivariate Data Analysis - an Introduction to Concepts and Methods." *British Journal of Cancer* 89 (2003): 431 - 36.

———. "Survival Analysis Part Iii: Multivariate Data Analysis - Choosing a Model and Assessing Its Adequacy and Fit." *British Journal of Cancer* 89 (2003): 605 - 11.

Dixon, Matthew C. "The Costs of Aging Aircraft: Insights from Commercial Aviation." Dissertation, Pardee RAND Graduate School, 2006.

GAO. "Opportunites to Reduce Costs and Increase Readiness." edited by United States Government Accounting Office, 2003.

———. "Report to Congressional Committees, High-Level Leadership Commitment and Actions Are Needed to Address Corrosion Issues." edited by United States Government Accounting Office. Washington, DC, 2007.

———. "Status of Department of Defense (Dod) Corrosion Prevention and Mitigation Efforts (Preliminary Observations)." edited by United States Government Accounting Office, 2002.

Greenfiled, Victoria A., and David M. Persselin. "How Old Is Too Old? An Economic Approach to Replacing Military Aircraft." *Defence and Peace Economics* 14, no. 5 (2003): 357-68.

Guedes, Soares, and Garbatov. "Reliability of Corrosion Protected and Maintained Ship Hulls Subjected to Corroson and Fatigue,." *Journal of Ship Research* 43, no. 2 (1999): 65-78.

Harter, J. *Afgrow Users Guide and Technical Manual*: AFRL-VA-WP-TR-2004-XXX.

Hougaard, Philip. *Analysis of Multivariate Survival Data*: Springer, 2000.

Industry, Defense Daily.

Klein, John P., and Melvin L. Moeschberger. *Survival Analysis, Techniques for Censored and Truncated Data*. New York: Springer, 2003.

Kleinbaum, David G., and Mitchel Klein. *Survival Analysis, a Self-Learning Text*. New York: Springer, 2005.

Kock, Gerhardus H., Michiel P.H. Brongers, Neil G. Thompson, Y. Paul Virmani, and Joe H. Payer. "Corrosion Cost and Prevention Strategies in the United States." 773. Dublin, OH: CC Technologies Laboratory, NACE International, 2001.

Kreisher, Otto. "Aircraft Geriatrics."

Kuo, Yong-Fang. "Statistical Methods for Determining Single or Multiple Cutpoints of Risk Factors in Survival Data Analysis." The Ohio State University, 1997.

Li, Zhiguo, S. Zhou, S. Choubey, and C. Sievenpiper. "Failure Event Prediction Using the Cox Proportional Hazard Model Driven by Frequent Failure Signatures." *IIIE Transactions* 39 (2007): 303-15.

Magnuson, Stew. "Aging Aircraft, War Costs Weigh Heavily in Future Budgets." *National Defense* 91, no. 638 (2007): 40.

Melchers, R.E. "Transition from Marine Immersion to Coastal Atmospheric Corrosion for Structural Steels." *The Journal of Science and Engineering Corrosion* 63, no. 6 (2007): 501.

Milliman, John. "The War on Aging Aircraft: One Battle Down, Many to Go." *Naval Aviation News*, July-August, 2002.

NTSB. "Aloha Airlines, Flight 243, Boeing 737-200, N737311, near Maui, Hawaii." edited by National Transportation Safety Board, 1988.

Pelletier, Genevieve, Alain Maihot, and Jean-Pierre Villenueve. "Modeling Water Pipe Breaks - Three Case Studies." *Journal of Water Resources Planning and Management* 129, no. 2 (2003): 115-23.

Pillsbury, Major General James. "Aging Aircraft: An Army Perspective." Paper presented at the 10th Joint Dod/NASA/FAA Conference on Aging Aircraft, Palms Spring, CA 2007.

Rudnicki, Krzyszt Janusz. "A Dynamic Model for Survival Data with Longitudinal Covariates." Rice University, 2006.

Satagopan, J.M., L. Ben-Porat, M. Berwick, M. Robson, D. Kutler, and A.D. Auerbach. "A Note on Competing Risks in Survival Data Analysis." *British Journal of Cancer* 91 (2004): 1229 - 35.

Seher, Chris. "Managing the Aging Aircraft Problem." In *The AVT Symposium on Aging Mechanishms and Control the Specialist Meeting on Life Management Techniques for Aging Air Vehicles*. Manchester, England.

Sparling, Yvonne Marie Herbert. "Parametric Survival Models for Interval-Censored Data with Time-Dependent Covariates." The George Washington University, 2002.

Stillman, R.H. "Modeling Failure Data of Overhead Distribution Systems." *IEEE Transactions on Power Delivery* 15, no. 4 (2000): 1238-42.

Therneau, Terry M., and Patricia M. Grambsch. *Modeling Survival Data, Extending the Cox Model*. New York: Springer, 2001.

Ullett, J.S. "Prediction of Corrosion Growth Rates in Legacy Alloys." Paper presented at the U.S. Air Force Corrosion Conference, Macon, GA, 6-8 March, 2007.

Wang, Yuhong, Kamyar C. Mahboub, and Donn E. Hancher. "Survival Analysis of Fatigue Cracking for Flexible Pavements Based on Long-Term Pavement Perfromance Data." *Journal of Transportation Engineering* 131, no. 8 (2005): 608 - 16.