APPENDIX BB

DEFENSE


High-mobility multipurpose wheeled vehicle


F-18 Fighter Jet


Towed howitzer


KC-135 tanker


Harrier jump jet


Towed howitzer


Rocket launcher on helicopter


Helicopter

APPENDIX BB

DEFENSE

GERHARDUS H. KOCH, PH.D.[1]

SUMMARY AND ANALYSIS OF RESULTS

Corrosion Control and Prevention

The ability of the U.S. Department of Defense (DOD) to respond rapidly to national security and foreign commitments can be adversely affected by corrosion. Corrosion of military equipment and facilities has been, for many years, a significant and ongoing problem. The effects of corrosion are becoming more prominent as the acquisition of new equipment is slowing down and the services of aging systems and equipment are increasingly relied upon. The data provided by the military services indicate that corrosion is the number one cost driver in life-cycle costs. The total annual cost of corrosion incurred by the military services (Army, Air Force, Navy, and Marine Corps) for both systems and infrastructure was estimated at $20 billion.

A considerable portion of the cost of corrosion to the Army is attributed to ground vehicles, including tank systems, fighting vehicle systems, fire support systems, high-mobility multipurpose wheeled vehicles (HMMWV), and light armored vehicles. Other systems that are affected by corrosion include firing platforms and helicopters. Many of the Army systems are well beyond their design service lives and because of the generally aggressive operating environments, corrosion is becoming increasingly severe and costly. While often replacement of the aging systems is not budgeted for, insufficient use is being made of existing technology to maintain these systems in a cost-effective way. Even with the procurement of new weapons systems, the use of corrosion-resistant materials and design are often neglected. For example, when the HMMWV was procured, corrosion was completely ignored in the design and manufacturing of the vehicle. Without corrosion design and the incorporation of corrosion-resistant material, the acquisition cost of the vehicle could be reduced. However, costly corrosion problems were experienced on the vehicles only a few months after delivery. Similar problems were found with the acquisition of other systems, such as the medium tactical vehicles (MTV).

In recent years, the Air Force has experienced considerable corrosion problems. As with the commercial aircraft industry, corrosion on the airframe has, in the past, not been considered to have an impact on the structural integrity; therefore, a “find it and fix it” approach has long been the preferred way to deal with corrosion in aircraft. With no significant funding available for new systems acquisition, the Air Force is forced to extend the operational life of many of the aircraft far beyond their design service lives. For example, the KC-135, which is the backbone of the Air Force tanker fleet, and which was built between 1955 and 1963, will have to serve until the year 2040. This aircraft, which was built with 1950s corrosion control technology (none), was never meant to serve this long, and hence, severe corrosion has been experienced. The results of all the corrosion problems with the KC-135 have led to a significant increase in depot maintenance over the past 10 years. Mainly as a result of corrosion, the depot overhaul flow days have increased from less than 100 days in 1990 to approximately 350 days in 2000.

Because of their missions, the Navy and Marine Corps have always operated in aggressive corrosive environments. The Navy operates the fleet as well as naval aircraft, and harbor and dock facilities. The fleet consists of various types of surface ships and submarines, which are continuously exposed to marine environments. The primary defense against corrosion is the diligent use of protective coatings. In addition to coatings, cathodic protection systems are used for corrosion protection of the underwater hull. In recent years, more durable and longer lasting paint systems have been introduced to replace what used to be very labor-intensive paint systems.

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[1] CC Technologies Laboratories, Inc., Dublin, Ohio.

Navy aircraft systems require constant maintenance due to operation in predominantly marine environments. As in the Air Force, many aircraft systems are operating beyond their design service lives, which leads to an increasing cost of corrosion maintenance.

Opportunities for Improvement and Barriers to Progress

The aging of military systems poses a unique challenge for maintenance and corrosion engineers in all four Services. The most serious problem facing the military is aging equipment, with no immediate promise of replacement; therefore, there is a need to develop corrosion maintenance programs that can carry the various aging systems well into the 21st century. Such a program requires cooperation between all the services and the commitment of systems management and maintenance personnel to succeed. Developing an optimum approach to inspection, monitoring, and maintenance is necessary to maintain the readiness of the nation's military systems in a cost-effective manner until replacement by new systems is possible. Awareness of the corrosion problems and knowledge about state-of-the-art corrosion control techniques will be essential in developing and carrying out a successful corrosion control and maintenance program.

Although each of the services is trying to deal with its own aging systems problem, it is of the utmost importance that a cooperative corrosion/integrity program is implemented. For example, while the Navy has been dealing with corrosion on its aircraft on a daily basis, the Air Force has, until recently, ignored corrosion unless it becomes clearly visible. Although the Air Force currently has a well-developed program in place to monitor and control fatigue cracking [i.e., Air Force Structural Integrity Program (ASIP)], corrosion was not considered to be a structural threat and was therefore essentially treated on a "find it and fix it" basis, but only when it was clearly visible.

When new systems are procured, the design service lives, as determined by corrosion, have often taken a backseat to immediate performance and quantity of procurement.

Recommendations and Implementation Strategy

In order to preserve the aging military assets, a DOD corrosion control and maintenance program must be developed and implemented for all of the services. An important component of such a program is the increase in awareness and recognition by all military personnel from systems management to procurement and maintenance personnel that corrosion is an important factor in the life of any military system. Courses and training will be needed to develop the knowledge to deal with corrosion. Funding needs to be made available to develop predictive corrosion models and new inspection and monitoring techniques, which will enable systems management to maintain their systems in a cost-effective manner.

Life-cycle costing must be considered when new systems are procured. This will allow acquisition of systems with the best available corrosion protection.

Summary of Issues

Increase consciousness of corrosion costs and potential savings.	Both personnel responsible for the procurement of new systems and those responsible for maintaining existing systems must be aware of the effects of corrosion, as well as the corrosion control techniques and methods that are available to cost-effectively mitigate these effects.
Change perception that nothing can be done about corrosion.	Although corrosion is a well-known phenomenon in the military, state-of-the-art mitigation techniques are generally not used.
Advance design practices for better corrosion management.	When new systems are procured, performance and quantity are emphasized at the expense of corrosion control.
Change technical practices to realize corrosion cost-savings.	The key is to incorporate state-of-the-art inspection monitoring and other corrosion control techniques into a corrosion management system.
Change policies and management practices to realize corrosion cost-savings	Systems management must appreciate the importance of corrosion and understand its impact on total life maintenance costs. Cooperation between the services to manage the military's new and aging assets is a necessity. The "find it and fix it" mentality to corrosion maintenance should be changed.
Advance life prediction and performance assessment methods.	The development of corrosion life prediction and performance models is critical to cost-effective asset management. Effective predictive models are currently not available.
Advance technology (research, development, and implementation).	Technological advances that are needed include a better understanding of the corrosion process and improved inspection and monitoring techniques.
Improve education and training for corrosion control.	Education and training of engineering personnel and technicians are necessary if a cost-effective corrosion control and maintenance program is to be implemented.

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SECTOR DESCRIPTION

The ability of the U.S. Department of Defense (DOD) to respond rapidly to national security and foreign policy commitments can be adversely affected by equipment-related factors. Using available resources, minimization of downtime and maximization of battle readiness must be accomplished through the useful operational life of the equipment. If this is done effectively, equipment can be deployed in a timely and responsive manner and maintained in the field with a minimum of downtime.

Corrosion of military equipment and facilities has been a significant and on-going problem. Large yearly costs are incurred to protect these assets from corrosion, affecting procurement, maintenance, and operations. The effect of corrosion on various systems is a problem that is becoming more prominent as the acquisition of new equipment slows and more reliance is placed on modifications and upgrades to extend the life of the current systems. As the intention to operate the aging fleets of aircraft, ships, land combat vehicles, and submarines continues into the 21st century, the potentially detrimental effects of corrosion on the cost of ownership, safety, and readiness must be fully appreciated. The effects of corrosion of the DOD equipment will continue to get worse unless and until new technologies can be utilized to reduce the cost of ownership. Within the DOD, the annual costs are very difficult to ascertain; however, from available data obtained from the individual services (Army, Air Force, Navy, and Marine Corps), it can be estimated that the total annual cost of corrosion to the DOD is approximately $20 billion for systems and infrastructure.(1)

Available data from the services indicate that corrosion in DOD weapons systems is the number one cost driver in life cycle-costs.(2) While the individual services have attempted to quantify the cost of corrosion, neither the mechanisms nor the methodologies exist to accurately quantify what appears to be an enormous problem. Moreover, analysis of field data reveals instances where questionable materials selection early in the acquisition process has led to enormous unanticipated increases in life-cycle costs due to corrosion.(3) Finally, with ongoing force reduction and a reduction in budgets, serious consideration must be given to the selection of advanced materials, processes, and designs that will require less manpower for corrosion inspection and maintenance. The following sections provide specific information on the corrosion costs incurred by the Army, the Air Force, the Navy, and the Marine Corp. It should be noted that the corrosion costs of selected components in these services do not add up to the $20 billion that was referenced above. They only serve as examples of how corrosion can significantly affect the equipment and facilities of the armed services.

Army

The Army, which is a major branch of the armed forces, owns and operates a range of facilities and equipment. These include buildings, vehicles and trucks, aircraft and helicopters, missiles, and weapons storage facilities. Corrosion creates a significant burden for the Army, affecting the Army's readiness, equipment reliability, troop morale, and, in particular, the cost of maintenance of the weapons systems.

Vehicles

A considerable portion of the corrosion cost ($2 billion) is attributed to Army ground vehicles. The major types of vehicles operated by the Army are listed below:

- Abraham Tank Systems – M1 Abrams
- Bradley Fighting Vehicle Systems
  - M2 Infantry Fighting Vehicles (IFV)
  - M3 Cavalry Fighting Vehicles (CFV)
  - Multiple-Launch Rocket Systems (MLRS)
  - Command and Control Vehicles (C2V)

- Bradley Carrier Systems
- Bradley Fire Support Vehicles
  - Medium Tactical Vehicles
  - 2½-Ton Cargo Trucks
  - 5-Ton Cargo Trucks
- High-Mobility Multipurpose Wheeled Vehicles (HMMWV)
- Light Armored Vehicles

Generally, little attention is given to corrosion and corrosion control of Army vehicles. In fact, corrosion on these vehicles is allowed to occur until it affects their load-carrying capacity. Moreover, little has been done to incorporate corrosion protection and control in the design and manufacturing of Army vehicles. For example, none of the medium tactical vehicles has galvanized steel in the body. The high-mobility multipurpose wheeled vehicle (HMMWV) (see figure 1) is known to have several corrosion control shortcomings that result in very high corrosion maintenance costs.(2,4) In designing the HMMWV, several corrosion control features that are now common in commercial vehicles have not been applied.(2) One of the most glaring faults with the HMMWV is that the frame is built of ordinary 1010 steel and that no galvanizing or other corrosion protection is applied. A further problem with the frame is that holes are drilled into the sides of the frame with no drain holes in the bottom. This allows water and dirt to enter and stand inside the frame. Other problems include the use of 1010 carbon steel for components such as fasteners, handles, and brackets, as well as the use of dissimilar metal couples, such as aluminum frames bolted to the steel frames. These and other omissions of corrosion control have led to costly maintenance and repair. During an Inspector General's Audit, various areas prone to corrosion were identified(4) (refer to Case Study 1). The significant shortcomings identified by this audit included:

- use of 1010 carbon steel without galvanizing or any protective coating,
- presence of many galvanic couples and the use of more than 2,800 rivets that may act as possible locations for corrosion,
- use of painting procedures that are not state-of-the-art, and
- use of paint that provides little corrosion protection, such as the chemical agent-resistant coatings that deteriorate rapidly in the presence of a corrosive environment.

According to the Inspector General's report, the overall corrosion-related issues associated with the HMMWV and other vehicles cost the Army an estimated $2 billion to $2.5 billion per year.(4) The report points out that corrosion not only affects the cost of vehicle ownership, but also readiness and the overall life of the vehicle. Although there are no cost figures available, the Inspector General estimated that vehicles requiring corrosion repairs were out of service between 2 and 12 months. Furthermore, the threshold for replacement of wheeled vehicles is 65 percent of the acquisition cost of the vehicle. The Inspector General found several examples where the corrosion damage was actually greater than 65 percent of the replacement cost, resulting in vehicles as new as 5 years old being scrapped to be replaced by new vehicles. A more detailed description of corrosion issues with the HMMWV is provided as a case study.

A 1999 report by the U.S. General Accounting Office (GAO) reported that the Army plans to purchase, from 1991 through 2022 (a 32-year period), 85,488 medium tactical vehicles (MTVs) at a projected cumulative cost of $15.7 billion (85,488 x $200,000) to replace its aging medium truck fleet.(5) The report stated that the first 4,955 MTVs that were produced did not meet the MTV's corrosion protection requirements. The contract with the supplier specified that the trucks were to be designed to prevent corrosion from perforating or causing other damage requiring repair or replacement of parts during the initial 10 years of service. Corrosion was found on the cabs of trucks in less than 3 years. Rather than making the contractor replace all 4,955 truck cabs at a cost of $31 million, the Army accepted the contractor's proposal to repair the corrosion damage and to provide a 10-year warranty, not to exceed $10 million, against any future corrosion.

Figure 1. High-mobility multipurpose wheeled vehicle.

The Army also subjected one of the 4,955 trucks to contract-specified corrosion tests. It failed with corrosion being detected in 60 areas. Subsequently, the Army and the contractor agreed on modified production procedures for the next 2,491 produced trucks in order to address the corrosion problem. The contract's final 3,751 trucks were produced with galvanized steel cabs. The Army agreed to pay up to $7 million additional funding for these cabs and other corrosion improvements.

Firing Platforms

Other significant contributors to corrosion costs in the Army are the howitzer firing platforms. (3) The M119 is a 105-mm towed howitzer of British design (see figure 2). Procurement of the M119 started in the late 1980s and was completed in 1996, with a total of approximately 500. In early 1997, severe corrosion was detected on the platform. An investigation by the Army indicated several deficiencies that lead to severe corrosion, including various dissimilar metal contacts resulting in galvanic corrosion and areas on the platform where water could collect. The design of the howitzer platform was such that it needed to be replaced at a cost of $18,000 each; therefore, the total cost to remedy the corrosion problem is estimated to be approximately $9 million.

Figure 2. M119 105-mm towed howitzer.

A second howitzer corrosion problem is experienced with the towed M198 howitzer of which 1,800 are in service (see figure 3). In order to maintain system readiness, an annual expenditure of $5,300 for parts replacement is required for each M198. The total annual maintenance cost for just corrosion-related parts replacement is estimated at $10 million (1,800 x $5,300). Figure 4 shows an attempt to avoid corrosion in an M198 howitzer frame by drilling a drain hole; however, by not having the drain hole at the lowest point, water can still collect inside the frame.

Figure 3. M198 towed howitzer.

Figure 4. Drainhole in M198 towed howitzer.

Helicopters

The Army operates several helicopters for several different duties, with many of the helicopters dating back to the Vietnam era:

UH-1	Huey	personnel ferrying helicopter (900)
UH-60	Blackhawk	personnel ferrying helicopter

CH-47	Chinook	heavy-cargo lifting helicopter (431)
AH-1	Cobra	gunship (379)
AH-64	Apache	attack helicopter (743)
OH-58	Kiowa	reconnaissance helicopter
RAH-66	Comanche	reconnaissance, light attack, and air combat helicopter (1,213 starting deployment in 2008)
MH-6	Little Bird	light assault

In February 2000, the Army released a report indicating that 40 percent of its helicopter fleet is not combat-ready.(6) In addition, these problems are experienced particularly with aging equipment such as the Vietnam War-era Hueys and Cobras, which are assigned mostly to the National Guard and the Army Reserve Units. In addition, newer helicopters, such as the Apaches and Chinooks, also suffer from combat-readiness problems. Approximately 8 to 22 percent of overhaul and repair costs are due to corrosion. In fact, it was estimated that in 1998, approximately $4 billion was spent on corrosion control of helicopters alone.(3)

Air Force

As the fleet of military aircraft and support equipment ages, the damage caused by corrosion becomes of increasing concern. The aircraft spend a longer time in depots for maintenance and repair, which leads to a decrease in readiness and an increase in the cost to maintain the aircraft. Moreover, a possible loss of integrity of the structure is possible if the corrosion goes undetected and becomes severe.

Recently, a study was completed for the Air Force Corrosion Program Office to determine the annual cost of direct corrosion maintenance to the Air Force.(7) The Air Force study examined the cost for fiscal year 1996 and examined costs for all Air Force systems and equipment, including all aircraft, aircraft subsystems, ground systems, vehicles, missiles, munitions, ground support equipment, and space equipment. Corrosion maintenance was defined as a comprehensive inspection for corrosion, all repair maintenance due to corrosion, washing sealant application and removal, and all coating application and removal. Intangible or indirect costs, such as aircraft downtime; the impact on mission performance ability or readiness that results from downtime; and the depreciation effects that result from corrosion maintenance, such as repeated grind-outs of skin and structure, were not addressed in the study. Other intangible or indirect costs that were not addressed include the costs of building corrosion control facilities; the cost of building and maintaining formal corrosion maintenance schools for training of maintenance technicians; and the cost to produce, distribute, and install specialized corrosion control equipment in corrosion control shops.

The total cost of direct corrosion maintenance to the Air Force for fiscal year 1997 was estimated at approximately $800 million.(7) The elements that make up this total cost are summarized in table 1. The table clearly indicates that the majority of the cost can be attributed to aircraft repair and paint. There were also significant expenditures in washing and vehicle maintenance. In addition to the total cost findings, it was found that maintenance in the depot accounted for 80 percent of the total cost of corrosion maintenance. Moreover, it was found that while the total number of aircraft in the fleet has decreased by about 20 percent, the costs have only declined 10 percent, and that maintenance directly attributed to aircraft has actually increased.

The study further compared the 1997 fleet costs with the 1990 fleet costs (see table 2).(7) Changes in the overall corrosion maintenance costs and the contribution of different weapons systems were examined, as well as changes in the per plane costs within the specific weapons systems.

Table 1. Elements of total corrosion maintenance cost to the Air Force.(7)

TOTAL MAINTENANCE COST, FISCAL YEAR 1997	
Repair	$572,352,704
Wash	28,443,783
Paint	145,951,530
Vehicles	23,291,759
Munitions	6,247,341
Other	18,540,036
TOTAL	**$794,827,153**

Table 2. Corrosion maintenance cost for individual military aircraft in 1990 and 1997.(7)

AIRCRAFT	**1990 FLEET COSTS (1997 $)**	**NUMBER OF AIRCRAFT**	**CORROSION COST (%)**	**1997 FLEET COSTS (1997 $)**	**NUMBER OF AIRCRAFT**	**TOTAL CORROSION COST (%)**	**CHANGE IN NUMBER OF AIRCRAFT**
A-10	25,611,157	524	4.25	4,326,700	375	0.69	-149
B-1	1,267,086	76	0.21	7,326,979	95	1.17	19
B-52	95,751,947	228	15.90	39,545,321	94	6.29	-134
C-130	137,963,143	694	22.91	50,351,736	694	8.01	0
KC-135	113,554,678	644	18.86	205,561,487	602	32.72	-42
C-141	68,621,286	231	11.40	102,584,893	220	16.33	-11
C-5	17,019,858	126	2.83	104,595,003	126	16.65	0
CLS	3,286,630	180	0.55	6,301,275	321	1.00	141
E-3	3,698,062	32	0.61	19,851,017	32	3.16	0
F-111	41,778,986	245	6.94	7,749,299	37	1.23	-208
F-15	23,325,398	749	3.87	29,194,683	737	4.65	-12
F-16	17,010,711	1,260	2.83	15,728,095	1,513	2.50	253
Helos	4,854,452	179	0.81	2,511,531	215	0.40	36
C-10	666,302	52	0.11	7,439,773	59	1.18	7
T-37	2,278,434	527	0.38	1,326,593	420	0.21	-107
T-38	13,105,291	812	2.18	23,894,508	451	3.80	-361
A-7	1,600,922	214	0.27				-214
A-37	345,047	58	0.06				-58
F-4	26,867,597	746	4.46				-746
F-5	72,943	7	0.01				-7
OV-10	3,438,883	54	0.57				-54
TOTAL	**$602,118,813**	**7,638**	**100.01%**	**$628,288,893**	**5,991**	**99.99%**	**-1,647**

One of the most significant results was the effect of aging on weapon systems costs. Each of the oldest fleets of aircraft is a high-dollar driver where the difference in costs between these fleets is primarily a reflection of the difference in size and difference in age. Together, these fleets consume more than half of the total corrosion maintenance costs expended by the Air Force. It is anticipated that these corrosion maintenance costs will increase due to continued aging of the fleet. For example, the KC-135 fleet (see figure 5), which was built between 1955 and 1963, is, despite its age, the backbone of the Air Force's tanker fleet. The KC-135 was never meant to handle its mission for this long and was therefore not constructed with corrosion prevention as a primary concern. Moreover, since no funds are available for replacement tankers, it was decided to operate the fleet until the year 2040. Without extensive corrosion maintenance, structural degradation due to corrosion will limit the KC-135 life to less than the year 2040. Because of the decision to extend the service life of the KC-135 well beyond its corrosion design life, corrosion maintenance expenditures have increased from an average of $176,327 per aircraft in 1990 to $341,464 per aircraft in 1997, which is a 94 percent increase. Cost forecasts by the Air Force predict that during the first decade of 2000, the cost of airframe depot maintenance will increase by a factor of two to three. After this period, the costs are expected to level off if all critical components that are subject to corrosion damage are repaired or replaced. Case Study 2 will discuss the KC-135 in more detail.

Figure 5. KC-135 tanker aircraft.

Other significant observations reported in the Air Force Cost of Corrosion study are:

1. The A-10, C-130, and F-16 fleets experienced a reduction in the cost of corrosion maintenance greater than the reduction in fleet size. The decrease in A-10 costs is a strong indicator that corrosion problems with this particular aircraft have been largely resolved. Repeat maintenance has not been required in the areas that received extensive corrosion treatment.

2. The decrease in C-130 corrosion maintenance costs reflects the completion of a significant wing modification on the C-130E fleet and the continued delivery of C-130H models that are built with much more effective corrosion prevention technology than the A, B, and early E models they replaced.

3. The decrease in F-16 costs appears to be a reflection of a significant increase in the fleet size, which results in a younger fleet.

4. Increases are noted in the cost of corrosion maintenance for both the B-1 and E-3 fleets. During the earlier (1990) study, there were no depot corrosion costs reported and, since that time, programmed depot maintenance (PDM) programs have started up. Both aircraft have larger than average percentages going through PDM.

5. The F-111 PDM reduced dramatically because of a projected phase-out of the fleet.

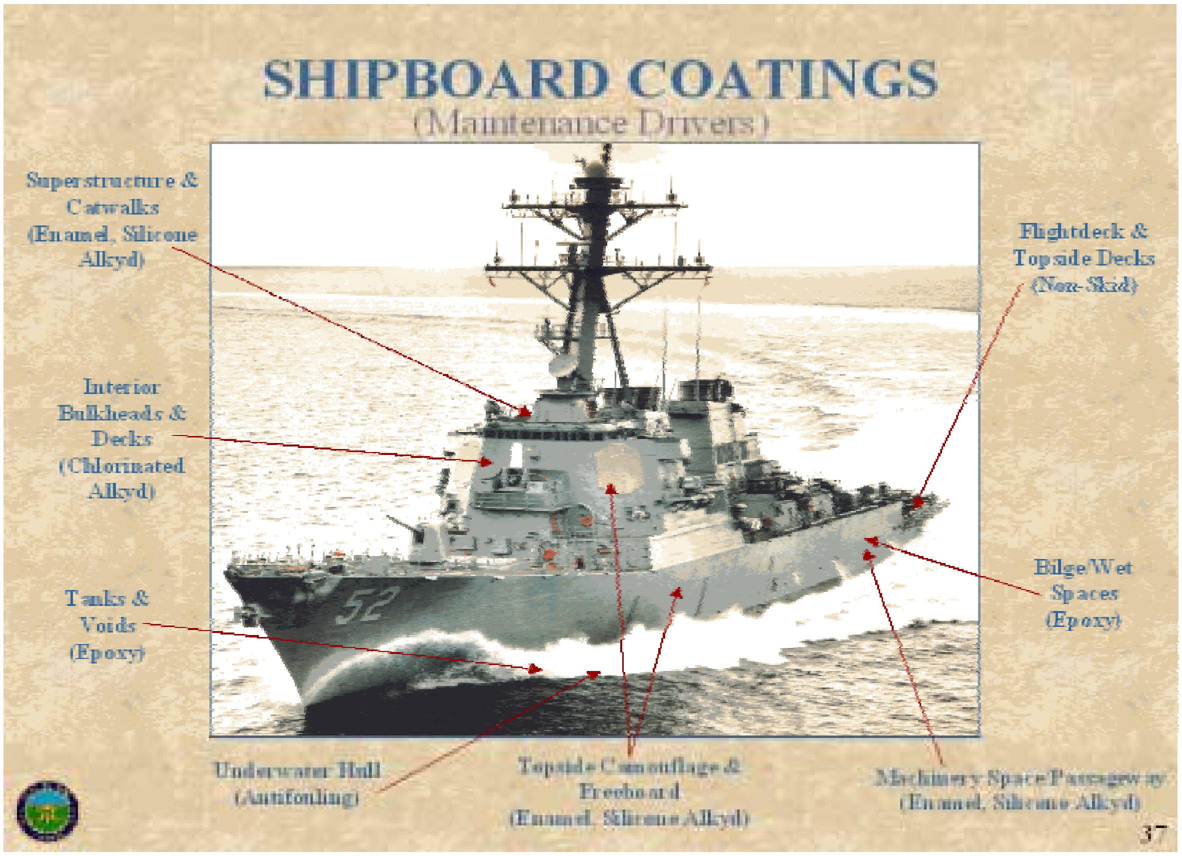
6. The T-38 Queen Bee flow is basically unchanged despite a significant reduction in fleet size. Corrosion maintenance remains a significant part of the T-38 workload.

Navy

The Navy is divided into several components, including ships, submarines, aircraft weapons, and facilities (buildings, piers, docks, and harbor structures). An internal Navy study conducted in 1993 estimated the total cost of corrosion for all naval systems at $2 billion per year.(8)

Ships

The Navy fleet consists of various surface ship battle forces, including 11 aircraft carriers, 106 surface combatants (i.e., cruisers, destroyers, and frigates), 39 amphibious warfare ships, 34 combat logistics ships, and 31 support/mine warfare ships (total of 221 ships). The surface ships are subject to extremely aggressive environments. An extensive corrosion control program is required to maintain the fleet during dry-dock cycles. The primary defense against corrosion is the diligent use of protective coatings. In addition to coating, cathodic protection is used for protection of the underwater hull. The cost to maintain the cathodic protection systems is low compared to the cost of maintaining the various protective coatings.(9) Figure 6 shows a photograph of a destroyer, indicating the different shipboard coatings that are currently in use. The traditional coatings indicated in the figure have a design life of 10 to 15 years, after which the ship has to be in dry dock to completely remove the "old" coatings and apply a "new" coat.


SHIPBOARD COATINGS

(Maintenance Drivers)

Figure 6. Destroyer with different shipboard coatings currently in use.(9)

Between the major maintenance cycles, there is an annual maintenance demand for continuous coating maintenance. Table 3 shows the breakdown in man-years per ship for the different painting activities.

Table 3. Annual maintenance demand on sailors for coating maintenance of Navy surface ships.(9)

MAINTENANCE ACTIVITIES	MAN-YEARS PER SHIP
Topside & Freeboard (Enamel, Silicone Alkyd)	9.0
Flight Decks & Topside Decks (Non-Skid)	4.0
Bilges/Wet Space Corrosion	4.5
Machinery Space/Passageways (Enamel, Silicone Alkyd)	2.25
Interior Bulkheads & Decks (Chlorinated Alkyd)	3.0
Superstructure, Catwalks, Mixing/Fan Room Corrosion (Epoxy)	3.25
TOTAL	**26.00**

Assuming that the cost of a man-year is $150,000, the average corrosion-related maintenance cost between dry-dock cycles can be estimated at $3.9 million per ship per year. When it is estimated that a total of 6,500 man-years are expended on the preservation of all surface ships in 1 year,(9) the total annual cost for corrosion-related maintenance between dry-dock cycles can be estimated at $975 million (6,500 man-years for all ships x $150,000 / man-year).

Submarines

The Navy operates 18 fleet ballistic missile submarines and 56 nuclear attack submarines. Because of the secretive nature of submarines, no information on corrosion maintenance could be obtained.

Aircraft

Corrosion has a significant impact on the life-cycle costs of naval aircraft. The Navy has three levels of aircraft maintenance, including organizational, intermediate, and depot maintenance. The organizational maintenance is performed on individual equipment and includes inspection, servicing, lubrication, adjustments, and replacement of parts, assemblies, and subassemblies. The intermediate maintenance is conducted on parts after removal from equipment and includes calibration, repair, or replacement of damaged or unserviceable parts and components or assemblies. Finally, depot maintenance involves major overhaul or complete rebuild of parts, assemblies, sub-assemblies, and end items, including the manufacture of parts, modifications, testing, and reclamation as required. A current estimate for corrosion maintenance costs is $200,000 per Navy aircraft per year,(8) which is approximately twice as much as the corrosion costs for Air Force aircraft ($100,000 per year) operating under less corrosive conditions. Note that the average corrosion maintenance cost for Naval aircraft is higher than the average cost for Air Force aircraft, which is reasonable considering the more severe environment in which Naval aircraft operate. With a total number of 4,000 naval aircraft, the annual corrosion cost can be estimated at $800 million.

One of the major tools to prevent corrosion on Navy aircraft is painting. In 1997, the Office of the Inspector General issued a report on the effectiveness of the Navy Aircraft Corrosion Prevention and Control Program at the organizational level.(10) The study focused on nineteen F-18 squadrons and seven F-14 squadrons. It was concluded that during the review period, from August 1, 1995 through August 1, 1996, 341 percent more paint than necessary was used for the prevention and control of corrosion damage of the F-18 aircraft and that the F-14 squadrons were painting large sections of their aircraft every 56 days. The report suggested that the Navy could reduce the organizational maintenance cost by $1.7 million over the next 6 years for the above-mentioned aircraft by limiting aircraft painting to touch-up painting only.

Facilities

All services own and operate extensive facilities, such as air and naval bases. The Air Force operates and maintains a 217 air bases (181 in the United States and 36 abroad) and the Navy operates 17 U.S. naval ports and 6 foreign ports. In addition, the Navy operates 20 Naval air stations and 4 submarine stations in the United States. In addition, the Army and the Marines operate numerous facilities for their troops, personnel, and equipment.

Many of the above facilities operate as ports or communities, respectively, with gas and electrical supply, drinking water, and sewer systems, and deal with corrosion issues similar to those discussed elsewhere in this report. Information on corrosion-related costs for these defense assets was not available; however, based on other studies described in this report, it is reasonable to assume that these costs are on the order of several billion dollars annually.

CASE STUDIES

Case Study 1. Army: High-Mobility Multipurpose Wheeled Vehicle

Introduction

Years of research and improvement by automobile manufacturers have led to the highly corrosion-resistant automobiles that most Americans drive today. Unfortunately, the lessons learned over the past 30 years are not always applied to new designs. A recent example of how poor design and material selection can lead to extensive corrosion problems is the Army's high-mobility multipurpose wheeled vehicle (HMMWV).(4)

The HMMWV is a light tactical vehicle procured by the Army and also used by the Marine Corps. The HMMWV is essentially a light truck that was designed for nearly any type of terrain or environment. While many modifications and variants are available, including heavily armored versions, the base structure and drivetrain of the HMMWV is very similar to many commercial vehicles. In fact, a civilian version of the vehicle with a more luxurious interior and non-camouflage paint is sold as the AM General Hummer.

The HMMWV first received attention during the Gulf War in the early 1990s. Since the Gulf War, the HMMWV has nearly become a symbol of the American Army during their missions to Bosnia, Somalia, Haiti, and Serbia. Unfortunately, along with all of the operational success, the Army and Marines began to notice that their HMMWVs were beginning to have severe corrosion problems after only a few years in operation. The Office of the Inspector General for the U.S. Department of Defense performed an evaluation on the corrosion prevention systems used on the HMMWV and published their findings in a 1993 report.(4)

Corrosion Control Shortcomings of the HMMWV

Government contracts on equipment such the HMMWV are written to emphasize performance specifications rather than design specifications. Performance specifications state that a piece of equipment must perform at a particular level for a given time frame. For example, the corrosion control specification on the 1989 contract for the HMMWV requires that:

> *The vehicle shall be capable of operating for a total service life of fifteen (15) years, which can include varying or extended periods in a corrosive environment involving high humidity, salt spray, road deicing agents, gravel impingement, and atmospheric contamination. During the 15-year service life, there shall be no corrosion past Stage One.*

> *Such a capability shall be achieved by a combination of design features (as found in, but not limited to, the* TACOM Design Guidelines for Prevention of Corrosion in Combat and Tactical Vehicles*), materials section (i.e., composites), production techniques, process controls, inspection, and documentation. No action beyond normal washing, periodic inspection, and repair of damaged areas shall be necessary to keep the corrosion prevention in effect.*

The advantage of using a broadly defined performance-based contractual specification is that making requirements too specific restricts the products and materials that can be used, and does not allow for new ideas and technologies. The Army does have a policy, however, indicating that state-of-the-art corrosion technology is to be used on the original equipment design, manufacturing, maintenance, supply, and storage for all Army systems and equipment. The design and manufacture of the HMMWV, however, fell short of this requirement for state-of-the-art corrosion technology with no overall corrosion protection and a lack of attention to corrosion control in the design of the vehicle.

An analysis of the corrosion control deficiencies of the HMMWV, presented in a 1995 report by Metals Information Analysis, indicated that the corrosion problems with the HMMWV are a result of design mistakes that had been eliminated in commercial vehicles years before the design of the HMMWV. One of the most glaring faults was in the design and construction of the steel frame. The frame was built out of ordinary 1010 steel and no galvanizing or other corrosion protection was applied to the steel to ensure its corrosion performance. Another problem with the frame was that holes were drilled into the sides of the frame members; however, no holes were drilled in the bottom of the frame to allow for drainage. This allowed water to enter the frame and stagnate on the interior of the frame, causing the frame to corrode from the inside out. The lack of drainage on a vehicle designed to be able to go through water up to 1.5 m (60 in) deep reveals the lack of thought that was initially put forth in the corrosion prevention during the design stage.

A problem throughout the vehicle is that 1010 carbon steel is used for many of the components, such as fasteners, handles, and brackets, as well as the frame. These parts have corroded on almost every HMMWV in service, leading to extensive repairs and maintenance. During the Inspector General’s Audit, an examination was performed on 275 vehicles, showing multiple areas of corrosion. The results of this survey are presented in table 4, summarizing the major vehicle parts that the auditors inspected and found to be corroded. Most of these corrosion problems could have been eliminated using galvanizing and high-quality coatings. Other problems could have been avoided using polymers and other alternate materials. Care must be taken, however, in selecting these materials. For example, the hood of the HMMWV is made out of a type of polymer called sheet molding compound. The hoods have not had any corrosion problems, but they have often cracked (due to soldiers jumping on them while performing their duties) because of the poor elastic properties of the polymer.

Several different metals were used on the HMMWV, leading to dissimilar or galvanic corrosion. Much of the body of the HMMWV is made out of aircraft grades of aluminum, while the frame and doors are made of 1010 carbon steel. The entire vehicle is secured with more than 2,800 rivets and while this design affords the HMMWV a high strength-to-weight ratio, each of the rivets is a preferential site for corrosion.

A particular weakness of the HMMWV, compared to standard commercial vehicles, are the coating systems used. Most commercial vehicles use a multi-step coating process to both protect the galvanized steel and to enhance the appearance of the vehicle. One of the most important parts of the coating application process is electrodeposition or E-coating technology. In electrodeposition, the part to be coated is immersed in the coating material while an electrical current is applied to the part. The advantage of using an electrodeposited primer is that the manufacturer can be assured of complete coverage of the surface, including otherwise inaccessible areas. On the HMMWV, E-coating technology was not used for coating application; rather, the coating was applied using the older technology of spraying.

Table 4. Number and percentage of corrosion-affected parts found during the Inspector General's investigation.(5)

VEHICLE PARTS	NUMBER OF VEHICLES AFFECTED (275 POSSIBLE)	PERCENTAGE OF VEHICLES AFFECTED
Engine Compartment		
- Heads	49	18
- Injectors	53	19
- Engine Mounts	78	28
- Valve Covers	87	32
- Radiator Assembly	131	48
Suspension and Steering		
- Idler Arms	48	17
- Control Arms	78	28
- Rie Rods	124	45
- Axle Housings	161	59
- Springs	205	75
Body		
- Fenders	72	26
- Bumpers	105	38
- Doorframes	115	42
- Beds	120	44
- Tie-Downs/Lift Points	209	76
Underbody		
- Metal Brake Lines	35	13
- Air Tanks	40	15
- Driveshafts	105	38
- Fuel Lines	106	39
- Universal Joints	135	49
Other		
- Welded Seams	73	27
- Fuel Tank Assemblies	135	49
- Nuts, Bolts, and Fasteners	177	64
- Frame	187	68

The corrosion protection of the HMMWV was to be provided exclusively by the military coating specification Mil-C-46164 and the Chemical Agent-Resistant Coating (CARC). The CARC paint system consists of a surface cleaning, epoxy primer, epoxy interior topcoat, and a polyurethane exterior topcoat. The purpose of this coating was to provide resistance to chemical penetration of the coating and to aid in decontamination of the vehicle in case of chemical attack. Other benefits of the coating were to provide corrosion protection as well as to provide camouflage protection, as the CARC paint was available in different camouflage colors. Unfortunately, as shown in table 5, the CARC coating has deteriorated much more quickly than was expected. There are several reasons for this failure, the most important being the physical properties of the CARC paint. The CARC paint hardens after application to an extremely inelastic material. The metals to which the paint was applied were much more elastic and also expanded and contracted more rapidly due to environmental conditions. The result is that the CARC paint is easily disbonded from the metal and often falls off; therefore, the protection that it would give is lost.

Table 5. Number and percentage of inspected HMMWVs found with deteriorated CARC paint in different locations with different services.(5)

OWNER	**LOCATION**	**NUMBER OF HMMWV INSPECTED**	**NUMBER OF INSPECTED HMMWV WITH DETERIORATED COATING**	
			Number	**Percent**
Army	Fort Bragg	17	4	24
Army	Fort Still	13	9	69
Army	Fort Knox	9	3	33
Army	Fort Drum	11	11	100
Marine Corp	MCLB – Atlantic	2	2	100
Marine Corp	Camp Lejeune	40	30	75
WI Nat'l Guard	Various	29	13	45

Another weakness of the CARC paint is that it is a relatively difficult coating to apply. Under ideal factory conditions, the necessary thickness levels are not too difficult to achieve; however, field repair of the coating has been difficult. The coating is difficult to apply in the field because the coating thickness must be correct. If the coating is too thick, the coating will fall off; if the coating is too thin, the coating is ineffective. Moreover, CARC paint for field application contains a high level of volatile organic compound (VOC). Strict environmental regulations now allow only 0.9 L (1 quart) per day per area to be used to reduce the level of VOC emissions. Thus, reapplication and touch-up are severely restricted.

Cost of Corrosion

The Inspector General's report contained the following recommendations with respect to corrosion problems on the HMMWV:

1. Incorporate state-of-the-art corrosion prevention technology for all future acquisitions and extended service programs for wheeled vehicle systems. Design specifications should be used in contractual documents.

2. Prepare life-cycle cost estimates that show the cost of corrosion-related maintenance and repair cost alternatives applicable to all future wheeled vehicle systems acquisitions and extended service programs.

The use of state-of-the-art corrosion prevention technology should be evaluated in terms of life-cycle costs associated with a system such as the HMMWV. There have been several attempts to assess the cost of corrosion on wheeled tactical vehicles. The Inspector General's report claimed that overall corrosion-related issues cost the Army an estimated $2 billion to $2.5 billion per year. During their study of several HMMWVs, the Inspector General found some significant corrosion costs in repairing the vehicles. One vehicle had only 89.5 km (55.6 mi) on the odometer; yet, it was estimated that it would cost $3,109 to repair the corrosion damage to the floor pans, transmission cooling line, cargo bed, body and frame bolts, rocker panels, fly wheel, tie rods, A-frame assembly, and other miscellaneous parts. A second vehicle, returned from operational service, had an estimated repair cost of $18,019, which is more than half of the $36,000 initial unit procurement cost.

The Inspector General found that the corrosion not only affected the cost of HMMWV ownership, but the operation readiness and overall life of the vehicles as well. The Inspector General was not able to calculate the precise impact on operational readiness, but it was estimated that vehicles requiring corrosion repairs were out of service between 2 to 12 months. The Inspector General did not calculate the cost of this downtime; however, other estimates suggest that if costs for downtime were considered, the cost of corrosion to the Army for wheeled vehicles would be higher than $2 billion. The Inspector General also calculated that extensive corrosion could shorten the life of the HMMWV, partly due to the low acquisition cost of the vehicle. The threshold for replacement is considered to be 65 percent of the cost of the vehicle. In fact, the Inspector General found several examples where the corrosion damage of existing vehicles was higher than 65 percent of the replacement cost. Vehicles as new as 5 years old were being scrapped for new vehicles.

Recommended Solutions

The Inspector General found that the lack of life-cycle cost analysis led to the corrosion problems with the HMMWV. If a life-cycle cost analysis were performed on the possible corrosion control alternatives, the analysis would have indicated that proper corrosion control measures would provide significant cost-savings in the long run. Unfortunately, this analysis was not performed and the use of these corrosion control technologies would have increased the procurement cost of the HMMWV. The Inspector General also found that individuals in acquisitions were rewarded for keeping the procurement cost low and that no reporting system was in place at Tank Automotive and Armaments Command (TAACOM) to estimate future repair needs.

The corrosion concerns were not addressed, even after the extent of the corrosion problems with the HMMWV was known. TAACOM’s Science and Technology Office put together the TAACOM CPC Acquisition (dated September 16, 1993) document for a procurement package for HMMWVs. This document stated the following:

> Corrosion Control – *The vehicle shall be capable of operating for a desired 20-year service life with a 15-year minimum which can include varying or extended periods in corrosive environments involving one or more of the following: high humidity, salt spray, road deicing agents, gravel impingement, atmospheric contamination, and temperature extremes. There shall be no corrosion past Stage One, nor corrosion impairment of fit or function. Corrosion control shall be achieved by a combination of design features, materials selection (e.g., composites, galvanized steel, E-coat, coil coating), production techniques, process controls, inspection, and documentation. The minimum requirement is galvanizing of ferrous components in accordance with the attached Galvanizing Policy, appropriate pretreatment, and E-coat primer. Subsequent use of rust-proofing materials, such as Mil-C-46164, is not a substitute for any of these minimum requirements.*

During the negotiations of the resulting contract, this section was deleted in order to reduce the procurement cost. The vehicles delivered under this contract were protected with Mil-C-46164 rust-proofing only. The most recent HMMWVs have been protected by using the methods outlined in the above paragraph; however, most of the 130,000 HMMWVs owned by the Army and Marines have virtually no corrosion protection due to the lack of life-cycle cost analysis before procurement. If TACOM follows the recommendations of their science and technology office and if life-cycle costing is performed on all systems before acquisition, the overall cost of ownership of the HMMWVs and other systems should be significantly decreased.

Case Study 2. Air Force: KC-135 Stratotanker

The KC-135 Stratotanker is a strategic air refueling tanker built by the Boeing Company, which can also be used as a cargo carrier or troop transport. The first KC-135 entered the Air Force fleet in 1957 and the last one was delivered in 1965. Currently, about 550 of the 732 tankers built remain in service. As a result of a decreasing DOD budget, there have been insufficient funds available to procure KC-135 replacement aircraft. Due to insufficient funding, the current KC-135 fleet has been projected to remain in service until 2040. With the average KC-135 tankers being more than 40 years of age, they will be more than 80 years old in 2040 and will have been in service for more than four times their original design service life. Generally, the structural life of both commercial and military aircraft is based on flight hours and number of fatigue cycles. In general, the life of aircraft is fatigue-limited, and corrosion is never considered to be a life-limiting factor. The minimum KC-135 structural fatigue life-limited components are the fuselage and the upper wing skin at 66,000 to 70,000 hours, while the actual fleet hours are only 15,000. Since the KC-135 utilization averaged only 300 to 400 flight hours per aircraft per year, it appears that the fleet can easily remain in service until 2040.

However, severe corrosion has been experienced on the aluminum alloy components of the KC-135 aircraft. This corrosion is the result of low utilization, where the majority of the time is spent on the ground being exposed to the corrosive atmospheric environments. In the 1950s, the KC-135 was never designed and constructed with corrosion prevention as a primary concern. The original structural alloys were aluminum alloys 2024-T3 and -T4, and 7075-T6 and 7178-T6, which are all susceptible to corrosion and stress corrosion cracking. The original construction was without any sealant in the lap joints and fuselage skins that had spot-welded doublers attached to them. Finally, the upper wing skins, which are made of the highly corrosion-susceptible aluminum alloy 7178, were attached with high-strength steel fasteners, causing dissimilar metal corrosion in certain areas.

A particularly severe problem is corrosion of the fuselage lap joints, where the voluminous corrosion products at the contact or faying surfaces of the lap joint cause deformation of the skin.(11-12) Figure 7 shows a photograph and a schematic cross-section of this so-called pillowing phenomenon. Because of the resulting stress fatigue and stress corrosion, cracks can nucleate near the fastener holes, jeopardizing the structural integrity of the fuselage. Other corrosion problems on the KC-135 aircraft include dissimilar metal corrosion and lap joint corrosion on the 7178 upper wing skin, lap joint corrosion on the 7075-T6 fuselage crown section, and stress corrosion cracking of the 7075-T6 forged frame sections.

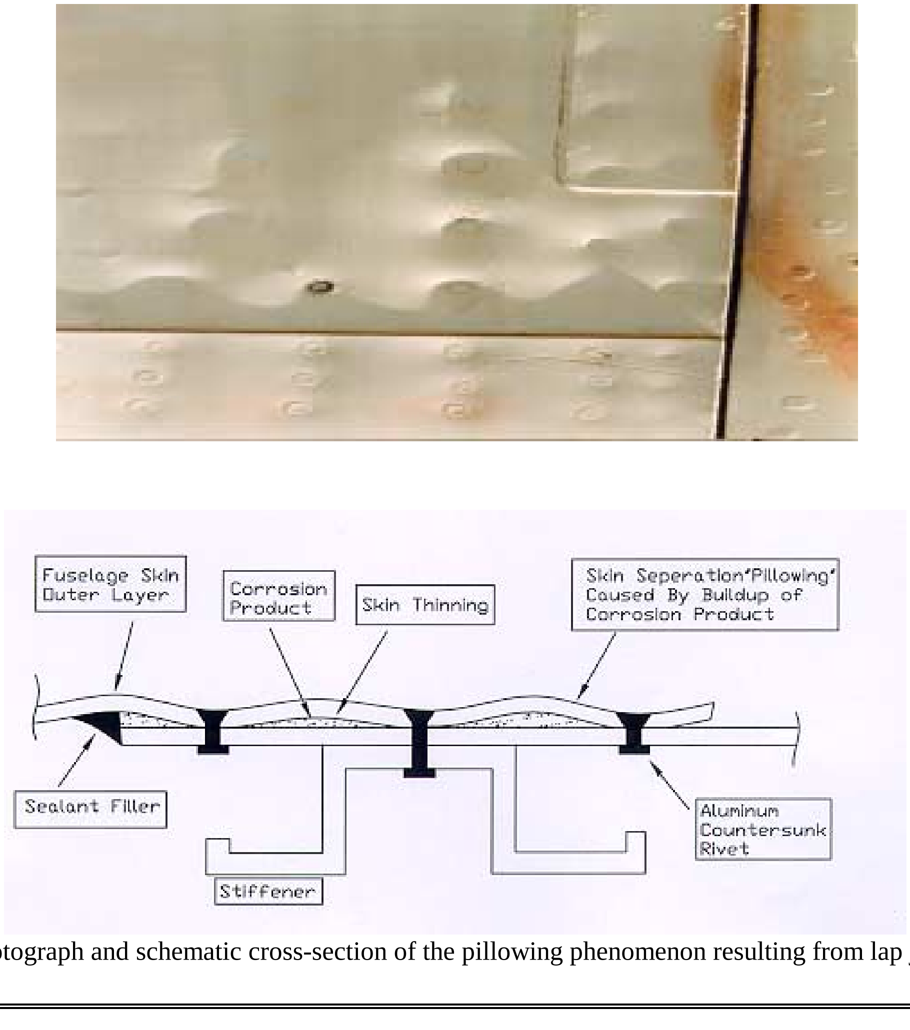


Figure 7. Photograph and schematic cross-section of the pillowing phenomenon resulting from lap joint corrosion.

As a result of all the corrosion problems of the KC-135, depot maintenance costs have increased significantly over the past 10 years. Figure 8 shows that the depot overhaul flows days have increased from less than 100 days in 1990 to approximately 350 in 2000.(13) The Air Force has expended considerable effort to develop methods to control the corrosion of the KC-135, ranging from characterizing the type and extent of the corrosion to developing new nondestructive inspection (NDI) techniques, to developing methods to slow down corrosion with corrosion preventative compounds (CPCs), to developing predictive models.

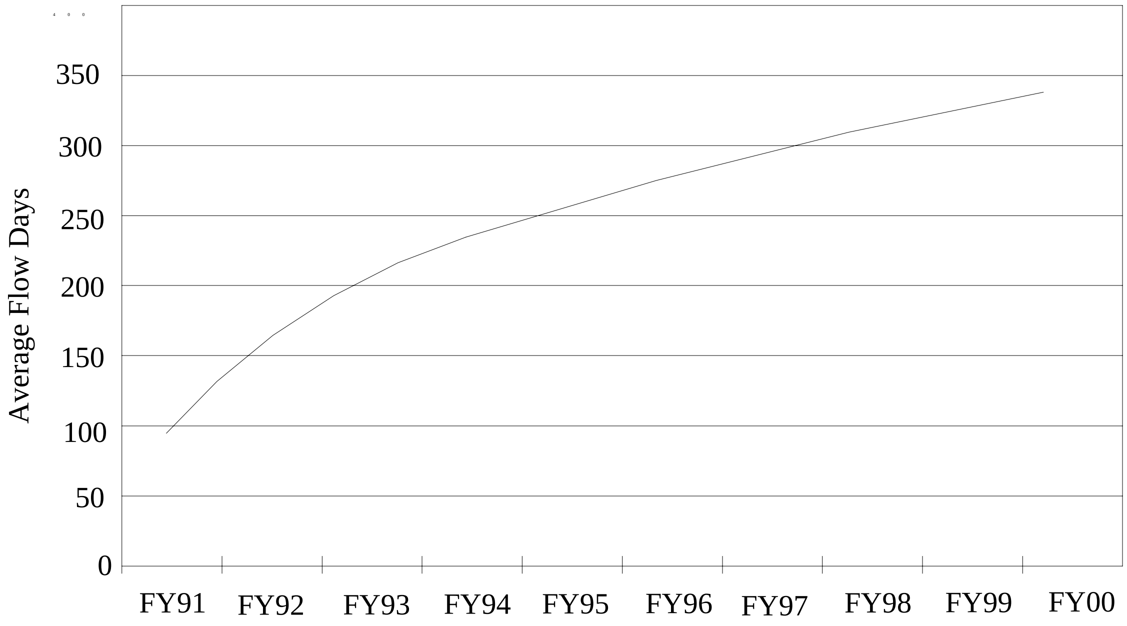


Figure 8. KC-135 periodic depot maintenance flow-day trend, for fiscal years 1991 through 1999.(13)

REFERENCES

1. *Science of Technology News*, Vol. 2, November 1997, HQ, U.S. Army Material Command.

2. H. Mindlin, B.F. Gilp, L.S. Elliot, and M. Chamberlain, *Corrosion in DoD Systems: Data Collection and Analysis (Phase I)*, MIAC Report 8, Metals Information Analysis Center, August 1995.

3. J. Argento, U.S. Army TACOM – ARDEC, Picatinny Arsenal, NJ, Personal Communication, 1999.

4. Audit Report on "High-Mobility Multipurpose Wheeled Vehicles" Office of the Inspector General, U.S. Department of Devense, 1993.

5. GAO Report on Army Medium Trucks Information on Delivery Delays and Corrosion Problems, January 1999, GAO/NSIAD – 99/2/6.

6. www.cnn.com/2000/US/04/04/army.helicopters.02/index.html.

7. G. Cooke et al., *A Study to Determine the Annual Direct Cost of Corrosion Maintenance for Weapon Systems on Equipment in the United States Air Force*, Final Report, CDRL No A001, February 1998.

8. J. Sedriks, Office of Naval Research, Personal Communication, July 2000.

9. *Preservation and Maintenance of U.S. Navy Ships*, Update for CINPACFLT N438 Staff, Naval Sea Systems Command, SEA 03M, February 1999, www.cpf.nav.mil/pages/n43/fleet%20corrosion/FCCF_III_mar%2099/na---/sld001.html.

10. *U.S. Navy Aircraft Corrosion Prevention and Control Program*, Audit Report, Report No. 97-181, Office of the Inspector General, U.S. Department of Defense, June 1997.

11. N.C. Bellinger, S. Krisnakumar, and J.P. Komorowski, “Modeling of Pillowing Due to Corrosion in Fuselage Lap Joints,” *Canadian Aeromautics and Space Journal*, Vol. 40, No. 3, September 1994, p. 125.

12. G.H. Koch, S. Styborski, and C.A. Paul “Effect of Corrosion in Lap Joints on Fatigue Crack Nucleation,” *Proceedings of Fourth Joint DoD/FAA/NASA Conference on Aging Aircraft*, March 2000.

13. D.E. Nieser, “Effects of Corrosion on KC-135 Structural Life and Flight Safety to 2040,” *Proceedings of Fourth Joint DoD/FAA/NASA Conference on Aging Aircraft*, May 2000.