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Ground Vehicle Corrosion

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THE U.S. ARMY has one of the largest tactical ground vehicle fleets in the world. These systems are continually being updated with the latest in weaponry, electronics, and fighting hardware. However, the basic structure of the vehicles remains largely unchanged. Most of this materiel was designed with automotive technologies for corrosion protection that were used in the 1970s and 1980s. These technologies cannot provide the level of corrosion protection necessary to maintain a vehicle for desired life of 15 to 25 years.

With a fleet of more than 120,000 vehicles for "High Mobility Multi-Wheeled Vehicles" (HMMWV or Humvees) alone, it is easy to see why deterioration due to corrosion is a major issue. As the average age of vehicles in the fleet is more than 17.9 years (Ref 1), which is 5 to 10 years longer than current commercial automotive standard warranties for corrosion, there is need for improved corrosion control to maintain a continually aging fleet.

An overall discussion of the Army's current position on corrosion control for wheeled tactical vehicles is presented here and includes:

- Army requirement for corrosion control
- Testing to meet the requirement
- Improving supplemental corrosion protection, the use of corrosion-inhibitive compounds, maintenance procedures, and design considering corrosion

Background

Wheeled tactical vehicles first saw widespread use after Word War I, following some initial limited use by the Marine Corps. At the time, the vehicles were manufactured using the same techniques and production lines as commercial automobiles. Today (2006), military vehicles are created with unique requirements, specifications, coatings, and equipment that are not common to commercial vehicles.

Army vehicles are developed and manufactured by contractors who specialize in making that specific item. Due to the unique requirements on these vehicles, hand assembly is needed along with automatic processes. The manufacturers do not always have large assembly plants like those of the U.S. automakers, and this sometimes limits the state-of-the-art technology that can be incorporated, such as hot-dip galvanizing, electrodeposition coatings, and other technologies that the automotive industry uses.

However, such technologies can often be found at subvendors, so leveraging their abilities allows manufacturers of wheeled tactical vehicles to improve the product without investment in costly infrastructure.

Requirements for Corrosion Control

The Army's requirements for corrosion control are based on protecting its materiel from deterioration due to operation under normal conditions. For ground vehicles, these requirements are often based on corrosion-control technologies developed by the commercial automotive industry. However, the tactical environment in which Army vehicles must operate is more severe, and so more robust technologies and more stringent requirements may be required. This is the case for vehicles deployed in Southwest Asia. The soil was an ancient sea bed and is full of salts and other minerals that are extremely hostile to coatings and metals. The weather extremes of high winds, abrasive sand, and temperatures ranging from daytime 53 °C (128 °F) to 15 °C (60 °F) at night play havoc on all equipment.

In addition to corrosion-control requirements for coatings, observability and chemical agent resistance are of paramount concern. To prevent detection by infrared (IR) and other scanners and to allow for decontamination after chemical agent exposure, the Army has developed a chemical agent resistant coating (CARC) system. This unique coating formulation reduces the IR signature of a vehicle, provides a dull flat finish, and can be cleaned using a highly basic decontamination solution. It is required on any Army tactical system, and it must be compatible with the corrosion-control methods.

In the past, corrosion control was not a primary concern as the tactical vehicle life expectancy was relatively short. However, for some current vehicles the life can be greater than 25 years. As such, better corrosion control is essential to producing an asset that can last for the specified life. The U.S. Army Tank-automotive and Armaments Command (TACOM) defines the corrosion prevention and control requirements in the procurement document.

Procurement Document

The requirements from a procurement document are summarized.

Corrosion Control Performance. The minimum service life in years of the vehicle, subsystem, or component is stated, and the operating conditions are given (high humidity, salt spray, gravel impingement, temperature range). The type and amount of maintenance to be given is stipulated.

A method of evaluating corrosion is given. The allowable level of corrosion is 0.1% of the surface (rust grade 8 per ASTM D 610, "Evaluating Degree of Rusting on Painted Steel Surfaces"). Further, a U.S. Army Corrosion Rating System is cited. There shall be no effect on form, fit, or function of any component due to corrosion.

Verification of Corrosion Control. The entire vehicle shall be evaluated for corrosion control by the accelerated corrosion test (ACT). The specified number of cycles that represents the vehicle service life is specified in the contract. For less than complete vehicles, the cyclic corrosion test per GM 9540P or equivalent such as the SAE J2334 shall be performed on the actual component for the number of cycles representing the service life (e.g., 160 cycles for the 20 year period of performance). All test panels and component parts shall be scribed per ASTM D 3359 prior to testing to validate performance of the paint or any other coatings. After completion of the test, the scribed area shall be scraped with a metal putty knife or equivalent to determine the extent of any coating undercutting/loss of adhesion of any coating and/or treatment. Alternative validation test methods must be approved by the government prior to fielding or manufacturing.

The pass/fail criteria for the ACT test and other tests is clearly defined. Any loss of form,

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fit, or function shall be considered a corrosion failure and requires the same type of corrective action during or after the ACT as any other failure occurring during or after the initial production test. Loss of coating adhesion or corrosion emanating from the scribe shall be limited to 3 mm maximum at any point at the scribe. There shall be no blistering of the coating film in excess of 5 blisters in any 24 square inch area. The maximum blister size is 1 mm. There shall be no more than 0.1% surface corrosion (ASTM D 610, rust grade 8) on any component part (exclusive of the scribe). In addition, there shall be no loss of original base metal thickness greater than 5% or 0.010 in., whichever is less. Expendable items (identified as exempted parts prior to the test) shall retain their function for their intended service life and are not subject to these criteria.

Notes of Guidance and Caution. The procurement document provides assistance to the vendor, such as:

- Corrosion control can be achieved by a combination of design features (as in TACOM Design Guidelines for Prevention of Corrosion in Combat and Tactical Vehicles, March 1988) or any automotive corrosion design guide such as SAE J447, material selection (e.g., composites, corrosion-resistant metal, galvanized steel), organic or inorganic coatings (e.g., zinc phosphate pretreatment, corrosion-resistant plating, E-coat, powder coating) and production techniques (e.g., coil coating, process controls, welding, inspection, and documentation).
- Corrosion protection for low-carbon sheet steel can be achieved by hot-dip galvanizing in accordance with ASTM A 123, or electrogalvanized 0.75 mil minimum thickness per ASTM B 633 (or minimum coating thickness of 0.75 mil on pregalvanized sheet 0.063 in. or less), with zinc phosphate pretreatment, epoxy prime preferably E-coat primer and CARC top coat. Alternate designs may be evaluated by comparison to a galvanized sample (as described previously) using ASTM D 522 Mandrel Bend Test and Accelerated Corrosion Test GM 9540P and gravelometer testing. Failure constitutes a defect such as extensive corrosion at scribe, chipping of coatings, loss of adhesion, or significant penetration of base material (per ASTM D 3359).
- Due to changes in climatic conditions and the development of newer materials and processes, all accelerated corrosion tests undergo a continuous adjustment to reflect these conditions. Therefore, modifications to the testing are to be expected over time. However, any changes need to be agreed upon with the government prior to testing.
- CARC coatings over steel is not expected to be sufficient corrosion protection to achieve 10 year service life. In marine environments such a system usually delivers only a 5 year performance.

The above requirements are capable of being met using already proven materials and processes for corrosion control (Ref 2). Using the processes and procedures already in use by commercial automotive manufacturers will help improve the corrosion resistance of military vehicles and make a design life of greater than 20 years achievable.

Testing Systems to Meet the Army's Needs

As required by the procurement contract, existing or new corrosion-control technologies used in a vehicle system need to be evaluated to determine their benefit. Accelerated corrosion test methods can demonstrate differences in performance of competing alternatives, identify areas requiring additional corrosion protection, and demonstrate the interaction between corrosion and operation of the vehicle.

Preproduction Testing. These initial tests are used to screen candidate materials to evaluate their inherent corrosion resistance. Most commonly, these are short-term aggressive tests performed in a laboratory corrosion chamber (see the article "Cabinet Testing" in Volume 13A). Traditionally, methods such as the ASTM B 117 salt spray (fog) test were used to compare relative performance, but they had very little if any relation to actual field use.

In the 1990s it was found that newer cyclic tests provide a better correlation to actual exposure environments. The GM9540P and SAE J2334 test methods are now commonly used to evaluate painted metals to determine relative corrosion resistance and select the best candidate system.

Cyclic corrosion tests are generically similar, although their exact makeup can vary. Corrosion specimens are exposed to a combination of corrosive electrolyte (salt-water solution), high temperature, high relative humidity (RH), and ambient conditions (nominally 70 °F, or 20 °C, <50% RH). These events are used to introduce corrosive species (e.g., chloride ions) to the samples, create conditions that accelerate corrosion (increase time of wetness, TOW), and "bake" the salts onto the specimens so they can be activated during TOW. Using combinations of these events over a period of time can accelerate levels of corrosion to represent years of exposure in a matter of weeks or months. Additionally, gravel impingement using a gravelometer is used in conjunction during a test to simulate events found in actual vehicle usage (Ref 3–5).

Prototype Testing. As major subsystems or complete vehicles are assembled into prototypes, more detailed evaluations can occur. These evaluations are used to determine if interactions exist between any of the components of these assemblies and if their normal operation is affected by corrosion. Prototype testing is performed by combining durability and corrosion inputs. For smaller subsystems, this can include periodic exercising of components during accelerated testing. For larger systems and vehicles, testing is performed using proving-ground-type accelerated corrosion tests (road tests).

A road test is a combination of driving mileage and corrosion inputs used to simulate the expected vehicle mission profile (Ref 6). A vehicle is run through road courses representative of various terrains (paved roads, gravel roads, cobblestone streets, cross-country trails) that the vehicle is designed to negotiate. Intermixed with these conditions are corrosion events to apply corrosive contaminants (electrolytes) to the vehicle and TOW. Operating this type of test exposes the vehicle to mechanical and corrosion stresses. This combination of tests can identify deficiencies in corrosion-control methods, which can then be remedied before large-scale production.

Analysis of Test Results. The nature of accelerated corrosion testing is such that a failure in the test increases the likelihood of observing the same failure in the field; however, *a lack of failure in the test does not mean a failure will not occur in the field.* This is the nature of accelerated testing, where the time for failures to occur is accelerated and not all failure mechanisms are accelerated at the same rate. This is why comparative testing is performed early in vehicle development, and road testing is used once all material choices have been made to identify any interactions between final assemblies.

Benefits. The results of accelerated corrosion tests are used as feedback to vehicle designers. These results can be used to improve the design of a vehicle, to identify other materials for certain systems, to improve maintenance requirements, or in cost-benefit analyses to identify trade-offs and value of adding additional corrosion protection. While it is often impractical to expect a tactical vehicle to last the desired 20+ years of service with no maintenance, accelerated tests can benchmark the relative life of specific systems and highlight maintenance activities that should be performed. This is used to develop the best possible system and to reduce life-cycle costs (LCC) to optimize service and performance.

Supplemental Corrosion Protection

Supplemental corrosion protection improves the corrosion resistance of a material. These methods can include:

- Galvanizing of steel
- Plating of metals
- Sacrificial coatings
- Organic coatings

Each of these can be used as part of a system to reduce corrosion. While individually each does increase service life, combinations of these are needed to reach the >20 year design life

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presently being requested of new wheeled tactical vehicles.

For example, a steel body using double-sided galvanized sheet steel and a CARC system will be protected more effectively than CARC or galvanizing alone. Using the above with a good pretreatment such as zinc phosphate, a high-performing primer such as E-Coat, followed by the top coat a 20+ year service life is economically achievable. The CARC system provides the first line of defense against contaminants. Without this coating, corrosion of the galvanized steel would begin immediately at voids. Conversely, if only the coating was used, once contaminants penetrated the CARC corrosion of steel substrate would begin immediately.

Corrosion-Inhibitor Compounds. For existing equipment, there may be components or locations (crevices, recesses, blind holes) that are vulnerable to corrosion attack. The entire vehicle may need extra protection during shipping or storage. Temporary inhibitive compounds may be used to reduce corrosive attack.

Corrosion-inhibitor compounds are most commonly liquid aerosols sprayed onto vehicles. Other forms include vapor-phase inhibitors, greases, and waxes. Most of these products are similar to other maintenance fluids used in motor pools and, as such, their use is implemented as maintenance procedures or in specialized service locations. However, similar to other lubricants and fluids, they need to be handled and applied with care. Some materials have been found to be detrimental to rubbers and plastics with prolonged exposure. Overspray can also be of concern, as this can attract dirt and contaminants and increase maintenance time by necessitating postapplication washing.

The U.S. Marine Corps have published guidance on the use of inhibitors with ground vehicles (Ref 7). These documents stress application of products to specific components and locations. This has helped alleviate some of the potential incompatibility issues. For example, certain inhibitors may reduce corrosion on one type of metal, but accelerate attack on others.

Improved Maintenance Procedures

Maintenance procedures can also be used to combat corrosion. More frequent lubrication, application of inhibitors, and repainting can reduce corrosion damage. Although these procedures do have benefits, excessive maintenance can be both time and readiness prohibitive. With steadily decreasing operating budgets and a need to have vehicles ready-to-go, continual maintenance is not practical. Often a compromise between maintenance and corrosion control needs to be developed and realistic maintenance goals established.

While maintenance can be used to reduce corrosion, it should not be relied upon as the major corrosion-control method. Emphasis should be placed on less labor-intensive methods.

Considerations for Corrosion in Design

Considerations for corrosion control during design of a vehicle goes beyond choosing proper base metals and coatings. It includes the geometry and manufacturing methods used to construct a vehicle. These methods are described in TACOM and Society of Automotive Engineers (SAE) guidance documents (Ref 8–10).

These documents stress using good construction practices and creating geometries that minimize water entrapment areas or promote drainage of those areas. Design of body panels and components should also minimize the use of sharp corners and edges, which reduce paint adhesion. Adhesives and seam sealants should be used along with continuous welds for joining to eliminate crevices and water seepage locations.

Conclusions

As new military vehicles are being produced and acquired, corrosion control is becoming a major component of the acquisition strategy. Requirements such as those discussed in this article are being used to improve the corrosion resistance of vehicles. Placing the focus on performance instead of materials allows manufacturers to select corrosion-control solutions that best work within their operations, yet provide the level of protection required. By looking to proven technologies already in use by commercial manufacturers, original equipment manufacturers can leverage this knowledge and improve their end product.

The Army has embraced accelerated corrosion test methods and evaluation techniques for tactical vehicles. These methods permit the demonstration of effective design choices. It provides the ability to evaluate new corrosion-control technologies as they become commercially viable for use on military vehicles.

REFERENCES

1. A.E. Holley, "Aging Systems 'Classic to Geriatric to Jurassic' When Will It Stop?" DoD Maintenance Symposium, Oct 29, 2002
2. J. Repp, "Corrosion Control of Army Vehicles and Equipment—Use of Existing Technologies for Corrosion Control," Army Corrosion Summit 2003, http://www.armycorrosion.com
3. C.H. Simpson, C.J. Ray, and B.S. Skerry, Accelerated Corrosion Testing of Industrial Maintenance Paints Using a Cyclic Corrosion Weathering Method, *J. Prot. Coat. Linings,* May 1991, p 28–36
4. Cleveland Society for Coatings Technology Technical Committee, Correlation of Accelerated Exposure Testing and Exterior Exposure Sites, *J. Coat. Technol.,* Oct 1994, p 49–67
5. B. Goldie, Cyclic Corrosion Testing: A Comparison of Current Methods, *Prot. Coat. Europe,* July 1996, p 23–24
6. J. Repp, Accelerated Corrosion Testing—Truth and Misconceptions, *Mater. Perform.,* Sept 2002, p 60–63
7. "Organizational Corrosion Prevention and Control Procedures for USMC Equipment," U.S. Marine Corps TM4795-12, Dec 1999
8. "Design Guidelines for Prevention of Corrosion in Combat and Tactical Vehicles," U.S. Army TACOM
9. "Prevention of Corrosion of Motor Vehicle Body and Chassis Components," Surface Vehicle Information Report, SAE International, 1994
10. "A Guide to Corrosion Protection for Passenger Care and Light Truck Underbody Structural Components," Auto/Steel Partnership, 1999

SELECTED REFERENCES

- R. Baboian, *Automotive Corrosion by Deicing Salts,* National Association of Corrosion Engineers, 1981
- R. Baboian, *Automotive Corrosion and Protection,* National Association of Corrosion Engineers, 1992
- F. Bouard, J. Tardiff, T. Jafolla, D. McCune, G. Courual, G. Smith, F. Lee, F. Lutze, and J. Repp, "Development of an Improved Cosmetic Corrosion Test by the Automotive and Aluminum Industries for Finished Aluminum Autobody Panels: Correlation of Laboratory and OEM Test Track Results," World Congress 2005, SAE International, April 2005
- I.C. Handsy and J. Repp, "Development and Use of Commercial Item Descriptions in Army Acquisition and Maintenance Activities," presented at *Corrosion 2002,* National Association of Corrosion Engineers, April 2002
- I.C. Handsy and J. Repp, "Corrosion Control of Army Vehicles and Equipment," presented at the Army Conference on Corrosion, Feb 2003
- J. Repp, "Comparison Testing of Environmentally Friendly CARC Coating Systems over Aluminum Substrates," presented at Joint Services Pollution Prevention Conference and Exhibition (San Antonio, TX), NDIA, Aug 1998
- J. Repp, "Update on the Development of SAE J2334 Accelerated Corrosion Test Protocol," presented at the Army Conference on Corrosion, March 2002
- J. Repp and T. Saliga, "Corrosion Testing of 42-Volt Electrical Components," presented at World Congress 2003, SAE International, March 2003

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Armament Corrosion

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ARMAMENT SYSTEMS comprise guns and ammunition ranging from the M-16 machine gun and ammunition (5.56 mm) to the 155 mm mortar rounds and M198 howitzers that fire the rounds. This includes weapon systems found on tanks and other mobile units, so the number of systems is large.

Armament systems, must meet specified requirements, including functionality, environmental, time, and cost requirements. Functional requirements are that the system performs its basic task, that includes the ability to fire a projectile, aim, and rotate. Another requirement is that there must be visual and spectral camouflage. Spectral camouflage refers to the infrared profile of the system and its ability to blend into the surrounding environment so the system is invisible to infrared-sighting equipment. This provides an extra level of tactical protection for the soldiers. The system must also be corrosion resistant and chemical-agent resistant. Chemical-agent resistance is the ability of the system to be decontaminated if it were to come in contact with chemical agents. These requirements are accomplished through the use of the chemical-agent resistant coating (CARC). It provides visual and spectral camouflage as well as corrosion and chemical-agent resistance. The CARC system consists of a primer and topcoat. The epoxy primer provides corrosion protection, while the urethane topcoat provides chemical-agent resistance and camouflage properties. Armament systems are exposed to some of the most severe environments on earth. Wars are not fought in a climate- and humidity-controlled environment. From arctic cold to desert heat the systems must be able to perform their function in all environments.

Overview of Design, In-Process, Storage, and In-Field Problems

Armaments corrosion problems must be looked at in four specific stages: design, in-process, storage, and in the field. To accurately understand the corrosion problems that are faced with today's (2006) armament systems, these aspects must be looked at individually and their effects analyzed over the useful life of the system. Design considerations include geometry, material selection, assembly, pretreatment, coatings, and working and storage environments. In-process corrosion concerns include: processing locations, in-process storage of parts, time between processing steps, and quality control of each processing step. How, where, and how long the systems will be stored before they are fielded must be considered. Finally, analysis of the in-field corrosion of the finish product should include: physical environments; repair of corrosion-protective coatings, shipment concerns, general corrosion-protection maintenance, and appropriate fixes and procedures that can be implemented by soldiers in-field to stop continued corrosion of armament equipment.

There are common corrosion problems associated with each stage in the life of an armament system. The three most common types of corrosion associated with design are uniform, galvanic, and crevice corrosion. The most common form of corrosion during processing is uniform corrosion of parts being exposed to corrosive environments before the corrosion protection is in place. The most common form of corrosion for equipment in storage is uniform corrosion. This is again from parts being exposed to corrosive environments or being stored for periods longer than the protection systems are designed. The three most common forms of corrosion found on in-field systems are crevice, galvanic, and uniform. All types of corrosion are evident in all the stages; the process by which the most common armament corrosion is addressed within the military to ensure functional equipment reaches the field is discussed with applicable examples.

Design Considerations

From a design standpoint, one must be aware of the eight types of corrosion and consciously design the system for corrosion resistance. The functional goals of the system must be established in a set of requirements determining what is to be accomplished by this part, how the system will work, how long the system will need to function at a time, and what are the physical requirements on the system. In many cases, with the designer's concern for the functional requirements of the system, corrosion is not a major consideration.

Material Selection. To adequately design a part to be corrosion resistant, the design engineer must first make good decisions in the materials selection process. When placing materials in a system, the design engineer must not only know the physical and mechanical properties of the materials, but also the susceptibility to corrosion of the material in specified environments of the system. For example, aluminum is often assumed to be a corrosion-resistant material, and for 1000-series aluminum this is generally correct. Different aluminum alloys have different corrosion susceptibilities. The design engineer must understand that if a material passivates when exposed to oxygen and it is placed in an environment that is absent of oxygen, then the corrosion resistance of the material is significantly reduced, if not completely destroyed.

Dissimilar Metals. Design engineers must also look at the interface of dissimilar metals within a system. Galvanic corrosion can destroy systems rapidly, especially in the case of a very large cathode in direct contact with a small anode. A galvanic series appropriate to the environment can be consulted, and all efforts should be made by the design engineer to use materials combinations that do not cause galvanic corrosion. See the compatibility chart based on MIL-F-14072D in the article "Corrosion in Microelectronics" (Table 6) in this Volume.

Design geometry can also play a large role in the susceptibility of a system to corrosion. Good practice is to eliminate crevices or seal crevices and joints. The design engineer must assume that water will get into parts or trap and pool on the surface of the system. The systems must be designed to drain water through holes, channels, or other devices. In pipes, the design engineer must prevent turbulent flow in joints in high-speed flow conditions. Bends, kinks, corners, and the internal features of the pipe all affect the flow and can increase erosion-corrosion within the system.

Coatings applied to the systems must also be researched and chosen depending on the specific requirements of the system. The previously mentioned CARC system is designed to be a 15 year coating that provides chemical-agent

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resistance, spectral and visual camouflage, as well as corrosion protection. It is a two-part system that is applied over a zinc phosphate coating. The epoxy primer, 25 to 50 μm (1 to 2 mils) thick, provides corrosion protection. The urethane topcoat is applied 50 to 75 μm (2 to 3 mils) thick and provides the camouflage and chemical-agent resistance.

Examples of Design-Related Problems. An example of design affecting the corrosion resistance of an engineered system is the M198 howitzer. There is an anodized 7079-T6 aluminum alloy ring gear that connects the upper carriage and the gun tube to the lower carriage and the trails. The ring gear allows the gun tube to rotate and is fastened to the upper and lower carriage with mounting bolts. Figure 1 shows the results of a poor design on the system. The upper carriage of the ring gear has become completely disconnected from the lower carriage and the gun tube has fallen to the ground. There are multiple problems with the design of this system. First, the material selected, 7079-T6 aluminum, is susceptible to stress-corrosion cracking (SCC) in the transverse direction. For SCC to occur, a susceptible material, a specific corrodent, and a sustained tensile load are needed. 7079-T6 aluminum has a transverse SCC threshold of 55 MPa (8 ksi). The 13 mm (1/2 in.) and 16 mm (5/8 in.) mounting bolts used to secure the ring gear to the upper and lower carriage, when proper torque is applied, produce 110 and 172 MPa (16 and 25 ksi) sustained tensile loads, respectively, at the countersink. This load is sufficient to produce SCC if a corrodent is present, and for aluminum alloys, 50% relative humidity is sufficient. In this case, all three criteria for SCC are present and the material experienced a large amount of SCC. Figure 2 shows SCC at the countersink of the ring gear.

A second design problem deals with the anodized coating of the ring gear. The anodized coating is applied to the aluminum to reduce the susceptibility of the material to corrosion. For the M198 howitzer, the seal used to finish the anodized coating was deleted on the drawing. Without the seal, the anodized coating does not protect the ring gear from pitting, and the ring gear surface experienced extreme pitting (Fig. 3). The pitting that occurred in the countersink provided initiation points for the SCC to propagate and accelerate the corrosion damage. Both the SCC and pitting could have been easily avoided. If 7075-T73 aluminum had been selected, SCC would have been avoided since 7075-T73 has a SCC threshold of 303 MPa (44 ksi). Pitting would have been prevented by simply requiring the seal to be placed on the anodized coating.

A third example of design affecting corrosion resistance is the copper rotating band found on 40 mm grenades. The copper bands are swaged onto the steel or aluminum grenade body. This creates a crevice beneath the rotating band as well as creates a dangerous galvanic couple between base metal and copper. It is also common to find galvanic corrosion of steel adjacent to the copper-rotating band as seen with the 105 mm cartridge (Fig. 4). Another problem is that machining lubricants can become trapped in the crevice between the body and the rotating band. This lubricant can then seep out of the crevice and react with the copper band causing discoloration (Fig. 5).

Fig. 1 Results of ring gear failure in the M198 howitzer. Source: Ref 1

In-Process Considerations

In-Process Monitoring. If a part is not properly monitored during processing, there is no way to accurately determine the reliability of the resulting system. In-process corrosion will depend on the type of process and its sensitivity to changes in process variables. Where and for how long will the parts be stored between processing steps? Do the unfinished parts need to be transported for further processing? These are all questions that must be considered in the quality assurance (QA) program. Quality assurance uses

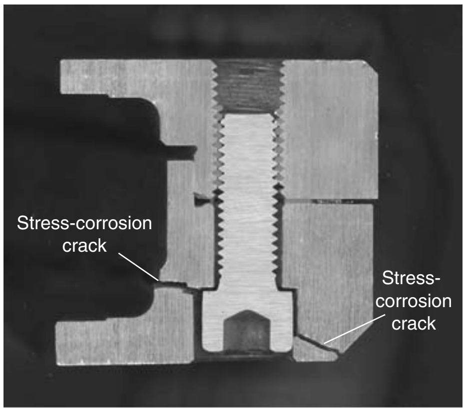

Fig. 2 Cut-away view of the ring gear and bolt showing stress-corrosion cracking. Source: Ref 1

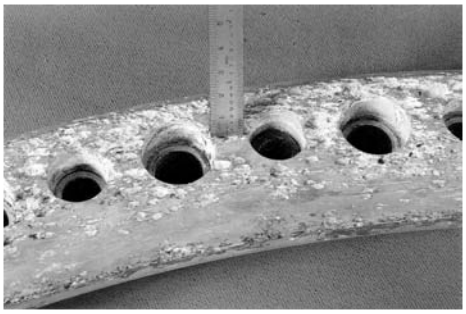

Fig. 3 Severe pitting on the surface of the aluminum alloy ring gear. Source: Ref 2

Fig. 4 Galvanic corrosion at the interface of the copper rotating band and the steel base metal in a 105 mm cartridge. Source: Ref 3

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a system of quality assurance representatives (QARs), who are government employees who travel to vendors' plants to monitor the actions of contractors and subcontractors to ensure compliance.

Adherence to Specifications and Standards. To monitor processing, the QARs must know how the quality of parts being produced is monitored, requirements for the part, how finishes are applied, and the tests used to verify these requirements. Specifications and standards are cited in purchasing documents that contractors and subcontractors must follow. These specifications and standards also define the engineering requirements. The goal of a specification or a standard is to establish critical criteria to ensure proper function of a part or system.

There are many cases of contractors certifying that the specifications were met while not stating which tests were performed. In military contracting, a contractor or subcontractor must perform three steps after the parts have been produced to ensure acceptance by the military inspector. First the parts must be tested and data must be collected. Secondly, the data are presented in a certified test report (CTR). The CTR lists the tests run and the test procedure, displays the data collected, and provides proof that the work meets the requirements. Once this document has been created, a second document, the certificate of conformance (COC), can be issued. A COC states that the contractor completed all the necessary tests on the produced parts and has fulfilled the other contractual obligations such as documentation and shipping requirements.

Conflicting Technical Data. A major problem for in-process corrosion control is the existence of conflicting technical data. For example, there may be a requirement on a drawing that a certain test is to be run, but the document also cites another drawing that says that the test is not required. In this case, the QAR cannot check the contractor for the requirement on the primary drawing because there are conflicting data. These conflicting requirements can be corrected for future contracts, but a new solicitation or a change to the contract would be required to fix the current contract, so the parts may be shipped as is. In armament corrosion, the person who suffers is the soldier who receives parts that do not function as they are supposed to or do not last as long as they are needed.

Examples of In-Process-Related Problems. An example of an in-process corrosion problem is 155 mm M549A1 ammunition rounds that needed a complete repainting only 4 months after the initial painting. M549A1 is a steel projectile that is phosphated and then painted with enamel. The rounds were produced in California and then shipped to Iowa to be filled. The rounds that arrived in Iowa were rusted and required complete repainting. This was due to incomplete application of the phosphate pretreatment. The benefit of the phosphate coating is lost if complete and uniform coverage is not obtained. Without a properly applied pretreatment, the original paint coating was unable to protect the surface of the ammunition.

Another example of an in-process corrosion problem is the M119 howitzer firing platform. The firing platform was required to be 7075-T73 aluminum with chromate conversion pretreatment and painted using the CARC primer and topcoat system. After five years of service in Hawaii, the firing platforms failed due to exfoliation corrosion. It was determined that new platforms were required and again the T73 heat treatment was specified. The new platforms with this heat treatment failed after 2 years of service. Figure 6 shows the failed firing platform. Figure 7 is a close-up of the exfoliation corrosion on the firing platform. The T73 temper was designated because it is highly resistant to exfoliation. Then why did the parts exfoliate in only two years of service? They were not tested or documented during production to verify that the parts had in fact been treated to the T73 condition. To obtain a T73 temper, a part must first be placed in a T6 temper. If the parts are not adequately heated, they will not achieve the T73 state and will not be resistant to exfoliation corrosion. In this case, the parts and the temper recipe were never tested under ASTM B 209, "Standard Specification for Aluminum and Aluminum Alloy Sheet and Plate." Based on the premature failure of the supposed 7075-T73 parts, it is apparent the treatment was not sufficient. To verify the heat treatment of the platforms, tensile bars where cut from a failed platform and tested. The results indicated that the parts were in fact not in the T73 condition. If the parts had been properly monitored with the heat

Fig. 5 Grenade body showing discoloration of copper rotating bands resulting from exposure to trapped machining lubricant. Source: Ref 4

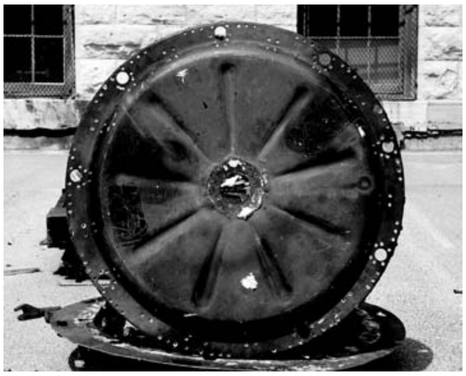

Fig. 6 Failed M119 firing platform. Source: Ref 5

Fig. 7 Firing platform exfoliation corrosion. Source: Ref 5

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treatment plan recorded or the parts tested, the inadequate heat treatment would have been discovered and corrective action taken.

Storage Considerations

Storage Practices. The third stage that must be considered for armament corrosion is storage. In armament systems, parts can and do sit in storage for extended amounts of time. The goal of storage is to have systems on hand that can be deployed on short notice. In this case, the military must use processes to prevent degradation without affecting the readiness of the systems. In some cases equipment is stored in climate-controlled facilities. Other common practices include volatile corrosion inhibitor (VCI) packaging, rust-preventative oils, and hermetically sealed packaging. These systems are designed to preserve the integrity of the system and not reduce readiness. Despite best practices, the most common type of corrosion during storage is general corrosion, caused by failed or nonexistent corrosion protection.

Examples of Storage-Related Problems. Military storage is not a perfect system, and in many cases, the storage is longer than the protection scheme life, or the packaging is compromised. If the packaging is compromised and goes unnoticed, the protection is completely lost. Loss of protection can be as simple as a tear in the packaging, or wrapping the items in VCI packaging designed to protect the system for 2 years, but storing them for 5 years. There have also been examples of oils used to preserve equipment that are capable of unzipping heat-sealed packages. One must also consider how the parts or systems will be stored. If a system is stored outdoors, will personnel be available to inspect and perform maintenance on the storage system and will readiness be affected?

An example of how storage can affect the readiness of equipment is again the M198 howitzer. Howitzers were stored outside in the elements, with individuals monitoring the systems to ensure their readiness. The howitzers were placed in the "ready" position, meaning that the trails were lifted off the ground so the howitzers were ready to be towed (Fig. 8). The problem is the howitzer was not designed to be stored in this position. Drain holes in the lower carriage were placed in the back by the trails to allow water to drain from the system. However, in the "ready" position water does not drain from the lower carriage. Thus water accumulated inside the carriage and caused corrosion damage. Adding holes in the front of the lower carriage so water could drain from the system while in the "ready" position corrected the problem.

In-Field Considerations

The final stage in the life of an engineered system is in-field or in-service. This is the place recognized as the cause for degradation and failure and provides the true test to parts, systems, and corrosion protection.

Preventive Maintenance and Cleaning. In armament systems, maintenance and cleaning must be performed to realize the useful life of systems. Common maintenance activities include cleaning, oiling, paint touchups, and parts replacement. The design engineer generates the required maintenance procedures. The goal is to create a maintenance system that anticipates problems and provides adequate guidance on how to prevent or repair them. For each part in the system there are cleaning and replacement requirements that lay out what must be done and when they should be completed. These requirements can be long and comprehensive. With maintenance crews seeing multiple systems, the sheer volume of manuals to be studied and reviewed before maintenance is performed is a daunting task. In this case, most crews develop a system of general practices for cleaning and repairing parts. The other case is that the crews will be told to clean this system. The crew will then determine the best way to clean it. They could clean it by hand using solvents, then let it dry, and finally re-oil the equipment, or they could simply power-wash the equipment and then re-oil. The process of solvent cleaning and drying can take upwards of 4 h, while power-washing the parts and oiling with a water-displacing oil will take 5 min. It is easy to see which is done more often, and without guidance or properly reading the manuals the soldiers do not see the benefit associated with the other process. Figure 9 shows a soldier using a pressure washer to clean ammunition containers. The problem with this process is that the rubber seals on the storage containers are only watertight to 21 kPa (3 psi), and the soldier is washing the containers at a pressure of 690 kPa (100 psi).

The real problem with this situation is that systems are often designed to require a large

Fig. 8 M198 howitzer in "ready" position. Source: Ref 5

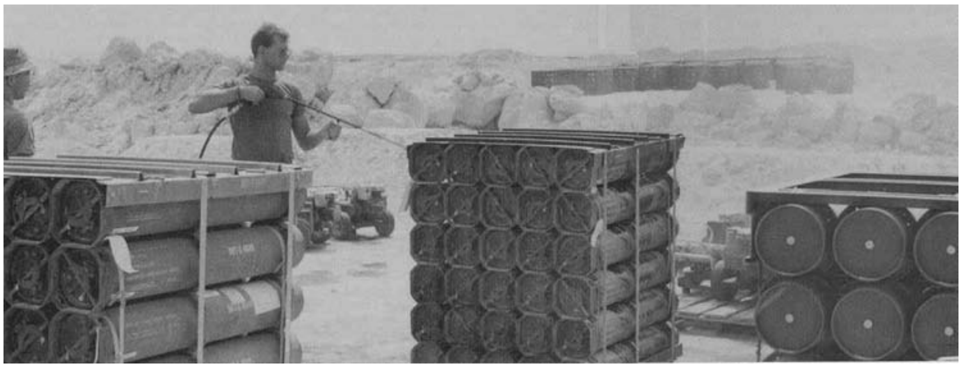

Fig. 9 Pressure washing of ammunition containers. Source: Ref 6

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Table 1 M119 operator preventive maintenance and lubrication requirements

	PMCS(b)					Lubrication(c)(d)		
M119 subassemblies and components(a)	B	D	A	W	M	D	W	Q
(5) Wheel and tire assembly	X				X			
(3) Handbrake assembly	X							
(4) Firing platform	X	X		X	X		GAA/CLP	
(3) Gun barrel assembly	X					CLP	GAA/CLP	
(3) Recuperator recoil mechanism	X	X	X	X	X	CLP/OHT		
(4) Elevation gear assembly	X	X			X	GAA		GAA
(2) Traversing mechanism	X	X		X		GAA	GAA	WTR
(3) Breech mechanism	X	X		X		CLP	CLP	CLP
(1) Balancing gear assembly							GAA/CLP	
(2) Gun barrel support army assembly						CLP	CLP	
(5) Hand spike, jack strut and platform clamps						CLP		
(2) Buffer recoil mechanism and slide assembly	X	X	X	X		OHT		
						CLP	CLP	
(3) Saddle assembly	X				X		GAA	
(2) Trail assembly, gun carriage	X				X			
(1) Traveling stays							CLP	
(4) Trail end hydraulic brake assembly							GAA	
							BFS	
(2) Suspension							GAA	
(3) Cam assembly							GAA	
(2) Traveling lock clamp assembly						CLP		

(a) Numbers in parenthesis in the left-hand column represent the number of corroded parts per assembly. (b) Planned maintenance checks and services (PMCS) requirements: B, before operation; D, during operation; A, after operation; W, weekly; M, monthly. (c) Lubrication requirements: D, daily; W, weekly; Q, quarterly. (d) Lubrication subentries: CLP, cleaner, lubricant, and preservative; GAA, grease, automotive, and artillery; OHT, hydraulic fluid, petroleum base; BFS, brake fluid, silicon; WTR, wide temperature range. Source: Ref 7

amount of maintenance. There is monthly, weekly, and in some cases daily maintenance required to keep systems functioning. This process removes the design engineer from responsibility if the system fails, because it is not the designer's fault that the maintenance was not completed. If a part is designed to require little or no maintenance and the part fails, then the design is faulty. Table 1 shows the maintenance schedule for the M119 howitzer. It is apparent the M119 requires a large amount of maintenance to keep parts in working order. For example, the recuperator recoil mechanism has planned maintenance checks and services before, during, and after use. There are also weekly and monthly checks. Hydraulic fluid and cleaner, lubricant, and preservative (CLP) must be applied daily. The M119 howitzer has daily maintenance requirements for 9 of the 19 subassemblies in the system. For armament corrosion, this raises the question whether it is realistic to assume soldiers will be able to complete required maintenance for equipment in a war-fighting condition. If parts will not receive the maintenance, then they have simply been designed to fail.

Conclusions

Of the forms of corrosion, the ones that are experienced most in armament systems are general or uniform corrosion, galvanic corrosion, and crevice corrosion. These types of corrosion account for a large portion of the corrosion problems found in armament systems, but are not the only causes of corrosion. In this case, everyone involved with an armament system needs to be aware of the types of corrosion, their causes, and steps that can be taken to prevent degradation. If everyone involved in a system is consciously trying to avoid problems associated with these types of corrosion then the readiness of equipment will be drastically increased and the total cost to the government associated with these systems will be reduced.

REFERENCES

1. J. Menke, "Executive Summary of M198 Howitzer Ring Gear Failure," United States Army, 2003
2. J. Menke, "Failure Analysis of the Ring Gear Bearing in The M198 Howitzer," United States Army ARDEC, presented at NACE International Regional Conference, 2001
3. R.C. Ebel, "Cartridge 105 MM: APFSDS-T M735 Corrosion Study," Technical Report ARLCD-TR-80004, U.S. Army Armament Research, Development and Engineering Center, Large Caliber Weapon Systems Laboratory, June 1980
4. "Corrosion of Rotating Band M918 TP," Quality Deficiency Report 03-013, U.S. Army ARDEC, 2004
5. J. Menke, "M119 Firing Platform Failure Analysis #2," U.S. Army ARDEC, 2003
6. K.G. Karr and R.G. Terao, Ammunition Retrograde from SWA, *Ordnance,* May 1992, p 44–47
7. *Technical Maintenance Manual for Howitzer, Medium, Towed: 155-MM, M198,* Army TM 9-1025-211-20&P Department of the Army, 1991

SELECTED REFERENCES

- M.F. Ashby, *Materials Selection in Mechanical Design,* 2nd ed., Butterworth Heinemann, 2001
- J.W. Bray, Aluminum Mill and Engineered Wrought Products, *Properties and Selection: Nonferrous Alloys and Special-Purpose Materials,* Vol 2, *ASM Handbook,* ASM International, 1990, p 29–61
- R.B.C. Caulyess, Alloy and Temper Designation Systems for Aluminum and Aluminum Alloys, *Properties and Selection: Nonferrous Alloys and Special-Purpose Materials,* Vol 2, *ASM Handbook,* ASM International, 1990, p 15–28
- M.G. Fontana and R.W. Staehle, *Advances in Corrosion Science and Technology,* Vol 2, Plenum Press, 1972
- J. Gauspari, *I Know It When I See It,* AMACOM, 1985
- L. Gilbert, Briefing Notes "U.S. Army Corrosion Control" (Rock Island, IL), April 18, 1979
- H.P. Godard, W.B. Jepson, M.R. Bothwell, and R.L. Kane, *The Corrosion of Light Metals,* John Wiley & Sons, 1967
- G.A. Greathouse and C.J. Wessel, *Deterioration of Materials: Causes and Preventive Techniques,* Reinhold Publishing, 1954
- E.H. Hollingsworth and H.Y. Hunsicker, Corrosion of Aluminum and Aluminum Alloys, *Corrosion,* Vol 13, 9th ed., *Metals Handbook,* ASM International, 1987, p 583–609
- R.J. Landrum, *Fundamentals of Designing for Corrosion Control, A Corrosion Aid for the Designer,* NACE International, 1989
- G. Lorin, *Phosphating of Metals: Constitution, Physical Chemistry, and Technical Applications of Phosphating Solutions,* Finishing Publications Ltd., 1974
- J.L. Parham, "Silicone Resin Reversion in the Army's Night Sights," U.S. Army Missile Command Technical Report-RD-ST-93-2, April 1993
- V.R. Pludek, *Design and Corrosion Control,* The Macmillan Press Ltd., 1977
- Properties of Wrought Aluminum and Aluminum Alloys, *Properties and Selection: Nonferrous Alloys and Special-Purpose Materials,* Vol 2, *ASM Handbook,* ASM International, 1990, p 62–122
- J. Senske, J. Nardone, and K. Kundig, "Corrosion Survey for Large Caliber Projectiles," Special Report CPCR-2 Project 1L1612105AH84, U.S. Army Armament Research, Development and Engineering Center
- G. Shaw, Optimizing Paint Durability, Part I, *Prod. Finish.,* Nov 2004, p 42–46
- H.H. Uhlig and R.W. Revie, *Corrosion and Corrosion Control, An Introduction to Corrosion Science and Engineering,* 3rd ed., John Wiley & Sons, 1985

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