

FINAL REPORT

Environmentally Friendly Fastener Coating Demonstration

ESTCP Project WP-201315

MARCH 2021

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ACRONYMS AND ABBREVIATIONS

ARL	U.S. Army Research Laboratory
ASTM	American Society for Testing and Materials
CARC	Chemical Agent Resistant Coating
CPAC	Corrosion Prevention and Control
Cr6 ⁺	Hexavalent Chromium
COF	Coefficient of Friction
DoD	Department of Defense
DP	Demonstration Plan
EC	Electrodeposition Coating
ESOH	Environmental, Safety and Occupational Health
ESTCP	Environmental Security Technology Certification Program
GMW	General Motors Worldwide
GSE	Ground Support Equipment
HAPs	Hazardous Air Pollutants
HazMat	Hazardous Material
HCP	Hexavalent Chrome Passivate
HPA(P)	High-Purity Aluminum Plating
JTP	Joint Test Protocol
JTR	Joint Test Report
MTVR	Medium Tactical Vehicle Replacement
N	Newton (force unit)
NaCl	Sodium Chloride
NFS	Notched Fracture Strength
Nm	Newton meter
NSS	Neutral Salt Spray
OEM	Original Equipment Manufacturer
Phos/Oil	Metal Phosphate plus light oil, plain fastener coating
PPG	PPG Industries, Inc.
PSI	Pounds per Square Inch
SAE	Society of Automotive Engineers
SERDP	Strategic Environmental Research and Development Program
SSPC	The Society of Protective Coatings

TACOM	U.S. Army Tank-Automotive and Armaments Command
TARDEC	U.S. Army Tank-Automotive Research, Development and Engineering Center
TCP	Trivalent Chrome Passivate
TRL	Technology Readiness Level
T/T	Torque/Tension
USCAR	United States Council for Automotive Research
VOC	Volatile Organic Compound
ZR (ZRC)	Zinc Rich Primer

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ABSTRACT

INTRODUCTION AND OBJECTIVES

Traditionally, steel fasteners have been used with cadmium electroplated coatings followed by a hexavalent chrome rinse. This provides effective and long lasting corrosion protection however environmental hazards associated with both cadmium and hexavalent chromium are well established and significant legislation has been put in place recently to limit their continued usage. The overarching objective of this project is a comprehensive evaluation of applications and requirements for environmentally friendly fastener coatings for military ground vehicles, characterization of the performance and maturity of available or proposed alternative fastener coating technology, and recommendations and actions for development, optimization, and demonstration/validation of toxic metal free fastener coatings.

TECHNOLOGY DESCRIPTION

Two separate fastener coatings systems were selected for the proposed demonstration and validation program. Both coating systems include a sacrificial metal base coat, zinc or aluminum, and an organic electrocoat topcoat technology that eliminates environmental concerns associated with currently fielded cadmium and/or chromium containing coating systems.

PERFORMANCE AND COST ASSESSMENT

Performance was through lab testing of coated coupons and fasteners as well as field testing of coated fasteners installed on MTRV assets in multiple locations. Performance measures included cyclic and neutral salt spray, hydrogen embrittlement, adhesion and torque tension among other tests. Both zinc rich and high purity plating systems performed nearly as well as the incumbent cadmium/hex chrome systems and significantly better than zinc phosphate only fasteners.

The zinc rich/electrodeposition topcoat option is cost effective for substantial corrosion improvement in applications where plain phosphated fasteners are currently being used. For applications where cadmium is currently being used, both of the candidates coating systems are potential replacement candidates depending on cost restraints and performance needs.

IMPLEMENTATION ISSUES

The electrodeposition topcoat is necessary over sacrificial coatings for lubricity and corrosion performance however this additional coating layer can exceed tolerances for fit and impair hand threadability. The fastener supply chain is also exceedingly complex due to the number and type of fasteners utilized. Much of the difficulty lies in changing supply chain at the depot refit level where most of the cadmium usage still occurs. Many OEMs have already transitioned to alternative coatings. However, depots are bound by legacy drawings and NSN designations. Therefore the task of implementing a new coating system is daunting.

PUBLICATIONS

Poster Presentation - Demonstrating Viability of Low VOC Electrocoat Primers for General Depot Use, SERDP-ESTCP Symposium, 2018.

EXECUTIVE SUMMARY

INTRODUCTION

ESTCP selected the “Environmentally Friendly Fastener Coating Demonstration” project, led by PPG, to identify environmentally friendly alternatives to cadmium plating and chrome rinses on fasteners used in assembly and maintenance of DoD ground vehicles (e.g. LTVR, MRAP). A successful candidate would result in the mitigation of the significant Environmental, Safety, and Occupational Health (ESOH) risks associated with the use of cadmium and chromium (6+) containing coatings for use on fasteners used on such land vehicles.

There is a need to implement innovative and cost effective replacement technologies to address the multiple health, safety and compliance issues associated with the current systems while maintaining military readiness for national defense. In addition, the new technology must have the following attributes: 1) compatibility with OEM/Depot infrastructure, 2) corrosion performance equivalent to (or better than) current fastener coatings in use, 3) broad compatibility with the current suite of military coatings and, 4) compatibility with substrates used by the DoD. The objective of the proposed program is to demonstrate two new fastener coating systems in DoD environments. The two new coatings will be shown to be both environmentally acceptable, (no heavy metals such as Cr^{6+} or Cd), and demonstrate corrosion resistance characteristics equal to, or nearly equal to that of Cd/Cr^{6+} plating.

Traditionally, steel fasteners have been used with cadmium electroplated coatings followed by a hexavalent chrome rinse. The environmental hazards associated with cadmium and hexavalent chromium are well established and significant legislation has been put in place recently to limit their continued usage. It is critical that suitable replacement technologies be identified that can provide these high performance characteristics in a cost effective manner.

There are a variety of coating systems commercially available which have been used for many years in the automotive, industrial, and construction industries. The non-toxic alternatives include zinc and nickel plating, zinc flake dip-spin primers, dip-spin organic topcoats, and electrodeposition topcoats. While zinc/nickel plating offers moderate corrosion protection, it is costly and suffers from the same possibilities of hydrogen embrittlement as does cadmium plating. In addition, plated surfaces can be problematic for adhesion of topcoats. Similarly, conventional dip-spin zinc flake primers are difficult to topcoat. Adhesion can be poor and corrosion performance (with topcoat) is inadequate.

Two candidate alternative coating systems will be applied to and tested on standard bolts for laboratory tests and on appropriate fasteners for field application on a DoD ground vehicle platform. One coating will include a zinc rich primer and the other will be treated with high purity aluminum plating. Both will be topcoated with a cationic epoxy electrodeposition layer. The parts selected for lab testing are of materials and types typical of those used for bolted joint applications found in military ground vehicles. Lab testing will also be performed on flat test panels for relative corrosion comparison, and for tape adhesion testing where fastener testing is not appropriate or would not provide adequate consistency. For control purposes, the target fasteners and panels will also be coated with electroplated cadmium plus hexavalent chromium conversion rinse. All parts are obtained from the manufacturers without coatings applied (bare or phosphated steel with oil only). Candidate coatings are then applied using the appropriate methods.

OBJECTIVES

The overarching objective of this project is a comprehensive evaluation of applications and requirements for environmentally friendly fastener coatings for military ground vehicles, characterization of the performance and maturity of available or proposed alternative fastener coating technology, and recommendations and actions for development, optimization, and demonstration/validation of toxic metal free fastener coatings.

The Demonstration Plan and Joint Test Protocol developed for this project serve to mature and evaluate the application processes of these fastener coatings which have high potential to meet the corrosion performance requirements of the DoD. Successful demonstrations will provide a body of data sufficient to draft military specifications which would make the coatings available for use on DoD assets. This also may create opportunities for additional demonstrations and validations in areas where current products are not good enough.

Two commercially available coating alternatives have been chosen. The first is a multilayer finish comprising a zinc phosphate conversion coating (PPG IRCOBOND® Z24) plus an inorganic zinc flake primer (PPG SPINCOAT® ZRC) plus cationic epoxy electrodeposition topcoat (PPG POWERCRON® XP). The second is a multilayer finish comprising high purity aluminum plating (HPAP, AlumiPlate®) plus trivalent chromium passivate (TCP, Alumiplate), plus cationic epoxy electrodeposition topcoat (PPG POWERCRON XP). This finish includes media blasting for surface preparation and no conversion (e.g. phosphate) is used. Each will be tested on bolts. The performance will be compared to cadmium plating with hexavalent chromium rinse.

- The coatings will be tested at the Army Research Laboratory (ARL) under laboratory conditions as described in the JTP. The coatings will also be tested in a field application on military vehicles. For field testing, a negative control will be included where no sacrificial coating is present; phosphate and oil only.
- For this project, cadmium and hexavalent chromium, as found in current fastener coatings, was identified as the target HazMat to be eliminated or reduced. Table ES-1 summarizes the target HazMat, process, application, current specifications, affected programs, and candidate parts/substrates.

Table ES-1. Target Hazardous Material (HazMat) Summary

Target HazMat	Current Process	Applications	Current Specifications	Affected Programs	Candidate Parts and Substrates
Cadmium	Electroplating	Corrosion protection of fasteners	SAE-AMS-QQ-P-416C.	All military ground vehicles and their fasteners	All steel bolts, nuts, washers, clips, and other small steel components.
Hexavalent Chromium Conversion Coating	Immersion and spray application	Used as a conversion coating for cadmium plating	MIL-DTL-5541	All military ground vehicles and their fasteners	All steel bolts, nuts, washers, clips, and other small steel components.

TECHNOLOGY DESCRIPTION

Both of the candidate coating systems include a sacrificial metal base coat, zinc or aluminum, and an organic electrocoat topcoat technology that eliminates environmental concerns associated with currently fielded cadmium and/or chromium containing coating systems. The zinc/electrocoat coating system consists of an inorganic metal flake dip-spin coating based on a unique inorganic binder and zinc flake technologies. This, in combination with the topcoat, will offer a high end corrosion option which is commercially available and is cost competitive versus cadmium or other plating alternatives. In contrast, the aluminum/electrocoat coating system consists of high purity aluminum plating, (HPAP), coupled with the electrocoat topcoat. This combination provides the highest level of corrosion performance, closest to that of cadmium, but at much higher cost versus cadmium.

Each of the basecoat technologies provides the corrosion resistance and performance characteristics required of high strength fastener designs. The organic electrocoat topcoat layer provides the additional barrier properties, corrosion resistance and the required torque tension characteristics.

The coating systems targeted for demonstration/validation on fasteners are coded and described as follows:

Type 1 - A multilayer fastener coating system comprising:

- Zinc Phosphate Conversion Coating - Cleaning and application of IRCOBOND® Z24, commercially available from PPG Industries, Inc. Application per manufacturer's recommendations, followed by heated drying stage and cooling. Conforms to TTC 490 Type 1.
- Zinc Rich Primer – Application of SPINCOAT® ZRC inorganic zinc rich primer, commercially available from PPG Industries, Inc. The coating is applied by conventional dip-spin methods for a dry film thickness of 0.25-0.45 mils. The coating is bake cured at 450°F and cooled prior to topcoat application.
- Epoxy Electrodeposition Coating – Application of POWERCRON® XP cationic electrodeposition coating, commercially available from PPG Industries, Inc. Coating is applied by barrel process according to manufacturer's recommendations for a dry film thickness of 0.30-0.50 mils. The coating is bake cured at a temperature of 375°F and cooled. This topcoat contains integral torque modifiers.

Type 2 - A multilayer fastener coating system comprising:

- High Purity Aluminum Plating – Application of a high purity aluminum plating (HPAP) for a film thickness of 0.3 mils, commercially available from the AlumiPlate company. The plating process is followed by a trivalent chromium Passivate (TCP).
- Epoxy Electrodeposition Coating – Application of POWERCRON® XP cationic electrodeposition coating, commercially available from PPG Industries, Inc. Coating is applied by barrel process according to manufacturer's recommendations for a dry film thickness of 0.30-0.50 mils. The coating is bake cured at a temperature of 375°F and cooled. This topcoat contains integral torque modifiers.

Type 3 - Positive Control Coating – Cadmium/Hex Chrome (Cd/HCP) with Dry Film Lube

- Cadmium plating plus hexavalent chromium conversion per specification SAE AMS QQ-P-416C, Type II, Class2. This includes a hydrogen relief bake.
- Dry film lubricant applied to the thread area. MIL-PRF-46147 Type 1 #28A lubricant available from Sandstrom, applied by dip to 0.3-0.7 mils, air dry minimum 6 hour. Conforms to MIL-STD-171 Type I and II, MIL-L-23398 Type I and II, SAE-AS1701 Class II, NSN 9150-00-954-7422.

Type 4 - Negative Control - No sacrificial coating

At the conclusion of laboratory scale accelerated testing and field testing on MTRs the following conclusions were reached with respect to performance and suitability of the candidate coating systems to replace cadmium/HCP fasteners.

- Neither coating Type 1 or Type 2 are 100% replacements for cadmium/HCP (Type 3).
- Electrodeposition topcoat is necessary over sacrificial coatings for lubricity and corrosion performance.
- Coating Type 1 (zinc rich dip-spin primer plus electrodeposition topcoat) offers a low cost alternative with significant corrosion performance over phosphate alone, and slightly weaker than cadmium/HCP. Thread fit is problematic except where plated nuts are used.
- Coating Type 2 (high purity aluminum plating plus electrodeposition topcoat) offers near cadmium/HCP corrosion performance. In the current state of commercial availability, aluminum plating is prohibitively costly for bulk fastener applications. Thread fit is problematic except where plated nuts are used.
- Corrosion performance can best be judged by accelerated tests or field exposure of coated fastener samples. Salt spray testing and flat cold rolled steel substrate are not good predictors of real world performance.
- Electrodeposition topcoat can be formulated to match torque/tension characteristics of cadmium plated fasteners.
- Electrodeposition topcoat reduces or eliminates installed galvanic corrosion effects.
- All coating types pass dry hydrogen embrittlement testing. All fail wet cell embrittlement test. Validity of wet cell testing is debatable.

COST ASSESSMENT

The successful implementation of the fastener coating technologies which are the subject of this demonstration, would involve simple substitution of one commercially available fastener for another. There would be no deviation from standard protocols in term of labor, facilities, or tooling.

In situations where fasteners plated with cadmium are being replaced by the subject coatings, there would be a small cost advantage since end-of-life disposal costs of the cadmium parts would not be incurred. Since fastener applications are so widely varied, it is impossible to quantify overall cost impacts of implementation of these technologies.

Although the goal of this project was to replace cadmium/chromium⁶⁺ coatings, these technologies are also candidates for replacement of high strength fasteners in applications where low corrosion performance coatings such as phosphate are currently employed. In these cases, there may be some cost benefit realized due to superior corrosion control. This may reduce the refit frequency for these parts. It also may decrease the time and labor required to remove and replace fasteners.

There is some cost impact related to the cost of the fasteners themselves. Fastener costs vary widely and are dependent on factors such as production volume and custom manufacture. The coating system used can represent a large or a very small percentage of the total part cost. For example, a review of industrial fastener suppliers shows that common size hex bolts plated with cadmium can range in price from \$0.50 each to \$14 each. However, for comparison purposes, Table 2 shows the relative cost of each coating system based on the processing prices incurred in producing the parts used for the JTP testing. For comparison, the prices are estimated for a 100 pound batch of 3/8-16 1¼ inch hex bolts purchased at \$0.18 each. This represents approximately 1800 pieces. Included are the costs for the multilayer coating systems and also a breakout of the individual coating layers.

An additional cost factor which must be considered is the cost of housekeeping to control Cd/Cr⁶⁺ dust generated from subsequent sustainment activities, which is very high, but is a cost that only comes in the next depot cycle or in the field. There are also costs associated with end-of-life disposal of cadmium plated parts.

Table ES-2. Coating Cost Comparison

Coating	Cost vs. Performance	Cost to apply coating to 100 lb. of parts	Cost impact on total price of 100 lbs. parts
Phosphate and Oil (as supplied) (Negative Control)	Lowest cost Very low corrosion resistance	\$0 Baseline	Baseline (\$324)
Cadmium Plating with chromate ⁶⁺ (positive control)	Small cost premium Highest corrosion resistance	\$200	1.6 X
Zinc Rich Primer plus Electrodeposition topcoat (Type 1)	Small cost premium High corrosion resistance	\$350	2.1 X
HPAP plus Electrodeposition topcoat (Type 2)	Very High Cost Very High corrosion resistance	\$3050	10.1 X

This comparison shows that the zinc rich/electrodeposition topcoat option is cost effective for substantial corrosion improvement in applications where plain phosphated fasteners are currently being used. For applications where cadmium is currently being used, both of the candidates coating systems are potential replacement candidates. The HPAP/Electrodeposition topcoat system offers high end corrosion resistance but at a very high cost. This may be appropriate in mission-critical applications where the cost premium is not a key factor. The zinc rich/electrodeposition topcoat option may be appropriate in applications as a cadmium replacement where cost is important and a solution with corrosion performance slightly less than cadmium is acceptable.

IMPLEMENTATION ISSUES

Analysis of the more aggressive lab accelerated corrosion test indicate that neither candidate coating is equal to cadmium/HCP. The Type 1 (zinc rich primer plus electrodeposition topcoat) and Type 2 (high purity aluminum plating plus electrodeposition topcoat) appear in all testing to be nearly equal but slightly inferior to Type 3 (cadmium/HCP), and far superior to the negative control Type 4 with no sacrificial metallic layer (phosphate plus oil only).

A significant drawback associated with the candidate coatings is the negative affect on thread gauging due to the thickness of the coating layers. For Type 1 the zinc rich dip-spin primer tends to be less even than plating layers and film thickness and can exceed 10 microns in thread roots. The plating layers of Types 2 and 3 at an average of 7-8 microns occupy essentially all of the thread allowance for a standard ISO or UNC external thread. With electrocoat added at an additional 7-8 microns, the bolt threads are extended beyond allowance and hand-threading is impaired or impossible. Even the Type 3 cadmium plating layer with an approved dry lube applied is difficult to hand thread.

The thread gauging is not problematic when the external threaded bolts are paired with zinc plated nuts as was the case for the samples used for friction testing. Zinc plated nuts are manufactured with expanded thread gauge to accommodate the thickness of plated bolts. Therefore, the candidate coating combinations tested here would only be acceptable when paired with plated nuts.

It become apparent during the course of this work that the path to introducing a new cadmium replacement coating into the DoD supply chain is very complex and difficult. There is not a well-established protocol beyond achieving specification approval and fasteners are especially complex since the number and variety is so great. Much of the difficulty lies in changing supply chain at the depot refit level where most of the cadmium usage still occurs. Many OEMs have already transitioned to alternative coatings. However, depots are bound by legacy drawings and NSN designations. Therefore the task of implementing a new coating system is daunting.

In attempt to gain a better understanding of what would be required to penetrate the supply chain. We contracted Cerrdesa, a consulting firm with knowledge of DoD operation, to compile a report on the subject. The Corrdesa report recommended a multi-pronged approach to getting the new PPG coatings into the defense market with the primary market being vheicle fasteners. Primary routes into the market include introduction of the technologies to OEMs such as BAE Land Systems, Engagement with TACOM Program managers, DLA enagement, and Revision of TT-C-490.

1.0 INTRODUCTION

1.1 BACKGROUND

ESTCP selected the “Environmentally Friendly Fastener Coating Demonstration” project, led by PPG, to identify environmentally friendly alternatives to cadmium plating and chrome rinses on fasteners used in assembly and maintenance of DoD ground vehicles (e.g. LTVR, MRAP). A successful candidate would result in the mitigation of the significant Environmental, Safety, and Occupational Health (ESOH) risks associated with the use of cadmium and hexavalent chromium (Cr6^+) containing coatings for use on fasteners used on such land vehicles.

There is a need to implement innovative and cost effective replacement technologies to address the multiple health, safety and compliance issues associated with the current systems while maintaining military readiness for national defense. In addition, the new technology must have the following attributes: 1) compatibility with OEM/Depot infrastructure, 2) corrosion performance equivalent to (or better than) current fastener coatings in use, 3) broad compatibility with the current suite of military coatings and, 4) compatibility with substrates used by the DoD. The objective of the proposed program is to demonstrate two new fastener coating systems in DoD environments. The two new coatings will be shown to be both environmentally acceptable, (no heavy metals such as Cr6^+ or Cd), and demonstrate corrosion resistance characteristics equal to, or nearly equal to that of Cd/ Cr6^+ plating.

Traditionally, steel fasteners have been used with cadmium electroplated coatings followed by a hexavalent chrome rinse. The environmental hazards associated with cadmium and hexavalent chromium are well established and significant legislation has been put in place recently to limit their continued usage. It is critical that suitable replacement technologies be identified that can provide these high performance characteristics in a cost effective manner.

There are a variety of coating systems commercially available which have been used for many years in the automotive, industrial, and construction industries. The non-toxic alternatives include zinc and nickel plating, zinc flake dip-spin primers, dip-spin organic topcoats, and electrodeposition topcoats. While zinc/nickel plating offers moderate corrosion protection, it is costly and suffers from the same possibilities of hydrogen embrittlement as does cadmium plating. In addition, plated surfaces can be problematic for adhesion of topcoats. Similarly, conventional dip-spin zinc flake primers are difficult to topcoat. Adhesion can be poor and corrosion performance (with topcoat) is inadequate.

Two candidate alternative coating systems will be applied to and tested on standard bolts for laboratory tests and on appropriate fasteners for field application on a DoD ground vehicle platform. One coating will include a zinc rich primer and the other will be treated with high purity aluminum plating. Both will be topcoated with a cationic epoxy electrodeposition layer. The parts selected for lab testing are of materials and types typical of those used for bolted joint applications found in military ground vehicles. Lab testing will also be performed on flat test panels for relative corrosion comparison, and for tape adhesion testing where fastener testing is not appropriate or would not provide adequate consistency. For control purposes, the target fasteners and panels will also be coated with electroplated cadmium plus hexavalent chromium conversion rinse.

All parts are obtained from the manufacturers without coatings applied (bare or phosphated steel with oil only). Candidate coatings are then applied using the appropriate methods.

ESTCP program requirements include the development of a Joint Test Protocol (JTP) (Appendix A). This JTP contains the technical requirements and tests necessary to evaluate non-toxic metal containing fastener coatings against qualified and approved cadmium and chromium containing fastener coatings.

1.2 OBJECTIVE OF THE DEMONSTRATION

The overarching objective of this project is a comprehensive evaluation of applications and requirements for environmentally friendly fastener coatings for military ground vehicles, characterization of the performance and maturity of available or proposed alternative fastener coating technology, and recommendations and actions for development, optimization, and demonstration/validation of toxic metal free fastener coatings.

The purpose of the Demonstration Plan (Appendix B) and JTP (Appendix A) is to mature and evaluate the application processes of these fastener coatings which have high potential to meet the corrosion performance requirements of the DoD. Successful demonstrations will provide a body of data sufficient to draft military specifications which would make the coatings available for use on DoD assets. This also may create opportunities for additional demonstrations and validations in areas where current products are not good enough.

Two commercially available coating alternatives have been chosen. The first is a multilayer finish comprising a zinc phosphate conversion coating (PPG IRCOBOND® Z24) plus an inorganic zinc flake primer (PPG SPINCOAT® ZRC) plus cationic epoxy electrodeposition topcoat (PPG POWERCRON® XP). The second is a multilayer finish comprising high purity aluminum plating (HPAP, AlumiPlate®) plus trivalent chromium passivate (TCP, Alumiplate), plus cationic epoxy electrodeposition topcoat (PPG POWERCRON XP). The TCP passivation was performed by Alumiplate, using their proprietary process, in accordance with MIL-DTL-5541F, Type II, Class IA. This finish includes media blasting for surface preparation and no conversion (e.g. phosphate) is used. Each will be tested on bolts. The performance will be compared to cadmium plating with hexavalent chromium rinse.

- The coatings will be tested at the Army Research Laboratory (ARL) under laboratory conditions as described in the JTP¹. The coatings will also be tested in a field application on military vehicles. For field testing, a negative control will be included where no sacrificial coating is present; phosphate and oil only.
- For this project, cadmium and hexavalent chromium, as found in current fastener coatings, was identified as the target HazMat to be eliminated or reduced. Table 1 summarizes the target HazMat, process, application, current specifications, affected programs, and candidate parts/substrates.

¹ Testing was performed by PPG (see Section 5).

Table 1. Target Hazardous Material (HazMat) Summary

Target HazMat	Current Process	Applications	Current Specifications	Affected Programs	Candidate Parts and Substrates
Cadmium	Electroplating	Corrosion protection of fasteners	SAE-AMS-QQ-P-416C.	All military ground vehicles and their fasteners	All steel bolts, nuts, washers, clips, and other small steel components.
Hexavalent Chromium Conversion Coating	Immersion and spray application	Used as a conversion coating for cadmium plating	MIL-DTL-5541	All military ground vehicles and their fasteners	All steel bolts, nuts, washers, clips, and other small steel components.

1.3 REGULATORY DRIVERS

Cadmium is a soft metal typically extracted from zinc ores which has been used as a pigment due to its ability to produce brilliant red-orange colors. More recently it's been used in nickel-cadmium batteries, electroplating, solar cells and alloys. Despite these applications, cadmium and its compounds are known to cause cancer and target cardiovascular, renal, gastrointestinal, neurologic, reproductive and respiratory systems. Accordingly, exposure is highly regulated in numerous industries. For example, 29 CFR 1910.1027 subpart Z, sets permissible airborne concentrations (PEL) at no more than 5 µg/m³ as calculated by an eight hour time-weighted exposure. The action level for exposure is only 2.5 µg/m³ at which point the employer must initiate a monitoring schedule and assure adequacy of engineering controls in the event exposures exceed the PEL. Further, OSHA includes specific directives regarding record keeping and medical surveillance of workers exposed to cadmium. Citations for non-compliance can ultimately result in penalties of up to \$10,000 for employers.

This report uses the terms Cr6⁺. The terms for chrome in the following paragraph come from the referenced document and differ from the terms in the rest of the document.

With respect to chromium compounds the U.S. Army policy mandates the use of the 2018 ACGIH TLVs® as the Army Occupational Exposure Limit (OELs) for Chromium Metal (Cr(0)), Trivalent Chromium (Cr(III)), and Cr(VI). The ACGIH TLVs® for Cr(0), Cr(III), and Cr(VI) are 0.5 milligrams per cubic meter of air (mg/m³), 0.003 mg/m³, and 0.0002 mg/m³, respectively which are all lower than previously published values. All chromium TLVs® exposures are measured as inhalable fraction of the aerosol.

Technical, economic, and resource challenges have thus far prevented immediate implementation of the 2018 ACGIH Cr(0), Cr(III), and Cr(VI) TLVs® which makes the topic of this report of particular importance.

2.0 DEMONSTRATION TECHNOLOGY

2.1 TECHNOLOGY DESCRIPTION

Two separate fastener coatings systems have been selected for the proposed demonstration and validation program. Both coating systems include a sacrificial metal base coat, zinc or aluminum, and an organic electrocoat topcoat technology that eliminates environmental concerns associated with currently fielded cadmium and/or chromium containing coating systems. The zinc/electrocoat coating system consists of an inorganic metal flake dip-spin coating based on a unique inorganic binder and zinc flake technologies. This, in combination with the topcoat, will offer a high end corrosion option which is commercially available and is cost competitive versus cadmium or other plating alternatives. In contrast, the aluminum/electrocoat coating system consists of high purity aluminum plating, (HPAP), coupled with the electrocoat topcoat. This combination provides the highest level of corrosion performance, closest to that of cadmium, but at much higher cost versus cadmium.

Each of the basecoat technologies provides the corrosion resistance and performance characteristics required of high strength fastener designs. The organic electrocoat topcoat layer provides the additional barrier properties, corrosion resistance and the required torque tension characteristics.

2.1.1 Technology Maturity

In July of 2008 PPG Industries entered into a contract with the Strategic Environmental Research and Development Program to perform research and development of a multi-layer fastener coating system (SERDP WP1617). Work on that program has been completed (see Final Report [1]). The result is a commercial product consisting of the three major components of the coating system; inorganic coating binder, engineered zinc flake and the electrodeposition topcoat. The various stages of the coating process are illustrated in Figure 1. Collectively the coating system design, formulation improvements, performance test results, and manufacturability assessments completed during the SERDP funded initiative make this project well suited to advance to a demonstration phase in an operational environment. Figure 1 depicts the zinc rich primer plus electrodeposition topcoat coating system.



Figure 1. Coating Layers of Zinc Rich/Electrocoat System Consisting of Zinc Phosphate Pretreatment (Left), Inorganic Zinc Rich Primer (Center) and Electrocoat Topcoat (Right)

The high purity aluminum plating process is also currently commercially available and is provided by AlumiPlate, Inc. of Minneapolis, Minnesota. Originally developed by Siemens AG, the finish for fasteners consists of a thin film, approximately 0.3 mils, of pure aluminum electrodeposited on steel fasteners followed by a trivalent chromium passivate (TCP) treatment. Control of torque tension is provided by the addition of an electrodeposition topcoat developed by PPG. The following sections describe each element of the fastener coating systems proposed for demonstration.

2.1.2 Demonstration Coating Systems

The coating systems targeted for demonstration/validation on fasteners are coded and described as follows:

Type 1 - A multilayer fastener coating system comprising:

- Zinc Phosphate Conversion Coating - Cleaning and application of IRCOBOND® Z24, commercially available from PPG Industries, Inc. Application per manufacturer's recommendations, followed by heated drying stage and cooling. Conforms to TTC 490 Type 1.
- Zinc Rich Primer – Application of SPINCOAT® ZRC inorganic zinc rich primer, commercially available from PPG Industries, Inc. The coating is applied by conventional dip-spin methods for a dry film thickness of 0.25-0.45 mils. The coating is bake cured at 450°F and cooled prior to topcoat application.
- Epoxy Electrodeposition Coating – Application of POWERCRON® XP cationic electrodeposition coating, commercially available from PPG Industries, Inc. Coating is applied by barrel process according to manufacturer's recommendations for a dry film thickness of 0.30-0.50 mils. The coating is bake cured at a temperature of 375°F and cooled. This topcoat contains integral torque modifiers.

Type 2 - A multilayer fastener coating system comprising:

- High Purity Aluminum Plating – Application of a high purity aluminum plating (HPAP) for a film thickness of 0.3 mils, commercially available from the AlumiPlate company. The plating process is followed by a trivalent chromium Passivate (TCP).
- Epoxy Electrodeposition Coating – Application of POWERCRON® XP cationic electrodeposition coating, commercially available from PPG Industries, Inc. Coating is applied by barrel process according to manufacturer's recommendations for a dry film thickness of 0.30-0.50 mils. The coating is bake cured at a temperature of 375°F and cooled. This topcoat contains integral torque modifiers.

Type 3 - Positive Control Coating – Cadmium/Hex Chrome (Cd/HCP) with Dry Film Lube

- Cadmium plating plus hexavalent chromium conversion per specification SAE AMS QQ-P-416C, Type II, Class2. This includes a hydrogen relief bake.
- Dry film lubricant applied to the thread area. MIL-PRF-46147 Type 1 #28A lubricant available from Sandstrom, applied by dip to 0.3-0.7 mils, air dry minimum 6 hour. Conforms to MIL-STD-171 Type I and II, MIL-L-23398 Type I and II, SAE-AS1701 Class II, NSN 9150-00-954-7422.

Type 4 - Negative Control - No sacrificial coating

- Fasteners as supplied with phosphate and oil coating (phos and oil).

CARC Primer and Topcoat – MIL-DTL-53022E Type II primer at 1.5 ± 0.2 mils (37.5 ± 5 microns), plus MIL-DTL-53039E Type IX topcoat at 2.0 ± 0.2 mils (50 ± 0.2 microns). The coatings are applied by spray and are allowed to cure for a minimum of 7 days prior to further handling or testing.

Note: For lab accelerated corrosion testing, Type 4 will consist of zinc phosphate plus electrodeposition topcoat as described in Section 5.

2.1.3 Zinc Rich Coating Binder

Conventional organic binder approaches have proven to be ineffective in thin film zinc rich application due to their tendency to encapsulate and electrically insulate the particles from each other. This makes sacrificial activity very difficult to achieve in films in the range of 5 to 8 microns. PPG developed a novel binder technology by replacing conventional silicate chemistry with analogous organo-titanate technology. As titanates are capable of reacting with organic polyols as well as self-condensation, hybrid binders with greater flexibility and rheology control were able to be formulated.

2.1.4 Zinc Flake Process

PPG has found that sacrificial corrosion performance in thin film zinc rich coatings is greatly enhanced by the use of flakey zinc particles versus spherical zinc dust particles. Flake particles are capable of overlapping to give high surface area contact between zinc particles and the substrate. PPG utilizes flakes made in a process in which the zinc dust and other additives are milled under controlled conditions to form flattened flake-like zinc particles. This process allows control of the flake shape and size distribution as well as the surface characteristics of the flake. The resulting film provides an excellent substrate for subsequent coatings as demonstrated with the electrodeposition topcoating. Figure 2 shows steps in application of the zinc rich plus electrodeposition topcoat coating system.



Figure 2. Process Steps for Coating Type 1 – Zinc Rich Primer Plus Electrocoat Coating System

2.1.5 High Purity Aluminum Plating (HPAP)

The performance of this system as a cadmium replacement has been investigated by TARDEC and has demonstrated good corrosion performance. It has, however, been demonstrated that the HPAP alone will deteriorate rapidly in a corrosive environment at points where it is damaged.

Damage can be caused in processing and installation. Also, the typical coefficient of friction for AlumiPlate aluminum is higher than cadmium necessitating application of a lubricant to adjust torque tension properties for most threaded applications. Testing has shown that application of PPG's cationic electrodeposition coating not only provides the lubricity, but also protects the HPAP in such a way that corrosion performance is boosted to a level nearly equal to cadmium.

PPG's electrodeposition process, described below, is well suited for providing topcoats for fasteners in a highly automated fashion. In testing by PPG the system of plated aluminum, TCP treatment and electrodeposition topcoat has significantly increased the corrosion resistance of plated only fasteners while providing torque tension equal to cadmium (Figure 3). The intention of this evaluation is to include the HPAP – electrodeposition system as a high performance, high cost comparison to the zinc-rich electrodeposition system. AlumiPlate Inc. can produce rack plated quantities of fasteners which will be more than adequate for this demonstration. However supplying the DoD market would require capital investment for bulk plating capability. Figure 3 depicts HPAP with and without electrodeposition topcoat. Figure 4 shows the application process steps.



Figure 3. High Purity Aluminum Plating on Steel Fasteners (Left), and Similar Fasteners with the Addition of an Electrodeposition Topcoat (Right)



Figure 4. Process Steps for Coating Type 2 Consisting of Aluminum Plating Followed by Electrodeposition Topcoat.

2.1.6 Electrocoat Topcoat

The performance of either metal rich basecoat technology has been augmented by the addition of a cationic epoxy electrodeposition topcoat. PPG cationic electrocoat is recognized worldwide as a state-of-the-art anticorrosion primer for OEM automotive body applications, as well as many industrial and appliance applications. PPG PPOWERCRON XP is specifically formulated for use on threaded fasteners and includes torque modifiers. This coating system has been demonstrated on a variety of automotive fasteners and small parts such as hose clamps, brackets, and clips. The fasteners are treated with a zinc phosphate conversion coating prior to primer application. The zinc rich primer is then applied by a conventional dip-spin method followed by oven curing at 450°F.

The parts are then electrocoated in a batch barrel process. A comparison of performance properties for the two types of coating system are illustrated in Table 2.

Table 2. Comparison of Zinc Rich and Alumiplate Based Fastener Coating Systems

(Summary data from previous testing by PPG Industries, Inc.)

	Zinc Rich Primer with Cationic Electrodeposition Topcoat	HPAP with Cationic Electrodeposition Topcoat
Part Type	M10 Grade 8 x 40mm Hex bolt	M12 Grade 9.8 Hex Bolts
ASTM B117 Salt Spray	1000 Hrs. no red rust, 3000 Hrs. <5% red rust	>3000 Hrs. no red rust, 5000 Hrs. <5% red rust
GM9540P Cyclic Test	120 Cycles <1% red rust	>120 Cycles no red rust
Torque Tension SAE/USCAR-11	meet GM spec of 48±8 NM on GM T/T test bolt	meet GM spec of 48±8 NM on GM T/T test bolt
F519 Hydrogen Embrittlement (1a.1)	Pass 200 hours at 75% of fracture strength of 391,300 psi.	Unknown

2.2 TECHNOLOGY DEVELOPMENT

All stakeholders have maintained a continuous and open dialogue discussing the technology readiness level (TRL) of the candidate fastener coatings. Over the past several years PPG has worked with TARDEC, Elzly, AlumiPlate, and NMP Corporation (fastener manufacturer) to test and validate the performance of these coating systems. Laboratory testing was done and a field demonstration on MRAP floor screws (unpublished reports). These studies support the proposal that these coatings are effective candidates for environmentally friendly cadmium replacements with equal or nearly equal corrosion performance.

Formulation and optimization of the PPG zinc rich primer (SPINCOAT ZRC) was done under the SERDP program WP-1617 “Environmentally Friendly Anticorrosion Coating for High Strength Fasteners” [1]. In addition to corrosion testing, hydrogen embrittlement was performed. This showed that the zinc rich primer and electrocoat topcoat did not cause direct embrittlement.

2.2.1 Prior Lab Validation Work

A significant amount of validation testing has since been performed. In one study, we examined the corrosion performance of fasteners with the subject coatings, including CARC topcoats. Figure 5, Figure 6, and Figure 7 illustrate the relative performance of the subject coatings versus Cd/Cr⁶⁺ in salt spray and in cyclic corrosion testing. These show the performance of HPAP/electrodeposition topcoat equivalent to Cd/ Cr⁶⁺, and zinc rich/electrodeposition topcoat slightly inferior, but very good, especially with CARC topcoat.



Figure 5. Corrosion Performance of Cadmium Plated, Hexavalent Chrome Rinsed Fasteners (Bottom), Inorganic Zinc Rich Primer with Electrodeposition Topcoat (Middle) and High Purity Aluminum Plating with Electrodeposition Primer (Top) After 2000 Hours Salt Spray (Left) or 100 Cycles GMW14872 (Right).

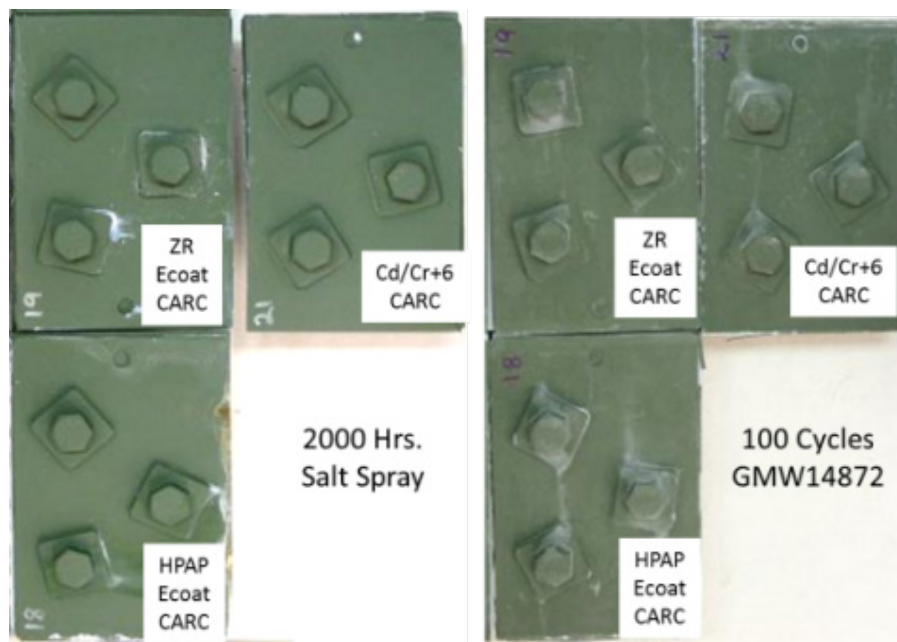


Figure 6. Assemblies of Steel Fasteners Mounted to Steel Plates Showing Salt Spray Performance (Left) and Cyclic Corrosion Testing (Right) for Cadmium Plated, Hexavalent Chrome Rinsed Fasteners, Inorganic Zinc Rich Primer with Electrodeposition Topcoat, and High Purity Aluminum Plating with Electrodeposition Primer.

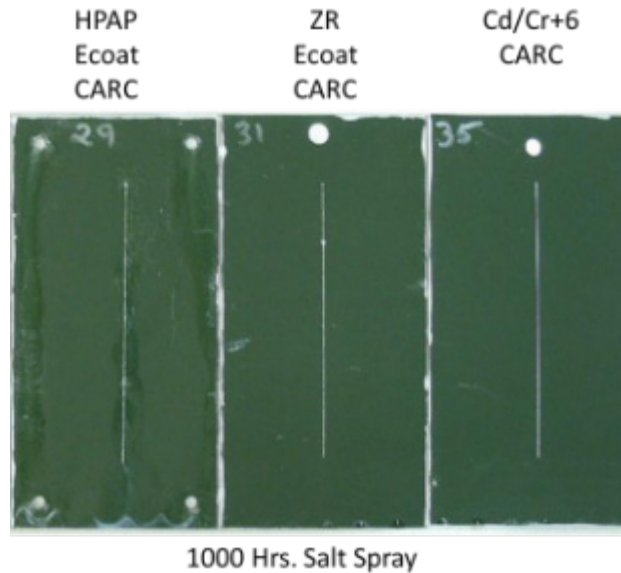


Figure 7. Flat Steel Coupons Illustrating Corrosion Performance After 1000 Hours ASTM B117 for Cadmium Plated, Hexavalent Chrome Rinsed Fasteners, Inorganic Zinc Rich Primer with Electrodeposition Topcoat, and High Purity Aluminum Plating with Electrodeposition Topcoat

2.2.2 Prior Field Demonstration

In addition to lab testing, we have conducted a field trial in conjunction with TARDEC, USMC, and Elzly. In this study, we identified a fastener application in which corrosion was causing significant problems for removal of fasteners. These are flush mount recessed head screws used to secure access panels on the interior floor space on the MRAP platform (Figure 8). This floor is diamond-plate steel.



Figure 8. MRAP Access Panel Screws Illustrating in Field Corrosion Issues

Coating variants in the study included zinc rich/electrocoat, HPAP/electrocoat, and an electrodeposition topcoat without sacrificial primer layer as a negative control. Also included are fasteners with no coating other than the phosphate and oil supplied by the manufacturer. This is the current type fastener being used in this application in which severe corrosion problems are being experienced.

Fasteners were installed on two vehicles at Camp Lejeune, NC in March of 2012. An inspection was performed in July of 2013. Table 3 shows an abbreviated summary of the results. Figure 9 shows the appearance of the exposed fasteners as installed, and after removal.

Table 3. Field Trial Results of MRAP Vehicle Retrofitted with Various Coated Fastener Systems

Fastener Finish	Head Corrosion	Thread Corrosion	Breaking Torque Range (in-lb.)
Control – Phos/oil only	100% red corrosion coverage. Beginning base metal loss	Slight corrosion on the threads and 90% red rust on bolt end	303-338
HPAP/Electrodeposition topcoat	No visible corrosion	No visible corrosion	217-377
Zinc rich primer/Electrodeposition topcoat	No corrosion on top, 0-25% on underside exposed surfaces	No visible corrosion	217-311
Electrodeposition topcoat only	Visible corrosion on 50% of the fastener heads	No visible corrosion	203-280

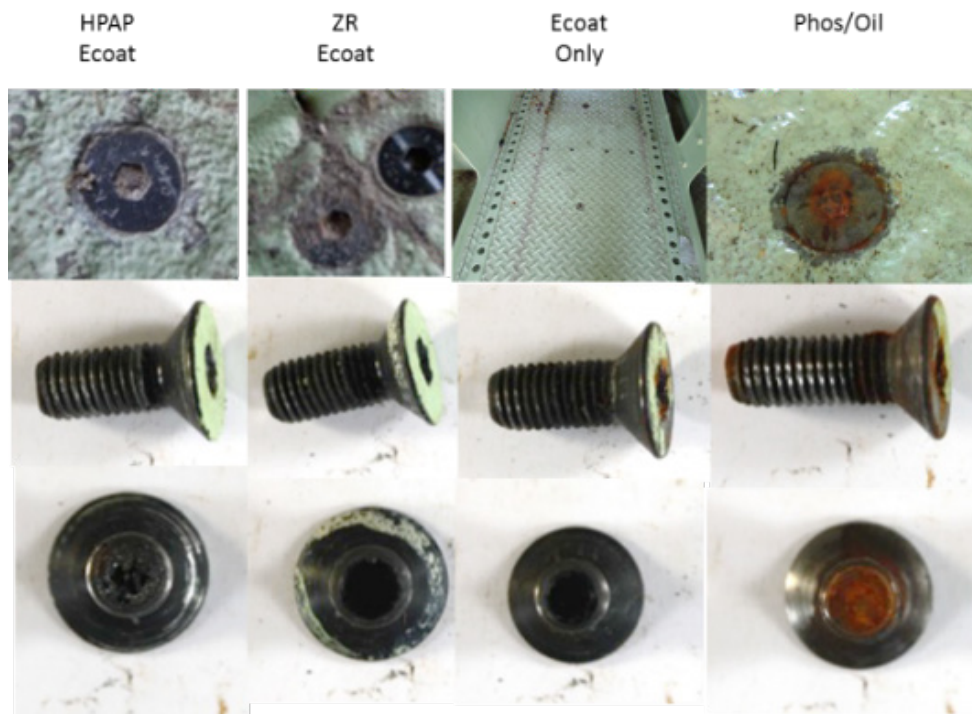


Figure 9. MRAP Field Test Results after 16 Months In-service Illustrating Superior Performance of All Coated Fastener Systems Relative to Incumbent Phosphate/Oil Only Fasteners.

This field trial was somewhat short in duration (~16 months) to show severe deterioration of the negative controls, however, there is evident differentiation in the coating variations. The electrodeposition topcoat only finish shows superior performance compared to phosphate and oil only. The zinc rich/electrodeposition topcoat finish is superior to electrodeposition topcoat only with only sporadic red spots on the underside of the screws. The HPAP/electrodeposition topcoat finish is the best with no red corrosion.

2.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

The PPG zinc rich plus electrodeposition topcoat finish represents a lower cost alternative to cadmium or other metal plating options. The finish is commercially available in any quantity from small batch jobs to very large bulk volumes. The corrosion resistance of this finish, however, is not a 100% equivalent to cadmium/chromium plating. It may be considered to be an approximately 95% equivalent solution. For the large number of applications across the DoD where no sacrificial fastener coatings are being used, this finish offers very significant corrosion resistance performance at reasonable cost.

The HPAP plus electrodeposition topcoat finish alternative has an advantage in that it closely approximates the performance properties of Cd/Cr6⁺ fasteners without the use of heavy metals. . However, this finish is currently available only for small batches of parts and is very costly. Another disadvantage is this coating process is proprietary and available from a single source. It should be noted that there is potential for reduction in the cost of HPAP in the future if larger scale commercial production would become available.

Both candidate finish systems may be limited in application due to the added film thickness. In applications where thread fit is tight in tolerance, the added finish thickness can make mating of nuts and bolts difficult. It is in the scope of this work to determine and specify the limitations of applicability and necessity for special sizing of threaded parts to account for film thickness.

The candidate finishes also offer alternatives with high end corrosion resistance in applications where cadmium plating is unacceptable. In applications where high strength fasteners (>Grade 5) are used in critical areas (e.g. suspensions, aerospace), the use of cadmium, or any other type of electrolytically applied plating, is unacceptable due to the risk of hydrogen embrittlement. The zinc rich primer used in this demonstration is a liquid applied by dip-spin. Testing has shown that it does not cause direct hydrogen embrittlement. Although the electrodeposition topcoat is electrolytically applied, testing has shown that the process does not induce hydrogen embrittlement. This likely due to factors such as, low applied current density, rapid deposition of coating under electrolysis conditions, and insulation of the iron by the zinc phosphate conversion coating layer. POWERCRON XP has been used for many years in a broad range of commercial applications, including fasteners, without reported embrittlement failure.

Note: Topcoat Electrodeposition and Hydrogen Embrittlement Concern: The electrodeposition process involves more than simple electrophoresis. Deposition and coalescence of the polymer at the substrate requires electrolysis of water and a resultant sharp gradient to low pH at the cathode surface. It is the low pH caused by H⁺ generation that neutralizes the basic groups on the polymer and renders it insoluble in the aqueous phase. Neutralized micelles at the surface rapidly coalesce, insulate and stop electrolysis.

3.0 PERFORMANCE OBJECTIVES

The stakeholders have reached consensus on tests with procedures and methodologies for evaluating the fastener coating systems against approved cadmium/chromium coating. Data developed from these tests is intended to be used as a guide for development of acceptance criteria and implementation for end applications. It is not intended to be used for qualifying or excluding any alternative. Users will select alternatives based on their need and respective business case.

The major requirements for which the tests in the JTP and Demonstration Plan were chosen are the following:

- Corrosion Resistance
- Galvanic Compatibility
- Tape Adhesion
- Torque/Tension, Coefficient of Friction
- Hydrogen Embrittlement (and Service Embrittlement)
- Field Exposure/On-Vehicle

3.1 SUMMARY OF ENGINEERING, PERFORMANCE, AND TESTING REQUIREMENTS

Table 4 lists the engineering and testing requirements identified for validating the fastener coatings to cadmium and chromate conversion coatings that are common to all affected defense systems.

Table 5 lists the performance objectives.

Testing is divided into two phases: performance testing and field demonstration /validation. The performance testing was performed by PPG instead of ARL as was originally stated in the JTP. The test parts and configurations differ somewhat from the JTP and are reflected in the descriptions in this document.

PPG and ARL coordinated with the USMC to facilitate installation of parts for the qualitative dynamic field exposure portion of the demonstration.

Table 4. Performance and Testing Requirements

Engineering Requirement	Test	JTP Section	Test Criteria	References
Corrosion Resistance	Neutral Salt Fog	3.1	500 hrs. Minimum with no red corrosion. To 2000 Hrs.<2mm scribe creep.	ASTM B 117 ASTM D1654
Corrosion Resistance	Cyclic Corrosion	3.2	40-80-120 cycles, <2mm scribe creep (panels). <5% red rust on significant surfaces (fasteners)	GMW 14872 ASTM D1654
Simulated Handling	Tumbled in metal can 10 times.	3.3	No significant paint loss. Test corrosion as in 3.1 and 3.2	GMW14872 ASTM B117
Adhesion	Tape Adhesion (Cross-cut)	3.4	Method A for CARC topcoated panels. Method B for electrodeposition topcoat only.	ASTM D 3359, Method A and B
Adhesion, Wet	Water Resistance, wet tape adhesion	3.5	No peel away; at least 4A per ASTM D 3359; no blistering of unscribed coating area, no delamination from substrate.	ASTM D 3359, Fed-Std-141, Method 6301
Hydrogen Embrittlement	Mechanical Hydrogen Embrittlement	3.6	Pass per ASTM F519 Type 1a.1	ASTM F 519
In-Service Hydrogen Embrittlement	Mechanical Hydrogen Embrittlement	3.7	Pass per ASTM F519 Type 1a.1 Annex 5 Section A5.3.2 with 3% NaCl solution 150 Hrs.	ASTM F 519 Annex 5
Torque	Torque/Tension COF	3.8	Per ISO 16047 Equal friction parameters to Cadmium/Lube control	ISO 16047
Galvanic Compatibility	Assembly in Aluminum 2024 Plate	3.9	No significant corrosion of 2024 aluminum under bolt head or washer of assembly after 500 cycles Salt Spray exposure	ASTM B117
Corrosion	Field Exposure, On-Vehicle	3.11	Exposure time of two years on vehicle platform. Evaluate performance versus cadmium plated parts.	ASTM D1654 SSPC-VIS-2

Table 5. Performance Objectives

Performance Objective	Data Requirements	Success Criteria	Results
Quantitative Performance Objectives (Lab Testing)			
<u>Product Testing</u> - Corrosion testing	Flat panel and bolts exposure in ASTM B117 Salt Spray and GMW14872 Cyclic corrosion testing.	Bolts, <5% red rust on significant surfaces at 2000 hrs. salt spray and 120 cycles GMW14872. Panels, no red rust in scribe at 500 hours.	Type 1 slightly weaker than Cd/Cr6 ⁺ , Type 2 equal for bolts. Panel testing inconclusive.
<u>Product Testing</u> - Adhesion testing	Wet and dry adhesion testing on flat panels per ASTM D 3359 (Methods A, B), and	4A or 4B tape adhesion rating minimum	Type 1, Type 2 Pass
<u>Product Testing</u> - Torque and Tension Testing	Torque/Tension, Coefficient of Friction of threaded fasteners per ISO 16047.	Equivalent to Cadmium plating and dry lube	Type 1 and Type 2 slightly higher for friction.
<u>Product Testing</u> - Hydrogen Embrittlement Resistance testing	Hydrogen embrittlement and In-service embrittlement testing per ASTM F519 type 1a.1 and Annex 5 wet cell test with 3% NaCl.	Pass at least three of four test bars at 200 hours under 75% proof load.	Type 1 and Type 2 pass dry test, both fail wet test. Cd/Cr6 ⁺ also fails wet test.
<u>Product Testing</u> - Galvanic Compatibility	Compatibility of fasteners mated into 2024 type aluminum after 500 hours salt spray exposure.	No significant pitting of the aluminum under the mating surfaces.	Type 1 and Type 2 pass with no pitting.
Qualitative Performance Objectives (Field Testing)			
<u>Product Testing</u> - Field exposure on DoD vehicle	Fasteners installed on MTRVs at USMC base(s). Include phosphate only negative control.	Compare to Cadmium (positive control), and phosphate only (negative control) performance	Type 1 and Type 2 equal to Cd/Cr6 ⁺ control. Much better than Phos/oil only.
- Field exposure testing	- Evaluate every 12 months for: - Degree of corrosion (visual) - Blistering (visual) - Film loss (visual assessment as percentage of total)		Cd/Cr6 ⁺ shows more corrosion than lab testing. No blistering Cd/Cr6 ⁺ has worst adhesion of CARC

4.0 SITES/PLATFORM DESCRIPTION

4.1 TEST PLATFORMS AND FACILITIES

Three demonstration sites have been identified as good candidates based on availability of vehicles and the range of environmental conditions the fasteners will be exposed to. These sites include USMC Camp Lejeune (North Carolina), USMC Camp Pendleton (California), and USMC Base Hawaii (Kaneohe Bay).

The platform chosen is the MTVR (Figure 10). The target fasteners are the bolts which attach the under ride bar to the rear of the vehicle (Figure 11, Figure 12). The fasteners consist of a $\frac{3}{4}$ " flange bolt and a $\frac{3}{4}$ " flange nut (Figure 13). The position on the vehicle is suitable for exposure to corrosive environment.

The bar is normally installed in the lower configuration shown in Figure 12. In this configuration, there are two unused holes in the mounting bracket which can be used to mount additional test fasteners. Figure 13 shows the bolt and nut used to attach the bar.



Figure 10. Representative Medium Tactical Vehicle Replacement (MTVR) to Be Used in Demonstrations



Figure 11. MTVR Under-Ride Bar Location at Rear of Vehicle Provides Unused Mounting Holes for Test Fasteners and Ready Access to Corrosive Environment



Figure 12. MTVR Under-Ride Bar Mounting Showing Four Mounting Fasteners Per Side Plus Two Additional Holes for Non-functional Fastener Sets (12 Total) Per Vehicle



Figure 13. Under-Ride Bar Fasteners to be Used in the Demonstrations Consist of a $\frac{3}{4}$ " Flange Bolt and a $\frac{3}{4}$ " Flange Nut

4.2 PRESENT OPERATIONS

The current process for mounting the MTRV under ride bar utilizes stock fasteners which have no sacrificial coating. They are supplied with a phosphate and oil coating which conforms to ASTM F1137 Type D. This coating offers little corrosion protection. After installation, the exposed surfaces of the fasteners and under-ride bar are topcoated with a CARC touch-up finish system.

4.3 SITE-RELATED PERMITS AND REGULATIONS

There are no regulatory issues or permits related to this demonstration.

5.0 TEST DESIGN

5.1 LAB TEST DESIGN

Lab validation testing was performed on four coating systems which differ somewhat from the field demonstration coating systems. It would not be appropriate to use accelerated corrosion environments to test a phosphate conversion coating with only oil as in Type 4 described in Section 2. Therefore, as a negative control we used zinc phosphate (PPG CHEMFOS C700) conversion coating plus the cationic electrodeposition topcoat used for Types 1 and 2. For flat panels, corrosion testing was performed with and without CARC primer/topcoat.

It should be noted that the testing protocol including part types differ significantly from the test protocol described in the JTP document. In the original plan, the lab testing was to be conducted by ARL in order to provide validation by a DoD source. However, ARL was unable to perform the testing as described in the JTP. Therefore, test methods and results generated by PPG for the same coating systems are reported here.

- Coating Type 1 Inorganic zinc rich/Electrodeposition topcoat
- Coating Type 2 HPAP/Electrodeposition topcoat
- Coating Type 3 Cd/Cr6⁺
- Coating Type 4 Phosphate/Electrodeposition topcoat

The test parts (including flat panels) were obtained by PPG. PPG applied the zinc phosphate conversion coating, the zinc rich primer, and the epoxy electrodeposition topcoat at their Euclid, Ohio plant. The high purity aluminum plating was applied by the AlumiPlate Company and subsequently topcoated with epoxy electrodeposition topcoat by PPG. The cadmium control parts were processed by DeTray Plating according to SAE-AMS-QQ-P-416C specification. These will not receive any topcoat and will have dry film lubricant applied to the threads only. Lubricant is SANDSTROM 28. Table 6 shows details of the test parts used.

Table 6. Substrate Descriptions and Test Specimen Codes

Substrate	Source P/N	
Cold Rolled Steel Flat Panel 4"x6"x0.032"	ACT (#28110)	Corrosion and adhesion testing
Hex Cap Screw M10-1.5x40 Class 10.9	Fastenal 40696	Corrosion Testing
Hex Cap Screw M16-2.0x40 Class 10.9	Fastenal 40758	Corrosion Testing
Hex Cap Screw 1"-8x3" Grade 8	Fastenal 14465	Corrosion Testing
Surrogate Bolt M10 1.5 40 9.8	Wilson/Garner 11516105	Torque/tension testing
Torque Control Nut M10 9.8 Zinc	Wilson Garner 11516090	Torque/tension testing
Torque Control Washer M10 Zinc	Wilson Garner 11502644	Torque/tension testing
Plastic (PP) Panel 1/8"x4"x12"	McMaster-Carr 8782K69	Mounting for corrosion testing
Aluminum 2024 1/8"x4"x12"	McMaster-Carr 89215K26	Assembly plate for galvanic corrosion testing

5.2 LAB TEST DESCRIPTIONS

This section includes test descriptions used to generate the test results reported in Section 7 of this report.

5.2.1 Neutral Salt Spray (ASTM B117)

Test Description

Salt fog chamber was operated in accordance with ASTM B 117 (*Standard Practice for Operating Salt Spray (Fog) Apparatus*).

Salt Spray Testing - Flat Panels

For each coating system described in Section 1.0, three flat panel specimens 70 x 150 mm, composed of cold rolled steel were tested. Each panel was scribed with an X using a sharp utility knife (scribe width approximately 0.5 mm). The samples were inspected every 500 hours for a total exposure time of 2,000 hours. At each inspection interval, the test specimens were removed and cleaned by gently flushing with running tap water and allowed to dry under ambient conditions. The percentage of white and red corrosion in the scribe areas and on the face areas was rated. The degree of blistering at the scribe was expressed as millimeters of total blistering measured perpendicular to the scribe at the widest point of blistering. Specimens were not be scraped or abraded before returning to the test chamber for continued exposure. The surface condition of each of the test specimens was photographically captured.

At the conclusion of the exposure period, the test specimens were allowed to recover for 24 hours and then evaluated in the same manner as for the interim test intervals without scraping. After photographic documentation, test specimens were scraped side-to-side with a putty knife at 30-degree contact angle. The corrosion resistance and creepage of the test specimens was determined in accordance with the latest version of ASTM D1654, "Standard Test Method for Evaluation of Painted or Coated Specimens Subjected to Corrosive Environments." The corrosion or loss of coating extending back from the scribe mark was rated and the unscribed areas examined for corrosion spots, blisters, and any other types of failure that may occur. Surface condition was photographically documented for each of the test specimens using the imaging system.

Salt Spray Testing – Bolts

Salt Spray testing was performed on sets of ten coated fasteners mounted in a plastic panel with no subsequent CARC coating. This illustrates the relative corrosion performance of the coating systems without topcoat or the influence of any bimetallic contact. For the M10 and M16 size bolts, this same configuration was assembled using fasteners which have been damaged by simulated bulk handling. This was accomplished by placing a set of ten parts in a one quart metal can with a lid and quickly inverting the container ten times such that the parts contact each other with force sufficient to damage the coatings. Due to their size and weight, the 1 inch bolts are not subjected to simulated handling. It is expected that these would be processed in rack type processes where part-to-part contact would be minimized.

The mounted sets were placed in the test chamber with the long aspect in the horizontal position and leaning at an angle of between 15 and 30 degrees. The specimens were evaluated at 500 hour intervals. At each inspection interval, the test specimens were removed from the chamber and cleaned by gently flushing with running tap water then allowed to dry at ambient conditions. Ratings were performed by visual estimation, to assess the total percentage of white and red rust present. If red rust is evident in only very small areas, the number of “spots” was recorded along with the surface location. The presence of any blistering on the fastener surfaces was also noted. Photos were taken to document the surface condition of each of the test specimens. The test continued until each specimen shows greater than five percent red corrosion (total), at which time the failed specimen was removed from the test.

5.2.2 Cyclic Corrosion (GMW 14872)

Test Description

Cyclic corrosion test specimens are analogous to those used for Salt Spray Testing. The test chamber meets the specification outlined in GMW14872. The samples were examined at intervals of 40 cycles for a total exposure of 120 cycles. Samples were removed from the test at the intervals if they show failure.

5.2.3 Tape Adhesion (ASTM D3359)

Test Description

This test method covers a procedure for establishing adequacy of intercoat and surface adhesion of an organic coating in ambient conditions by applying pressure sensitive tape over a scribed area of the coating. The test was performed in accordance with ASTM D 3359 (Standard Test Methods for Measuring Adhesion by Tape Test).

At least two specimens were prepared for adhesion testing using 70 x 152 mm (4" x 6") cold rolled steel test panels. Using test specimens incorporating the fastener coating systems and the referenced specification epoxy primers, dry film thickness was measured in at least five areas. Cuts were made in the coating system per the latest version of ASTM D3359, “Standard Test Methods for Measuring Adhesion by Tape Test – Cross-Cut Tape Test.” To have a fresh adhesive surface to work with two laps of tape were pulled and discarded.. An additional length of tape approximately 76 mm (3") long was removed and centered over the grid. The tape was smoothed into place by firmly rubbing a pencil eraser over the area. Within 90 ± 30 seconds of tape application, it was removed by holding the free end and rapidly pulling (not jerking) back upon itself at as close to an angle of 180 degrees as possible. Area was inspected for removal of coating from the substrate or from an underlying coating. Adhesion was rated in accordance with the latest version of ASTM D3359. For panels which are not coated with the CARC primer and topcoat system, the crosshatch grid were evaluated per Method B. For panels which are topcoated with the CARC system, the scribed X were rated per Method A.

5.2.4 Wet Tape Adhesion and Water Resistance

Test Description

This test method covers a procedure for establishing adequacy of intercoat and surface adhesion of an organic coating immersed in water by applying pressure sensitive tape over a scribed area of coating. The test also measures the coating's ability to resist penetration by water. Test is performed in accordance with Method 6301 of Fed-Std-141 (*Paint, Varnish, Lacquer and Related Materials; Methods of Inspection Sampling and Testing*) and is rated according to ASTM D 3359. Passing performance is evidenced by no wrinkling or blistering immediately after removal of the panel from the water. The CARC coatings can be no more than slightly affected when examined 2 hours after removal. After 24 hours air drying, each test panel is subjected to a tape test in the same manner as described for dry adhesion testing (Method A or B).

5.2.5 Hydrogen Embrittlement

Test Description

This test method describes a procedure to evaluate the tendency of the fastener coating systems to embrittle steel by causing absorption of hydrogen into the steel crystal structure. The testing was conducted according to the latest version of ASTM F 519 Type 1a.1. The procedure involves the coating of standardized notched steel bars with the fastener coating systems. The specimens are then subjected to a tensile load for a specified period of time. Hydrogen embrittlement is evidenced in fracture of the sample during the test period. The three target coating systems, without subsequent CARC topcoat, as described in section 1.0 were tested. The bars were subjected to continuous tensile force equal to 75% of the stated NFS for a period of 200 hours. If at least three of the four bars in a set show no fracture failure, the coating is considered to be non-embrittling.

5.2.6 In-Service Hydrogen Embrittlement

Test Description

In-service embrittlement testing describes a procedure to evaluate the tendency of the coating systems to induce hydrogen embrittlement under simulated service environment. The test is carried out according to the latest version of ASTM F 519 Annex 5 using the parameters listed below. The method and parameters of testing are the same as described in Section 3.6.1, with the addition of an initial immersion of the notch in a 3% solution of sodium chloride (NaCl). The immersed specimen is subjected to a tensile pre-load for the specified time, after which the sample is rinsed, dried and tested as in section 3.6.1. The NaCl solution is encased around the notch of Type 1a.1 specimen after application of the fastener coating systems. Figure 14 shows an example of a possible immersion setup. Table 7 describes the test parameters.

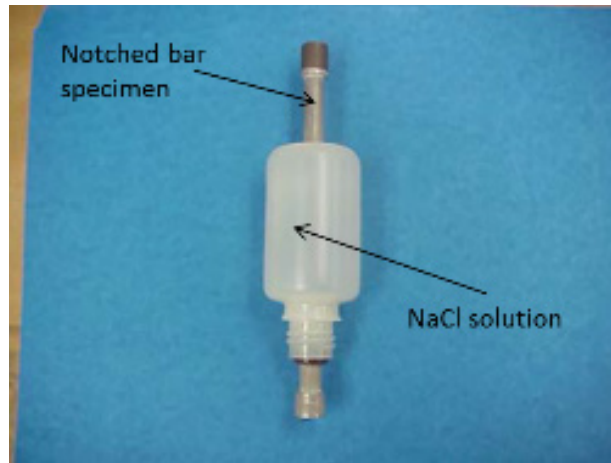


Figure 14. Notched Bar with Salt Solution Immersion for In-service Hydrogen Embrittlement Simulation

Table 7. In Service Embrittlement Test Parameters

Specimen Type	Type 1a.1 notched bar
Number of samples per coating system	4
Preload Conditions:	
Immersion Solution	3% by weight NaCl in deionized water
Immersion Temperature	68-86°F (20-30°C)
Immersion load	45% of NFS
Preload Duration	150 Hours
Neutralization	Deionized water rinse and air dry
Post Immersion Test Conditions:	
Tensile Load	75% of stated tensile NFS
Load Duration	200 hours

5.2.7 Torque / Tension / Friction

This method allows determination of the tightening characteristics of threaded fasteners and related parts. The test was carried out according to SAE/USCAR-11 except the tightening speed was 30 +/- 3 RPM. The testing was conducted using surrogate bolt M10x1.5 40mm Grade 9.8 and the corresponding M10 nut and control washer. Surrogate bolts were tested in combination with standard zinc plated nuts and washers (per GMW3359).

To perform the test a tightening torque is steadily applied to a bolt/nut or screw/nut assembly to generate a clamp force, and to measure and/or determine one or more of the tightening characteristics, which can include torque coefficient, coefficient of total friction, coefficient of friction between threads, and coefficient of friction between bearing surfaces. These quantities are calculated using methods described in ISO 16047.

A quantity of ten parts were tested for each coating system. The data was then used to describe the friction characteristics of the coating systems. It is intended to provide guidance for end users in determining suitability of a particular finish in various applications. The test is also intended to determine the effect of the coatings on the thread gauge tolerances. This will allow judgments to be made concerning the required size and geometry limitations and requirements for meeting typical performance properties.

5.2.8 Galvanic Compatibility

This method shows the galvanic corrosion performance of fasteners with the target coating systems against an aluminum surface. Assemblies are prepared by attaching the bolt-washer-nut sets directly into untreated 2024 aluminum mounting panels. The assemblies are then exposed to ASTM B117 Salt Spray corrosion test for 500 hours.

After testing, the fasteners are removed from the mounting panel, and the area under the test washer is cleaned, examined and photographed. Galvanic incompatibility is evidenced by pitting, exfoliation and localized corrosion in the vicinity of the fastener. One assembly consisting of ten M10 bolt/washer/nut combinations was tested for each coating system.

5.3 FIELD DEMONSTRATION TEST DESIGN

Table 8 lists general descriptions of the demonstration fasteners. The DoD MSN designations and detailed characteristics are listed in Appendix E.

Table 8. Field Fastener Types

Fastener	Description	Source
Bolt	3/4-10 x 1 3/4 Grade 8 Hex Flange Bolt – Manganese Phosphate and Oil	National Bolt and Nut Corporation Part Number 9896
Nut	3/4-10 Grade 8 Hex Locking Flange Nut – Zinc Phosphate	National Bolt and Nut Corporation Part Number 5276

5.3.1 Fastener Installation

The coated test fasteners and uncoated controls were delivered by PPG to the USMC team members for installation on the specific platform. Fastener were marked in order to determine the coating configuration during installation as follows:

- Coating Type 1 (Zinc Rich/Electrodeposition topcoat) – Black coating with a single silver dot on each part.
- Coating Type 2 (HPAP/Electrodeposition topcoat) – Black coating marked with two silver dots on each part.
- Coating type 3 (Cd/Cr6⁺) – Yellow, bright plated finish.
- Coating Type 4 (phosphate/oil) – Gray oily steel with no finish.

5.3.2 Fastener Evaluation

The installed fasteners were visually examined in intervals of approximately 12 months and compared against controls. At each interval, a subset of the test fasteners were removed to measure breaking torque. These were then replaced with new fasteners with the same coating system.

5.3.3 Conceptual Experimental Design

Fasteners coated with the candidate fastener coatings and legacy control coatings were installed on MTRV assets as described above. The candidate coatings include the types 1 and 2 described in Section 2.1 as well as the positive and negative controls described therein. Each fastener set consisted of a bolt and nut which was tightened to a torque of 175 ft.lb. Each vehicle has twelve positions available for fastener sets. Three of each type of coating system will be installed on each vehicle. Ten vehicles will be used at each of three USMC bases. This makes a total of 90 fastener set of each variety in the experimental population. After installation, the exposed surfaces of the fasteners were overcoated with an appropriate CARC topcoat. All fasteners will be inspected for corrosion and adhesion failures every twelve months.

5.3.4 Pre-Demonstration Testing and Analysis

Prior to installation of fastener sets in the field, the coated fasteners were tested for thread fit and run-in torque. This was done to ensure that the thickness of the applied coatings do not inhibit proper clamping force when applying the target torque.

5.3.5 Design and Layout of Technology Components

Each fastener set as obtained by PPG consisted of one bolt and one nut. As supplied the fasteners have a phosphate and oil finish. This finish was stripped prior to application of the zinc rich primer, aluminum plating, and cadmium plating. It is common practice to strip phosphate and oil prior to subsequent finishes.

Coating type 1 was applied by PPG at their Euclid, OH plant. Coating type 2 was treated with HPAP by the AlumiPlate Company, and then finished with epoxy electrocoat at PPG's Euclid, OH plant. The positive control coating consisting of cadmium plating with hexavalent chromium conversion was applied by DeTray Plating of Independence, MO. The negative control parts were supplied to the USMC as received from the manufacturer with only zinc phosphate and oil coating. All parts were staged and distributed from the PPG Coatings Innovation Center in Allison Park, PA.

5.3.6 Field Testing

Upon completion of the pre-work and approval of the coated fasteners by the USMC, the coated specimens were delivered to each test site. Arrangements were made to identify and document the test vehicles. For each vehicle, the rear under-ride bar was removed, cleaned and reinstalled using the test fasteners. Reinstallation was performed per standard procedures, including touch-up of the exposed fastener surfaces with an appropriate CARC coating (Technical Manual MTRV24, and TM10629A-24P).

Figure 15 shows the positions on the vehicle in which each type of fastener was installed. This placement is designed to place each coating type in each of three geometrically equivalent positions. The three positions are different enough in their geometry such that it could affect the corrosion result. Therefore, one of each type coating will occupy each position on each vehicle.

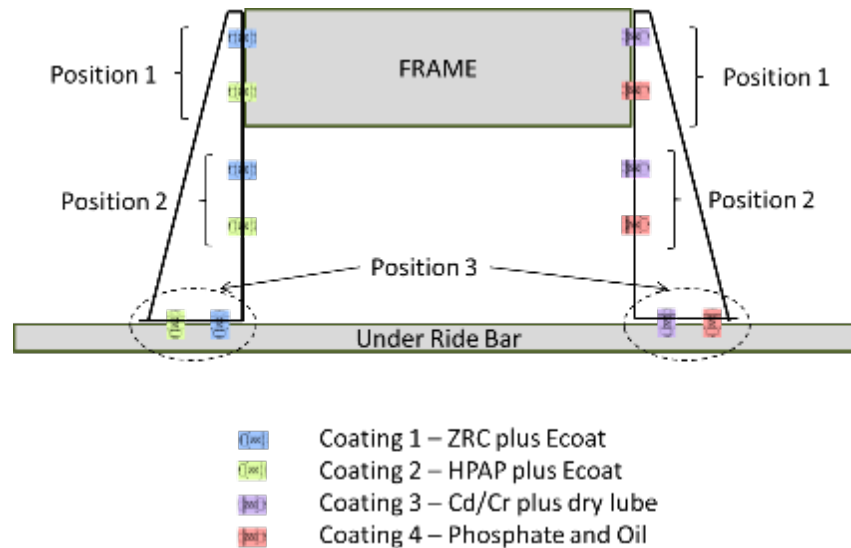


Figure 15. Fastener Installation Positions

Each fastener set was identified for tracking purposes with a unique designation indicating the test site, vehicle position, and coating type (Table 9). Additionally, the CARC paint used for touch-up was identified and documented. To simplify field evaluation and to maintain some degree of blind data acquisition, performance ratings were tabulated according to fastener position as illustrated in Figure 16.

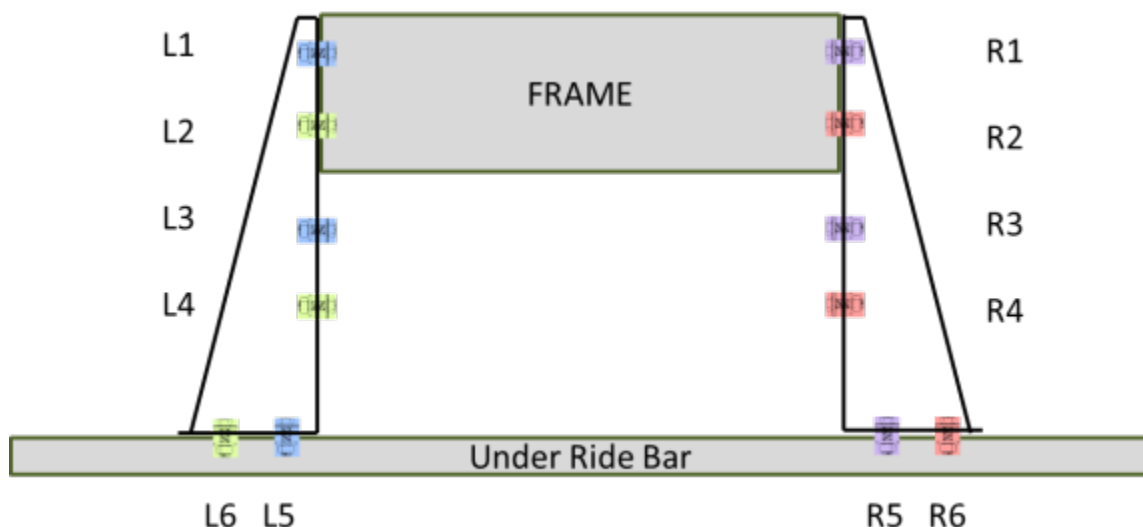


Figure 16. Fastener Assessment Designations

Table 9 lists the cross-reference. Forms for data entry at the demonstration site were included in the assessment log folder.

Table 9. Field Fastener Code Reference

Fastener Identifier Code Reference

Site-Vehicle-Position-Coating

Example: S1-V1-P1-C1

Site	S1	Camp Lejeune, NC
	S2	Camp Pendleton, CA
	S3	Marine Corps Base Hawaii (Kaneohe Bay).
	S4	The Marine Corps Bases Japan (Okinawa, JP)
Vehicle	V1-V10	USMC Serial Numbers
Position	P1	Frame Mounting (horizontal)
	P2	Open Hole (horizontal)
	P3	Under Ride Bar Mount (Vertical)
Coating	C1	Zinc Rich-Ecoat (black/one silver dot)
	C2	HPAP-Ecoat (black/two silver dots)
	C3	Cadmium-Dry Lube (yellow plating)
	C4	Phos and Oil (no finish)

Table 10. Fastener Assessment Code Cross Reference

Fastener Log Code	Position	Coating	Type
L1	P1	1	ZR/Electrodeposition topcoat
L2	P1	2	HPAP/Electrodeposition topcoat
L3	P2	1	ZR/Electrodeposition topcoat
L4	P2	2	HPAP/Electrodeposition topcoat
L5	P3	1	ZR/Electrodeposition topcoat
L6	P3	2	HPAP/Electrodeposition topcoat
R1	P1	3	Cd/ Cr ⁶⁺
R2	P1	4	Phosphate/Oil
R3	P2	3	Cd/ Cr ⁶⁺
R4	P2	4	Phosphate/Oil
R5	P3	3	Cd/ Cr ⁶⁺
R6	P3	4	Phosphate/Oil

The fastener sets were be installed using standard protocol at each site. If possible, each set was tightened by hand using a torque indicating device to a torque of 175 foot pounds. The installer made note of the ease of installation for each fastener and the maximum torque required for threading (run-in). Each test site was provided with a documentation containing installation and monitoring data entry forms (see Demonstration Plan). This folder contained instructional information, project documentation, and inspection results.

After installation, the fastener sets were inspected approximately every twelve months. Each fastener was rated for the degree of red rusting per ASTM D-610. Rating according to this method includes assessment of the degree of general rust, pinpoint rust, and spot rust. The ratings are assigned by comparison to the diagrams in the method. The units were also rated for degree of blistering per ASTM D714. An assessment of the size and density of blisters is made by comparison to diagrams in the test method and the corresponding rating is recorded. The adhesion of the paint stack was assessed visually and recorded as a percentage of paint loss and to which layer of the paint stack there is adhesion failure. The rating was expressed as a percentage of the fastener surface area.

At each twelve month interval, one set of fasteners comprising one of each coating type from one vehicle, was tested for breaking torque. The breaking torque is expressed as the initial torque to break the fastener loose, and the maximum torque required to completely separate the nut from the bolt. These sets were returned to PPG for examination. In addition to the assessment and ratings, all fasteners were photographed at each inspection interval.

6.0 PERFORMANCE ASSESSMENT

6.1 LAB TEST RESULTS

6.1.1 Flat Panel ASTM B117 Salt Spray Corrosion Results:

ASTM B117 salt spray corrosion results are shown for the various systems on cold rolled steel panels in Tables 11 and 12. An image of the final appearance is shown in Figure 17. There is good consistency across the data for the positive and negative controls. Cadmium with HCP performs very well to the maximum test duration while electrodeposition topcoat over phosphate with no sacrificial coating performs poorly at short test duration. Although the photo of the zinc phosphate/electrodeposition primer panel would suggest performance was better than the systems with sacrificial corrosion protection, significant pitting of the base metal was observed which would be expected to contribute to earlier in service failure than the systems with sacrificial protection. However, it is also clear from the data that neither of candidate test coatings in flat panel testing is equal to the performance of cadmium/HCP as assessed through ASTM B117 testing.

Table 11. Salt Spray Corrosion Results Without Primer or Topcoat

Finish	Type	No Primer or CARC Topcoat								
		1000 hours			1572 hours			2000 hours (cleaned)		
		% Red Rust	White Rust Rating	Creep (mm)	% Red Rust	White Rust Rating	Creep (mm)	% Red Rust	White Rust Rating	Creep (mm)
Zinc Rich/Electrocoat	1	0	2	3	0	2	6	10	3	10
HPAP/Electrocoat	2	0	3	0	0	4	0	0	5	Severe
Cadmium/Hexavalent Cr	3	0	NA	0	0	NA	0	0	NA	0
Zinc Phosphate/Electrocoat	4	100	NA	0	100	NA	2	100	NA	4

Table 12. Salt Spray Corrosion Results with Primer and Topcoat

Finish	Type	With Primer or CARC Topcoat								
		1000 hours			1572 hours			2000 hours (cleaned)		
		% Red Rust	White Rust Rating	Creep (mm)	% Red Rust	White Rust Rating	Creep (mm)	% Red Rust	White Rust Rating	Creep (mm)
Zinc Rich/Electrocoat	1	10	2	0	20	2	0	50	2	10
HPAP/Electrocoat	2	0	3	0	0	3	0	0	5	20
Cadmium/Hexavalent Cr	3	0	NA	0	0	NA	0	0	NA	0
Zinc Phosphate/Electrocoat	4	100	NA	1	100	NA	0	100	NA	4

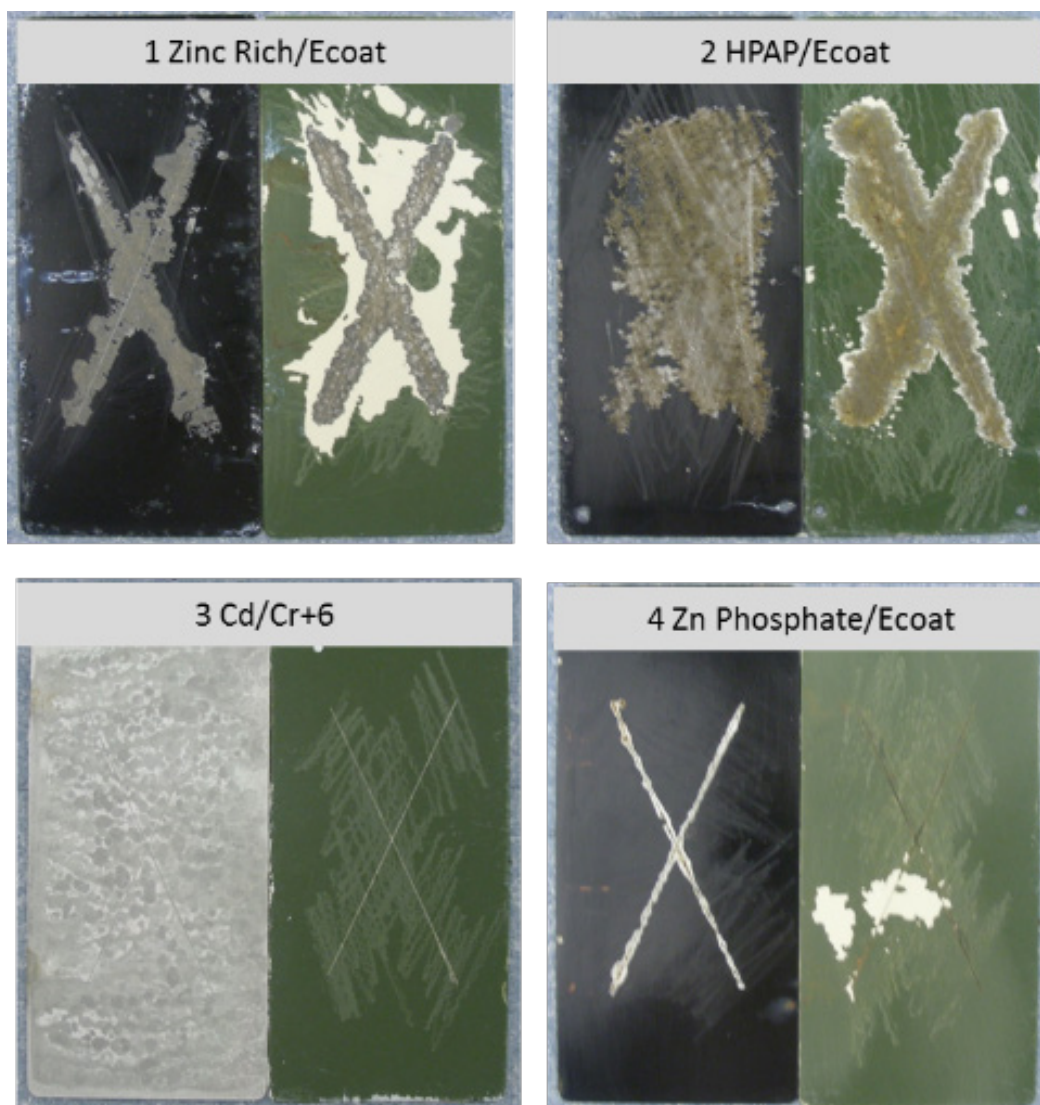


Figure 17. Final Appearance at the Completion of 2000 Hours Salt Spray Testing

Panels have been scraped to reveal extent of scribe creep.

6.1.2 Flat Panel GMW 14782 Cyclic Corrosion Results:

A somewhat different picture emerges when evaluating performance through GMW14782 cyclic corrosion. As evidenced in Tables 13 and 14 and Figure 18, the zinc rich/electrodeposition primer system appears competitive with the positive control of cadmium/hexavalent chrome. Both of these systems performed well enough to complete 120 cycles of testing whereas the HPAP/Electrocoat and zinc phosphate/ electrocoat systems were pulled from testing after only 40 cycles. In the case of HPAP/electrocoat the failure centered on extensive creep from the scribe while the zinc phosphate/electrocoat system exhibited extensive red resting and pitting. These trends were consistent when tested without primer or topcoat (Table 13) or with a MIL-DTL-53022 primer and MIL-DTL-53039 topcoat (Table 14). In general, cyclic corrosion testing, such as GMW14782, is viewed as more predictive of in-field performance than ASTM B117.

Table 13 GMW14782 Testing of Candidate Systems Without Primer or Topcoat

Finish	Type	No Primer or CARC Topcoat								
		40 Cycles			91 Cycles			120 Cycles		
		% Red Rust	White Rust Rating	Other	% Red Rust	White Rust Rating	Other	% Red Rust	White Rust Rating	Other
Zinc Rich/Electrocoat	1	Slight	2		10	2	6	50	3	
HPAP/Electrocoat	2	20	2	4mm Creep	Removed from test					
Cadmium/Hexavalent Cr	3	0	NA	0	0	NA	0	0	NA	0
Zinc Phosphate/Electrocoat	4	100	NA	Pitting	Removed from test					

Table 14 GMW14782 Testing of Candidate Systems with Primer and Topcoat

Finish	Type	with Primer or CARC Topcoat								
		40 Cycles			91 Cycles			120 Cycles		
		% Red Rust	White Rust Rating	Other	% Red Rust	White Rust Rating	Other	% Red Rust	White Rust Rating	Other
Zinc Rich/Electrocoat	1	0	1		Slight	1		Slight	1	
HPAP/Electrocoat	2	50+	1	5mm creep	Removed from test					
Cadmium/Hexavalent Cr	3	0	NA	0	0	NA	0	0	NA	0
Zinc Phosphate/Electrocoat	4	100	NA	Pitting	Removed from test					

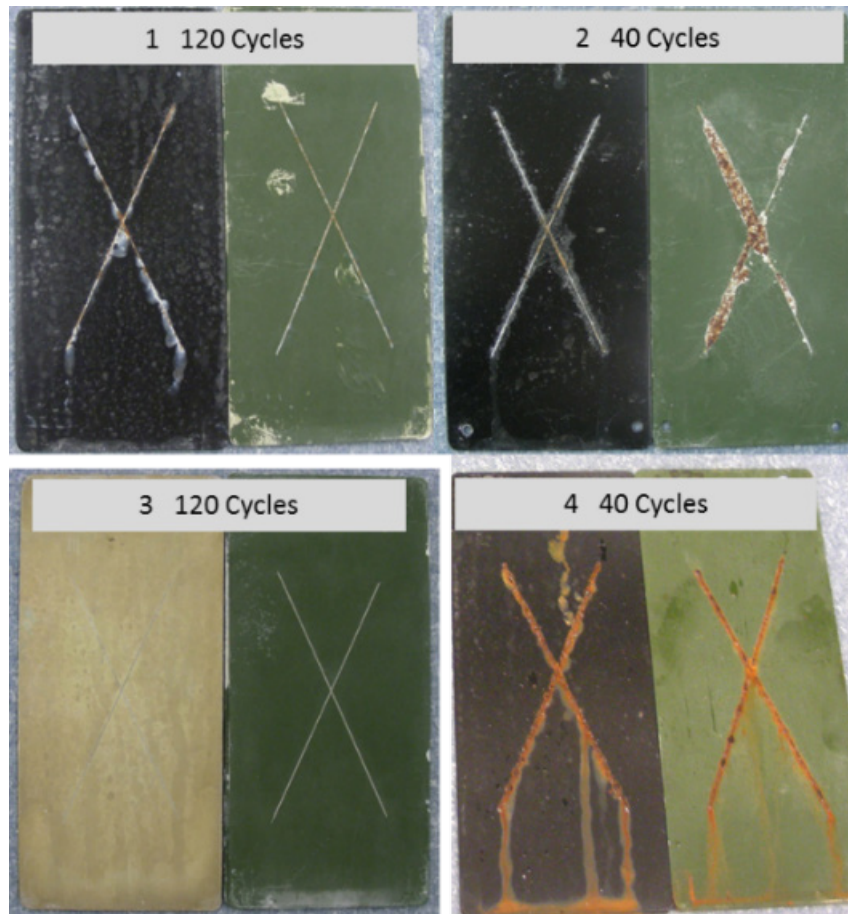


Figure 18. Final Appearance of Candidate Coating Systems after GMW 14782 Cyclic Corrosion Testing

In each pair the un-topcoated panel is at left.

6.1.3 Fastener Corrosion Test Results

Yet a third picture emerges when examining accelerated corrosion testing of coated fasteners. This is likely due to the difference in the nature of the damaged area. For fasteners, the localized damage spots are “touch marks” caused by contact between parts in handling. These tend to be small, with little area of base metal exposed. Scribed areas however expose larger areas of base metal in relation to the exposed area of sacrificial metal, zinc flakes or aluminum plating. If there is not enough sacrificial metal corrosion product to “heal” the damage area before base metal corrosion begins, red rust will appear and undercutting will be more prevalent. Therefore, it is best to judge the corrosion performance for a fastener coating with data generated on example fasteners. It is also important to note that fastener metallurgy is significantly different from the cold rolled steel base used for flat panel samples. It is expected that the corrosion behavior would be different. Table 15 provides details of fastener performance after 2000 hours ASTM B117. Here again the cadmium treated fasteners perform best while electrocoated fasteners without sacrificial corrosion protection perform the worst. In fact the phosphate pretreated/electrodeposition primer fasteners were removed from testing after only 500 hours. When a sacrificial protection layer is added (either zinc rich or high purity aluminum plating) performance is good out to at least 1500 hours.

To simulate fastener abrasion and impacts, as might occur during routine handling, a portion of the fasteners were tumbled in a metal can to create defects in the coatings from fastener to fastener impacts.

Table 15. Salt Spray Exposure Results for Coated Bolts

Finish	Size	As Coated				Tumbled			
	Hours	500	1000	1500	2000	500	1000	1500	2000
Phos/Zinc Rich Ecoat	M10-C	SP WR	5 WR	10 WR	5 HD, 5 TH	5 WR	10 WR	1 RR, 20 WR	20 TH, 30 HD
	M16-C	CLEAN	SP WR	5 WR	10 WR	5 WR	5 WR	20WR	5 TH, 1 HD
	1"-C	SP WR	SP WR	20 WR	20 WR				
HPAP / TCP Ecoat Type 1	M10-C	SP WR	SP WR	SP WR	3 WR	10 WR	10 WR	20 WR	5 RR, 10 WR
	M16-C	SP WR	SP WR	SP WR	3 WR	SP WR	5 WR	10 WR	SP RR, 10 WR
	1"-C	SP WR	SP WR	2 WR	3 WR BL				
Cadmium Dry Lube*	M10-C	CLEAN	BLUSH	BLUSH	BLUSH	CLEAN	BLUSH	BLUSH	BLUSH
	M16-C	BLUSH	BLUSH	10 WR	10 WR	BLUSH	BLUSH	BLUSH	BLUSH
	1"-C	BLUSH	BLUSH	BLUSH	BLUSH				
Phos only Ecoat	M10-C	5 TH,HD	out			10 TH,HD	out		
	M16-C	5 TH,HD	out			10 TH,HD	out		
	1"-C	5 TH,HD	out						

% Corrosion on Significant Surfaces

* Sandstrom 28A dry film moly lube dip and dry

RR=Red Rust

WR=White Rust

BL=Blisters

SP=Spots

TH=Thread RR

HD=Head

FAIL
MARGINAL
GOOD

Figure 19 shows the fasteners after up to 200 hours salt spray. Here the effect of tumbling the fasteners is evident by the increased white or red rust appearing on the bolt threads and heads relative to untumbled samples.



Figure 19. Salt Spray on Bolts (2000 hrs. for All, Except 500 for Set 4)

Cyclic corrosion testing of coated fasteners in accordance with GMW 14782 shows similar trends with the phosphate/electrocoat only samples performing very poorly. However in this test the zinc rich and high purity aluminum samples perform as good as or better than the cadmium control. As cyclic corrosion tests are generally expected to be more representative of real world conditions, the zinc rich and aluminum plated (plus electrodeposition primer) samples compare very favorably. Table 16 and Figure 20 provides the observations and photographic record of performance up to 120 cycles. Again the phosphate/electrocoat only samples could not complete the testing and were removed after 40 cycles.

Table 16. GMW14872 Cyclic Corrosion Results for Coated Bolts

Finish	Size	As Coated			Tumbled		
	Cycles	40	80	120 (9/14)	40	80	120
Phos/Zinc Rich Ecoat Type 1	M10-C	CLEAN	WR 1	WR 1	CLEAN	WR 2	WR1, SP TH
	M16-C	CLEAN	SP WR	WR 1	CLEAN	SP WR	WR1, SP TH
	1"-C	CLEAN	CLEAN	WR 1			
HPA / TCP Ecoat Type 2	M10-C	CLEAN	CLEAN	SP WR	CLEAN	CLEAN	SP WR, 10 TH
	M16-C	CLEAN	CLEAN	SP WR, 5 TH	CLEAN	SP WR	SP WR, 20 TH
	1"-C	CLEAN	SP WR	SP WR, 5 TH			
Cadmium Dry Lube* Type 3	M10-C	CLEAN	CLEAN	10 TH	CLEAN	CLEAN	10 TH
	M16-C	CLEAN	CLEAN	10 TH	CLEAN	CLEAN	10 TH
	1"-C	CLEAN	CLEAN	BLUSH			
Phos only Ecoat Type 4	M10-C	10 RR	out		15 RR	out	
	M16-C	10 RR	out		20 RR	out	
	1"-C	10 RR	out				

* Sandstrom 28A dry film moly lube dip and dry

RR=Red Rust

WR=White Rust

BL=Blisters

SP=Spots

TH=Thread RR

HD-Head RR

BLUSH=White staining from salts only

FAIL
MARGINAL
GOOD



Figure 20. Cyclic Corrosion on Bolts (120 Cycles for All Except 40 for Set 4)

6.1.4 Tape Adhesion

Adhesion testing was carried out according to ASTM D3359. Method B is used to determine adhesion of the electrodeposition topcoat layer to the underlying substrate. This crosshatch grid method is recommended for thinner films. Method B is an X pattern crosscut test used for thick coating stacks where the spray primer and CARC topcoat are applied. Both methods were run on all for information. The test was also run on dry panels versus panels which had been soaked in water for 24 hours. The results are shown in Table 17.

Table 17. Tape Adhesion Results – Dry and Wet

Type	Base	Ecoat	Primer	CARC	DFT*	Dry		Wet**	
1	Zinc Rich Primer	X	X	X	4.4	5A	2B	4A	4B
		X			0.7	5A	5B	5A	5B
2	HPAP/TCP	X	X	X	4.2	5A	2B	4A	4B
		X			0.6	5A	5B	5A	5B
3	Cd/HCP		X	X	4.3	5A	5B	3A	4B
4	Zn Phosphate	X	X	X	4.4	5A	0B	4^	3^
		X			1.0	5A	5B	5A	5B

* Total for Ecoat/Primer/CARC

** 24 Hour water soak + 24 Hour Recovery

^ Intercoat between CARC primer and topcoat.

The panels with electrodeposition topcoat only (Types 1, 2, and 4) all show perfect adhesion both wet and dry by Method B. For panels with spray primer and CARC topcoat, Types 1 and 2 show complete adhesion for Method A. The cadmium control (no electrodeposition topcoat) shows some loss of adhesion after wet exposure. (It should be noted that Type 3 also showed delamination of primer/CARC in the field demonstration.) The Type 4 panels showed only adhesion loss of the CARC topcoat from the spray primer. There was no loss at the electrodeposition topcoat interface.

Overall, it can be concluded that electrodeposition topcoat is an acceptable base for this primer plus CARC system.

6.1.5 Hydrogen Embrittlement

The testing was done per ASTM F519, including Annex 5. The test specimens were type 1a.1 threaded notched bars. Four bars were run for each set. In addition to testing the as-coated bars, a set was subjected to a salt solution soak during tension testing per Annex 5 of the method. This is designed to simulate in-service embrittlement caused by cathodic protection mechanism of sacrificial coatings. Testing was performed by Omega Research.

We encountered some difficulty in coating the bars. Through multiple coating applications, the threads had to be masked, cleaned and remasked since it is required that the threads are bare to fit into the test equipment. We were able to accomplish this, however, exposure to moisture during phosphating and electrodeposition topcoat application caused some flash corrosion in the threads which needed to be mechanically cleaned.

This test method was designed primarily to test plating materials. Some of the coating stacks under investigation include multiple coatings and bake exposures as high as 240°C. This temperature exposure may have affected the integrity of the tempered steel.

Table 18 shows the results of the testing. Hours to failure are shown for each bar set. The test is run under load for 200 hours or until failure. Failure is fracture of the bar at the notch. The coating is considered to pass if at least three of the four bars show no fracture at 200 hours.

Table 18. Hydrogen Embrittlement Results

4 bars per set - Hours to failure under load			
Type	Base	A Dry	B Wet Cell (Annex 5)
1	Zn Phos / Zinc Rich Dip-Spin	P/P/P/P	0.4/0.9*/14.6/125.6
2	HPAP/Ecoat	P/P/P/P	102.6/102.7/149.8/P
3	Cadmium Plating / HCP	P/P/P/P	1.5/113.1/138.3/138.4
4	Zinc Phosphate	P/P/P/P	P/P/P/P

P=Pass no failure

*Failed in threads

The re-embrittlement results are less positive. All coatings with sacrificial metal coating failed. Even the cadmium/HCP control failed, although it lasted longer.

After discussion with an industry expert in plating, fasteners, and embrittlement, there seems to be some debate about the suitability of the re-embrittlement testing to these type of coatings. The test bars are made from steel of a higher strength and hardness class than most fasteners used for construction of military ground vehicles. Even LHE process cadmium fails in this test. Therefore, it may be unrealistic to expect this level of performance when considering cadmium replacement technologies. It may well be appropriate in specialty applications such as aerospace. However, in critical applications of very high strength fasteners, plating, including cadmium, are generally forbidden.

6.1.6 Torque / Tension/ CoF

The goal for frictional characteristics is to equal the torque versus tension relationship of cadmium/HCP with dry lube on the threads. If a candidate replacement coating can achieve this, then fasteners coated with the replacement finish could be installed at the OEM and depot refit level using the same torque tables which have been used for cadmium fasteners. If the T/T relationship is not equal, then new torque values would be necessary for every bolted joint application. This would be a huge task and would represent a significant impediment to implementation of a new coating system.

Table 19 shows the T/T values for the coating systems of this demonstration. The frictional values and K Factor for the cadmium control with dry lube are within expected range (e.g. K=0.12 to 0.25 with $\pm 1 \sigma$). Coating Type 4 also falls within expected values although they are slightly higher than Type 3. For candidate coatings Type 1 the values are also acceptably close to cadmium. Type 2 values are the highest and the K factor is outside of the acceptable margin.

Table 19. Coefficient of Friction and Torque Values

Type	Description	Peak Tension (N)	Peak Torque (NM)	Torque at 35KN (NM)	Head CoF	Thread CoF	K (Nut Factor)	Hand Threadable	Run-Down Torque (NM)
1	Phos/ZR	36256	51.8	50.1	0.11	0.08	0.14	Easy	1
2	HPA / TCP	36403	53.6	51.8	0.11	0.10	0.15	Easy	1
3	Cadmium	36313	47.9	46.5	0.10	0.08	0.13	Difficult	4
4	Phos/Ecoat	36254	51.4	49.7	0.11	0.09	0.14	Easy	1

It is clear that the electrodeposition topcoat layer does an adequate job of acting as a lubricant and equalizing the T/T behavior of the underlying substrate. Given established commercial means, it is expected that the frictional characteristics of the electrodeposition topcoat could easily be adjusted to match the cadmium/dry lube results.

6.1.7 Galvanic Compatibility

Galvanic compatibility testing was done as described in section 5.2.10. After salt spray exposure, the face surfaces of the 2024 aluminum were quite badly corroded. The panels were disassembled and blasted clean with 80 grit aluminum oxide. The degree of pitting was assessed at the area where the coated bolt mated with the aluminum surface. Figure 21 shows the results. There was no pitting of the aluminum under the bolt heads for any of the coating types. For the Type 3 cadmium/hcp control, there appears to be more pitting of the aluminum panel face at areas removed from the bolt contact area. This pitting is slight but noticeable. Overall, it can be concluded that the bolts with electrodeposition topcoat were sufficiently insulated from bimetallic contact that galvanic corrosion does not occur in this test scenario.

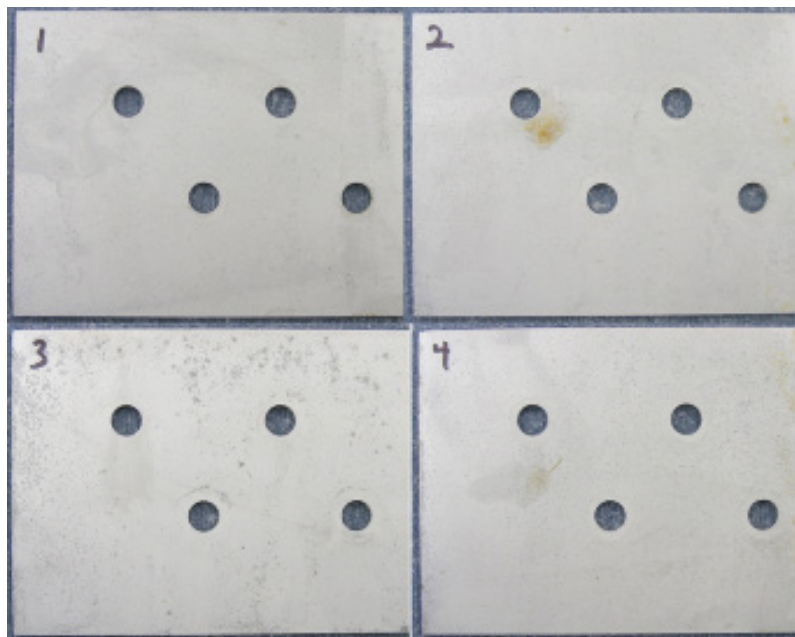


Figure 21. Galvanic Compatibility Results

6.2 FIELD EXPOSURE ANALYSIS

6.2.1 Performance Assessment Design

At the conclusion of the demonstration the data for each coating type was compiled. The analysis evaluated the performance as a collective group and was also be broken down by site and by position of installation. Deviations in each set were analyzed to identify outliers and assess the overall performance of each coating. The goal of the assessment, as stated previously, was to assess the performance of the two candidate coating systems relative to the positive and negative controls. This performance assessment allowed us to rate the coatings as to their suitability as a replacement for Cd/Cr6⁺ in high end corrosion resistance applications. It also demonstrated the corrosion improvement to be expected if replacing fasteners in applications where no sacrificial coating is currently being used. This is the case for the current demonstration application. Table 20 lists the variables which will be used in assessment of performance.

Table 20. Field Data Variables

Fastener type, nut or bolt
Site designation
Vehicle designation
Installation Position on vehicle
Installation run-in torque
Installation ultimate torque
Corrosion rating
Blister rating
Loss of adhesion (visual assessment)
Breaking torque to remove fastener

The data and comments were recorded on the assessment forms (see Demonstration Plan). The forms were kept in the folder provided.

This demonstration was considered successful as the candidate coatings offer new, environmentally friendly corrosion solutions for end users and Program Managers. The comparative data may be used to develop performance based MIL specs for the coatings. This will allow end users to determine suitability of these options for specific fastener needs.

Summary: In general, the field exposure environment proved not to be very aggressive in terms of fastener corrosion. This is validated by the mass-loss coupon data below. Some general observations:

- Of the five positions on the vehicle in which the parts were installed, the lower positions (L5, L6, R5, R6) showed the greatest amount of corrosion. This is consistent for all exposure sets. The results and conclusions presented here are based on analysis of those four positions.

- For the three demonstration sites chosen, the rank of severity based on negative control performance is MCBH > Lejeune > Pendleton. The differences in total corrosion were small but significant. The trends and ranking of the coating systems is consistent among the sites so no further site specific analysis is necessary.
- The negative control with no sacrificial coating did not show a level of red rust corrosion to be considered a “problem”. There was no evidence of structural failure or running red staining.
- While cadmium performed well for corrosion resistance, it was poor for adhesion of the CARC topcoat system. There was considerable delamination caused by tool interaction during removal.
- The candidate coatings Type 1 and Type 2 perform nearly equally for red corrosion. Both were slightly weaker than the Type 3 cadmium/ Cr^{6+} control but much stronger than the negative Type 4 control phosphate/oil only. Note: Type 4 is currently used in this and many other applications on the MTVR.

6.2.2 Installations (by Elzly Corp)

Information in this section is taken from a report generated by Elzly Corporation. The report in its entirety, is included in Appendix D.

Initial installations were performed between December 2014, and March 2015 at three USMC locations (Camp Lejeune, NC, Marine Corps Base Hawaii, and Camp Pendleton, CA), on 10 MTVRs per location. An interim inspection after approximately one-year of exposure was conducted between December 2015 and February 2016, during which fasteners were removed from one MTVR per location; the results of this inspection were previously reported.

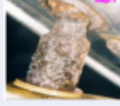
6.2.3 Inspection Methods

Inspections included visual evaluation of the fasteners for corrosion, and breaking torque measurements of fasteners on a demonstration vehicle prior to removal.

Visual Inspections

Visual inspections were done to determine the severity of corrosion observed on fasteners. Corrosion severity was rated based on the Stage of Corrosion observed. This is a rated on a 0 to 4 scale, with 0 being no corrosion, and 4 being complete perforation (complete metal loss). Table 21 shows an example of Corrosion Stages on fasteners. Visual inspections were made prior to removing the fasteners to observe the undisturbed corrosion products. During visual inspections, photographs were taken of the fasteners.

Table 21. Visual Rating Scale for Identification of Corrosion Severity

Stage of Corrosion	Example	Description
0		No visible corrosion, paint discoloration (not caused by corrosion) is permissible
1		Surface corrosion, red rust or paint blistering is present
2		Beginning of base metal loss, characterized by moderate corrosion products, blistering may be present
3		Significant base metal loss, pin holes may be present
4		Perforation of base metal, no metal remains at location of severest corrosion, loss of structural integrity

6.2.4 Visual Inspection Results

During the inspections at Camp Lejeune, NC, PPG took initial photographs and performed visual inspections. At the Marine Corps Base Hawaii (MCBH) and Camp Pendleton, CA locations, USMC CPAC and Elzly personnel performed all visual inspections. Breaking torque measurements were performed by USMC CPAC and Elzly personnel at all locations.

Table 22 and 23 present the stage of corrosion observations for each of the vehicles inspected at MCBH and Camp Pendleton, respectively.

Table 22. Stage of Corrosion Observations - MCBH MTRVs.

Serial No.	L1	L2	L3	L4	L5	L6	R1	R2	R3	R4	R5	R6
592426	0	0	0	0	0	0	0	0	0	0	0	0
592425	0	0	0	0	0	0	0	0	0	1	0	0
592373	0	0	0	0	0	0	0	0	0	0	1	1
594584	0	0	0	2	0	0	0	0	1	2	0	0
594585	0	0	1	1	0	0	0	2	2	2	0	2
594589	0	0	1	2	2	2	0	0	1	2	0	2
594625	0	0	1	2	1	1	0	0	1	2	0	2
594672	0	1	1	2	1	1	0	1	1	2	0	2
595148	0	0	1	2	1	2	0	0	1	1	0	1

Table 23. Stage of Corrosion Observations - Camp Pendleton MTVRs.

Serial No. ²	L1	L2	L3	L4	L5	L6	R1	R2	R3	R4	R5	R6
596577	0	0	0	0	0	0	0	0	0	0	0	0
597114	0	0	0	0	0	0	0	0	0	0	0	0
596117	0	0	0	0	0	0	0	0	0	1	0	1
595412	0	0	0	0	0	0	0	2	0	0	0	0
638496	0	1	0	0	0	0	0	1	0	0	0	0

Figure 22 shows the number of observations for each Stage of Corrosion by coating system (for readability, this plot starts at 50%).

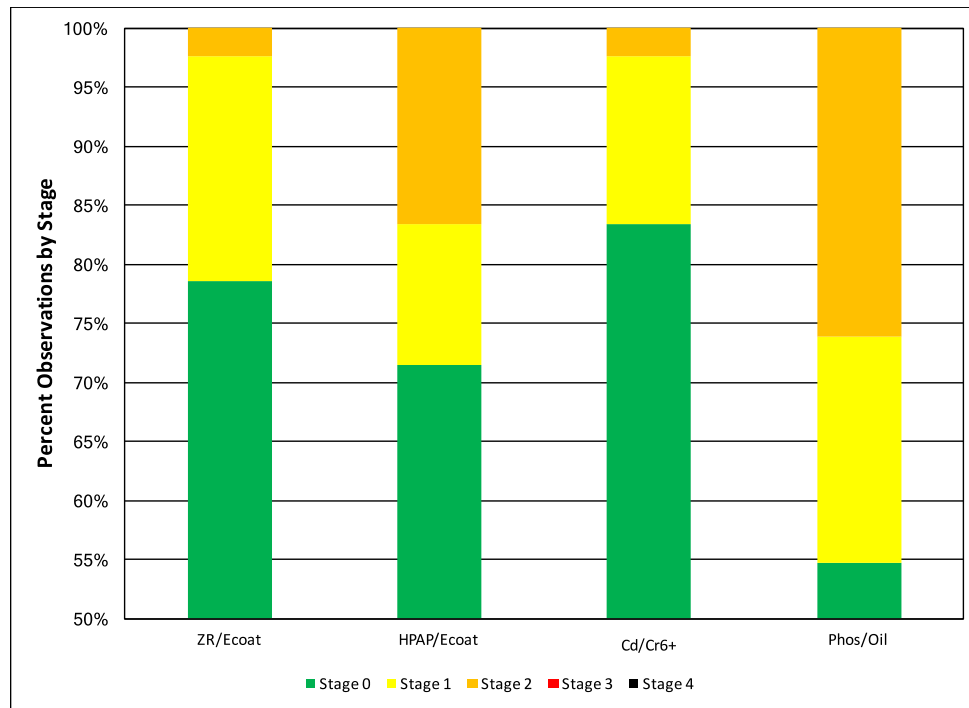


Figure 22. Percent of Observations for each Corrosion Stage

6.2.5 Breaking Torque

Breaking torque measurements were made in both the tightening and then loosening directions for the fasteners on one MTVR per location. Initial measurements were made in the tightening (ON) direction, where torque was applied to the fastener until an initial movement was achieved. Measurements were then made in the loosening (OFF) direction, where torque was applied to the fastener until movement was achieved. In both instances, the maximum torque observed was recorded, which was achieved just prior to movement of the fastener.

² Due to unit activity, only five of the remaining nine MTVRs could be inspected and have their fasteners replaced.

Torque measurements were made using a Cooper Instruments LXT 954-6000, Reaction Socket Extension Torque Sensor, which is a ¾-inch square drive sensor capable of reading torque values up to 6,000 in-lb. (500 ft-lb). The output of this sensor was displayed on an Omega HHP-SG digital indicator set to display the maximum torque values measured for each fastener removal. An IOTech data acquisition system was also used to monitor the torque values throughout the initial breaking.

Table 24 shows the maximum breaking torque values observed for MTVRs 594120 (Camp Lejeune), 592426 (MCBH), and 596577 (Camp Pendleton), respectively.

NOTE: Starting with readings made at MCBH, the initial readings before applying force to the fasteners was not reading at, or near, zero (ranging from -70 to 60 ft-lb). This initial offset was recorded and the maximum torque was corrected by subtracting this amount for all MCBH and Camp Pendleton readings.

Table 24. Breaking Torque (ft-lb) Values for MTVR 594120 (Camp Lejeune).

Fastener	ON Direction	OFF Direction
L1	887	615
L2	731	596
L3	732	383
L4	431*	543
L5	615	416
L6	503	344
R1	696	502
R2	599	482
R3	1,329	701
R4	1,292	1,054
R5	814	570
R6	955	696

* Omega HHP-SG digital indicator was set to track instead of maximum when readings started, this was the maximum value observed.

Table 25. Breaking Torque (ft-lb) Values for MTVR 592426 (MCBH)

Fastener	ON Direction	OFF Direction
L1	473	396
L2	401	280
L3	396	238
L4	298	198
L5	446	269
L6	592	406
R1	531	370
R2	613	410
R3	156	159
R4	156	127
R5	530	280
R6	708	569

Table 26. Breaking Torque (ft-lb) Values for MTVR 596577 (Camp Pendleton).

Fastener	ON Direction	OFF Direction
L1	445	207
L2	246	165
L3	323	234
L4	301	187
L5	344	173
L6	352	246
R1	566	379
R2	680	595
R3	342	206
R4	299	247
R5	316	284
R6	523	428

Figure 23 and 24 show comparisons of the breaking torque values for all three vehicles in the ON and OFF directions, respectively.

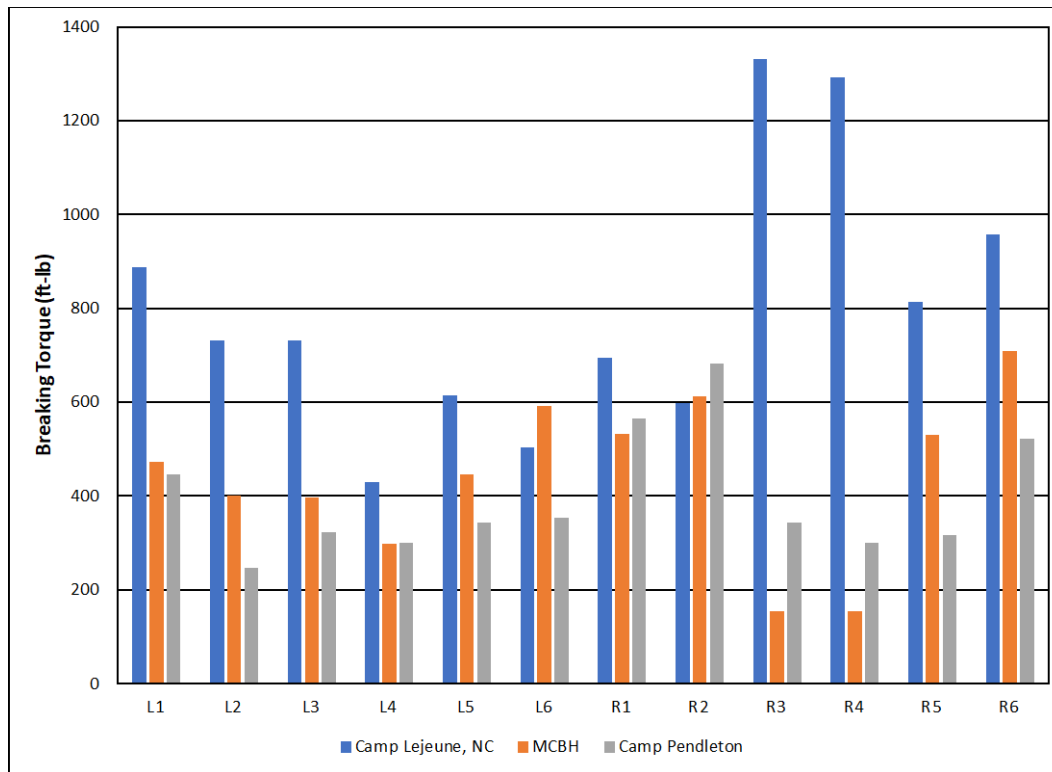


Figure 23. Breaking Torque Value - ON Direction.

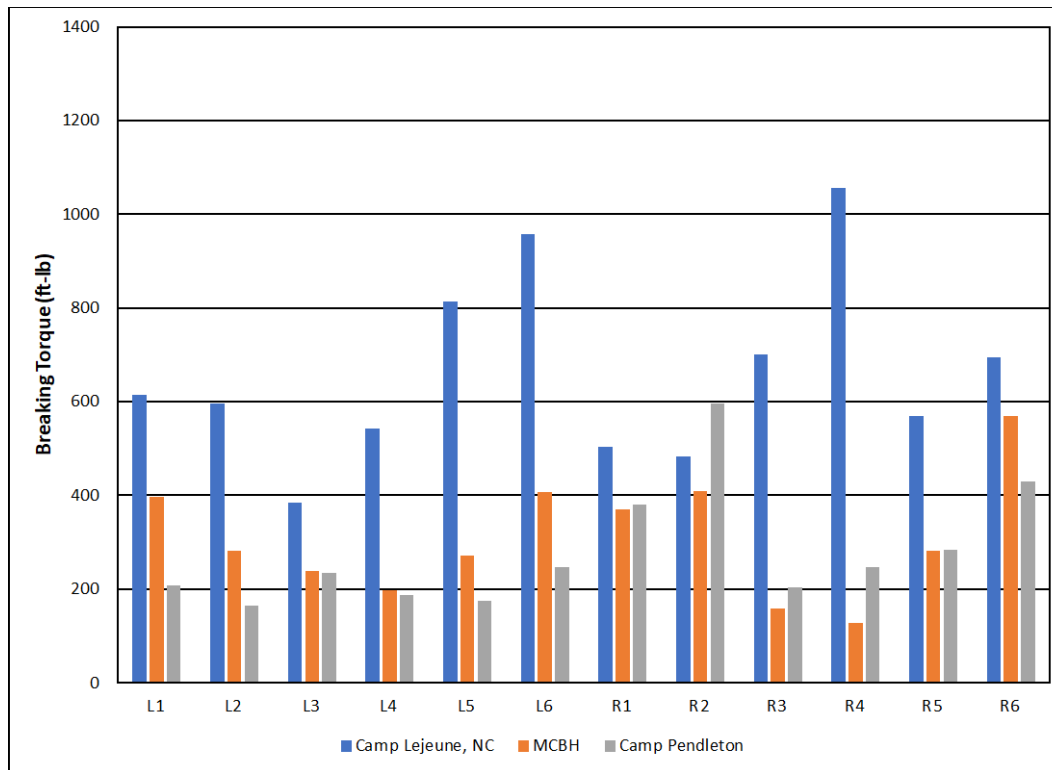


Figure 24. Breaking Torque Value - OFF Direction.

Overall, the data for breaking torque is very scattered. There is not enough consistency among coating types to draw any conclusions about the effect of the coating on breaking torque. This may be, at least in part, due to the manual oversizing of the nuts which was done to accommodate film thickness. However, no such treatment was performed on Type 3 and Type 4 parts.

The values for Camp Lejeune are much higher because they were installed without the use of a torque wrench. These were obviously applied at too high a torque value.

6.2.6 Removal of Mass Loss Coupons

During the inspection mass loss coupons (mounted during the original installation) were removed and returned to PPG for further analysis. At Camp Lejeune, the entire coupon rack was removed and returned with the fasteners. At MCBH and Camp Pendleton, the coupon racks were left installed on the vehicles, with select coupons removed and returned to PPG.

6.2.7 Evaluation of Fasteners Removed from Vehicles

Fasteners removed and returned to PPG were assessed for corrosion, blistering, and paint adhesion. Sets of bolts and nuts were inspected visually for overall appearance of red rust, blistering, and coating loss. Figure 25, 26 and 27 represent all parts removed at the 2¼ year exposure end point. They are from positions L5, L6, R5, and R6. These exposure positions showed the greatest amount of corrosion and the greatest differentiation between coating types. These support the conclusion that the two candidate coating systems are similar to cadmium controls in corrosion performance in this particular environment.

It is interesting to note that although the corrosive environment relative to lab cyclic exposure was mild as evidenced by mass loss coupon data, the cadmium parts showed red rust failure whereas they did not in the cyclic test.

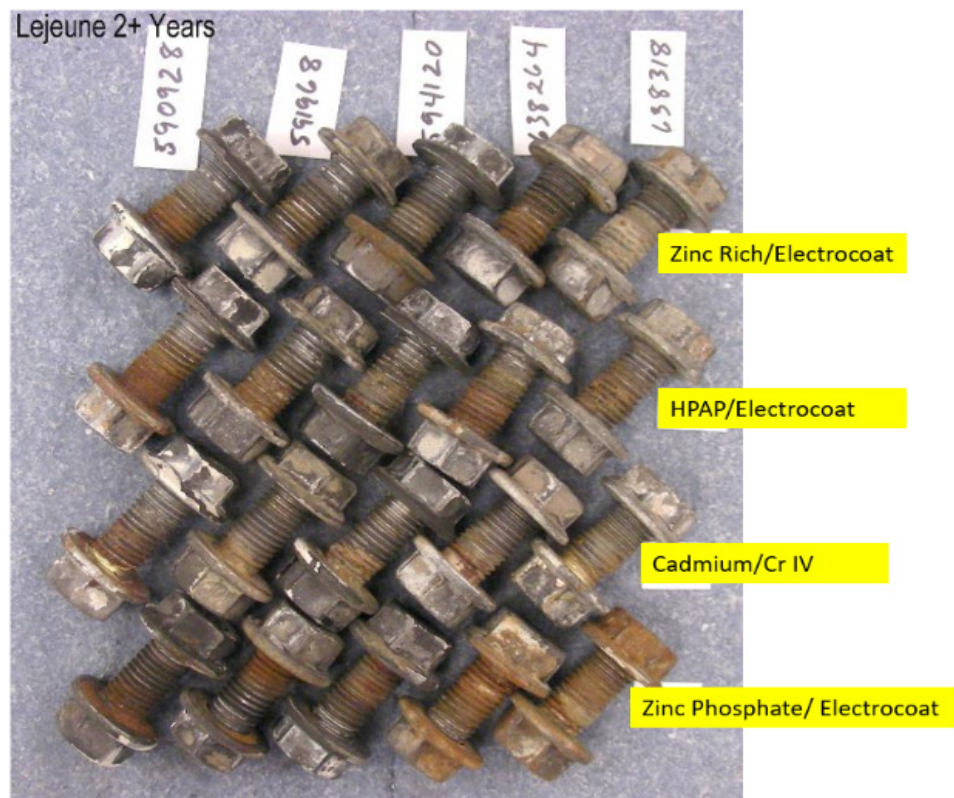


Figure 25. 2¼ Year Exposure at Camp Lejeune

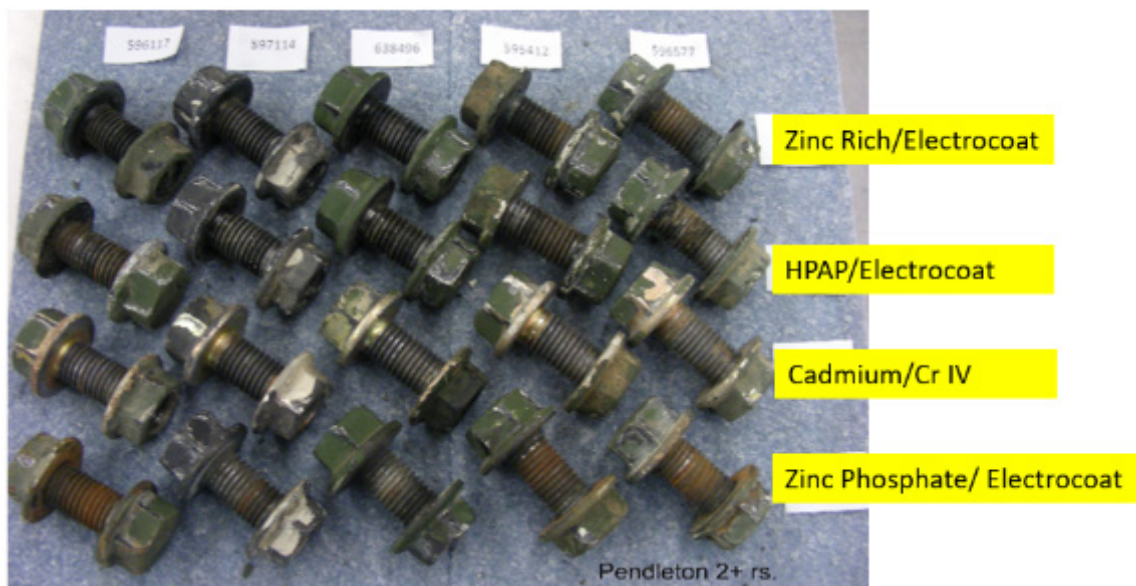


Figure 26. 2¼ Year Exposure at Camp Pendleton

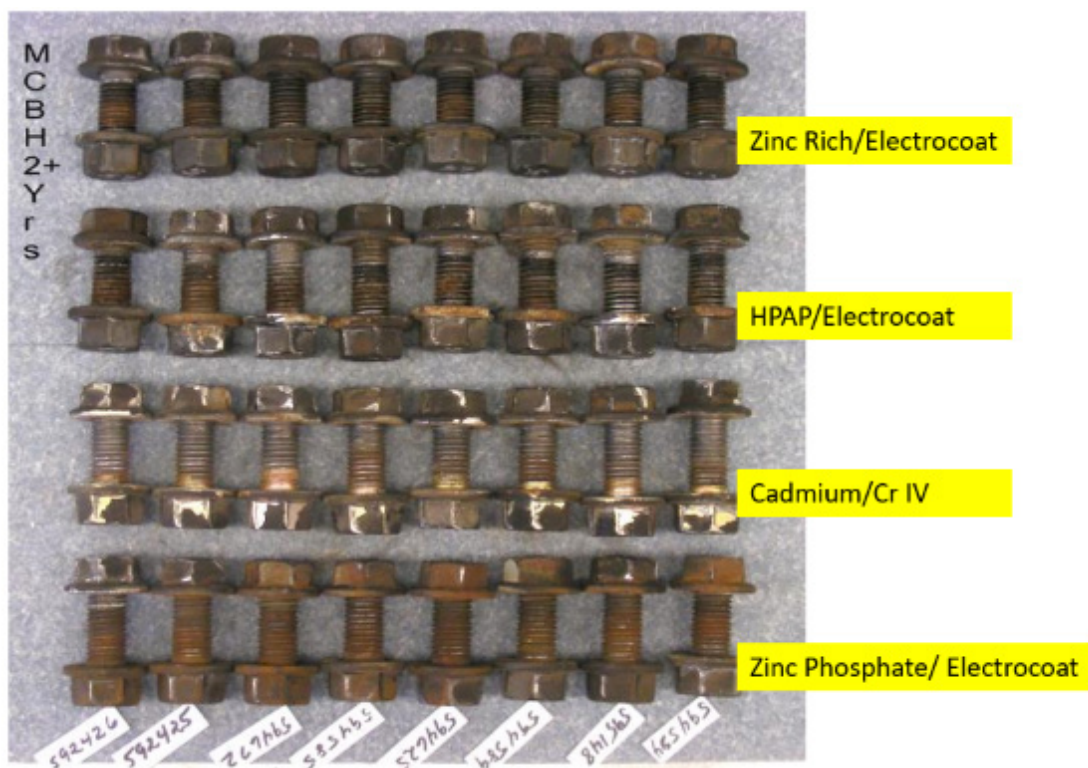


Figure 27. 2¼ Year Exposure at MCB Hawaii

6.2.8 Mass Loss Coupon Validation

Certified mass loss coupons were preweighed and installed on racks which were mounted to the rear of the MTRV test vehicles. The coupons were mounted in very close proximity to the test fasteners in a vertical orientation. At the end of the test fastener exposure, two coupons were removed from each vehicle and returned to PPG. These samples were cleaned by grit blasting to white metal. The average weight loss of all of the samples from each demonstration site was analyzed in aggregate. This average weight loss per coupon was translated into an approximate cycle equivalence according to GMW14872. These results are shown in Table 27.

Table 27. Field Mass Loss Coupon GMW14872 Cyclic Equivalent

	Actual Exposure (Months)	GMW14872 Cycle Equivalent
Camp Lejeune	27	4
Camp Pendleton	28	1
MCB Hawaii	28	6

7.0 COST ASSESSMENT

The successful implementation of the fastener coating technologies which are the subject of this demonstration, would involve simple substitution of one commercially available fastener for another. There would be no deviation from standard protocols in term of labor, facilities, or tooling.

In situations where fasteners plated with cadmium are being replaced by the subject coatings, there would be a small cost advantage since end-of-life disposal costs of the cadmium parts would not be incurred. Since fastener applications are so widely varied, it is impossible to quantify overall cost impacts of implementation of these technologies.

Although the goal of this project was to replace Cd/Cr⁶⁺ coatings, these technologies are also candidates for replacement of high strength fasteners in applications where low corrosion performance coatings such as phosphate are currently employed. In these cases, there may be some cost benefit realized due to superior corrosion control. This may reduce the refit frequency for these parts. It also may decrease the time and labor required to remove and replace fasteners.

There is some cost impact related to the cost of the fasteners themselves. Fastener costs vary widely and are dependent on factors such as production volume and custom manufacture. The coating system used can represent a large or a very small percentage of the total part cost. For example, a review of industrial fastener suppliers shows that common size hex bolts plated with cadmium can range in price from \$0.50 each to \$14 each. However, for comparison purposes, Table 28 shows the relative cost of each coating system based on the processing prices incurred in producing the parts used for the JTP testing. For comparison, the prices are estimated for a 100 pound batch of 3/8-16 1¼ inch hex bolts purchased at \$0.18 each. This represents approximately 1800 pieces. Included are the costs for the multilayer coating systems and also a breakout of the individual coating layers.

An additional cost factor which must be considered is the cost of housekeeping to control Cd/Cr⁶⁺ dust generated from subsequent sustainment activities, which is very high, but is a cost that only comes in the next depot cycle or in the field. There are also costs associated with end-of-life disposal of cadmium plated parts.

Table 28. Coating Cost Comparison

Coating	Cost vs. Performance	Cost to apply coating to 100 lb. of parts	Cost impact on total price of 100 lbs. parts
Phosphate and Oil (as supplied) (Negative Control)	Lowest cost Very low corrosion resistance	\$0 Baseline	Baseline (\$324)
Cadmium Plating with chromate ⁶⁺ (positive control)	Small cost premium Highest corrosion resistance	\$200	1.6 X
Zinc Rich Primer plus Electrodeposition topcoat (Type 1)	Small cost premium High corrosion resistance	\$350	2.1 X
HPAP plus Electrodeposition topcoat (Type 2)	Very High Cost Very High corrosion resistance	\$3050	10.1 X

This comparison shows that the zinc rich/electrodeposition topcoat option is cost effective for substantial corrosion improvement in applications where plain phosphated fasteners are currently being used. For applications where cadmium is currently being used, both of the candidates coating systems are potential replacement candidates. The HPAP/Electrodeposition topcoat system offers high end corrosion resistance but at a very high cost. This may be appropriate in mission-critical applications where the cost premium is not a key factor. The zinc rich/electrodeposition topcoat option may be appropriate in applications as a cadmium replacement where cost is important and a solution with corrosion performance slightly less than cadmium is acceptable.

8.0 CONCLUSIONS AND DISCUSSION

8.1 CONCLUSIONS

- Neither coating Type 1 or Type 2 are 100% replacements for cadmium/HCP (Type 3).
- Electrodeposition topcoat is necessary over sacrificial coatings for lubricity and corrosion performance.
- Coating Type 1 (zinc rich dip-spin primer plus electrodeposition topcoat) offers a low cost alternative with significant corrosion performance over phosphate alone, and slightly weaker than cadmium/HCP. Thread fit is problematic except where plated nuts are used.
- Coating Type 2 (high purity aluminum plating plus electrodeposition topcoat) offers near cadmium/HCP corrosion performance. In the current state of commercial availability, aluminum plating is prohibitively costly for bulk fastener applications. Thread fit is problematic except where plated nuts are used.
- Corrosion performance can best be judged by accelerated tests or field exposure of coated fastener samples.
- Electrodeposition topcoat can be formulated to match torque/tension characteristics of cadmium plated fasteners.
- Electrodeposition topcoat reduces or eliminates installed galvanic corrosion effects.
- All coating types pass dry hydrogen embrittlement testing. All fail wet cell embrittlement test. Validity of wet cell testing is debatable.

8.2 DISCUSSION

Table 29 shows a summary of performance for the coating types.

Table 29. Performance Comparison

	Type 1	Type 2	Type 3	Type 4
Description	Zinc Rich Primer plus Electrodeposition topcoat	High Purity Aluminum Plating/ TCP plus Electrodeposition topcoat	Cadmium/HCP	Phosphate plus oil
Corrosion	Second best. More white corrosion.	Weaker than Type 3 especially on flat panels cyclic	Best overall. Only small amounts of red corrosion.	Much weaker. Base metal pitting.
CARC Adhesion	Pass	Pass	Pass	Pass
Hydrogen Embrittlement	Pass Dry Fail Wet	Pass Dry Fail Wet	Pass Dry Fail Wet	Pass Dry Pass Wet
Galvanic Corrosion	None	None	Slight	None
Torque/Tension	High	High	Equivalent to Cd ⁶⁺ with lube control point	High
Thread Fit (hand threadability)	Only acceptable with galvanized nut. Poor with demo parts.	Only acceptable with galvanized nut. Poor with demo parts.	Only acceptable with galvanized nut. Poor with demo parts.	Only acceptable with galvanized nut. Poor with demo parts.

It is clear that the field demonstration did not represent as corrosive an environment as was anticipated. Therefore it is difficult to conclude that one or both of the candidate coatings tested here would be more appropriate in this application than the simple phosphate plus oil coating currently used. The field data do show some indication of the corrosion resistance of the candidate coating systems versus cadmium with hexavalent chrome. It is interesting to note that although the field conditions were not aggressive versus lab accelerated corrosion methods, the cadmium control showed red rust corrosion only in the field testing. Based on field testing alone, we would conclude that both candidate coatings are nearly equal to cadmium/HCP in these environments.

Analysis of the more aggressive lab accelerated corrosion test indicate that neither candidate coating is equal to cadmium/HCP. The Type 1 (zinc rich primer plus electrodeposition topcoat) and Type 2 (high purity aluminum plating plus electrodeposition topcoat) appear in all testing to be nearly equal but slightly inferior to Type 3 (cadmium/HCP), and far superior to the negative control Type 4 with no sacrificial metallic layer (phosphate plus oil only).

A significant drawback associated with the candidate coatings is the negative affect on thread gauging due to the thickness of the coating layers. For Type 1 the zinc rich dip-spin primer tends to be less even than plating layers and film thickness and can exceed 10 microns in thread roots. The plating layers of Types 2 and 3 at an average of 7-8 microns occupy essentially all of the thread allowance for a standard ISO or UNC external thread. With electrocoat added at an additional 7-8 microns, the bolt threads are extended beyond allowance and hand-threading is impaired or impossible. Even the Type 3 cadmium plating layer with an approved dry lube applied is difficult to hand thread.

The thread gauging is not problematic when the external threaded bolts are paired with zinc plated nuts as was the case for the samples used for friction testing. Zinc plated nuts are manufactured with expanded thread gauge to accommodate the thickness of plated bolts. Therefore, the candidate coating combinations tested here would only be acceptable when paired with plated nuts.

In the case of the demonstration fasteners, the nuts are a standard flanged locknut which was not available in a plated version with oversized threads. Therefore it was necessary to manually expand the thread size of each nut by threading onto a thread-cutting tap in such a way as not to affect the top-lock prevailing torque feature. This was necessary for the demonstration but is not realistic for standard application.

Demonstration Coating Systems supersede specifications and allow the Manager to use the new technology across the platform. There Program could also then create new NSNs which would call the new finish. Once demand is created, manufacture and supply can more easily be engaged. This strategy would need to be driven by the DoD project stakeholders, TARDEC and ARL.

The team has contemplated future cooperative funded initiatives to address implementation. This type of project may involve engagement of a consulting firm familiar with DoD operations. It might include investigation of the actual DoD fastener market needs.

It has become apparent during the course of this work that the path to introducing a new cadmium replacement coating into the DoD supply chain is very complex and difficult.

It seems there is not a well-established protocol beyond achieving specification approval. It seems that fasteners are especially complex since the number and variety is so great. Much of the difficulty lies in changing supply chain at the depot refit level where most of the cadmium usage still occurs. Many OEMs have already transitioned to alternative coatings. However, depots are bound by legacy drawings and NSN designations. Therefore the task of implementing a new coating system is daunting.

In attempt to gain a better understanding of what would be required to penetrate the supply chain. We contracted a consulting firm with knowledge of DoD operation to compile a report on the subject. The report authored by Corrdesa LLC is attached in Appendix C.

9.0 REFERENCES

1. SERDP WP-1617 Final Report - <http://www.serdp.org/Program-Areas/Weapons-Systems-and-Platforms/Surface-Engineering-and-Structural-Materials/Coatings/WP-1617>

2. ASTM INTERNATIONAL STANDARDS:

- ASTM B117-11 - Standard Practice for Operating Salt Spray (Fog) Apparatus. (DoD adopted)
- ASTM D1654-08 - Standard Test Method for Evaluation of Painted or Coated Specimens Subjected to Corrosive Environments. (DoD adopted)
- ASTM F519-13 - Standard Test Method for Mechanical Hydrogen Embrittlement Evaluation of Plating/Coating Processes and Service Environments
- ASTM D610-08 - Standard Practice for Evaluating Degree of Rusting on Painted Steel Surfaces
- ASTM D714-02 - Standard Test Method for Evaluating Degree of Blistering of Paints
- ASTM D3359 - Standard Test Methods for Measuring Adhesion by Tape Test

(Copies of these documents are available from www.astm.org or ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959.)

3. GENERAL MOTORS ENGINEERING STANDARDS:

- GMW 14872 - Cyclic Corrosion Laboratory Test

(Copies of this document are available from www.ihs.com or General Motors International, General Motors Technical Center, Warren, MI 48092.)

4. SAE INTERNATIONAL

- SAE USCAR 10-2:2007 - Test For Evaluating The Torque-tension Relationship Of Both External And Internal Metric Threaded Fasteners
- SAE/USCAR 11-2:2007 - Torque-Tension Testing and Evaluation of Fastener Finishes
- SAE/USCAR 32:2007 - New Finish Development Document

(Copies of these documents are available from <http://standards.sae.org>)

APPENDIX A JOINT TEST PROTOCOL



JOINT TEST PROTOCOL

Environmentally Friendly Fastener Coating Demonstration

ESTCP Project WP-201315

Revision 2

July, 2014

Distribution Statement "A" applies.
Approved for public release; distribution is unlimited.

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PREFACE

This report was prepared under Weapons Project 201315 for the Environmental Security Technology Certification Program (ESTCP). The structure, format, and technical content were determined by ESTCP, government technical representatives and government contractors in response to the specific needs of the project and eventual users of this technology.

We wish to acknowledge the invaluable contributions by the following organizations involved in the creation of this document:

Army Research Laboratory (ARL)

US Marine Corps (CPAC)

PPG Industries, Inc

Elzly Technology Corporation

Army Tank Automotive Research, Development and Engineering Center (TARDEC)

Army Aviation and Missile Command (AMCOM)

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ACRONYM LIST

AISI	American Iron and Steel Institute
AMCOM	Army Aviation and Missile Command
ANSI	American National Standards Institute
ARL	U.S. Army Research Laboratory
ASTM	American Society for Testing and Materials
CARC	Chemical Agent Resistant Coating
Cd	Cadmium
Cr6 ⁺	Hexavalent Chromium
COF	Coefficient of Friction
DoD	Department of Defense
EC	Electrodeposition Coating
Ecoat	Electrodeposition Coating
ESOH	Environmental, Safety and Occupational Health
ESTCP	Environmental Security Technology Certification Program
ft	foot
GMW	General Motors Worldwide
GSE	Ground Support Equipment
HAPs	Hazardous Air Pollutants
HazMat	Hazardous Material
HPAP	High-Purity Aluminum Plating
in	Inch
JTP	Joint Test Protocol
JTR	Joint Test Report
lb	Pound
mg	Milligram
mm	Millimeter
NaCl	Sodium Chloride
NFS	Notched Fracture Strength
Nm	Newton meter
NSS	Neutral Salt Spray
OEM	Original Equipment Manufacturer
PPG	PPG Industries, Inc.
PSI	Pounds per Square Inch
SAE	Society of Automotive Engineers
SERDP	Strategic Environmental Research and Development Program
SSPC	The Society of Protective Coatings
TACOM	U.S. Army Tank-Automotive and Armaments Command
TARDEC	U.S. Army Tank-Automotive Research, Development and Engineering Center
TRL	Technology Readiness Level
USCAR	United States Council for Automotive Research
VOC	Volatile Organic Compound
ZR	Zinc Rich Primer

1.0 INTRODUCTION

ESTCP selected the “Environmentally Friendly Fastener Coating Demonstration” project, led by PPG to define the performance of alternative coatings on fasteners in order to replace cadmium plating. A successful candidate would result in the mitigation of the significant Environmental, Safety and Occupational Health (ESOH) risks associated with the use of cadmium and chromium(6+) containing coatings for use on fasteners.

There is a need to implement innovative and cost effective replacement technologies to address the multiple health, safety and compliance issues associated with the current systems while maintaining military readiness for national defense. In addition, the new technology must have the following attributes: 1) compatibility with OEM/Depot infrastructure, 2) corrosion performance equivalent to (or better than) current fastener coatings in use, 3) broad compatibility with the current suite of military coatings and, 4) compatibility with substrates used by the DoD. The objective of the proposed program is to demonstrate two new fastener coating systems in DoD environments. The two new coatings will be shown to be both environmentally acceptable, (no heavy metals such as Cr6+ or Cd), and demonstrate corrosion resistance characteristics near that of Cd/Cr+6 plating.

The coating systems targeted for demonstration/validation are coded and described as follows:

Type 1 - A multilayer fastener coating system comprising:

- Zinc Phosphate Conversion Coating - Cleaning and application of IRCOBOND® Z24, commercially available from PPG Industries, Inc. Application per manufacturer’s recommendations, followed by heated drying stage and cooling. Conforms to TTC 490 Type 1.
- Zinc Rich Primer – Application of SPINCOAT® ZRC inorganic zinc rich primer, commercially available from PPG Industries, Inc. The coating is applied by conventional dip-spin methods for a dry film thickness of 0.25-0.45 mils. The coating is bake cured at 450°F and cooled prior to topcoat application.
- Epoxy Electrodeposition Coating – Application of POWERCRON® XP cationic electrodeposition coating (ECOAT), commercially available from PPG Industries, Inc. Coating is applied by barrel process according to manufacturer’s recommendations for a dry film thickness of 0.30-0.50 mils. The coating is bake cured at a temperature of 375°F and cooled. This topcoat contains integral torque modifiers.

Type 2 - A multilayer fastener coating system comprising:

- High Purity Aluminum Plating – Application of a high purity aluminum plating (HPAP) for a film thickness of 0.3 mils, commercially available from the AlumiPlate company. The plating process is followed by a trivalent chromium Passivate (TCP).
- Epoxy Electrodeposition Coating – Application of POWERCRON® XP cationic electrodeposition coating (ECOAT), commercially available from PPG Industries, Inc. Coating is applied by barrel process according to manufacturer’s recommendations for a dry film thickness of 0.30-0.50 mils. The coating is bake cured at a temperature of 375°F and cooled. This topcoat contains integral torque modifiers.

Type 3 - Cadmium (Cd) Control Coating

- Cadmium plating plus hexavalent chromium conversion per specification SAE AMS QQ-P-416C, Type II, Class2. This includes a hydrogen relief bake.

Type 3A - Cadmium plating plus dry film thread lubricant

- Type 3 coating plus dry film lubricant applied to the thread area. MIL-PRF-46147-#28 lubricant available from Sandstrom, applied by dip to 0.3-0.7 mils. and air dry minimum 1 hour. Conforms to MIL-L-6010 and NASM 25027.

Type 4 - Multilayer coating for application to steel mounting plates which form test assemblies.

- Zinc Phosphate conversion coating - Cleaning and application of CHEMFOS® C700 C59, commercially available from PPG Industries, Inc. Application per manufacturer’s recommendations.
- Epoxy Electrodeposition Primer – Application of FRAMECOAT® II cationic electrodeposition coating (ECOAT), commercially available from PPG Industries, Inc. Coating is applied according to manufacturer’s recommendations for a dry film thickness of 0.80-1.20 mils. The coating is bake cured at a temperature of 350°F and cooled.

Type 5 - CARC system for flat panels and assemblies.

- CARC Primer and Topcoat – MIL-DTL-53022E Type II primer at 1.5 ± 0.2 mils (37.5 ± 5 microns), plus MIL-DTL-53039E Type IX topcoat at 2.0 ± 0.2 mils (50 ± 0.2 microns). The coatings are applied by spray and are allowed to cure for a minimum of 7 days prior to further handling or testing.

These coating systems will be applied to and tested on standard bolts, nuts and washers for laboratory tests, and on appropriate fasteners for field application to be determined. The parts selected for lab testing are of materials and types typical of those used for bolted joint applications found in military ground vehicles. Lab testing will also be performed on flat test panels for relative corrosion comparison, and for tape adhesion testing where fastener testing is not appropriate or would not provide adequate consistency. For control purposes, the target fasteners and panels will also be coated with electroplated cadmium plus hexavalent chromium conversion rinse. All parts are obtained from the manufacturers without coatings applied (bare steel with oil only). Candidate coatings are then applied using the appropriate methods. Table 2 details an overview of the coatings applied to the test parts.

ESTCP program requirements include the development of a Joint Test Protocol (JTP). This JTP contains the technical requirements and tests necessary to evaluate non-toxic metal containing fastener coatings against qualified and approved cadmium and chromium containing fastener coatings. It also includes the technical requirements of the US Marine Corps, which also plans to evaluate the test results to select materials for implementation. Alternative materials are expected to be validated with these technical requirements under this project.

The overarching objective of this project is a comprehensive evaluation of applications and requirements for environmentally friendly fastener coatings, characterization of the performance and maturity of available or proposed alternative fastener coating technology, and recommendations and actions for development, optimization, and demonstration/validation of toxic metal free fastener coatings.

The stakeholders are as follows:

PPG Industries, Inc.....	Matthew Scott (PI), Larry Fitzgerald
Army Research Laboratory.....	Fred Lafferman
US Marine Corps (CPAC)	Andrew Sheetz
TARDEC.....	Daniel Nymberg
Army Aviation and Missile Command (AMCOM).....	Mark Feathers
Elzly Corporation.....	John Repp

All stakeholders maintained a continuous and open dialogue discussing the technology readiness level (TRL) of the candidate fastener coatings. Over the past several years PPG has worked with TARDEC, Elzly, AlumiPlate, and NMP Corporation (fastener manufacturer) to test and validate the performance of these coating systems. Laboratory testing was done and a field demonstration is still underway on MRAP floor screws. Formulation and optimization of the PPG zinc rich primer (SPINCOAT ZRC) was done under the SERDP program WP-1617 “Environmentally Friendly Anticorrosion Coating for High Strength Fasteners”.

For this project, cadmium and hexavalent chromium, as found in current fastener coatings, was identified as the target HazMat to be eliminated or reduced. Table 1 summarizes the target HazMat, process, application, current specifications, affected programs, and candidate parts/substrates.

The purpose of this JTP is to mature and evaluate the application processes of these fastener coatings that have high potential to meet the corrosion performance requirements of the DoD. Successful demonstrations will provide a body of data sufficient to draft MIL Specifications which would make the coatings available for use on DoD assets. This also may create opportunities for additional demonstrations and validations in areas where current products are not good enough.

Table 1: Target HazMat Summary.

Target HazMat	Current Process	Applications	Current Specifications	Affected Programs	Candidate Parts & Substrates
Cadmium	Electroplating	Corrosion protection of fasteners	SAE-AMS-QQ-P-416C.	All military GSE platforms and their assets	All steel bolts, nuts, washers, clips, and other small steel components.
Hexavalent Chromium Conversion Coating	Immersion and spray application	Used as a conversion coating for cadmium plating	MIL-DTL-5541	All military GSE and aviation platforms and their assets	<i>Substrates:</i> AA2024-T3 AA7075-T6 AA6061-T6

Table 2: Overview of Coating Systems for Fasteners

Fastener Coating System Designation	Type 1	Type 2	Type 3 Control
Bolt	Hex Head Cap Screw; 3/8" - 16 x 1/1/2"; Grade 8 J429; Full Thread; Bare machined surface; Torque to 47 – 52 ft. lb. See Table 4for tolerances and surrogates.	Hex Head Cap Screw; 3/8" -16 x 1/1/2"; Grade 8; J429; Full Thread; Bare machined surface; Torque to 47 – 52 ft. lb. See Table 4for tolerances and surrogates.	Hex Head Cap Screw; 3/8" -16 x 1/1/2"; Grade 8 J429; Full Thread; Bare machined surface; Torque to 47 – 52 ft. lb. See Table 4for tolerances and surrogates.
Nut	To fit screw, see Table 4 for substrate material, surface and tolerance	To fit screw, see Table 4 for substrate material, surface and tolerance	To fit screw, see Table 4 for substrate material, surface and tolerance
Fastener Conversion Coating	PPG; IRCOBOND® Z24, Zinc Phosphate: Application per manufacturers recommendations; followed by heated drying stage and cooling.	None	Hexavalent Chromium
Fastener Plating	None	AlumiPlate Co.; High Purity Aluminum Plating (HPAP) followed by trivalent chrome passivate (TCP); Thickness is 0.30 mils	Cadmium Plating per SAE-AMS-QQ-P-416C, Type II, Class 2; followed by hydrogen relief bake; Thickness is 0.3 mils minimum no bare areas; followed by chromate treatment.
Fastener Primer	PPG; SPINCOAT® ZRC Inorganic Zinc Rich Primer ; followed by heated drying stage; DFT of 0.25 – 0.45 mils; 450 °F bake cure and cool	None	None
Fastener Topcoat	PPG; POWERCRON® XP cationic electro deposition coating (ECOAT); Application by barrel process; DFT of 0.30-0.50 mils; 375 °F bake cure and cool; contains integral torque modifiers	PPG; POWERCRON® XP cationic electro deposition coating (ECOAT); Application by barrel process; DFT of 0.30-0.50 mils; ; 375 °F bake cure and cool; contains integral torque modifiers	None
	Type 1A	Type 2A	Type 3A
Bolt Thread Torque Modifier	PPG; SEALCOAT 424 S/B (Application is Optional, by Dipping)	PPG; SEACOAT 424 S/B (Application is Optional, by Dipping)	MIL-PRF-46147-#28 lubricant available from Sandstrom, applied by dip to 0.3-0.4 mil.

Table 3: Overview of Coating Systems for Assembly Panels

Panel Coating System Designation	Type 4	Type 5	No Coating System Fastener Only	No Coating System Fastener Galvanic
Flat Panels	Cold Rolled Steel; minimum dimensions of 3" wide, 6" long; 1/16" thick; place ten predrilled holes, 13/16" dia. and deburred with arrangement per Figure 2.	Cold Rolled Steel; minimum dimensions of 3" wide, 6" long; 1/16" thick; place ten predrilled holes, 13/16" dia. and deburred with arrangement per Figure 2.	Polymer Sheet; minimum dimensions of 3" wide, 6" long; 1/16" thick; place ten predrilled holes, 13/16" dia. and deburred with arrangement per Figure 2	2024 Aluminum; minimum dimensions of 3" wide, 6" long; 1/16" thick; place ten predrilled holes, 13/16" dia. and deburred with arrangement per Figure 2
Plating	None	None	None	None
Conversion Coating	PPG; CHEMFOS® C700 C59, Zinc Phosphate; Apply per Mfgr.'s Recommendations	PPG; CHEMFOS® C700 C59, Zinc Phosphate; Apply per Mfgr.'s Recommendations	None	None
Primer	PPG; FRAMECOAT® II electro deposition coating (ECOAT); Epoxy, ; Apply Mfgr.'s Recommendations; DFT of 0.80 – 1.20 mils; 350 °F bake cure and cool	MIL-DTL-53022E Type IV; Apply by Spray per MIL-DTL-53072; DFT of 1.5±0.2 mils (37.5±5 microns); dry for 1 hour.	None	None
Fasteners	Installation between prime and topcoat. See Table 5	Installation between prime and topcoat. See Table 5	Installation on bare panel. See Table 5	Installation on bare panel. See Table 5
Topcoat	None	MIL-DTL-53039E Type IX; Apply by Spray per MIL-DTL-53072; DFT of 2.0±0.2 mils (50.0±0.2 microns); Cure for 7 days.	None	None

2.0 PERFORMANCE AND TESTING REQUIREMENTS

The technical team has reached consensus on tests with procedures and methodologies for evaluating the fastener coating systems against approved cadmium/chromium coating. Data developed from these tests is intended to be used as a guide for development of acceptance criteria and implementation for end applications. It is not intended to be used for qualifying or excluding any alternative. Users will select alternatives based on their need and respective business case.

The major requirements for which the tests in this JTP were chosen are the following:

- Corrosion Resistance
- Galvanic Compatibility
- Tape Adhesion Dry and/ Wet
- Torque/Tension, Coefficient of Friction
- Hydrogen Embrittlement (and Service Embrittlement)
- Field Exposure/Static
- Field Exposure/On-Vehicle

Tests in this JTP may involve the use of hazardous materials, operations, and equipment. This JTP does not address all safety issues associated with its use. It is the responsibility of each user of this JTP to establish appropriate safety and health practices and to determine the applicability of regulatory limitations prior to its use. Refer to the Health and Safety Plan developed for the Demonstration Plan corresponding to this JTP.

Section 2.1 summarizes the requirements and tests agreed upon by the joint technical team.

Appendix B describes additional mixed substrate testing to be performed by PPG. This testing was added as a supplement to the original JTP.

2.1 Summary of Engineering, Performance, and Testing Requirements

Table 3 lists all engineering and testing requirements identified for validating the fastener coatings to cadmium and chromate conversion coatings that are common to all affected defense systems.

Testing is divided into two phases: performance testing and field demonstration /validation. The performance testing will begin as soon as parts can be obtained and processed. Testing will be performed by ARL or an external testing facility of their choosing. Concurrent testing of selected tests may be done by PPG. The test parts (including flat panels) will be obtained by PPG. PPG will apply the zinc phosphate conversion coating, the zinc rich primer, and the epoxy electrodeposition topcoat at their Euclid, Ohio plant. The high purity aluminum plating will be applied by the AlumiPlate Company and subsequently topcoated with epoxy electrodeposition topcoat by PPG. The cadmium control parts will be sent to an external plating company capable of processing the parts to SAE-AMS-QQ-P-416C specification. These will not receive any topcoat. Some will have dry film lubricant applied to the threads only.

The field testing protocol, vehicle types, fastener types, and location shall be defined in the Demonstration Plan. This activity will begin as soon as possible, and will run concurrent with lab testing. The field test parts will be coated in the same manner as the lab test parts.

Table 4: Performance and Testing Requirements.

Phase	Engineering Requirement	Test	JTP Section	Test Criteria	References
I	Corrosion Resistance	Neutral Salt Fog – Flat Panels	3.1.1	500 hrs. minimum with no red scribe corrosion. To 2000 Hrs.	ASTM B 117 ASTM D1654
I	Corrosion Resistance	Neutral Salt Fog – Fastener Assembly	3.1.2	1,000 hrs. minimum with <5% red rust on significant surfaces. To 2000 Hrs.	ASTM B 117 ASTM D1654
I	Corrosion Resistance	Cyclic Corrosion – Flat Panels	3.2.1	20-40-60-80 cycles, no red scribe corrosion. Test to failure.	GMW 14872 ASTM D1654
I	Corrosion Resistance	Cyclic Corrosion – Fastener assembly	3.2.2	20-40-60-80 cycles, <5% red corrosion on significant surfaces. Test to failure.	GMW 14872 ASTM D1654
I	Simulated Handling	Drop Test	3.3	1 Kg parts dropped 1 meter. Test GMW14872 as in 3.2.1	GMW14872 SAE/USCAR-32 - 3.19
I	Adhesion, Dry	Dry Tape Adhesion (Cross-cut)	3.4	4B rating minimum.	ASTM D 3359, Method B
I	Adhesion, Wet	Water Resistance, wet tape adhesion	3.5	No peel away; at least 4A per ASTM D 3359; no blistering of unscribed coating area, no delamination from substrate.	ASTM D 3359, Fed-Std-141, Method 6301
I	Hydrogen Embrittlement	Mechanical Hydrogen Embrittlement	3.6	Pass per ASTM F519 Type 1a.2	ASTM F 519
I	In-Service Hydrogen Embrittlement	Mechanical Hydrogen Embrittlement	3.7	Pass per ASTM F519 Type 1a.2 Annex 5 Section A5.3.2 with 3% NaCl solution 150 Hrs.	ASTM F 519 Annex 5
I	Torque	Torque/Tension COF	3.8	Per SAE/USCAR-11	SAE/USCAR-10, SAE/USCAR-11
I	Galvanic Compatibility	Assembly in Aluminum 2024 Plate	3.9	No significant corrosion of 2024 aluminum under washer of assembly after 120 cycles GMW14872 cyclic corrosion	GMW14872 SAE/USCAR 32 3.7
I	Outdoor Exposure	Canaveral, FL Exposure	3.10	2 years – Inspect every 6 months for visible corrosion. Compare to Cd control. Photograph.	SSPC-VIS-2
II	Corrosion, Adhesion, Breaking Torque	Field Exposure, On-Vehicle	3.11	Exposure time of two years on vehicle platform or panels attached to platform. Evaluate performance versus cadmium plated parts.	ASTM D1654 SSPC-VIS-2

3.0 TEST DESCRIPTIONS

The tests identified in Table 4 are further defined in Sections 3.1 through 3.11 below to include test description, rationale, and methodology. Also included, as needed are any major or unique equipment requirements, as well as data reporting and analysis procedures. Test methodology includes the definition of test parameters, test specimens, number of trials per specimen, experimental control specimens required, and test duration or criteria. The primary purpose of this JTP is to provide data to the joint user community, which it can use to select alternatives, if any, for field testing. Decision criteria will vary by user, and it is likely that different users will choose different alternatives based on their business cases.

Test coupons (also referred to as “flat panels”) will be at least 3 inches wide by 6 inches long and of suitable thickness (0.032 inch). Coating adhesion testing shall be conducted on test panels made from cold rolled steel (CRS) and subsequently coated with the target coating systems. The processes to be used in the preparation of the test panels shall be outlined in the JTR. Performance and Special Tests shall be conducted on fasteners that accurately simulate current production material and manufacturing processes. The actual processes used in the test specimen preparation shall be outlined in the JTR.

An “Assembly” shall consist of ten sets of fasteners mounted in mounting plate. The sets consist of a bolt-plate-nut combination. Five of the sets are mounted with the bolt head on the test face, and the other five with the nut on the outer test surface (Figure 1). The sets shall be staggered on the mounting plate such that, when tested in a corrosive environment, the condensation and corrosion products from one set do not contact another set (Figure 2). The sets shall be installed using a standard hex socket wrench on the nut and a hex socket attached to a torque indicating wrench on the bolt. The installation torque shall be 47-52 ft.lb.. The mounting plate holes shall be pre-drilled to 13/32” and de-burred.

For assemblies which are mounted in steel plates (A1.3, A2.3, A3.3), the mounting plates (MP3) are precoated with coating system Type 4. This consists of cleaning, phosphate conversion, and epoxy electrocoat. The fasteners are then mounted in the plate. The entire assembly (front and back) is then coated with CARC primer and topcoat described in Type 5. The assemblies are then allowed to cure for an additional 7 days. This coating scheme is designed to simulate field repair of a bolted joint.

For assemblies utilizing the Type 3 Cadmium plated fasteners, all bolt threads are coated with dry film lubricant as described in coating type 3A.

NOTE: It is necessary for proper thread fit and gauging that an oversize threaded nut be used where the total thickness of the coating and bolt and nut are too great for proper run-down torque. Oversized nut threads have been used for coating types 1 and 2. A standard thread nut is used for type 3.

Users of this JTP should check the project’s Joint Test Report (JTR), if available, for additional test details or minor modifications that may have been necessary in the execution of testing. Any test procedure modifications will have been agreed upon by the technical stakeholders.

Table 5: Substrate Descriptions and Test Specimen Codes

Specimen Code	Substrate	Source	Coating
P1.1 P1.2 P2.1 P2.2 P3.1 P3.2	Cold Rolled Steel Flat Panel 4"x6"x0.032"	ACT (#28110)	Type 1 Type 1 + Type 5 Type 2 Type 2 + Type 5 Type 3 Type 3 + Type 5
B1 B2 B3 B3A	3/8 - 16 X 1-1/2" full thread hex head bolt SAE GR 8 J429 Standard Thread Tolerance	Trinity Hardware Davenport, IA PN 1694265	Type 1 Type 2 Type 3 Type 3A
N3	3/8 – 16 hex nut Grade 8 Standard Thread Tolerance	Trinity Hardware Davenport, IA Quote# 3185721	Type 3
NO1 NO2	3/8 – 16 hex nut 0.017" Oversize Thread Tolerance (required for gauging with added film thickness)	Decker Mfg. Corp. Albion, MI PN 026-616-00	Type 1 Type 2
SB1 SB1A SB2 SB2A SB3 SB3A	Surrogate Bolt M10 1.5 40 9.8	Wilson/Garner 11516105	Type 1 Type 1A Type 2 Type 2A Type 3 Type 3A
SN1 SN2 SN3	Surrogate Nut M10 9.8	Wilson/Garner HNM010150AS	Type 1 Type 2 Type 3
CN1	Torque Control Nut M10 9.8	Wilson Garner 11516090	Zinc Plated
CW1	Torque Control Washer M10	Wilson Garner 11502644	Zinc Plated
MP1	Plastic (PP) Panel 1/8"x4"x12"	McMaster-Carr 8782K69	None
MP2	Aluminum 2024 1/8"x4"x12"	McMaster-Carr 89215K26	Clean Only
MP3	Hot Rolled Steel 1/8"x4"x12" (Conforming to SAE1008) 10 holes punched and deburred	Laser Precision Libertyville, IL (custom fab.)	Type 4
Assemblies			
A1.1 A1.1D	Assembly: B1-MP1-NO1 Assembly A1.1 with Drop Test		ZR/EC in Plastic “ Drop Tested

A1.2	Assembly: B1-MP2-NO1		ZR/EC in Al
A1.3	Assembly: B1-MP3-NO1		ZR/EC/Type 5 in Steel
A1.3D	Assembly A1.3 with Drop Test		“ Drop Tested
A2.1	Assembly: B2-MP1-NO2		HPA/EC in Plastic
A2.1D	Assembly 2.1 with Drop Test		“ Drop Tested
A2.2	Assembly: B2-MP2-NO2		HPA/EC in Al
A2.3	Assembly: B2-MP3-NO2		HPA/EC/Type 5 in Steel
A2.3D	Assembly 2.3 with Drop Test		“ Drop Tested
A3.1	Assembly: B3A-MP1-N3		Cd/Cr6+ in Plastic
A3.1D	Assembly 3.1 with Drop Test		“ Drop Tested
A3.2	Assembly: B3A-MP2-N3		Cd/Cr6+ in Al
A3.3	Assembly: B3A-MP3-N3		Cd/Cr6+/Type 5 in Steel
A3.3D	Assembly 3.3 with Drop Test		“ Drop Tested

Figure 1: Fastener Mounting for Assemblies

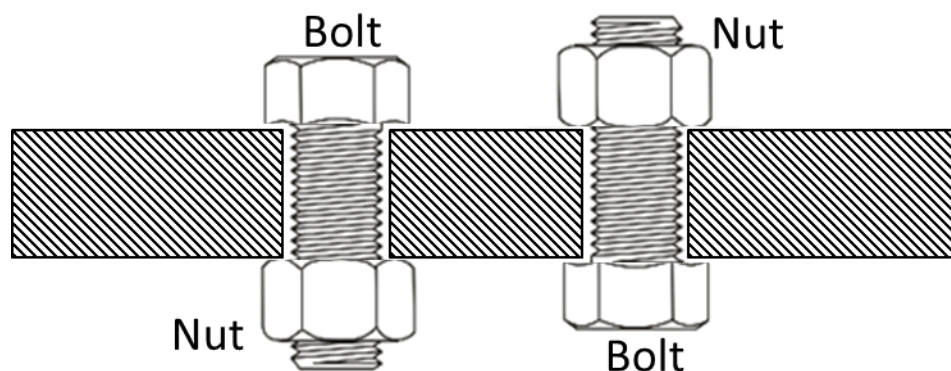
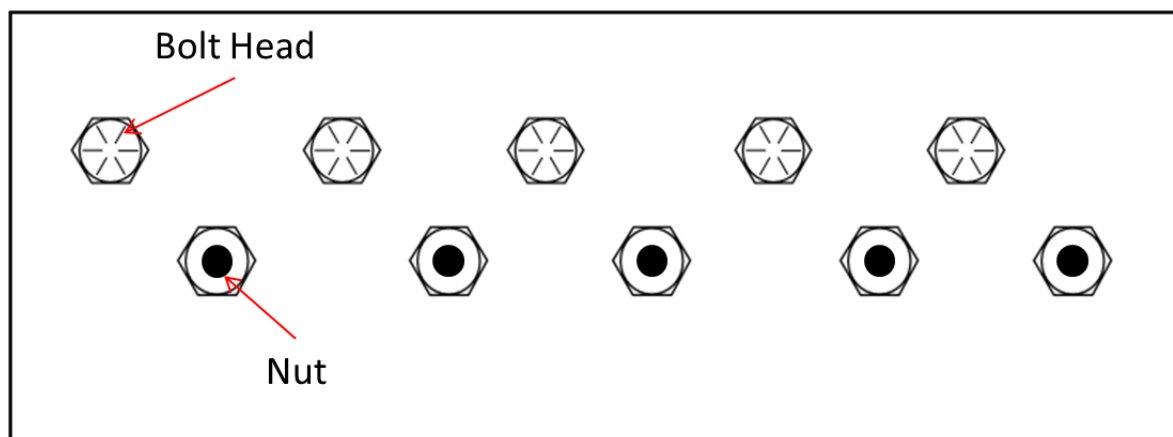


Figure 2: Fastener Set Placement in Assemblies



3.1 Neutral Salt Fog (ASTM B117)

Test Description

This test method describes the procedure and conditions required to create and maintain the neutral salt spray (NSS) (fog) test environment and the evaluation of specimens incorporating the coating systems with respect to corrosion, blistering associated with corrosion, loss of adhesion at a scribe mark, or other corrosive attack.

Operate the fog chamber for this test in accordance with ASTM B 117 (*Standard Practice for Operating Salt Spray (Fog) Apparatus*).

3.1.1 Flat Panel Salt Fog Testing

At least three flat panel specimens shall be used for Common Performance Testing. Common Performance Testing shall be conducted with 102 x 152 mm (4" x 6") test panels, composed of cold rolled steel and subsequently treated with the coating systems as described in Section 1.0. Each test specimen shall contain a clear identification mark. The coated specimens are described in Table 5 (P1.1,P1.2,P2.1,P2.2,P3.1,P3.2). Using test specimens incorporating the coating systems, scribe a "X" incision through the coating making sure that the scribed line is all the way through to the substrate. The scribe shall not exceed 0.5 mm in width. Place the scribed test specimens in the chambers, leaning at an angle between 15 and 30 degrees from the vertical with the scribed surface facing upwards. The samples shall be inspected at every 500 hours for a total exposure time of 2,000 hours. At each inspection interval, remove the test specimens and clean them by gently flushing with running tap water and drying them with a stream of clean, dry compressed air. Rate the percentage of white and red corrosion in the scribe areas and on the face areas. Rate the degree of blistering at the scribe expressed as millimeters of total blistering measured perpendicular to the scribe at the widest point of blistering. Rate the degree of corrosion and blistering in unscribed areas according to ASTM D1654. Specimens shall not be scraped or abraded before returning to the test chamber for continued exposure. Photographically document the surface condition of each of the test specimens using the imaging system.

At the conclusion of the exposure period, remove the test specimens and clean them by gently flushing with running tap water and drying them with a stream of clean, dry compressed air. Allow the test specimens to recover for 24 hours. Evaluate in the same manner as for the interim test intervals without scraping. After photographic documentation, scrape the test specimen's side-to-side with the putty knife at 30-degree contact angle. Evaluate the corrosion resistance and creepage of the test specimens in accordance with the latest version of ASTM D1654, "Standard Test Method for Evaluation of Painted or Coated Specimens Subjected to Corrosive Environments." Rate the corrosion or loss of coating extending back from the scribe mark and evaluate the unscribed areas for corrosion spots, blisters, and any other types of failure that may occur. The rating system for corrosion per ASTM D1654 is shown in Table 6. Photographically document the surface condition of each of the test specimens using the imaging system.

3.1.2 Assembly Salt Fog Testing

Salt Spray testing shall be performed on four types of assemblies as described in Table 4.

Coated fasteners mounted in plastic (A1.1,A2.1,A3.1) with no subsequent CARC coating will show the relative corrosion performance of the coating systems without topcoat or the influence of any bimetallic contact. This same configuration is assembled using fasteners which have been damaged by the Drop Test as described in section 3.3 (A1.1D,A2.1D,A3.1D).

Coated fasteners mounted in a hot rolled steel plates (A1.3,A2.3,A3.3). The steel plates are precoated with Ecoat (Type 4) prior to assembly. After assembly, the front and back are coated with CARC primer and topcoat. This type of assembly is intended to mimic conditions in a service environment. This same configuration is assembled using fasteners which have been damaged by the Drop Test as described in section 3.3 (A1.1D,A2.1D,A3.1D).

The assemblies shall be placed in the test chamber with the long aspect in the horizontal position and leaning at an angle of between 15 and 30 degrees. Each assembly shall have a clear identifying mark. The specimens shall be

evaluated at 500 hour intervals. At each inspection interval, remove the test specimens and clean them by gently flushing with running tap water and drying them with a stream of clean, dry compressed air. Rate, by visual estimation, the total percentage of white and red rust present. Record separately a rating for each of the following surfaces: bolt heads, bolt threads, nuts, washers, and total for all surfaces. If red rust is evident in only very small areas, indicate the number of “spots” and the surface location. Note the presence of any blistering on the fastener surfaces. Do not include surface on the back of the assembly in the rating. Photographically document the surface condition of each of the test specimens using the imaging system. The test shall continue until each specimen shows greater than five percent red corrosion (total), at which time the failed specimen is removed from the test.

In addition to corrosion evaluation, the assemblies shall be tested for “breaking torque” and “run-out torque”. At the conclusion of cyclic testing, each bolted set shall be disassembled using a torque measuring device. The “breaking torque” is defined as the minimum torque required to free the bolt/nut set and relieve the applied tension. The “run-out” torque shall be measured as the maximum torque necessary to completely run out the thread length and separate the bolt from the nut. Data shall be recorded for each bolt/nut set.

Rationale

Salt Spray testing on scribed flat panels is used only to gauge the relative corrosion protection of candidate coating systems. It is not an indicative of field performance or even of Salt Spray performance of coated fasteners. Salt Spray testing of coated fasteners also is not necessarily indicative of field performance, but is widely used in industry to measure and specify fastener coating performance.

Test Methodology

Parameters	• Test coupons and assemblies at a 15° angle • Temperature of exposed salt spray zone = 35 ± 1.7°C (95 ± 3°F) • Every 80 cm² horizontal area, two collectors gather 1.0-2.0 ml fog/hr. • 5% salt solution (5 ± 1 parts by weight of NaCl in 95 parts of water). • pH = 6.5 – 7.2 when atomized at 35°C (95°F)
Number and Type of Specimens per Coating System	1 ea. Assemblies A1.1,A2.1,A3.1,A1.1D,A2.1D,A3.1D, A1.3,A2.3,A3.3, A1.1D,A2.1D,A3.1D

Table 6: ASTM D1654-08 Corrosion Rating System

Representative Mean Creepage From Scribe		
Millimetres	Inches (Approximate)	Rating Number
Zero	0	10
Over 0 to 0.5	0 to 1/64	9
Over 0.5 to 1.0	1/64 to 1/32	8
Over 1.0 to 2.0	1/32 to 1/16	7
Over 2.0 to 3.0	1/16 to 1/8	6
Over 3.0 to 5.0	1/8 to 3/16	5
Over 5.0 to 7.0	3/16 to 1/4	4
Over 7.0 to 10.0	1/4 to 3/8	3
Over 10.0 to 13.0	3/8 to 1/2	2
Over 13.0 to 16.0	1/2 to 5/8	1
Over 16.0 to more	5/8 to more	0

Equipment and Instrumentation

- NSS (Fog) Chamber. This equipment shall consist of a heated fog chamber, a salt solution reservoir, a supply of conditioned (oil- and contaminant-free) compressed air, atomizing nozzles, and specimen supports.

- **Imaging System.** A means of visually recording corrosion effects on all tested specimens, such as a digital camera or scanner/software system.
- **Scribe Tool.** A very sharp knife, scribe, or other cutting device having a cutting edge (tip) angle between 15 and 30 degrees.
- **Straightedge.** Any straightedge of sufficient length to guide the scribing tool in a straight line across the specimen surface.
- **Air Source.** A source of clean, dry compressed air capable of delivering at least 10 cubic feet per minute (cfm) at 80 pounds per square inch (psi).
- **Air Gun and Guard.** An air dusting gun and nozzle combination to meet the specification in ASTM D1654. A guard to protect the operator, such as a sandblasting cabinet.
- **Scale.** A ruler with 1-mm (0.04") divisions.
- **Putty Knife.** Blunt-edged, 38 mm (1.5") wide.

Data Analysis

Report all information required in ASTM B117 and D1654, and include the images from the imaging system. Report the final corrosion test results and the specified interval visual observations. Ratings are based on condition of scribe, amount and size of undercutting, and number and size of face blisters. The rating system used to quantify results is frequency of blisters measured according to ASTM D 1654.

3.2.1 Cyclic Corrosion on Flat Panels (GMW 14872)

Test Description

This test method describes a field-correlated, laboratory corrosion test method for determining cosmetic corrosion performance that provides a combination of cyclic conditions (salt solution immersion, temperature, and humidity) to accelerate the corrosion process.

Operate the fog chamber for this test in accordance with GMW 14872 (*Accelerated Corrosion Test*). Utilize the Underbody mode of test cabinet operation, using four salt solution applications per 8-hour ambient cycle (see Figure 1).

Flat test panels shall be used for Section 3.2.1 as described in Table 5 (P1.1,P1.2,P2.1,P2.2,P3.1,P3.2). The number of test specimens depends on the number of cycles selected for the test exposure duration. Use reference coupons consisting of uncoated 25 x 51 x 3 mm (1" x 2" x 1/8") pieces of any alloy American Iron and Steel Institute (AISI) 1006 through 1010 steel to monitor the average general bare steel corrosion produced by the test environment. The coupon weight in milligrams shall be recorded and retained for future reference. The number of coupons also depends on the number of cycles selected for the test exposure duration. Each test specimen and reference coupon shall be permanently identified by stamping numbers onto the surface. Using test specimens incorporating the candidate, scribe an X scribe through the coating, making sure that the scribed line is all the way through the coating to the substrate. Place the scribed test specimens and reference coupons in the chamber, leaning at an angle of at most 15 degrees from the vertical with the scribed surface facing upwards. Prepare the salt solution per GMW 14872 and measure the pH prior to the start of the test and on a weekly basis thereafter. Do not attempt to adjust the pH. Clean the reference coupons (bare steel bars) thoroughly with the cleaning solution prior to placing them in the exposure chamber. Use test duration of 20, 40, 60, and 80 cycles. After initially weighing each reference coupon and test specimen, install both the reference coupons and test specimens in the exposure chamber. After every 20 cycles, remove two coupons and two test specimens. Weigh each reference coupon (after removal of the rust layers) and determine the average weight loss for that specific number of cycles. For the test specimens, record the scribe creepback values with respect to average, ASTM-D1654. For the interim creepback measurements, conduct them in a rinsed-only condition. At the final number of cycles, two sets of creepback values will be recorded – one set in a rinsed-only condition and one set after the scrape-and-tape process. At the conclusion of the exposure period (or interim period), remove the test specimens and rinse. Scrape the specimens' side-to-side with the putty knife at a 30-degree contact angle. Evaluate the creepage of the test specimens per the latest version of ASTM D1654. Rate

the corrosion or loss of coating extending from the scribe mark (using the worst case for the rinsed or scraped methods) and evaluate the unscribed areas for corrosion spots, blisters, and any other types of failure that may occur. Photographically document each of the test specimens and the reference coupons using the imaging system. Clean the reference coupons using a mild sand (or glass bead) blast to remove all corrosion by-products. Once they are clean, wipe the coupons with methanol and weigh to determine weight loss. Corrosion losses may also be expressed in terms of average corrosion rates from the weight loss, coupon area, test duration, and metal density by use of the calculation described in ASTM G1.

3.2.2 Cyclic Corrosion on Fastener Assemblies (GMW 14872)

Cyclic Corrosion testing shall be performed on five types of assemblies as described in Table 5.

Coated fasteners mounted in plastic (A1.1,A2.1,A3.1) with no subsequent CARC coating will show the relative corrosion performance of the coating systems without topcoat or the influence of any bimetallic contact. This same configuration is assembled using fasteners which have been damaged by the Drop Test as described in section 3.3 (A1.1D,A2.1D,A3.1D).

Coated fasteners mounted in a hot rolled steel plates (A1.3,A2.3,A3.3). The steel plates are precoated with Ecoat (Type 4) prior to assembly. After assembly, the front and back are coated with CARC primer and topcoat. This type of assembly is intended to mimic conditions in a service environment. . This same configuration is assembled using fasteners which have been damaged by the Drop Test as described in section 3.3 (A1.1D,A2.1D,A3.1D).

In addition, assemblies mounted in aluminum plates shall be tested for Galvanic Compatibility as required in Section 3.8 (A1.2,A2.2,A3.2) for a duration of 80 cycles. These shall be rated as described in Section 3.8 and are excluded from rating of the fastener corrosion.

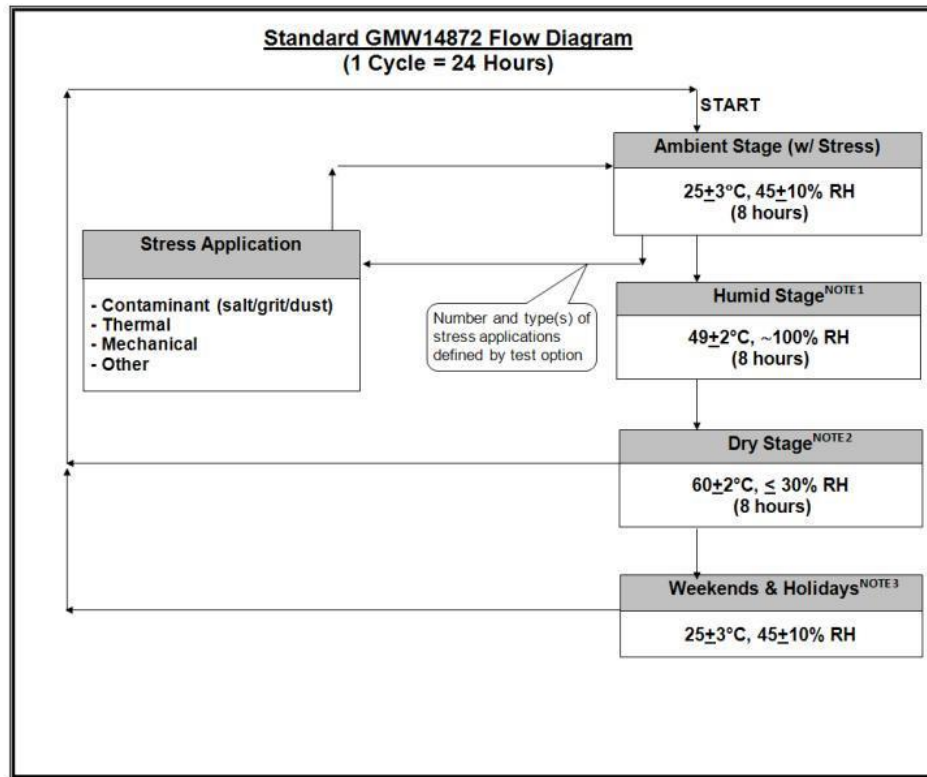
One of each type of assembly shall be tested for duration of 80 cycles, with evaluation at 20, 40, 60 and 80 cycles. The specimens shall be placed in the test chamber in the test chamber with the long aspect in the horizontal position and leaning at an angle of 15 degrees. Each assembly shall have a clear identifying mark. At each inspection interval, remove the test specimens and clean them by gently flushing with running tap water and drying them with a stream of clean, dry compressed air. Rate by visual estimation the total percentage of white and red rust present. Record separately a rating for each of the following surfaces: bolt heads, bolt threads, nuts, washers, and total for all surfaces. If red rust is evident in only very small areas, indicate the number of “spots” and the surface location. Note the presence of any blistering on the fastener surfaces. Do not include surface on the back of the assembly in the rating. Photographically document the surface condition of each of the test specimens using the imaging system. The test shall continue until each specimen shows greater than five percent red corrosion (total), at which time the failed specimen is removed from the test. Evaluate corrosion and blistering per the latest version of ASTM 1654.

In addition to corrosion evaluation, the assemblies shall be tested for “breaking torque” and “run-out torque”. At the conclusion of cyclic testing, each bolted set shall be disassembled using a torque measuring device. The “breaking torque” is defined as the minimum torque required to free the bolt/nut set and relieve the applied tension. The “run-out” torque shall be measured as the maximum torque necessary to completely run out the thread length and separate the bolt from the nut. Data shall be recorded for each bolt/nut set.

Rationale

The cyclic accelerated corrosion test on scribed, painted substrates is a key accelerated test to determine overall corrosion inhibition compared to controls. Testing at various cycles will provide the information necessary to compare the performance of the fastener coating systems to the baseline Cadmium plating.

Figure 3: GMW14872 Cycle Description



Note 1: The typical ramp time from the ambient stage to the humid stage is 1 h and is part of the 8 h humid stage

Note 2: The typical ramp time from the humid stage to the dry stage is 3 h and is part of the 8 h dry stage

Note 3: For extended down time, refer to 4.3.6 of test method

Test Methodology

Parameters	• Test Coupons at 15° angle • Up to 120 cycles. • 1 cycle: see Figure 1. • Fog humidity: per GM 4465P at $49 \pm 2^\circ\text{C}$. • Salt solution: 0.9% sodium chloride, 0.1% calcium chloride, 0.25% sodium bicarbonate; pH of 6 to 9. • Drying environment: $60 \pm 2^\circ\text{C}$, < 30% relative humidity (RH); Ambient environment: $25 \pm 2^\circ\text{C}$, 40-50% RH
Number and Type of Specimens	1 ea. Assemblies A1.1,A2.1,A3.1,A1.1D,A2.1D,A3.1D, A1.3,A2.3,A3.3, A1.3D,A2.3D,A3.3D, A1.2,A2.2,A3.2

Equipment and Instrumentation

- **Test Cabinet.** Test cabinet with the ability to obtain and maintain the required environmental conditions as specified in GMW14872.
- **Scribe Tool.** A very sharp knife, scribe, or other cutting device having a cutting edge (tip) angle between 15 and 30 degrees.

- Imaging System. A means of visually recording corrosion effects on all test specimens, such as a camera or scanner/software system.
- Air Source. A source of clean, dry compressed air capable of delivering at least 10 cfm at 80 psi.
- Scale. A ruler with 1-mm (0.04") divisions.
- Balance. A digital electronic balance capable of weighing up to 10,000 mg with an accuracy of $\pm 1\%$.
- Straightedge. Any straightedge of sufficient length to guide the scribing tool in a straight line.
- pH Meter. A meter to measure the pH of the salt solution prior to the start of the test and on a weekly basis thereafter.
- Putty Knife. Blunt-edged, 38 mm (1.5") wide.

Data Analysis

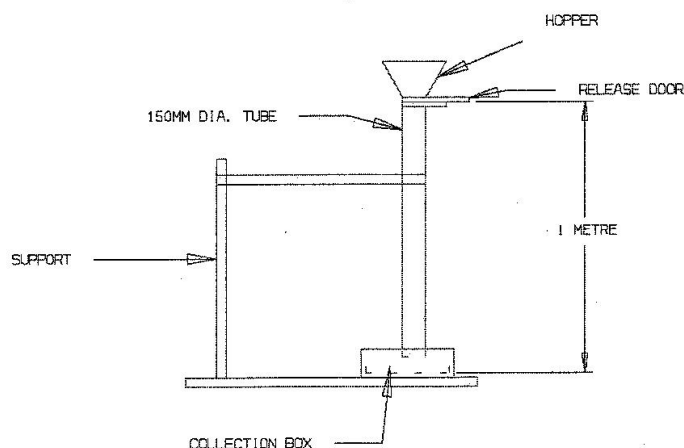
Report all information required as described above, including the photographs from the imaging system, and weight loss and/or corrosion rate of the reference coupons.

3.3 Drop Test

Test Description

The Drop Test is intended to provide guidance as to a fastener coating's ability to withstand damage from processing, shipping, and handling. The equipment consists of a round or square shaped hopper connected to a non-metallic tube of approximately 150 mm (six inches) diameter. A sliding release door is fitted between the hopper and the top of the tube (Figure 4). One kilogram (2.2 pounds) of coated fasteners is loaded into the hopper. (Nuts, bolts and washers shall not be mixed in a single drop batch.) The sliding trap door is opened allowing the test fasteners to drop 1 meter into a non-metallic collection box. The procedure is repeated three times. These fasteners are incorporated into test assemblies with a D designation as described in Table 5. The assemblies are placed in Salt Spray and Cyclic Corrosion testing as described in Sections 3.1.2 and 3.2.2. The results are compared to the analogous specimens which were not subjected to the Drop Test.

Figure 4 - Drop Test Apparatus



Rationale

This test is included to show relative resistance to process damage between the target coating systems. It is not intended to correlate with the actual degree or severity of damage from any specific process or handling scenario. It

is included for informational purposes and is not necessarily intended for development of acceptance criteria for any particular coating system.

3.4 Dry Tape Adhesion (ASTM D3359)

Test Description

This test method covers a procedure for establishing adequacy of intercoat and surface adhesion of an organic coating in ambient conditions by applying pressure sensitive tape over a scribed area of the coating. Perform this test in accordance with ASTM D 3359 (Standard Test Methods for Measuring Adhesion by Tape Test).

Prepare at least three test specimens for Performance Testing using 102 x 152 mm (4" x 6") test panels on Cold Rolled steel as described in Table 5 (P1.1,P1.2,P2.1,P2.2,P3.1,P3.2). Using test specimens incorporating the fastener coating systems and the referenced specification epoxy primers, measure the dry film thickness in at least five areas. Make cuts in the coating system per the latest version of ASTM D3359, "Standard Test Methods for Measuring Adhesion by Tape Test – Cross-Cut Tape Test." Remove two laps of tape and discard. Remove an additional length of tape and cut a piece approximately 76 mm (3") long. Place the center of the tape over the grid and smooth into place by firmly rubbing a pencil eraser over the area. Within 90 ± 30 seconds of tape application, remove the tape by holding the free end and rapidly pulling (not jerking) back upon itself at as close to an angle of 180 degrees as possible. Inspect the grid area for removal of coating from the substrate or from an underlying coating. Rate the adhesion in accordance with the latest version of ASTM D3359, Test Method B. If ratings differ by more than one rating unit, the results are considered suspect and three additional test specimens shall be prepared and the tests repeated. If applicable, use these latter ratings in the report.

Rationale

This test was identified as a performance requirement for the baseline pretreatment specifications TT-C-490 and MIL-DTL-5541 when applying specified primers. Loss of paint adhesion is the primary failure mode on ferrous substrates.

Test Methodology

Parameters	As defined in ASTM D 3359, test method B
Number and Type of Specimens per Coating System	Three each of P1.1,P1.2,P2.1,P2.2,P3.1,P3.2

Equipment and Instrumentation

- Cutting Tool. A very sharp razor blade, scalpel, knife, or other cutting device having a cutting edge (tip) angle between 15 and 30 degrees.
- Cutting Guide. Steel or other hard metal straightedge to ensure straight cuts.
- Rule. A steel rule graduated in 0.5-millimeter (mm) (0.02") increments for measuring individual cuts.
- Tape. 3M 250 Flatback Masking Tape manufactured by 3M. This tape was chosen for its performance over the MIL-DTL-64159 and MIL-DTL-53039 polymer bead versions of CARC. Care should be taken to use only tape within its reported shelf life. Utilizing the tape after the manufacturer's recommended storage may yield inaccurate results.
- Pencil with eraser. To be used to make sure the tape is firmly adhered.
- Illumination. A light source to determine whether the cuts have been made through the coating into the substrate.
- Dry Film Thickness Gage. A device to measure the thickness of the applied coating.

Data Analysis

Report all information per the latest version of ASTM D3359 Test Method B. In addition, report the average of the five dry film thickness measurements (as measured by thickness gauge).

3.5 Wet Tape Adhesion and Water Resistance

Test Description

This test method covers a procedure for establishing adequacy of intercoat and surface adhesion of an organic coating immersed in water by applying pressure sensitive tape over a scribed area of coating. The test also measures the coating's ability to resist penetration by water. Perform this test in accordance with Method 6301 of Fed-Std-141 (*Paint, Varnish, Lacquer and Related Materials; Methods of Inspection Sampling and Testing*) and is rated according to ASTM D 3359. Coated specimens shall show no wrinkling or blistering immediately after removal of the panel from the water. The CARC coatings shall be no more than slightly affected when examined 2 hours after removal. After 24 hours air drying, each test panel will be subjected to a crosshatch tape test. A crosshatch tool making eleven cuts 2mm apart will be used. All cuts should be through the coating and into the substrate, and no closer than 12 mm from any edge. Each line of the cross-hatch should be at least 1.5 inches in length. Immediately place a piece of tape over the incision parallel to the bottom edge of the panel, ensuring that the tape completely covers the "square" formed by the cross-hatch, and smooth out the tape by rolling a 3-lb. roller over it once. Remove the tape rapidly at approximately a 180-degree angle. Inspect the incision area for peel away. Loss of two or more complete squares shall constitute failure.

Rationale

This test was identified as a performance requirement for the baseline pretreatment specifications TT-C-490 and MIL-DTL-5541 when applying specified primers. Loss of paint adhesion is the primary failure mode on ferrous and aluminum substrates.

Test Methodology

Parameters	7 day cured CARC panels; 24 hour DI water immersion at room temperature
Number and Type of Specimens per Candidate Alternative	Three each of P1.1,P1.2,P2.1,P2.2,P3.1,P3.2

Equipment and Instrumentation

- 1-inch masking tape, 3M Company Type 250 only, less than 1 year old
- Cross-hatch cutter such as PA-2056 and PA-2053 available from Gardco
- 3-pound rubber covered roller

Data Analysis

Report all information per the latest version of ASTM D3359, Method A. Report also any delamination or blistering in areas away from the scribes.

3.6. Hydrogen Embrittlement

Test Description

This test method describes a procedure to evaluate the tendency of the fastener coating systems to embrittle steel by causing absorption of hydrogen into the steel crystal structure. The testing is conducted according to the latest version of ASTM F 519 Type 1a.2. The procedure involves the coating of standardized notched steel bars with the fastener coating systems. The specimens are then subjected to a tensile load for a specified period of time. Hydrogen embrittlement is evidenced in fracture of the sample during the test period. The three target coating systems, without subsequent CARC topcoat, as described in section 1.0 shall be tested.

Test Parameters:

Specimen Type	Type 1a.2 notched bar
Number of samples per coating system	4
Tensile Load	75% of stated tensile NFS
Load Duration	200 hours

Data Analysis

Report all information per the latest version of ASTM F 519 Section 12. Report must include sensitivity certification for the specimen lot tested.

Rationale

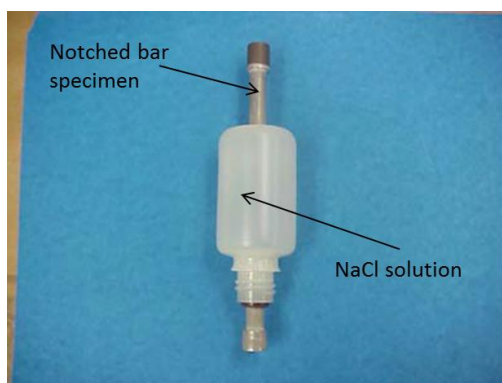
Hydrogen embrittlement testing is critical in ensuring that fastener coating systems do not compromise the strength and structural integrity of fasteners. It is especially critical for high strength fasteners such as Grade 8 and above.

3.7. In-Service Hydrogen Embrittlement

Test Description

In-service embrittlement testing describes a procedure to evaluate the tendency of the coating systems to induce hydrogen embrittlement under simulated service environment. The test is carried out according to the latest version of ASTM F 519 Annex 5 using the parameters listed below. The method and parameters of testing are the same as described in Section 3.6.1, with the addition of an initial immersion of the notch in a 3% solution of sodium chloride (NaCl). The immersed specimen is subjected to a tensile pre-load for the specified time, after which the sample is rinsed, dried and tested as in section 3.6.1. The NaCl solution is be encased around the notch of Type 1a.2 specimen after application of the fastener coating systems. Figure 5 shows an example of a possible immersion setup.

Figure 5 - Notched Bar - Solution Immersion Example



Test Parameters:

Specimen Type	Type 1a.2 notched bar
Number of samples per coating system	4
Preload Conditions:	
Immersion Solution	3% by weight sodium chloride in deionized water
Immersion Temperature	68-86°F (20-30°C)
Immersion load	45% of NFS
Preload Duration	150 Hours
Neutralization	Deionized water rinse and air dry

Post Immersion Test Conditions:	
Tensile Load	75% of stated tensile NFS
Load Duration	200 hours

Data Analysis

Report all information per the latest version of ASTM F 519 Section A5.6.1.2 and A5.6.2.

Rationale

The target coating systems, including the cadmium plating control coating, are all based on metal content which is sacrificial in corrosion behavior when in contact with the steel substrate. Sacrificial, or cathodic, protection is an electrochemical process which has potential for hydrogen gas generation. It can be anticipated that there is potential for steel embrittlement by such coatings in corrosive environments. It should be noted that In-Service embrittlement testing parameters are not widely standardized. The results and data are not well correlated with field exposure. The testing is included here for information purposes and is not necessarily adequate for developing acceptance criteria of candidate coating systems.

3.8 Torque / Tension / COF

This method allows determination of the tightening characteristics of threaded fasteners and related parts. The test shall be carried out according to SAE/USCAR-11 except the tightening speed shall be 30 +/- 3 RPM. The testing shall be conducted using surrogate bolt (SB1) M10x1.5 40mm Grade 9.8 and the corresponding M10 nut and control washer as specified in GMW3359. In addition, thread run-in torque shall be measured using bolt/nut/washer combinations, all of which are coated with the candidate coatings herein.

Surrogate bolts coated with the three coating system types shall be tested in combination with standard zinc plated nuts and washers (per GMW3359). Surrogate nuts coated with each coating system shall be tested in combination with cadmium plated bolts and washers. In addition, a combination of surrogate bolt, surrogate nut, and washer, all coated with the same coating type shall be tested.

A tightening torque is steadily applied to a bolt/nut or screw/nut assembly to generate a clamp force, and to measure and/or determine one or more of the tightening characteristics, which can include torque coefficient, coefficient of total friction, coefficient of friction between threads, coefficient of friction between bearing surfaces, yield clamp force, yield tightening torque, rotation angle and ultimate clamp force. In the range of elastic deformation, a linear relationship is assumed between torque and clamp force. These quantities are calculated using methods described in ISO 16047.

Part Combinations for Torque/Tension/COF analysis (10 sets each):

Test Bolt	Test Nut	Test Washer	Description
SB1	CN1	CW1	Bolt with Type 1, plated nut and bare washer
SB2	CN1	CW1	Bolt with Type 2, plated nut and bare washer
SB3	CN1	CW1	Bolt with Type 3, plated nut and bare washer
SB3	SN1	CW1	Coated Nut Type 1, Cad bolt, bare washer
SB3	SN2	CW1	Coated Nut Type 1, Cad bolt, bare washer
SB3	SN3	CW1	Coated Nut Type 1, Cad bolt, bare washer
SB1	SN1	SW1	Type 1 coated bolt, nut, and washer
SB2	SN2	SW2	Type 1 coated bolt, nut, and washer
SB3	SN3	SW3	Type 1 coated bolt, nut, and washer
SB1A	CN1	CW1	Bolt with Type 1A, plated nut and bare washer
SB2A	CN1	CW1	Bolt with Type 2A, plated nut and bare washer
SB3A	CN1	CW1	Bolt with Type 3A, plated nut and bare washer

Data Analysis

A quantity of ten parts shall be tested for each coating system. The data shall be used to describe the friction characteristics of the coating systems. It is intended to provide guidance for end users in determining suitability of a particular finish in various applications. The test is also intended to the effect of the coatings on the thread gauge tolerances. This will allow judgments to be made concerning the required size and geometry limitations and requirements for meeting typical performance properties. Torque / Tension tables may be generated from the tensile test curves generated.

3.9 Galvanic Compatibility

Test Description

This method shows the galvanic corrosion performance of fasteners with the target coating systems against an aluminum surface. Assemblies (A1.2,A2.2,A3.2) are assembled by attaching the bolt-washer-nut sets directly into untreated 2024 aluminum mounting panels. The assemblies are then exposed to GMW14872 cyclic corrosion test for 60 cycles.

Data Analysis

After testing, the fasteners are removed from the mounting panel, and the area under the test washer shall be examined and photographed. Galvanic incompatibility is evidenced by pitting, exfoliation and localized corrosion in the vicinity of the fastener. One assembly shall be tested for each coating system.

Rational

Steel fasteners are used in wide variety of joining applications. In addition to steel, joining surfaces may consist of aluminum. This method tests the ability of the coating systems to insulate the steel fastener from the aluminum surface, thereby preventing galvanic incompatibility and corrosion.

3.10. Outdoor Coastal Exposure

Coated specimens shall be exposed to sea coat environment to provide addition field data. The exposure shall be conducted at the Canaveral Air Force Station, Cap Canaveral, Florida. Exposure specimens shall include full system coated flat panels and assemblies; 3 each P1.2, P2.2, P3.2, and 1 each A1.3, A2.3, A3.3. The specimens shall be exposed for a total duration of two years with visual and photographic examination every six months. For assemblies, rate by visual estimation of the total percentage of white and red rust present. Record separately a rating for each of the following surfaces: bolt heads, bolt threads, nuts, washers, and total for all surfaces. If red rust is evident in only very small areas, indicate the number of “spots” and the surface location. Note the presence of any blistering on the fastener surfaces. Do not include surface on the back of the assembly in the rating. Photographically document the surface condition of each of the test specimens using an appropriate imaging system. Flat Panels are scribed, exposed, and evaluated in the same manner as described in section 3.2.1.

At the conclusion of this test, the assemblies will be disassembled using a torque recoding device. This will generate tensile curves indicating breaking torque and run-out removal torque.

Further details of the exact mounting, location, and orientation of the test specimens will be added hereto when available.

3.11 Field Exposure, On-Vehicle (ASTM D 1654)

Test Description

This test method describes a basic procedure for conducting on-vehicle testing of candidates. This may be performed by selective replacement of an appropriate representative fastener or group of fasteners on a vehicle incorporating the coating systems. The vehicle shall be a military ground vehicle which will be in service during the test period. This method describes a procedure for monitoring of coated fastener performance when applied to specific target areas of an operational platform as compared to the baseline system. The coating system's ability to maintain adhesion to the substrate after exposure to field conditions and to prevent corrosion will be analyzed.

At a minimum, the process shall be conducted to replace a fastener or set of fasteners comprising a bolted joint of the vehicle in accordance with the suggested finishing parameters and the controls established by the CARC applications specification MIL-DTL-53072. Identify target components of the platform (this will depend on agreements among programs, depot or logistics center personnel, manufacturers, and the principal investigator) which will observe a significant amount of operational exposure to the environment, representative of the demonstration site. Representative fasteners will be coated in accordance with manufacturers recommended specifications finishing parameters. The fasteners will be evaluated during periodic inspections by visual comparison with the base vehicle or control samples attached to the vehicle. Inspection of the demonstration platform or target areas of the demonstration platform shall be at approximate intervals of three months, six months, one year, and two years. The Society for Protective Coatings SSPC-VIS-2 "Standard Method for Evaluating the Degree of Rusting on Painted Steel Surfaces" shall be used for evaluating component substrates and control samples. The success criteria for field testing will be performance greater than or equal to the base vehicle (baseline) or control sample.

At the conclusion of this test, the assemblies will be disassembled using a torque recoding device. This will generate tensile curves indicating breaking torque and run-out removal torque.

Full details of the field exposure testing will be available in the Demonstration Plan document, in which this JTP document will comprise an Appendix.

Rationale

Fastener coatings must perform successfully in the field before they are transitioned to the end users via revisions of technical manuals, military specifications and qualified products databases.

Test Methodology

Parameters	Steel bolts, nuts, and washers.
Number and Type of Specimens per Candidate Alternative	Number of platforms required is determined by cognizant authority
Trials per specimen	1
Experimental Control Specimens	Fasteners coated with CD/Cr+6 plating

Equipment and Instrumentation

Military Ground Vehicle. A vehicle used for standard deployment.

Data Analysis

After a predetermined exposure agreed upon by the stakeholders, the affected vehicles/parts shall be evaluated for coating adhesion and corrosion resistance in accordance with SSPC-VIS-2, MIL-DTL-53072 and ASTM D 1654. Breaking torque and ease of disassembly shall also be assessed.

4.0 Mixed Substrate Corrosion Testing

This testing was added to provide supplemental information outside of the performance criteria of the original JTP.

It is necessary to test the new technology bolts mated to old technology (phosphated or Cd plated) nuts. There could be numerous applications, especially in legacy systems, where the new bolts might be used to secure components to captive nuts, tapped holes, and similar arrangements. With mixed fasteners the new bolts should not cause damage or corrosion in the existing system or vice versa.

We will perform limited testing of assemblies with different combinations of bolt and nut coatings. The same nut and bolt types will be used as described in Table 5. In addition to the three coating types being tested in the body of the JTP, we will include bare, oily steel fasteners with no additional coating. This is included as a negative control as well as to simulate assembly situations where captive nuts are present or legacy bare steel fasteners are used. The combinations are described in Table 7.

The Assemblies will be constructed as in Figures 1 and 2. The mounting plates for each assembly will be of Type MP3 as described in Table 4 with coating Type 4 consisting of zinc phosphate and electrodeposition topcoat. The assembled panels will be coated, front and back, with a CARC paint system as described in Section 1.0 as Type 5. The installation torque for all will be 25 ft.lbs.

The completed assemblies will be tested as follows:

1. Corrosion – Exposure in GMW14872 cyclic corrosion test as described in Section 3.2.2.
2. Breaking torque – At the conclusion of corrosion testing (80 cycles or failure) the maximum torque to break the fasteners free and completely disassemble will be recorded.

Table 7 – Mixed Substrate Matrix

Bolt		Nut	
Type	Coating	Type	Coating
B1	Type 1 (ZR/EC)	NO1	Type 1 (ZR/EC)
		NO2	Type 2 (HPAP/EC)
		N3	Cadmium
		N (bare)	Bare (phos and oil)
B2	Type 2 (HPAP/EC)	NO1	Type 1 (ZR/EC)
		NO2	Type 2 (HPAP/EC)
		N3	Cadmium
		N (bare)	Bare (phos and oil)
B3	Type 3 (Cd/Cr)	NO1	Type 1 (ZR/EC)
		NO2	Type 2 (HPAP/EC)
		N3	Cadmium
		N (bare)	Bare (phos and oil)
B	Bare (phos and oil)	NO1	Type 1 (ZR/EC)
		NO2	Type 2 (HPAP/EC)
		N3	Cadmium
		N (bare)	Bare with oil

5.0 REFERENCE DOCUMENTS

Table 8: Reference Documents

Reference Document	Title	Date	Applicable Sections of Reference Document	JTP Test	JTP Section
ASTM B 117	Standard Practice for Operating Salt Spray (Fog) Apparatus	2007	All	Neutral Salt Fog for Flat Panels	3.1
GMW 14872	Cyclic Corrosion Laboratory Test	2010	All	Cyclic Corrosion on Flat Panels	3.2, 3.9
GMW 3359	Non-Electrolytically Applied Zinc Rich Coating	2007	All	Torque/Tension	3.8
ASTM D 1654	Standard Test Method for Evaluation of Painted or Coated Specimens Subjected to Corrosive Environments	2008	All	Neutral Salt Fog for Flat Panels; Cyclic Corrosion on Flat Panels; Outdoor Exposure; Field Exposure,	3.1, 3.2, 3.10, 3.11
ASTM D 3359	Standard Test Methods for Measuring Adhesion by Tape Test	2009	All	Dry Tape Adhesion; Wet Tape Adhesion and Water Resistance	3.4, 3.5
FED-STD-141	Paint, Varnish, Lacquer and Related Materials; Methods of Inspection Sampling and Testing	1986	Method 6301	Wet Tape Adhesion and Water Resistance	3.5
MIL-DTL-53072	Chemical Agent Resistant Coating (CARC) System Application Procedures And Quality Control Inspection	2011	All	All application and performance testing requirements	1.0
SAE/USCAR 10	Test for Evaluating the Torque-Tension Relationship of External and Internal Metric Threaded Fasteners	2007	All	Torque/Tension COF	3.8
SAE/USCAR 11	Torque-Tension Testing and Evaluation o Fastener Finishes	2007	All	Torque/Tension COF	3.8
SAE/USCAR 32	New Finish Development Document	2007	3.7, 3.19	Galvanic Compatibility, Drop Damage Test	3.3, 3.9
SSPC-VIS-2,	Standard Method of Evaluating Degree of Rusting on Painted Steel Surfaces	2008	2000	Outdoor Exposure, Field Exposure, On-Vehicle	3.10, 3.11
ASTM F 519	Standard Test Method for Mechanical Hydrogen Embrittlement Evaluation of Plating/Coating Processes and Service Environments	2012	1a.2 Annex 5	Hydrogen Embrittlement In Service Hydrogen Embrittlement	3.6, 3.7

Appendix A

Participating Organizations and Representatives

Organization	Representative	Type
PPG Industries, Inc	Matt Scott (412) 492-5594	Contractor
PPG Industries, Inc	Larry Fitzgerald (412) 492-5396	Contractor
Army Research Laboratory (ARL)	Fred Lafferman (410) 306-1520	Government
Tank and Automotive Research, Development, and Engineering Center (TARDEC)	Daniel Nymberg (586) 282-7445	Government
Naval Surface Warfare Center - Carderock Division (NSWCCD)	Andrew Sheetz (301) 227-5037	Government
Army Aviation and Missile Command (AMCOM)	Mark Feathers (256) 842-7355	Government
Elzly Corporation	John Repp (609) 545-8751	Contractor

APPENDIX B DEMONSTRATION PLAN

Distribution C – not available in public version of the final report

To access this Appendix, posted separately, please visit the DTIC website.

APPENDIX C TECHNOLOGY IMPLEMENTATION REPORT



Bringing Fastener Coatings into the Defense Market



By: Ralph Alexander, Keith Legg

Date: August 1, 2017

Corrdesa Report Number: R17_004_02



REVISION CONTROL PAGE

APPROVAL

	Name	Signature	Date
Approved	Keith Legg		8/2/17
Approved	Alan Rose		8/2/17

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EXECUTIVE SUMMARY

This report is intended to assist PPG with introducing their new fastener coatings into the defense market. It is the result of evaluations of documents and databases, together with discussions with engineers involved in the area.

Our primary conclusion is that four main approaches should be used simultaneously:

1. OEMs: BAE Land Systems would be the best manufacturer to approach initially. Jim Dorsch (James.Dorsch@baesystems.com) and Peter Wan (peter.wan@baesystems.com) at BAE are the two principal engineers who should be approached to discuss the performance data for the PPG coatings. Jim Dorsch has told us that BAE Land Systems is looking for fastener coatings with better endurance than the existing dip-spin Magni and Geomet coatings.
2. TACOM Program Managers: Following a recommendation from Fred Lafferman (fred.l.lafferman@us.army.mil), the various TACOM program managers for the different vehicle weapon systems should be identified and approached, paying special attention to new programs.
3. DLA: Since the MMPV has already been moved to Magni-coated fasteners, these fasteners must be available through DLA for depot rework, unless the depots are simply replacing them with standard Cd-plated alternatives, which would be readily available at the depots. Letterkenny should be approached to determine what fasteners are currently being used on the MMPV, and what the NSNs (National Stock Numbers) are.
4. TT-C-490: TT-C-490 is intended to become the primary Army specification for coatings. Getting the coating into TT-C-490 should be discussed with the owner, John Escarsega (john.a.escarsega@us.army.mil) and Tom Braswell (Thomas.braswell2.civ@mail.mil), the Team Lead for this specification.

Other approaches are suggested, but they are of secondary importance.



1. Specification and usage of fasteners in defense

Under funding from SERDP-ESTCP, PPG has developed a new fastener coating system to replace chromated Cd on military fasteners. This report was assembled from a combination of telephone interviews with industry and DoD engineers, and evaluations of extensive documents and briefings, many of which are available on the ASETSDefense database at <http://db2.asetsdefense.org/fmi/webd/#Surface%20Engineering>.

At the present time the only major route into the military supply chain for polymer-coated fasteners is through their specification by OEMs. Only then, when the same fastening system is required by depots, will these types of fasteners be carried by DLA and GSA. A search of the DLA [Qualified Products Database](#) does not bring up any of today's common fastener dip-spin coatings (Magni, Geomet, etc.) or coating manufacturers (Magni, NOF, Metal Improvement, etc.).

Fasteners are primarily specified by OEMs and their supply chains. Typically the OEMs will decide what types of finishes to use dependent on the requirements of the specific weapon system they are building. They then flow down these requirements to their supply chain. DoD weapon system contracts are increasingly requiring that OEMs avoid use of hexavalent chrome either in the original system or in sustainment. The primary guiding document for this is the "Young Memo" which was issued as a DFARS modification¹, which states:

"223.7303 Prohibition. (a) Except as provided in 223.7304 and 223.7305, no contract may include a specification or standard that results in a deliverable or construction material containing more than 0.1 percent hexavalent chromium by weight in any homogeneous material in the deliverable or construction material where proven substitutes are available that provide acceptable performance for the application."

But the regulation also states:

"Homogeneous material does not include conversion coatings that chemically modify the substrate"

This regulation does not require the elimination of hexavalent chromium, but it does mean that any OEM deciding to use it must justify the use. Note that a major loophole is the statement that it does not include conversion coatings (such as chromated aluminum or zinc and cadmium plate used on screws). This means in effect that it is primarily directed at chromated paints, primers, sealers etc. Nevertheless, this rule and the general concern over Cr6 has driven most new weapon system contracts to require that OEMs eliminate Cr6 wherever possible, although there are usually waivers to permit its use if there are no viable alternatives.

With certain exceptions (e.g. where military organizations themselves build equipment) fastening systems are almost always specified by the OEM. Fasteners are then ordered for sustainment depots following the OEM requirements of the weapon system. At the present time metal-pigmented dip-spin coated fasteners are used on military vehicles but are, as far as we know, not used on aircraft. The reason for this is primarily a concern over adequate conductivity in the event of lightning strikes on aircraft.

However, there is an interesting wrinkle now emerging in sustainment of military aircraft. The use of metal-pigmented coatings is becoming accepted for the outer mold line OML of aircraft as a result of extensive development, beach exposure testing, and flight testing. USAF has carried out very extensive testing on Mg-rich primers and is moving to adopt them into the fleet in place of chromated primer.. At the same time NAVAIR has developed a new generation of Al-rich primers which appear to offer very substantial benefits in preventing pitting corrosion in aluminum panels and airframes. Given that most OML fasteners are wet-installed (ie dipped in primer before installation in order to prevent water ingress), it would seem to be a fairly short step to consider the use of Al- or Mg-rich primers for wet-install, and therefore another relatively small step to consider the same materials for dip-spin coated fasteners (although quite probably without an outermost, insulating, friction-modifying layer).

1.1. DoD specification methods

1.1.1. Spec by drawing

Because of the difficulty of developing a spec for a process or material, DoD organizations frequently specify it via a drawing, as Dave Frederick has done for ZnNi on landing gear at Hill AFB². Similarly, Rock Island Arsenal



has implemented Magni 575N dip-spin coated fasteners via Drawing # RIA153105 (see Section 2.2.1). This is one way into the system that circumvents the complex DoD specification system. But it requires a DoD engineer sufficiently interested in the technology to qualify it and put it on a drawing.

1.1.2. Mil Specifications

Military specifications are of course the traditional way that DoD specifies everything, including coatings and fasteners. There are a very large number of fastener specifications, most of which refer to QQ-P-416 (Cd plating) or QQ-Z-325 (Zn plating). At this point there are no specs for metal-rich organic fastener coatings.

The Army's overarching coating specification is TT-C-490, which is owned by ARL. The process owner is John Escarsega of the Army Research Lab (john.a.escarsega@us.army.mil). At this point the spec is primarily concerned with pretreats, but John is revitalizing it as the primary spec for Army coatings of all types, as discussed in the 2011 ASETSDefense Workshop³. Therefore it is almost certain that sooner or later fastener coatings of the type developed by PPG will need to be included in this spec, and the PPG coating will need to be on the QPL for this spec. The Army Team Lead for this spec is Tom Braswell (Thomas.braswell2.civ@mail.mil). John Escarsega intends to encompass all metal-filled primers in a single specification (Type VIII). Logically, therefore he may be willing to do the same with other metal-filled coatings. We have e-mailed John on this, but have not yet received a reply.

1.1.3. Commercial specs

It is common for DoD to turn to commercial specs when there are no Mil Specs. There is a commercial specification for dip-spin and similar pigmented polymer coatings on fasteners:

[ASTM F2833-11 Standard Specification for Corrosion Protective Fastener Coatings with Zinc Rich Base Coat and Aluminum Organic/Inorganic Type](#)

This is a rather poor specification since, instead of being generic, it is written to fit one manufacturer's (Magni's) coating design of a Zn-rich basecoat and Al-rich topcoat.



2. Previously implemented fastener changes

2.1. BAE Land Systems (Jim Dorsch)

BAE Land Systems was one of the first OEMs to adopt Cd alternative coatings. They adopted Magni 565 Al-rich epoxy dip spin coating for the MMPV as part of their BAE Combat Systems “Clean Hardware” Initiative. See Appendix A for BAE presentation, also available on-line at

http://www.asetsdefense.org/2010_vehicleworkshop.aspx

2.1.1. Qualification method

The Magni 565 coated fasteners were qualified by extensive testing of several alternative coating methods. ARL carried out a test program on several coatings, and ranked them as follows:

Final performance ranking:

1. Magni 565
2. Magni 594
3. Alumiplate
4. Hex Chrome Zinc plate
5. Trivalent Chrome Zinc

2.1.2. Implementation method

As the OEM, BAE Land Systems was able to implement on one of their own production vehicles⁴. The vehicle chosen was the Medium Mine Protected Vehicle (MMPV) Panther (Figure 1), an engineering ordnance disposal vehicle based on the US Army MRAP (Mine Resistant Ambush Protected) vehicle.

Following the test program on several different fastener coatings, BAE settled on Magni 565, and their fastener supplier, Military & Commercial Fasteners, assisted in procuring the coatings. BAE developed a base drawing (# 3000000) and then created one drawing for each fastener family, referred to this base. Figure 2 is an example of one of the fastener drawings. **They took this approach so that they can easily add or change coatings as the technology matures, or as better coatings become available, by adding them to the base drawing, in which case they would then be carried into all of the drawings that reference it.**



Figure 1. BAE Land Systems MMPV Panther.

Since this vehicle was already in production it was necessary to clear the production line of Cd plated fasteners. To accomplish this BAE carried out the change over a single weekend. They removed all fastener hardware from their Letterkenny plant, where most of the assembly took place, and substituted the dip-spin coated hardware. On Monday morning all of the assembly technicians were retrained on installing the new hardware. The process went smoothly for the most part – the new fasteners were drop-in replacements, although small threads were a little more difficult to start. The only other significant issue was with poor grounding in some locations, which was fixed by moving the ground strap.

The primary engineers driving this work at BAE Land Systems are Jim Dorsch (James.Dorsch@baesystems.com) and Peter Wan (peter.wan@baesystems.com).

2.2. US Army

The US Army is the only defense organization that has looked closely at polymer-coated fasteners and adopted them on some systems. Army contracts are mostly performance-based. The advantage of this is that the vendor only has to show that the fastener performs the same as the existing fastener (whether that is Cd plated, Zn plated, dip-spin or e-coated).

Carl Handsy at TACOM (now retired) took the view that the best approach for replacing Zn and Cd was a single metallic coating, and the best option for that from his testing was aluminum. Therefore he developed a significant amount of testing on AlumiPlate electrodeposited aluminum. Although in many tests the AlumiPlate coatings perform best, the fact that AlumiPlate is a sole-source with limited production capacity makes wide adoption of the process very problematic. Dan Nymberg is currently the main fastener engineer at TACOM, and is on the project team for WP-201315, developing the new PPG coatings.



2.2.1. Rock Island Arsenal

SUGGESTED SOURCE(S) OF SUPPLY				REVISIONS			
PART NUMBER	VENDOR	CAGE CODE	VENDOR ITEM DESCRIPTION	REV	ZONE	DATE	APPROVED
RIA153099	RIE COATINGS 221 LOGEAVIS ST. P.O. BOX 350 EDEN VALLEY, MN 55329-1646 PH. 320-453-8311	OZDN7	MAGNI 575N, BLACK, .20 COEFFICIENT OF FRICTION				

NOTES:

1. APPLICABLE STANDARDS/SPECIFICATIONS:
ASME Y14.24
ASME Y14.100
ASME Y14.5M-1994
2. IDENTIFICATION OF THE "SUGGESTED SOURCE(S) OF SUPPLY" HEREON IS NOT TO BE CONSTRUED AS A GUARANTEE OF PRESENT OR CONTINUED AVAILABILITY AS A SOURCE OF SUPPLY FOR THE ITEM(S).

CAD MAINTAINED. CHANGES SHALL BE INCORPORATED BY THE DESIGN ACTIVITY.

PURCHASED ITEM DESCRIPTION		
FIELD	FIELD NAME	FIELD VALUE
1	COATING TYPE	DUPLEX FASTENER COATING
2	BASECOAT	INORGANIC, ZINC RICH, DARK GRAY
3	TOP COAT	ALUMINUM-RICH ORGANIC TOPCOAT, W/ TEFLON, COLOR: BLACK
4	SALT SPRAY (AW SAE/USCAR-1)	1000 HRS.
5	COATING THICKNESS	DIP SPIN- .4 MIL TO .7 MIL, SPRAY .75 TO 1.25 MIL
6	COEFFICIENT OF FRICTION	.20 (AW DIN 946, ±.03)
7	FINISH PERFORMANCE	1AW FORD MOTOR CO. WSS-M2IP37-A1
8	QUALIFICATION TESTING	CERTIFICATION OF COMPLIANCE WITH ORDNANCE DRAWING 12469122 REQUIRED
9	SPECIAL REQUIREMENT	COATING APPLICATION MUST NOT INCLUDE THE FOLLOWING PROCESSES: ELECTROLYTIC APPLICATION OF UNDER/TOP COATINGS, ACID CLEANING, DESCALING, OR ANY OTHER PROCESS THAT COULD CAUSE ATOMIC HYDROGEN TO BE ABSORBED INTO THE FASTENER (HYDROGEN EMBRITTLEMENT)

DISTRIBUTION STATEMENT A
THIS IS APPROVED FOR PUBLIC RELEASE; DISTRIBUTION IS UNLIMITED.

INTERPRET DRAWING IN ACCORDANCE WITH STANDARDS PRESCRIBED BY MIL-STD-100		MECHANICAL PROPERTIES		TOLERANCES UNLESS OTHERWISE SPECIFIED		CONTRACT NO.		U.S. ARMY / ROCK ISLAND ARSENAL ROCK ISLAND ARSENAL AND TECHNOLOGY CENTER ROCK ISLAND, ILLINOIS 61286-5000	
MARKING REQUIREMENTS PER MIL-STD-130	VS MIN			ANGLES: 1		DATE	122809	FRS DUPLEX FASTENER COATING SIZE: C 19204 DRAWING NO. RIA153105 SCALE: NA SHEET 1 OF 1	
☒ DO NOT APPLY MARKING	VS MAX			3 PLACE DECIMALS & 3 PLACE DECIMALS &		PREPARED	DATE		
DO APPLY:	EL 2			FILETS: 1		DRAWN	DATE		
19204-MFR-19204	RA			FINISH: 1		DESIGN APPROVAL			
METHOD:	PH			MATERIAL:					
SIZE:				RIA149000	FRS				
				NEXT ASSY:	USED ON:				
				APPLICATION:					
				FINAL PROTECTIVE FINISH:					

Figure 2. Drawing for Magni 575N coated fasteners for US Army FRS.

Rock Island Arsenal manufactures a vehicle, the Forward Repair System (Figure 3), used for field repair of Army assets. They have implemented Magni 575N dip-spin coated fasteners on this system via Drawing # RIA153105 (Figure 3).

Note that this is a very low-volume application.



Figure 3. US Army Forward Repair System, manufactured by Rock Island Arsenal.



3. Market needs and technical requirements for military fasteners

Jim Dorsch at BAE Systems sees definite potential for a military fastener coating with better durability than metal-filled polymer Magni and Geomet coatings – the coatings that BAE has used to replace chromate-converted Cd plating in some of their vehicle systems. He made the point that fasteners in military vehicles are mostly external, and exposed to the environment far more than in automotive applications, where fasteners are often not even visible.

Magni and Geomet coatings are now used extensively on cars and trucks for their ability to meet current regulations for industrial coatings, which exclude toxic and environmentally unfriendly materials such as cadmium and hexavalent chromium. However, Magni and Geomet coatings are not robust enough to stand up to the arduous conditions encountered by military vehicles over prolonged periods that include exposure to salt water, sea air and temperature extremes. The typical B117 salt spray resistance of Magni 565 and 575 coatings is <1000 hours; Geomet coatings are similar. The much higher corrosion resistance of the PPG coating, showing less than 5% red rust after 3000 hrs of B117 salt spray, will be a distinct advantage over Magni and Geomet in military applications, especially if the coating cost is only 30% higher than Cr⁶⁺-converted Cd as PPG estimates.⁵

The K value of the PPG coating appears to be comparable to those for typical Magni and Geomet coatings, which are lower than those for alternative Zn or Zn/Ni coatings. According to the PPG SERDP report, the coefficient of friction determined by torque-tension testing on M10 bolts for the PPG dip-spin + E-Coat coating is 0.13 (torque 48 N.m).⁶ A coefficient of friction of 0.13 on M10 bolts corresponds to a coefficient of torque (K value) of approximately 0.17.⁷ The K values for Magni 565 and Magni 575 coatings, used on the Humvee, are both 0.13, the value for Geomet L is 0.15, and that for Cd plating is 0.19.⁸ If the K values for other fastener sizes are, like these numbers for M10 bolts, closer than either Magni or Geomet to the Cd-plate K value, torque-tension should not be an issue for the PPG coating.

However, as Jim Dorsch pointed out, the **thickness** of the PPG coating may present a problem in maintaining thread dimensions on smaller fasteners. The combined thickness of PPG's dip-spin + E-Coat coating is 0.55-0.95 mils,⁹ slightly higher than the range of 0.5-0.8 mils for Magni 565 and Magni 575,¹⁰ and much thicker than Geomet coatings that do not exceed 0.5 mils⁷. We have seen this issue in coatings for commercial products, where the specification has had to be changed to accommodate thicker coatings or different K values. One must pay special attention to thread accuracy requirements and the impact of possible changes in thread crown and root dimensions.



4. Requirements for DoD coating adoption

In order to have a new coating for military vehicle fasteners, with a new specification, adopted by DoD, ARL's Fred Lafferman suggested three entities that need to be contacted. In order of importance, these are:

1. The TACOM Program Managers (PMs) or Program Executive Officers (PEOs) for the various vehicles involved. As there are likely to be multiple vehicles and each PEO oversees 4 or 5 PMs, it probably makes the most sense for PPG to approach PEOs. From a practical viewpoint, there are fewer PEOs than contractors to deal with.
2. Contractors (OEMs). As we have noted in Section 1, it is OEMs who put together the drawings for a new finish on a part such as fasteners; the coating requirement itself is usually spelled out in the contract, not in the drawings. For example, Humvee manufacturer AM General assembled the drawings for the Magni 565 and Magni 575 coatings on new vehicles; Abrams tank manufacturer General Dynamics Land Systems did the same for Zn plating. Once the drawings are submitted to a stakeholder such as TARDEC, TARDEC allocates a part number – from which the DLA later assigns an NSN. Fred noted that PPG already has a good relationship with TARDEC. As mentioned previously, Dan Nymberg is on the PPG Team, which should be very helpful in navigating TACOM.
3. Depot commanders. Working top down at each depot, commanders could be briefed on the application(s) proposed for vehicles under their command.

Both Fred Lafferman and Dan Nymberg at TARDEC, who used to work in the automotive industry where fastener volumes are in the millions, emphasized that whatever route is followed for coating adoption, it will be a slow process since quantities of fasteners for military vehicles are small.



5. Requirements for navigating the DoD acquisition system

Fred Tramontin at the DLA told Rowan that the starting point in the DoD procurement system is the Federal Supply Class (FSC) for the part. Many Cd plated fasteners are in FSC 5305 and 5306. In the case of PPG's coating, (rather than a coated fastener) the FSC would probably be 8010 (paints), 8030 (preservative and sealing compounds) and/or 8040 (adhesives). Normally, the FSC is associated with a Mil Spec(s). If no Mil Specs exist yet, as for the PPG coating, the appropriate FSC is usually identified from the established Mil Specs for the existing Cd/Cr coating.

The appropriate FSC leads the prospective vendor to one or more Inventory Control Points (ICPs) in the supply system for the fasteners to be used in the cited application and/or for the coatings associated with the application. It is the ICPs that enable procurement.

BAE's Jim Dorsch had an interesting suggestion regarding Mil Specs. Instead of trying to create a new Mil Spec, he thinks it may be easier for PPG to have their new coating included in the fastener finishes listed in the ASME B18.24 PIN code system for fasteners. Jim told us that the B18.24 system, which defines PIN codes for over 700 different types of fasteners, is now being used more and more by the DoD, in preference to Mil Specs, for ordering parts.



6. Commercial interest in PPG's coating

Kevin Menke at fastener manufacturer Fastenal told us that Fastenal mainly supplies the commercial, not military market. Like BAE Systems, however, they would be interested in a coating like PPG's, if they can be convinced that it has better corrosion performance than the Magni and Geomet coatings they currently use on their fasteners (such as Fastenal's EcoGuard, which consists of a Plus L topcoat over a Geomet basecoat and provides corrosion resistance exceeding 1000 B117 hours to red rust). Fastenal finds that in general Magni coatings hold up as well as Geomet. Several different applicators supply each type of coating, in addition to coating suppliers such as Ellison Surface Technologies.

We spoke to Ellison, who are one of the leading U.S. suppliers of industrial coatings, including dip-spin coatings, on fasteners. They see potential for PPG's coating in the oil & gas market, especially on offshore drilling platforms where fasteners and other parts are exposed to harsh environmental conditions. Ellison asked if PPG had considered applications of their new coating to components other than fasteners, such as brackets or flat surfaces – even though these are not normally Cd plated.

Ellison expressed interest in **licensing** the PPG coating before it is actually available to the military. Although each of the three components of the coating (Zn phosphate conversion coating, Zn-rich primer, and E-coat) are commercially available from PPG, it is not clear whether all three would need to be licensed separately, or whether PPG would license them as a package. As Ellison has a dip-spin facility but not an electrocoating line for E-coat, they would want to explore options for acquiring an electrocoating capability.



7. Recommendations

We suggest a multi-pronged approach to getting the new PPG coatings into the defense market. Clearly at this point the primary market to aim for is vehicle fasteners. This is because vehicles are so far the only place where metal-filled organic coatings on fasteners have been adopted, and therefore the only market where there are specifications and drawings for these types of coatings. Furthermore, new vehicles are being fielded at a far higher rate than new aircraft or ships. The Navy is always very slow to adopt any new coating. In aircraft it is necessary first to overcome the perception (assuming it is only a perception) that one cannot use organic coatings on fasteners because they do not permit adequate power dissipation of lightning strikes. The following routes into the market are in order of importance. The first four should be followed simultaneously. The others are additional possible approaches that would be likely to lead to only low volume sales.

1. OEMs: BAE Land Systems would be the best manufacturer to approach initially. As we have pointed out, BAE Land Systems has developed a set of fastener drawings for different size fasteners, which all refer to a base drawing that is specifically designed to accept new coatings and treatments for fasteners. Jim Dorsch (James.Dorsch@baesystems.com) and Peter Wan (peter.wan@baesystems.com) at BAE are the two principal engineers who should be approached with the performance data for the PPG coatings, especially since Jim Dorsch has told us that they are looking for fastener coatings with better endurance than the existing dip-spin Magni and Geomet coatings. Since BAE manufactures a great many military vehicles, the probability of finding a fit in a new or existing vehicle program is quite high. In addition, BAE has (or has had) a program at Letterkenny to [convert MRAPs into MMPVs](#). This would presumably involve using the new fastener system.
2. TACOM Program Managers: Following Fred Lafferman's (fred.l.lafferman@us.army.mil) recommendation, the various TACOM program managers for the different vehicle weapon systems should be identified and approached, paying special attention to new programs. It should be possible to identify most of these through Dan Nymberg. It should also be possible to watch for new military vehicle procurements or planned weapon systems. Getting in at the very beginning of one of these programs is an effective, but slow way to get the PPG fastener technology into use. That in turn will require that the same fasteners be available through DLA for depot rework.
3. DLA: Since the MMPV has already been moved to Magni-coated fasteners, these fasteners must be available through DLA for depot rework, unless the depots are simply replacing them with standard Cd-plated alternatives, which would be readily available at the depots. Determining the best approach would mean approaching Letterkenny, where the MMPV is currently being overhauled, to determine what fasteners are currently being used, and what the NSN (National Stock Numbers) are. At this point we have found no QPL callouts for Magni, but it is quite likely that the coating is simply subsumed under the callout for a specific fastener.
4. TT-C-490: TT-C-490 is intended to become the primary Army specification for coatings. Getting the coating into TT-C-490 should be discussed with the owner, John Escarsega (john.a.escarsega@us.army.mil) and Tom Braswell (Thomas.braswell2.civ@mail.mil), the Team Lead for this specification.
5. Depots: There are one or two depots that do manufacturing in-house. As we have mentioned above, the Rock Island Arsenal manufactures some low-volume vehicles such as the FRS, and it might be worth approaching them, although the volumes would be very small. Another depot that carries out manufacturing and remanufacturing is Letterkenny Army Depot. They manufacture various kinds of field shelters as well as carrying out upgrades of MRAPs to MMPVs.
6. Fastener manufacturers: It would be worth approaching DoD fastener manufacturers such as Military & Commercial Fasteners Corp, who specifically advertise their [Environmentally Friendly Fasteners](#) based on the Magni coatings that they implemented for BAE.
7. GSE: Ground Support Equipment is a way into the defense aerospace industry. GSE includes power generators, washdown systems, tow trucks, and all of the other support equipment that aircraft need. Since none of this flies, most of it is made of standard low strength alloys.



REFERENCES

- ¹ “Minimizing the Use of Materials Containing Hexavalent Chromium”, Federal Register / Vol. 76, No. 87 / Thursday, p. 25569 (May 5, 2011). <http://db2.asetsdefense.org/fmi/webd/#Surface%20Engineering> Doc-529
- ² Pessetto, Frederick et al., “[Low Hydrogen Embrittlement Zinc-Nickel Qualification Test Results & Process Parameters Development](#)”, ASETSDefense Workshop 2011 (<http://www.asetsdefense.org/SustainableSurfaceEngineering2011.aspx>)
- ³ John Escarsega, “[TT-C-490 - Implementing Alternatives Through Specifications](#)”, ASETSDefense Workshop 2011 (<http://www.asetsdefense.org/documents/Workshops/2014/1/6%20Escarsega%20Kelley%202014.pdf>)
- ⁴ Jim Dorsch, Peter Wan, Angela Ton, BAE Land Systems “Hex-Chrome Free Hardware – BAE Experience”, ASETSDefense DoD Vehicle Workshop (2010) [http://www.asetsdefense.org/documents/Workshops/Vehicle2010/9%20Ton%20BAE%20Systems%20\(June%2015-16%20DoD%20Workshop\).pdf](http://www.asetsdefense.org/documents/Workshops/Vehicle2010/9%20Ton%20BAE%20Systems%20(June%2015-16%20DoD%20Workshop).pdf)
- ⁵ PPG Technology Demonstration Plan WP-201315, Tables 3 and 10
- ⁶ PPG SERDP Report WP-1617, Tables 6 and 7
- ⁷ GEOMET fastener coatings, http://michiganmetalcoatings.com/yahoo_site_admin/assets/docs/GEOMET.16981609.pdf
- ⁸ Crest Fasteners, “Fastener Tightening”, <http://crestfasteners.com/catalogs/general%20info/Fastener%20Tightening.pdf>
- ⁹ PPG Technology Demonstration Plan WP-201315, p. 6
- ¹⁰ Magni Product Data Sheets



APPENDIX A. BAE LAND SYSTEMS ADOPTION OF MAGNI COATINGS ON ARMY VEHICLE FASTENERS

Click icon to open document:



APPENDIX B. CONTACTS INTERVIEWED

Data for this report have been drawn from a variety of sources, including various fastener reports, briefings, discussions, and visits over a number of years, including with TARDEC, Carl Handsy (TARDEC, now retired) Rock Island Arsenal, BAE Land Systems, DLA, PMO-SBCT - Environmental Team, PM HBCT - Environmental Team, Boeing, Emerson Electric, RIE Coatings, SWD Coatings, Ellison Coatings. Ralph Alexander interviewed the following specifically for this report, but was unable to reach any of the PMs or PEOs:

John Escarsega (Army Research Laboratory)
john.a.escarsega@us.army.mil

Fred Lafferman (Army Research Laboratory)
(410) 306-1520, (443) 510-9515 cell
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APPENDIX D VEHICLE INSPECTION REPORT – ELZLY



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856/ 839-2435 (f)

September 13, 2017

PPG Industries Inc.
Attn: Matt Scott
Via email: msscott@ppg.com

RE: Fastener Demonstrations on USMC Tactical Wheeled Vehicles

Dear Mr. Scott:

This letter report details the final inspection results for the demonstration fasteners installed on US Marine Corps (USMC) Medium Tactical Vehicle Replacement (MTVR) assets. Inspections were performed over the period of March through September 2017. This included visual assessments for corrosion, photographs, and breaking torque measurements on test fasteners.

Following inspections, fasteners and mass loss coupons were removed, and returned to PPG Industries, Inc. (PPG) for further analysis. New fasteners, provided by PPG, were installed on the test assets, restoring them to their original configuration.

Please review this report at your convenience. If you have any questions or require any additional information, please do not hesitate to contact me in our Vineland, NJ office or via email at jrepp@elzly.com.

Sincerely,

A handwritten signature in black ink that reads "John Repp".

John Repp, P.E.
Senior Consultant

ENVIRONMENTALLY FRIENDLY FASTENER COATING DEMONSTRATION

Fastener Demonstrations on USMC Tactical Wheeled Vehicles

Background

The US Marine Corps (USMC) Corrosion Prevention and Control (CPAC) Program was requested to support demonstration of alternative fastener coatings being evaluated as part of the Environmental Security Technology Certification Program (ESTCP) Project WP-201315, "Environmentally Friendly Fastener Coating Demonstration." The USMC CPAC Program identified the fasteners on the Under Ride Bar on the Medium Tactical Vehicle Replacement (MTVR) for this demonstration. Figure 1 shows an example of this bar and the 3/4-inch flange fasteners used on this part.



Figure 1. MTVR Under Ride Bar.

PPG Industries Inc. (PPG) utilized this information to develop an installation schematic for fasteners with one of four coating systems applied. Figure 2 shows this schematic and the corresponding coating systems.



Installation Locations

Fastener Log Code	Position	Coating	Type
L1	P1	1	ZR/Ecoat
L2	P1	2	HPAP/Ecoat
L3	P2	1	ZR/Ecoat
L4	P2	2	HPAP/Ecoat
L5	P3	1	ZR/Ecoat
L6	P3	2	HPAP/Ecoat
R1	P1	3	Cd/Cr+6
R2	P1	4	Phos/Oil
R3	P2	3	Cd/Cr+6
R4	P2	4	Phos/Oil
R5	P3	3	Cd/Cr+6
R6	P3	4	Phos/Oil

Fastener Coatings

Figure 2. Schematic of Fastener Installation and list of Coating System.

Initial installations were performed between December 2014, and March 2015 at three USMC locations (Camp Lejeune, NC, Marine Corps Base Hawaii, and Camp Pendleton, CA), on 10 MTVRs per location. An interim inspection after approximately one-year of exposure was conducted between December 2015 and February 2016, during which fasteners were removed from one MTVR per location; the results of this inspection were previously reported.

This report covers the inspections performed after two years of exposure.

Inspection Methods

Inspections included visual evaluation of the fasteners for corrosion, and breaking torque measurements of fasteners on a demonstration vehicle prior to removal.

Visual Inspections

Visual inspections were done to determine the severity of corrosion observed on fasteners. Corrosion severity was rated based on the Stage of Corrosion observed. This is rated on a 0 to 4 scale, with 0 being no corrosion, and 4 being complete perforation (complete metal loss). Figure 3 shows an example of Corrosion Stages on fasteners.

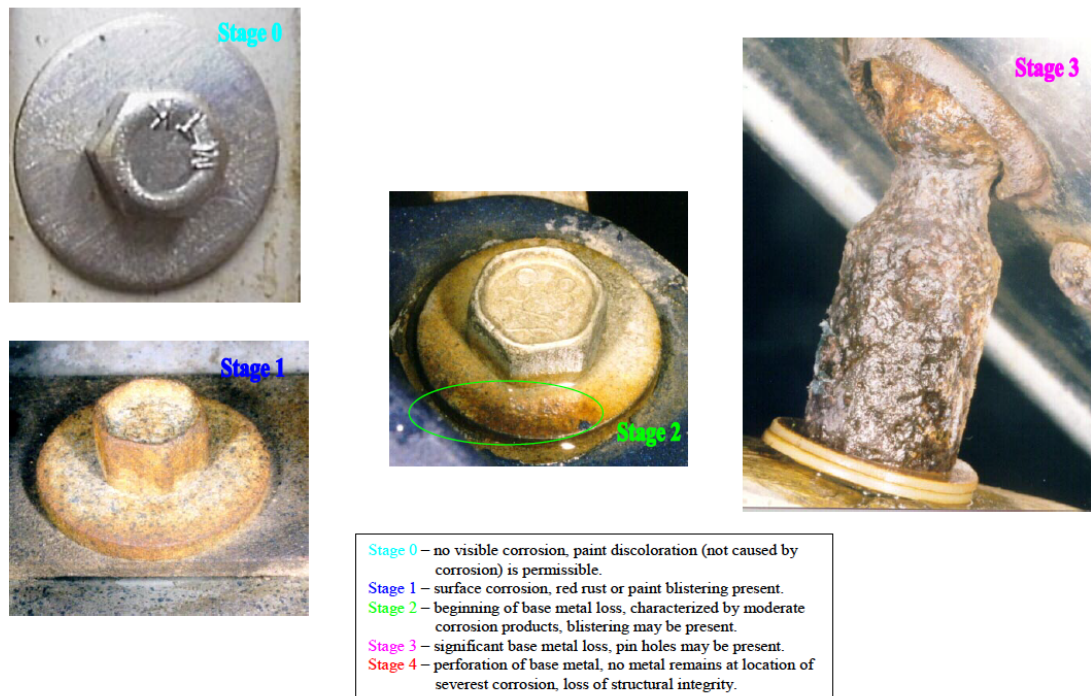


Figure 3. Examples of Corrosion Stages on Fasteners.

Visual inspections were made prior to removing the fasteners to observe the undisturbed corrosion products. During visual inspections, photographs were taken of the fasteners.

Breaking Torque

Breaking torque measurements were made in both the tightening and then loosening directions for the fasteners on one MTRV per location. Initial measurements were made in the tightening (ON) direction, where torque was applied to the fastener until an initial movement was achieved. Measurements were then made in the loosening (OFF) direction, where torque was applied to the fastener until movement was achieved. In both

instances, the maximum torque observed was recorded, which was achieved just prior to movement of the fastener.

Torque measurements were made using a Cooper Instruments LXT 954-6000, Reaction Socket Extension Torque Sensor, which is a ¾-inch square drive sensor capable of reading torque values up to 6,000 in-lb (500 ft-lb). The output of this sensor was displayed on an Omega HHP-SG digital indicator set to display the maximum torque values measured for each fastener removal. An IOTech data acquisition system was also used to monitor the torque values throughout the initial breaking.

Inspection Results

During the inspections at Camp Lejeune, NC, PPG took initial photographs and performed visual inspections. At the Marine Corps Base Hawaii (MCBH) and Camp Pendleton, CA locations, USMC CPAC and Elzly personnel performed all visual inspections. Breaking torque measurements were performed by USMC CPAC and Elzly personnel at all locations.

Visual Inspections

Tables 1 and 2 present the stage of corrosion observations for each of the vehicles inspected at MCBH and Camp Pendleton, respectively.

Table 1. Stage of Corrosion Observations - MCBH MTVRs.

Serial No.	L1	L2	L3	L4	L5	L6	R1	R2	R3	R4	R5	R6
592426	0	0	0	0	0	0	0	0	0	0	0	0
592425	0	0	0	0	0	0	0	0	0	1	0	0
592373	0	0	0	0	0	0	0	0	0	0	1	1
594584	0	0	0	2	0	0	0	0	1	2	0	0
594585	0	0	1	1	0	0	0	2	2	2	0	2
594589	0	0	1	2	2	2	0	0	1	2	0	2
594625	0	0	1	2	1	1	0	0	1	2	0	2
594672	0	1	1	2	1	1	0	1	1	2	0	2
595148	0	0	1	2	1	2	0	0	1	1	0	1

Table 2. Stage of Corrosion Observations - Camp Pendleton MTRs.

Serial No. ¹	L1	L2	L3	L4	L5	L6	R1	R2	R3	R4	R5	R6
596577	0	0	0	0	0	0	0	0	0	0	0	0
597114	0	0	0	0	0	0	0	0	0	0	0	0
596117	0	0	0	0	0	0	0	0	0	1	0	1
595412	0	0	0	0	0	0	0	2	0	0	0	0
638496	0	1	0	0	0	0	0	1	0	0	0	0

Figure 4 shows the number of observations for each Stage of Corrosion by coating system (for readability, this plot starts at 50%).

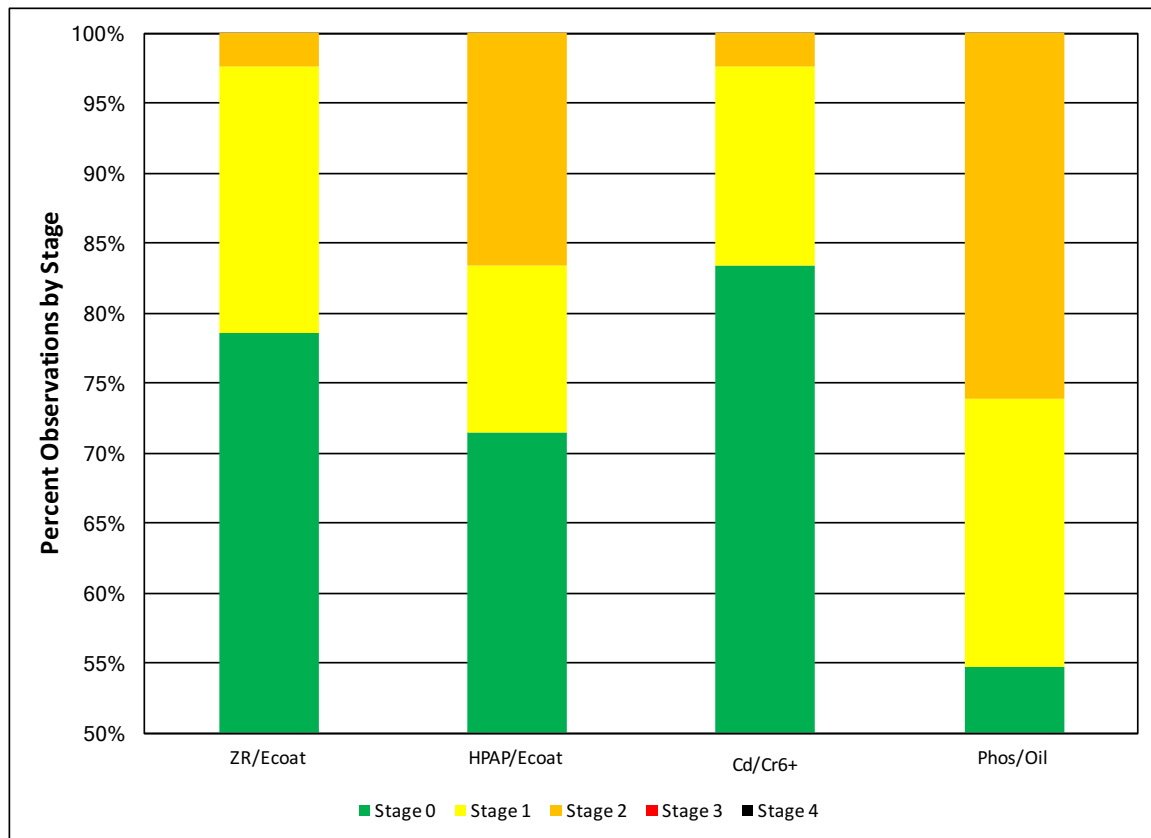


Figure 4. Percent of Observations for each Corrosion Stage.

Photographs of the fasteners are included in Attachment I.

NOTE: In some photographs the presence of red colored dirt appears similar to the corrosion products observed on other fasteners. This difference was more readily apparent during in-person visual inspections; the corrosion rating reflect these in-person observations.

¹ Due to unit activity, only five of the remaining nine MTRs could be inspected and have their fasteners replaced.

Breaking Torque

Tables 3, 4, and 5 show the maximum breaking torque values observed for MTVRs 594120 (Camp Lejeune), 592426 (MCBH), and 596577 (Camp Pendleton), respectively.

NOTE: Starting with readings made at MCBH, the initial readings before applying force to the fasteners was not reading at, or near, zero (ranging from -70 to 60 ft-lb). This initial offset was recorded and the maximum torque was corrected by subtracting this amount for all MCBH and Camp Pendleton readings.

Table 3. Breaking Torque (ft-lb) Values for MTVR 594120 (Camp Lejeune).

Fastener	ON Direction	OFF Direction
L1	887	615
L2	731	596
L3	732	383
L4	431*	543
L5	615	416
L6	503	344
R1	696	502
R2	599	482
R3	1,329	701
R4	1,292	1,054
R5	814	570
R6	955	696

* Omega HHP-SG digital indicator was set to track instead of maximum when readings started, this was the maximum value observed.

Table 4. Breaking Torque (ft-lb) Values for MTVR 592426 (MCBH).

Fastener	ON Direction	OFF Direction
L1	473	396
L2	401	280
L3	396	238
L4	298	198
L5	446	269
L6	592	406
R1	531	370
R2	613	410
R3	156	159
R4	156	127
R5	530	280
R6	708	569

Table 5. Breaking Torque (ft-lb) Values for MTRV 596577 (Camp Pendleton).

Fastener	ON Direction	OFF Direction
L1	445	207
L2	246	165
L3	323	234
L4	301	187
L5	344	173
L6	352	246
R1	566	379
R2	680	595
R3	342	206
R4	299	247
R5	316	284
R6	523	428

Figures 5 and 6 show comparisons of the breaking torque values for all three vehicles in the ON and OFF directions, respectively.

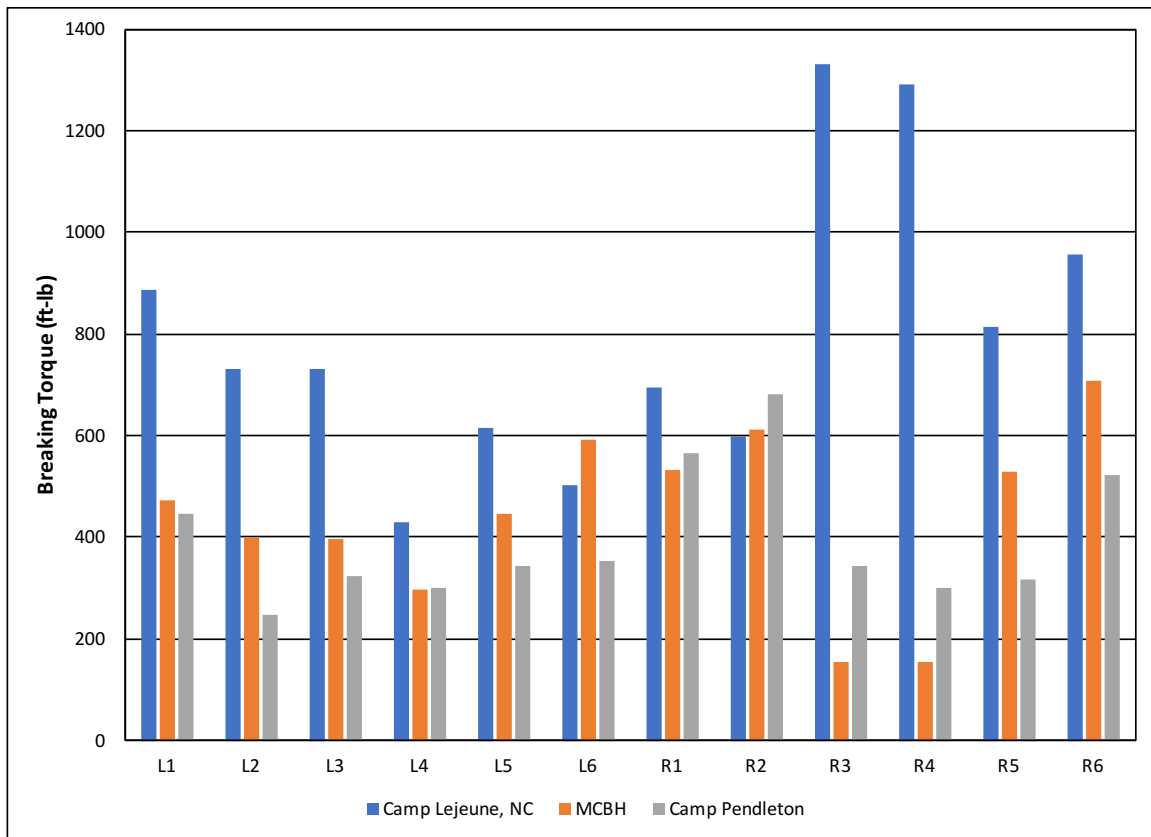


Figure 5. Breaking Torque Value - ON Direction.

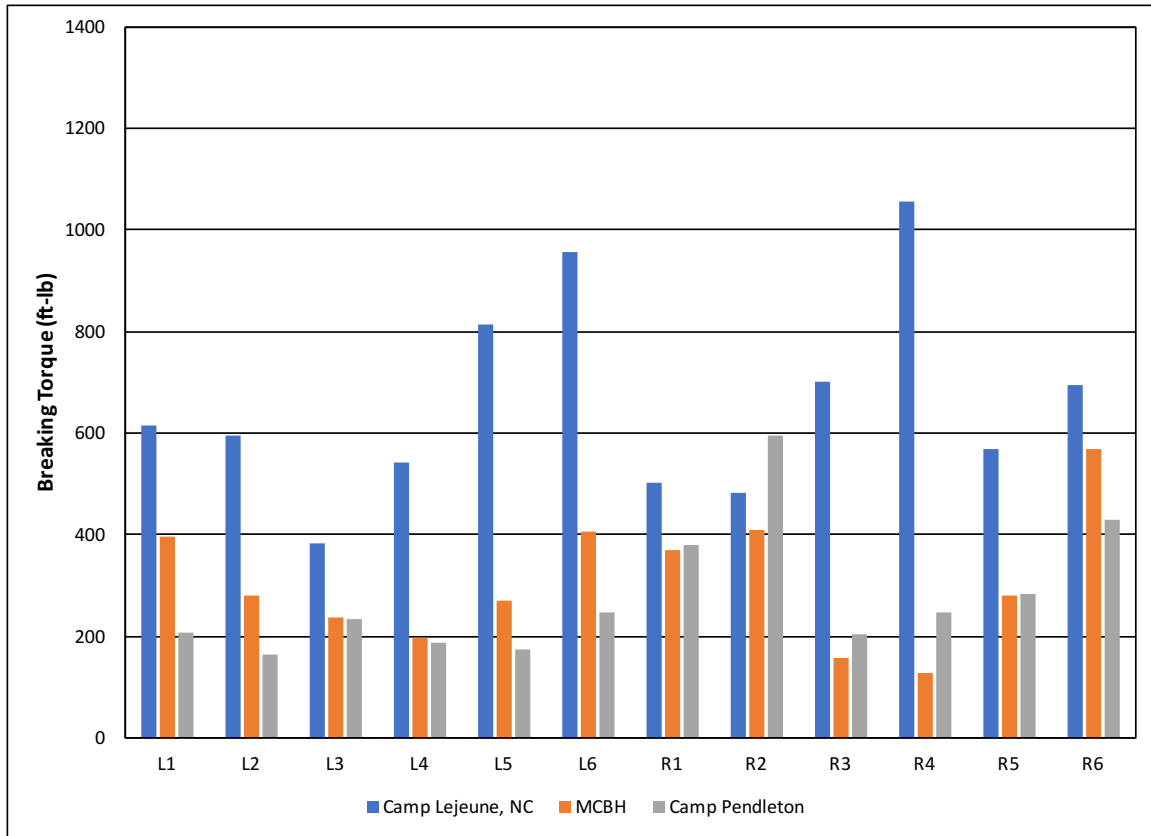


Figure 6. Breaking Torque Value - OFF Direction.

Plots of the torque values monitored during testing are included in Attachment II.

Removal of Mass Loss Coupons

During the inspection mass loss coupons (mounted during the original installation) were removed and returned to PPG for further analysis. At Camp Lejeune, the entire coupon rack was removed and returned with the fasteners. At MCBH and Camp Pendleton, the coupon racks were left installed on the vehicles, with select coupons removed and returned to PPG.

Table 6 lists the coupons removed for each location.

Installation	Serial No.	Coupons Removed
Camp Lejeune	638318	D575 through D579, A780
	592121	B563 through B568
	591968	C975 through C979, A080
	638264	B600, B608
	593510	B615, C536
	594120	C527, C532
	590928	C963, C968
MCBH	592426	B508 through B511
	592425	B504 through B507
	592373	A096 through A099
	594584	A3568, A369, A378, A379
	594585	D084, D085, D094, D095
	594589	A680, A681, A698, A699
	594625	E380, E381, E390, E391
	594672	B624, B625, B634, B635
	595148	B516, B517, D146, D147
Camp Pendleton	597114	D148, D159
	596117	A000, A011
	595412	E392, D523
	638496	E492, C519
	596577	C500, C511

Replacement of Fasteners

Upon removal of the test fasteners, replacement fasteners were installed into the MTRV assets. Fasteners were only replaced in locations L1, L2, L5, L6, R1, R2, R5, and R6. The remaining locations (L3, L4, R3, and R4) are designed to remain open allowing the Under Ride Bar to be adjusted up, if necessary.

NOTE: Due to damage to the Under Ride Bar on MTRV 592373, only the fasteners in positions L3, L4, R3, and R4 (adjustment holes) were removed. Figure 7 shows this damage.



Figure 7. Damage to MTRV 592373.

During installation, the fasteners were installed using an electric impact wrench, and verified to be installed to a minimum 175 ft-lb torque using an Armstrong Industrial Hand Tools torque wrench serial #5140901333. The Field Service Representative (FSR) at each location was requested to have the Corrosion Service Team (CST) perform touch-up painting of the fasteners.

Installation of the replacement fasteners restores these assets to their original configuration.

ATTACHMENT I – FASTENER PHOTOGRAPHS

Marine Corps Base Hawaii (MCBH)

USMC 592426

L1 and L2		
L3 and L4		
L5 and L6		

R1 and R2		
R3 and R4		
R5 and R6		

USMC 592425

L1 and L2		
L3 and L4		
L5 and L6		

R1 and R2		
R3 and R4 (Stage 1)		
R5 and R6		

USMC 592373

L1 and L2		
L3 and L4		
L5 and L6		

R1 and R2		
R3 and R4		
R5 (Stage 1) and R6 (Stage 1)		

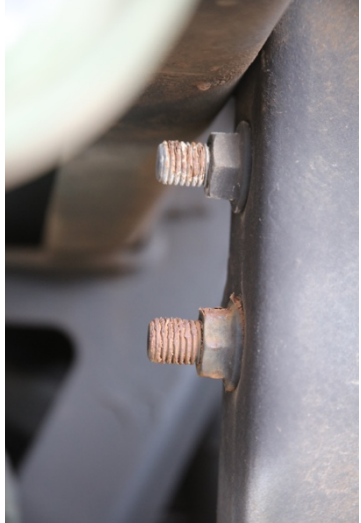
USMC 594584

L1 and L2		
L3 and L4 (Stage 2)		
L5 and L6		

R1 and R2		
R3 (Stage 1) and R4 (Stage 2)		
R5 and R6		

USMC 594585

L1 and L2		
L3 (Stage 1) and L4 (Stage 1)		
L5 and L6		

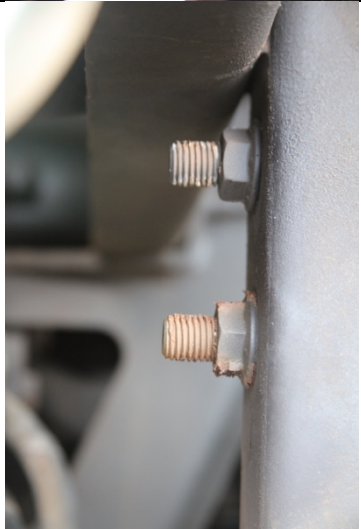
R1 and R2 (Stage 2)		
R3 (Stage 2) and R4 (Stage 2)		
R5 and R6 (Stage 2)		

USMC 594589

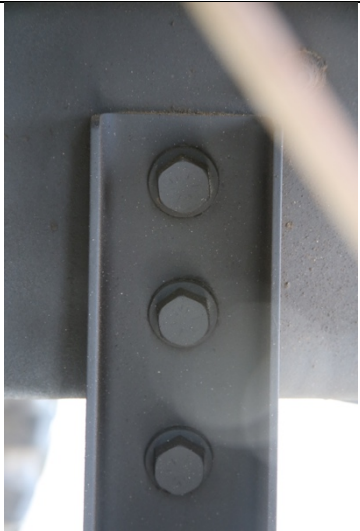
L1 and L2		
L3 (Stage 1) and L4 (Stage 2)		
L5 (Stage 2) and L6 (Stage 2)		

R1 and R2		
R3 (Stage 1) and R4 (Stage 2)		
R5 and R6 (Stage 2)		

L1 and L2		
L3 (Stage 1) and L4 (Stage 2)		
L5 (Stage 2) and L6 (Stage 2)		

R1 and R2		
R3 (Stage 1) and R4 (Stage 2)		
R5 and R6 (Stage 2)		

USMC 594672

L1 and L2 (Stage 1)		
L3 (Stage 1) and L4 (Stage 2)		
L5 (Stage 1) and L6 (Stage 1)		

R1 and R2 (Stage 1)		
R3 (Stage 1) and R4 (Stage 2)		
R5 and R6 (Stage 2)		

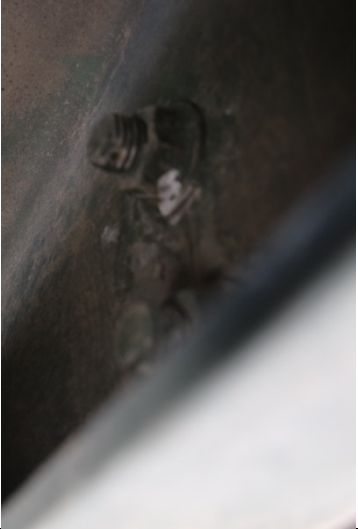
L1 and L2		
L3 (Stage 1) and L4 (Stage 2)		
L5 (Stage 1) and L6 (Stage 2)		

R1 and R2		
R3 (Stage 1) and R4 (Stage 1)		
R5 and R6 (Stage 1)		

Camp Pendleton

USMC 596577

L1 and L2		
L3 and L4		
L5 and L6		

R1 and R2		
R3 and R4		
R5 and R6		

USMC 597114

L1 and L2		
L3 and L4		
L5 and L6		

R1 and R2		
R3 and R4		
R5 and R6		

USMC 596117

L1 and L2		
L3 and L4		
L5 and L6		

R1 and R2		
R3 and R4 (Stage 1)		
R5 and R6 (Stage 1)		

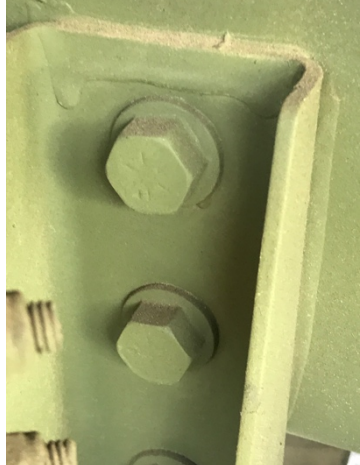
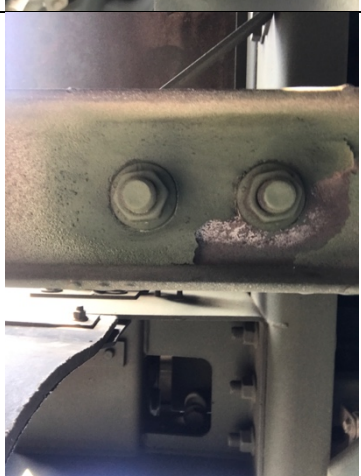
USMC 595412

L1 and L2		
L3 and L4		
L5 and L6		

R1 and R2 (Stage 2)		
R3 and R4		
R5 and R6		

USMC 638496

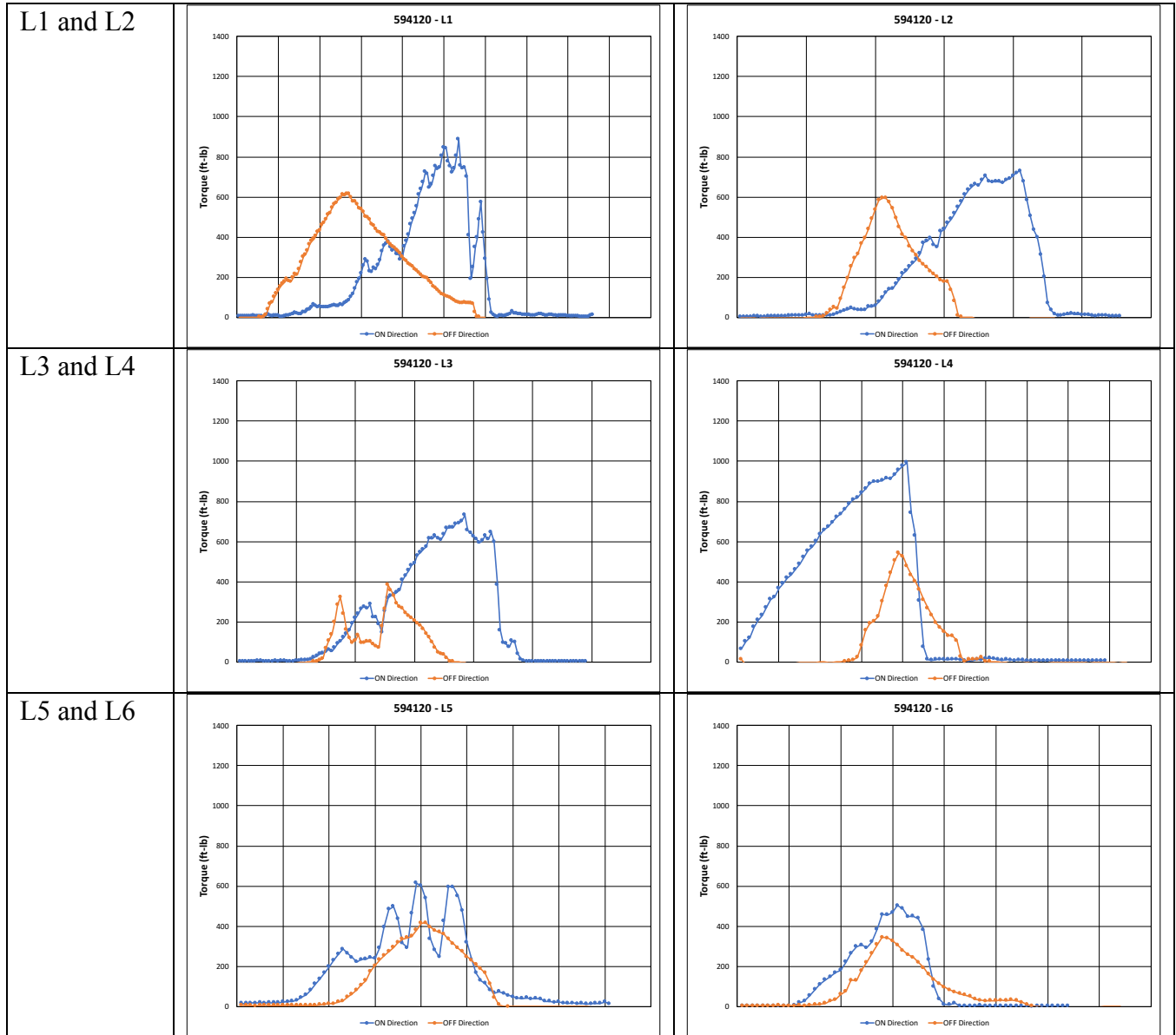
L1 and L2 (Stage 1)		
L3 and L4		
L5 and L6		

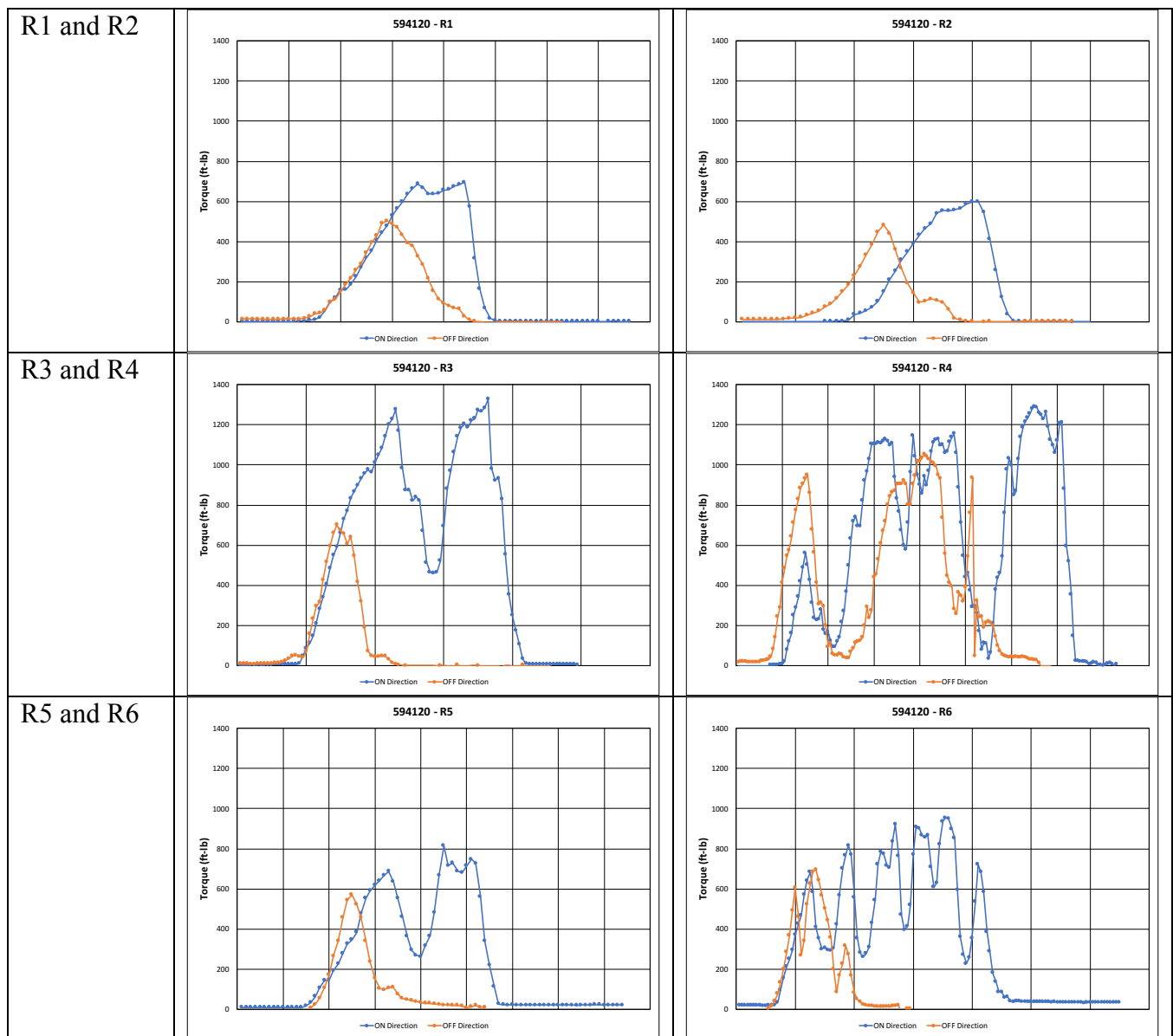
R1 and R2 (Stage 1)		
R3 and R4		
R5 and R6		

ATTACHMENT II – TORQUE PLOTS

Camp Lejeune

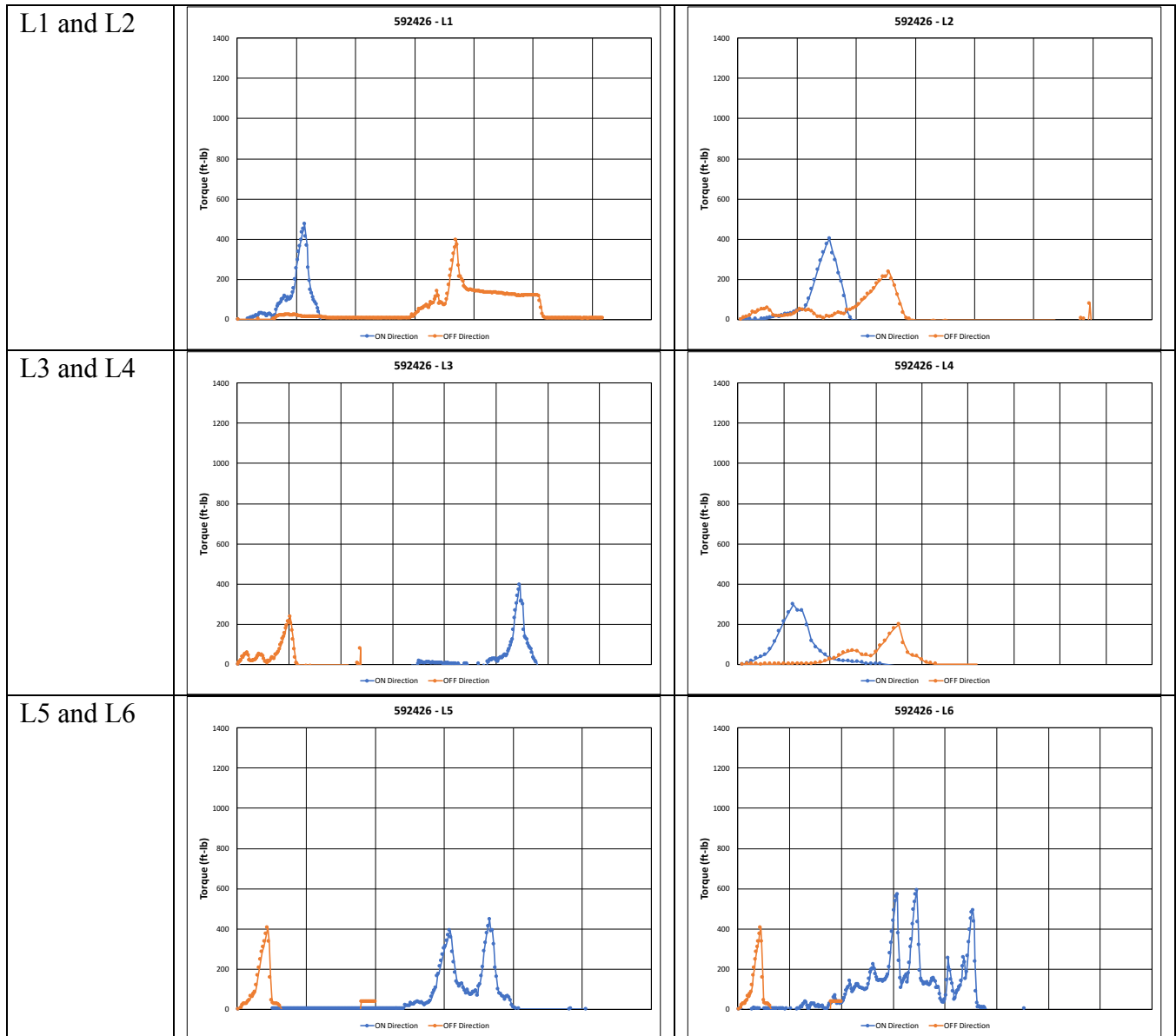
USMC 594120

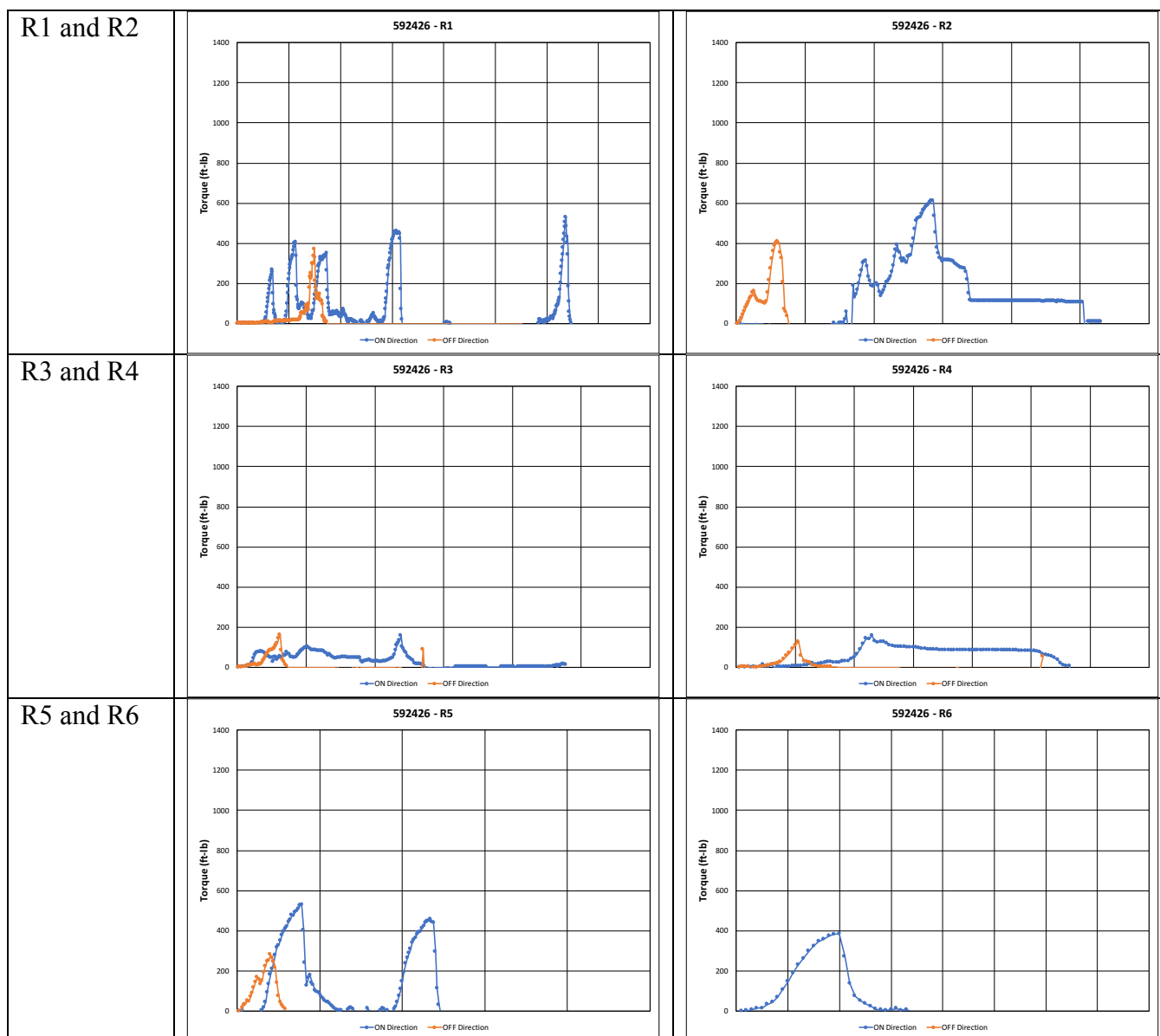




Marine Corps Base Hawaii (MCBH)

USMC 592426

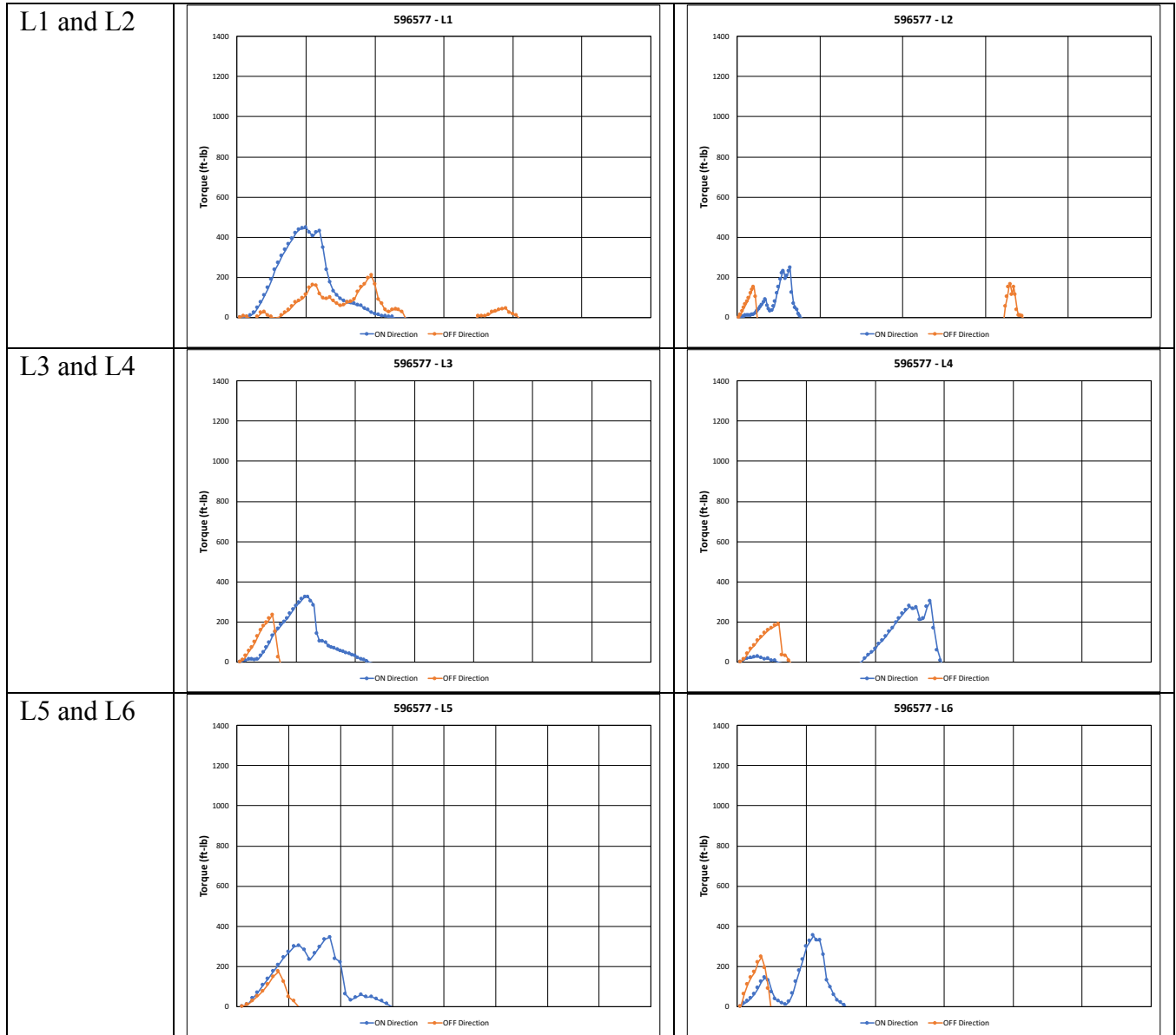


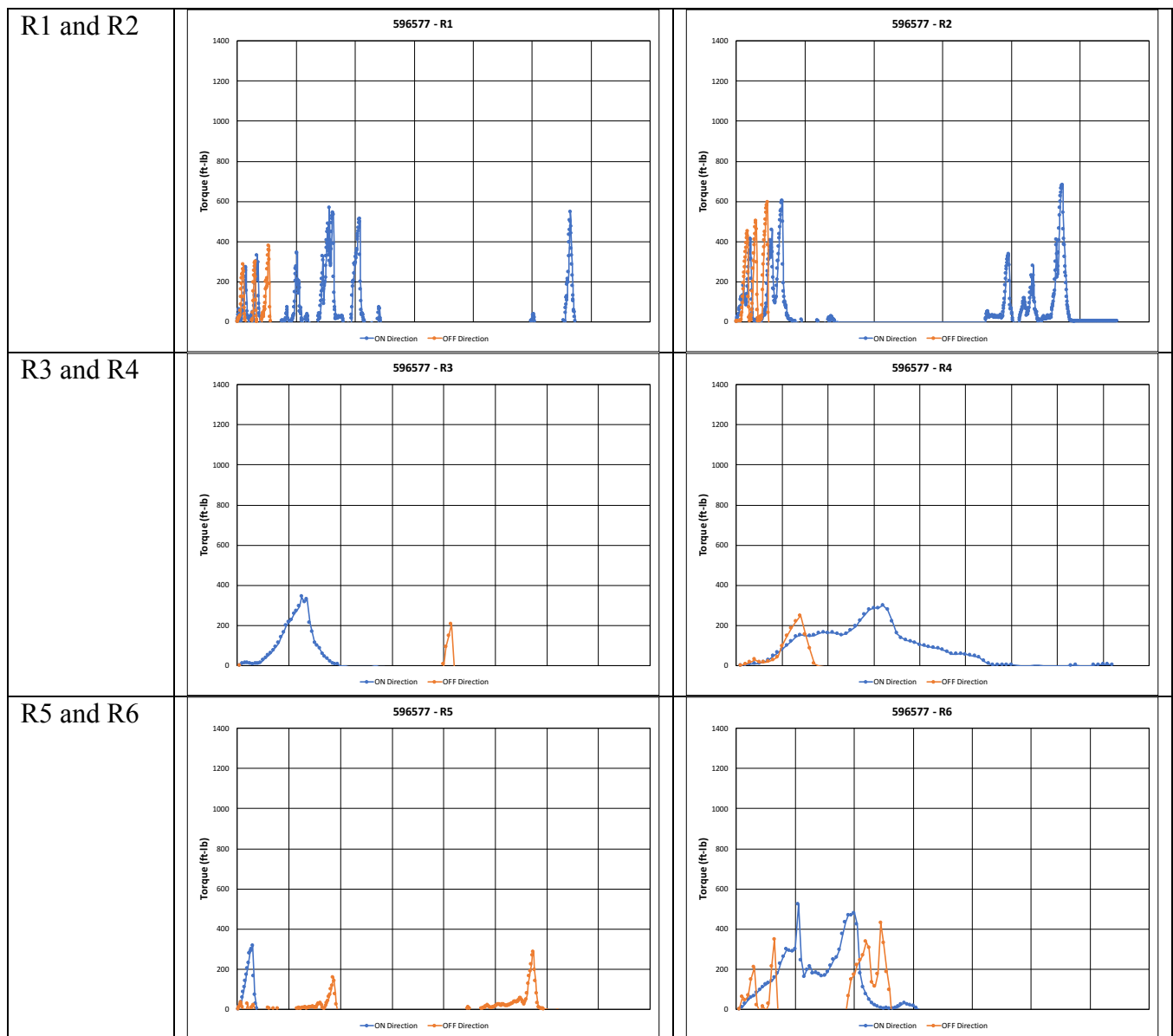


**OFF Direction data recorded for R6 never exceed 1 ft-lb, whereas observed maximum was 569 ft-lb; therefore this data was not plotted.*

Camp Pendleton

USMC 596577





APPENDIX E POINTS OF CONTACT

POINT OF CONTACT Name	ORGANIZATION Name Address	Phone Fax E-mail	Role in Project
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APPENDIX F DEMONSTRATION PARTS DETAIL

5310-01-150-5918 (NT-2419, S075460, 110312A, 01-150-5918)

Flange Locking Nut - Characteristics Data

MRC	Criteria	Characteristic
BZRR	THREAD SERIES	UNC
CQJX	NOMINAL THREAD SIZE	0.750 INCHES
CMLP	THREAD QUANTITY PER INCH	10
AAJD	THREAD CLASS	2B
AAJF	THREAD DIRECTION	RIGHT-HAND
MATT	MATERIAL	STEEL COMP 1013 OR 1015 OR 1016 OR 1017 OR 1018 OR 1019 OR 1020 OR 1021 OR 1022 OR 1023 OR 1524 OR 1025 OR 1026 OR 1527 OR 1029 OR 1030 OR 1033 OR 1034 OR 1035 OR 1536 OR 1037 OR 1038 OR 1039 OR 1040 OR 1541 OVERALL
SFTT	SURFACE TREATMENT	PHOSPHATE OVERALL
STDC	SURFACE TREATMENT DOCUMENT AND CLASSIFICATION	DOD-P-16232 MIL SPEC SINGLE TREATMENT RESPONSE OVERALL
CQFM	HARDNESS RATING	NOT RATED
ACTA	NUT STYLE	A294 HEXAGON
AAVX	WASHER OUTSIDE DIAMETER	1.585 INCHES NOMINAL
ABKW	OVERALL HEIGHT	0.825 INCHES MAXIMUM
ADEM	WASHER THICKNESS	0.110 INCHES MINIMUM
ASDB	WIDTH ACROSS FLATS	1.088 INCHES MINIMUM AND 1.127 INCHES MAXIMUM
AAUM	LOCKING FEATURE	PREVAILING TORQUE ALL METAL DESIGN
AZKQ	TEMP RATING	NOT RATED
FEAT	SPECIAL FEATURES	WEAPON SYSTEM ESSENTIAL
CRTL	CRITICALITY CODE JUSTIFICATION	FEAT
AGAV	III END ITEM IDENTIFICATION	NSN 2320-01-150-5918 HEMTT (HEAVY EXPANDED MOBILITY TACTICAL TRUCK); NSN 2320-01-304-2277 PLS (PALLETIZED LOADING SYSTEM); W/S: TRUCK, FIRE/CRASH P15; HEAVY EQUIPMENT TRUCK TRACTOR, M1070; TRUCK, HEAVY EXPANDED MOBILITY TACTICAL (HEMTT); TRUCK, AIRCRAFT CRASH/STRUCTURE FIREFIGHTING (A/332P-19A); PALLETIZED LOADING SYSTEM; TRUCK, FIRE/CRASH P19; MTVR FAMILY (INCLUDES TAMCNS D0198, D1062, D1073 & D1213; LVS POWER UNIT MK48 AND TRAILER FAMILY

5306-01-236-1585 (WE1018TB, 1336700, 01-236-1585)**Machine Bolt - Characteristics Data**

MRC	Criteria	Characteristic
THSD	THREAD SERIES DESIGNATOR	UNC
AHYM	NOMINAL THREAD DIAMETER	0.750 INCHES
CMLP	THREAD QUANTITY PER INCH	10
AAJD	THREAD CLASS	2A
AAJF	THREAD DIRECTION	RIGHT-HAND
AASA	THREAD LENGTH	1.550 INCHES NOMINAL
AASB	FASTENER LENGTH	1.750 INCHES NOMINAL
MATT	MATERIAL	STEEL COMP 1013 OR STEEL COMP 1015 OR STEEL COMP 1016 OR STEEL COMP 1017 OR STEEL COMP 1018 OR STEEL COMP 1019 OR STEEL COMP 1020 OR STEEL COMP 1021 OR STEEL COMP 1022 OR STEEL COMP 1023 OR STEEL COMP 1025 OR STEEL COMP 1026 OR STEEL COMP 1029 OR STEEL COMP 1030 OR STEEL COMP 1033 OR STEEL COMP 1034 OR STEEL COMP 1035 OR STEEL COMP 1037 OR STEEL COMP 1038 OR STEEL COMP 1039 OR STEEL COMP 1040 OR STEEL COMP 1524 OR STEEL COMP 1527 OR STEEL COMP 1536 OR STEEL COMP 1541 OVERALL
SFTT	SURFACE TREATMENT	PHOSPHATE MANGANESE OVERALL
STDC	SURFACE TREATMENT DOCUMENT AND CLASSIFICATION	MIL-P-16232 MIL SPEC SINGLE TREATMENT RESPONSE OVERALL
AASK	HEAD STYLE	C7 HEXAGON EXTENDED WASHER
AASU	HEAD HEIGHT	0.730 INCHES NOMINAL
AATB	WIDTH BETWEEN FLATS	1.120 INCHES NOMINAL
AATC	EXTENDED WASHER DIAMETER	1.590 INCHES NOMINAL
AATD	EXTENDED WASHER THICKNESS	0.110 INCHES NOMINAL
CBBL	FEATURES PROVIDED	FINISHED HEAD
FEAT	SPECIAL FEATURES	OIL COATING IN COMPLIANCE WITH MIL-P-16232
AGAV	III END ITEM IDENTIFICATION	HEMTT FAMILY (HEAVY EXPANDED MOBILITY TACTICAL TRUCKS); 2320-01-304-2277, TRUCK, PLS (PALLETIZED LOADING SYSTEM)