ESTCP
Cost and Performance Report

(WP-200527)

Validation of Novel Electroactive Polymers as Environmentally Compliant Coatings for Replacement of Hexavalent Chromium Pretreatments

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A four-year Environmental Security Technology Certification Program (ESTCP) (WP-200527) was undertaken to prove the viability of poly(2,5-bis(N-methyl-N-hexylamino)phenylene vinylene, BAM-PPV and to test other alternative pretreatment coatings as controls. Each service conducted field testing on non-critical military hardware using BAM-PPV as the pretreatment coating with a primer and topcoat specific for that service. The Air Force (AF) and Army coatings incorporated BAM-PPV as the pretreatment coating in full military coatings. After one-year of field testing, BAM-PPV pretreatment coating with primer and topcoat showed similar performance to a fully Cr(VI) system. However, testing by the Navy on support equipment showed that BAM-PPV as the pretreatment coating did not give any improved corrosion or abrasion resistance as compared to the control. The Cost and Performance report documents these results but shows that BAM-PPV is not a commercially viable alternative to current CCC or Prekote treatment coatings. BAM-PPV is 31.2X more expensive per gallon than the commercial CCC.

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TABLE OF CONTENTS

Page

EXECUTIVE SUMMARY ES-1

1.0 INTRODUCTION 1
- 1.1 BACKGROUND 1
- 1.2 OBJECTIVES OF THE DEMONSTRATION 1
- 1.3 REGULATORY DRIVERS 3

2.0 DEMONSTRATION TECHNOLOGY 5
- 2.1 TECHNOLOGY DESCRIPTION 5
  - 2.1.1 Technology Chronology 6
  - 2.1.2 Expected Applications 6
- 2.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY 7
  - 2.2.1 Advantages of BAM-PPV Pretreatment Coating 7
  - 2.2.2 Limitations of BAM-PPV Pretreatment Coating 7

3.0 PERFORMANCE OBJECTIVES 9

4.0 SITES/PLATFORM DESCRIPTION 11
- 4.1 TEST PLATFORM/FACILITIES 11
  - 4.1.1 Test Platforms/Facilities at WPAFB 11
  - 4.1.2 Test Platforms/Facilities at ARL 12
  - 4.1.3 Test Platform/Facilities at Fleet Readiness Centers (FRC) 12
  - 4.1.4 Test Platform/Facilities at National Aeronautics and Space Administration (NASA) - KSC 12
- 4.2 PRESENT OPERATIONS 13
  - 4.2.1 Present Operations at WPAFB 13
  - 4.2.2 Present Operations at ARL 14
  - 4.2.3 Present Operations at FRC-NW 14
  - 4.2.4 Present Operations at NASA-KSC 14
- 4.3 SITE-RELATED PERMITS AND REGULATIONS 15

5.0 TEST DESIGN 17
- 5.1 JTP TESTING OF BAM-PPV PRETREATMENT COATING 17
- 5.2 FIELD AND REAL-WORLD TESTING OF BAM-PPV PRETREATMENT COATING 19
  - 5.2.1 Outdoor Exposure Testing 19
  - 5.2.2 Marine Outdoor Exposure Testing 19
  - 5.2.3 Field Testing of BAM-PPV Pretreatment Coating 20
  - 5.2.4 Field Testing at WPAFB 20
  - 5.2.5 Field Testing at ARL 20
  - 5.2.6 Field Testing at FRC-NW 20

TABLE OF CONTENTS (continued)

Page

6.0 PERFORMANCE ASSESSMENT 21
6.1 JTP LABORATORY TESTING FOR BAM-PPV PRETREATMENT COATING 21
6.1.1 Adhesion Testing for BAM-PPV Pretreatment Coating 21
6.1.2 Accelerated Weathering Testing for BAM-PPV Pretreatment Coating 21
6.1.3 Additional Testing for BAM-PPV Pretreatment Coating 22
6.1.4 Toxicology Testing of BAM-PPV Powder 23
6.2 FIELD AND REAL-WORLD TESTING FOR BAM-PPV PRETREATMENT COATING 24
6.2.1 Outdoor Exposure Testing 24
6.2.2 Marine Outdoor Exposure Testing 24
6.2.3 Field Testing for BAM-PPV Pretreatment Coating 24

7.0 COST ASSESSMENT 27
7.1 COST MODEL 27
7.1.1 Performing Organization Example 27
7.1.2 Data Requirements 27
7.1.3 Performing Organization 28
7.1.4 Assumptions Based on BAM-PPV Coating Process 28
7.1.5 Emissions Monitoring and Reporting for BAM-PPV Applications 29
7.1.6 Scale of Operations 29
7.1.7 Life Cycle Costs Time Frame 29
7.2 COST ANALYSIS AND COMPARISON 29
7.2.1 EAP Primary Cost Element Categories 29
7.2.2 Facility Capital 30
7.2.3 Start-up and Operations & Maintenance 30
7.2.4 Equipment Replacement 31
7.2.5 ESOH and Cost Avoidance 31
7.2.6 Reprocessing/Reapplication 31
7.2.7 Hazardous Waste Storage and Disposal 31
7.2.8 Life Cycle Costs Comparison 32

8.0 IMPLEMENTATION ISSUES 35
8.1 IMPLEMENTATION STAKEHOLDERS 35
8.1.1 EAP Acceptance Process 35
8.1.2 Impact of ESOH Regulations 35
8.2 EAP PROCUREMENT 35
8.2.1 Process Equipment 35
8.2.2 Production and Scale-Up 35
8.2.3 Proprietary and Intellectual Property Rights 36
8.3 TECHNOLOGY TRANSFER EFFORTS 36

9.0 REFERENCES 37

TABLE OF CONTENTS (continued)

Page

APPENDIX A POINTS OF CONTACT..... A-1

LIST OF FIGURES

Page

Figure 1. BAM-PPV structure. 5
Figure 2. BAM-PPV on AA 2024-T3 panels at 336 hours NSS exposure. 6
Figure 3. Flow chart for EAP testing and down-selection for field studies during phases I and II. 17

LIST OF TABLES

Page

Table 1. Best/worst performing BAM-PPV pretreatment in full military coating systems. 2
Table 2. Environmental systems allocation database. 7
Table 3. Performance objectives. 9
Table 4. Engineering and testing requirements. 18
Table 5. Assessment of BAM-PPV field test on C-5 cargo aircraft rear hatch door. 24
Table 6. Assessment of BAM-PPV field test on headlight cover of Bradley vehicle. 25
Table 7. Assessment of BAM-PPV field test on bomb hoists and towbars. 25
Table 8. Environmental activity costs. 28
Table 9. Estimated cost of making BAM-PPV. 30
Table 10. Estimated compliance costs for general industry with new Cr(VI) guidelines. 32
Table 11. Costs comparison of BAM-PPV to CCC and Prekote pretreatments. 32

ACRONYMS AND ABBREVIATIONS

AA	aluminum alloy
AF	Air Force
AFRL	Air Force Research Laboratory
AFRL/RX	AFRL Materials and Manufacturing Directorate
APG	Aberdeen Proving Ground
ARL	Army Research Laboratory
ASTM	American Standard Test Method
ATC	Aberdeen Test Center
BAM-PPV	poly(2,5-bis(N-methyl-N-hexylamino)phenylene vinylene)
CARC	chemical agent resistant coatings
CCC	chromate conversion coating
CFR	Code of Federal Regulations
Cr(VI)	hexavalent chromium
CRADA	Cooperative Research and Development Agreement
CTIO	Coatings Technology Integration Office
DoD	Department of Defense
EAP	electroactive polymer
ECAM	Environmental Cost Analysis Methodology
ECR	electrical contact resistance
EPA	Environmental Protection Agency
ESOH	environmental safety and occupational health
ESTCP	Environmental Security Technology Certification Program
EU	European Union
FRC	Fleet Readiness Center
FRC-NW	FRC Northwest
FRC-SE	FRC Southeast
FSE	field service evaluation
GM9540P	General Motors accelerated corrosion test
HAP	hazardous air pollutant
HVLP	high volume low pressure
ISO	International Organization for Standardization
JTP	Joint Test Protocol
JTR	Joint Technical Report

KSC	Kennedy Space Center
LANL	Los Alamos National Laboratory
$\mu g/m^3$	micrograms per cubic meter
NASA	National Aeronautics and Space Administration
NAVAIR	Naval Air Systems Command
NAWCAD	Naval Air Warfare Center Aircraft Division
NAWCWD	Naval Air Warfare Center Weapons Division
NIOSH	National Institute for Occupational Safety and Heath
NSS	neutral salt spray
O & I	organizational and intermediate level maintenance
ONR	Office of Naval Research
OSHA	Occupational Safety and Health Agency
Oxsol-100	4-chlorobenzotrifluoride or 1-chloro-4-(trifluoromethyl)benzene
PANI	polyaniline
PATTI	pneumatic adhesion tensile test instrument
PEL	permissible exposure limit
PPE	personal protective equipment
PPV	poly(para-phenylene vinylene)
psi	pounds per square inch
REACH	registration, evaluation, authorization, and restriction of chemicals
S/cm	Siemens per centimeter
SAE	Society of Automotive Engineers
SBIR	Small Business Innovative Research
SERDP	Strategic Environmental Research and Development Program
SO_2	sulfur dioxide
sq. ft.	square foot
SVHC	substance of very high concern
TCP	trivalent chromium pretreatment
TWA	time weighted average
UDP	up and down procedure
UDRI	University of Dayton Research Institute
VOC	volatile organic compounds
WP	weapons platforms

WPAFB	Wright Patterson Air Force Base
WTA	wet tape adhesion

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EXECUTIVE SUMMARY

BACKGROUND

Chromate conversion coatings (CCC) are applied via immersion or spraying onto both aluminum and steel substrates. These coatings provide both corrosion inhibition and adhesion promotion between the primer and the pretreatment. Several recent studies have shown that residual hexavalent chromium [Cr(VI)] in chromate conversion coatings provides corrosion protection via a self-healing mechanism. However, Cr(VI) is a known carcinogen and is highly regulated by the Environmental Protection Agency (EPA) and Occupational Safety and Health Agency (OSHA).

A viable alternative to Cr(VI) coatings must meet or exceed the performance of Cr(VI). In addition, these alternative coatings must be able to passivate the metal surface allowing the corrosion current to shift to the noble metal region. Several studies over the past decade have focused on electroactive polymers (EAP) as corrosion preventive coating. Though very little work has been done on alternative pretreatments using EAPs; scientists at the Naval Air Warfare Center Weapons Division (NAWCWD) have successfully synthesized a poly(para-phenylene vinylene) (PPV) derivative that can perform as well as CCC. This polymer can meet the military pretreatment requirements for alternatives to CCC. This compound poly(2,5-bis(N-methyl-N-hexylamino)phenylene vinylene (BAM-PPV) has shown corrosion prevention in simulated seawater. Its corrosion prevention properties were also evaluated using accelerated weathering conditions to determine its effectiveness as an alternative pretreatment to CCC. These tests, conducted under a Strategic Environmental Research and Development Program (SERDP) Pollution Prevention (PP-1148) project from fiscal year 2000-2004 (FY00-04), showed conclusive evidence that BAM-PPV was a promising pretreatment coating as an alternative to CCC's.

OBJECTIVES OF THE DEMONSTRATION

A 4-year ESTCP (WP-200527) FY05-08 project was undertaken to prove the viability of this new compound and to test other alternative pretreatment coatings as controls. Each service, Wright Patterson Air Force Base (WPAFB), Army Research Laboratory (ARL), and NAWCWD and Naval Air Warfare Center Aircraft Division (NAWCAD) tested BAM-PPV as a pretreatment coating, trivalent chromium pretreatment (TCP) and PreKote. Each service tested these pretreatment coatings according to their military coating specification for alternatives to CCC. These tests were conducted with and without full military coatings containing Cr(VI) or non-chromium coatings in accelerated weathering chambers, adhesion testing, fluid resistance, and outdoor/marine outdoor exposure testing.

DEMONSTRATION RESULTS

After 3 years of extensive laboratory testing of these alternatives, a candidate was selected for field testing by the three services. The extensive laboratory testing validated the performance of BAM-PPV as an alternative to CCC in several specific Department of Defense (DoD) military laboratory requirements. The performance of BAM-PPV coated with chromated primers and topcoats exceeded the military requirements of 2000 hours neutral salt fog exposure without evidence of corrosion, blistering, or delamination. However, when BAM-PPV was coated with non-chromium primers and topcoats, the performance in most cases was marginal or failure was evident; however,

several non-chromium primers with BAM-PV as the pretreatment and topcoats did provide adequate corrosion protection. These samples met the minimum requirement of 2000 hours neutral salt spray (NSS) exposure. BAM-PPV along with the best performing primers (Cr(VI) and non-chromium) with topcoats was selected for field testing. Toxicology studies have also shown that BAM-PPV is a non-toxic material. There were no deaths or injuries to experimental laboratory animals that were administered doses of BAM-PPV for lethality, dermal, and ocular sensitization. Laboratory testing by both WPAFB and ARL showed in several cases that BAM-PPV used as the pretreatment layer in full military coatings (epoxy primer + polyurethane topcoat) showed acceptable corrosion performance, which warranted further evaluation in a field study. Furthermore, outdoor exposure testing was conducted at WPAFB and Kennedy Space Center (KSC). The outdoor exposure testing performed by WPAFB using BAM-PPV as the pretreatment layer with primers Cr(VI) and non-Cr(VI), and topcoat, showed comparable performance to a fully chromated system for 24 months of exposure. However, similar testing at the KSC showed that BAM-PPV after 6 months of marine outdoor exposure could not match a fully chromated control system. In this case, the BAM-PPV incorporated as the pretreatment layer with non-Cr(VI) epoxy primer and polyurethane topcoat could not match a fully chromated system (CCC+ Cr(VI) epoxy primer and polyurethane topcoat). This test using BAM-PPV as the pretreatment coating was considered a fail. In this type of severe marine outdoor exposure testing, BAM-PPV was not robust enough to survive this environment. A fully chromated coating can survive a 1-year marine outdoor exposure test and this is considered a pass.

Each service conducted field testing on non-critical military hardware using BAM-PPV as the pretreatment coating. The Air Force (AF) and U.S. Army (Army) field testing showed similar performance to a fully chromated system. However, testing by the Navy on support equipment showed that BAM-PPV as the pretreatment coating did not give any improved corrosion or abrasion resistance as compared to the control. This may be due to improper surface preparation of the aluminum alloy prior to coating with BAM-PPV pretreatment. Adhesion of the BAM-PPV onto the Navy aluminum support structures did not yield satisfactory results after 1 year of field testing.

IMPLEMENTATION ISSUES

Removal of chromates from the pretreatment process would allow for improved compliance with 29 Code of Federal Regulations (CFR) 1910.1026, which calls for a permissible exposure limit (PEL) on Cr(VI) of 5 micrograms per cubic meter and time weighted average (TWA) with an action level of 2.5 micrograms per cubic meter. This should not be an issue since the substitution involves trading one EPA/OSHA non-toxic pretreatment for a pretreatment containing a known human carcinogen that has prohibitive PELs and restrictive disposal options. The EAP coatings for the facility will be applied by the appropriate coatings group and each depot has the appropriate safety permits and EPA reporting requirements to implement this technology.

The only implementation issue that each co-performer identified was the number of passes that BAM-PPV requires for appropriate thickness.

Currently CCC, TCP and Prekote require only:

- Two passes to produce adequate thickness for pretreatment coatings; and

- BAM-PPV requires between seven to nine passes for adequate thickness.

This will be a problem for implementation as it will increase time and costs for applying BAM-PPV onto various metal substrates.

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1.0 INTRODUCTION

1.1 BACKGROUND

Polymers were originally thought of as electrical insulators, not electrical conductors. However, in the early 1960s Pohl, Katon, and others synthesized and characterized polymers (some conjugated) with conductivities in the semiconductor range [1,2]. The discovery that iodine-doped polyacetylene exhibited electrical conductivity many orders of magnitude higher than neutral polyacetylene shattered the belief that polymers were poor conductors. This discovery was made in 1976 by Hideki Shirakawa, Alan MacDiarmid, and Alan Heeger. They received the 2000 Nobel Prize in Chemistry for their work [3]. The discovery of electrically conducting polymers triggered the development of a new multidisciplinary field known as "synthetic metals" [4].

Electroactive polymers (EAP) are composed of conjugated chains containing π-electrons delocalized along the polymer backbone. In their neutral form, EAPs are semiconductive polymers that can be doped and converted into electrically conductive forms. The doping process can occur either by oxidative or reductive reactions, though oxidative reactions are more common. The conductivity is electronic in nature and does not involve concurrent ion migration in the solid polymer form. Some doping processes are reversible, with typical conductivities switching between those of insulators ($<10^{-10}$ Siemens per centimeter [S/cm]) to those of metals (10^5 S/cm) [5].

EAPs comprise a broad range of materials that are characterized by conjugated repeat units; this conjugation is responsible for the unique electronic and optical properties of EAPs ranging from low oxidation potential to third order optical nonlinear properties. Researchers have exploited these unique materials to synthesize a variety of EAPs. These polymers exhibit a broad range of conductivities (10^{-4} to 10^3 S/cm) in their doped (oxidized) states. There are several classes of EAPs: polyacetylenes, poly(p-phenylene)s, polyheterocycles, poly(phenylene vinylene)s, polyanilines (PANI) and conjugated ladder polymers.

Corrosion protection using EAPs was first suggested by MacDiarmid in 1985 [6]. It has been observed that most EAPs can be electrochemically produced by anodic oxidation, enabling one to obtain a conducting film directly on a surface. This fact has led researchers into the field of anti-corrosives. EAPs can go from the insulating to the conducting state through several doping techniques such as (a) chemical doping by charge transfer, (b) electrochemical doping, (c) doping of PANI by acid-base chemistry, (d) photodoping, and (e) charge injection at a metal-semiconducting polymer interface. Depending on the doping technique used, this will have a significant influence as to the potential application of the EAP.

1.2 OBJECTIVES OF THE DEMONSTRATION

The objectives of this ESTCP research program were to:

- Demonstrate an effective, environmentally benign, repairable coating using EAPs as a replacement for hexavalent chromium (Cr(VI)) chromium conversion coatings (CCC);

- Validate performance with non-chromated primers and topcoats on aluminum alloys against known American Standard Test Method (ASTM) testing standards;
- Validate performance on steel with non-chromated primers and topcoats against known ASTM testing standards; and
- Demonstrate via field tests using poly(2,5-bis(N-methyl-N-hexylamino)phenylene vinylene) (BAM-PPV) pretreatment coatings on non-critical military hardware showing equal to or superior performance as compared to CCC pretreatment full military coatings.

The laboratory tests were conducted with and without full military coatings containing Cr(VI) or non-chromium coatings by each co-performer. 4-Chlorobenzotrifluoride (Oxsol-100) was used as the volatile organic compounds (VOC)-exempt solvent to dissolve the BAM-PPV powder and apply the solution using standard high volume low pressure (HVLP) spray equipment.

Various laboratory tests were conducted, including: accelerated weathering testing, adhesion testing, fluid resistance, and outdoor exposure testing. Table 1 provides the best/worst full military coating systems in neutral salt spray (NSS) testing chamber and adhesion tests.

Table 1. Best/worst performing BAM-PPV pretreatment in full military coating systems.

Substrate	Pretreatment	Primer[a]	Topcoat[b]	NSS[c]	Adhesion[d,e]
AA2024-T3	BAM-PPV	MIL-PRF-23377N	MIL-PRF-85285	2,000 hours (pass, scribed)	4B[b] (pass)
AA7075-T6	BAM-PPV	MIL-PRF-23377N	MIL-PRF-85285	2,000 hours (pass, scribed)	4B[b] (pass)
AA6061-T6	BAM-PPV	MIL-DTL-53022	MIL-DTL-53039	2,016 hours (pass, no-scribe)	1,185 psi[c] (adhesive failure)
AA5083	BAM-PPV	MIL-DTL-53030	MIL-DTL-53039	2,016 hours (pass, no-scribe)	824 psi[c] (adhesive failure)
AA2024-T3	BAM-PPV	MIL-PRF-23377N	MIL-PRF-85285	1,500 hours (fail, scribed)	3A (marginal)
AA7075-T6	BAM-PPV	MIL-PRF-23377N	MIL-PRF-85285	1,500 hours (fail, scribed)	3A (marginal)
4130 steel	BAM-PPV	MIL-PRF-23377N	MIL-PRF-85285	124 hours (fail, scribed)	1,853psi[c] (adhesive/cohesive)
4130 steel	BAM-PPV	MIL-DTL-53022	MIL-PRF-85285	X	1A (fail)

a: Non-chromated primers
b: Aircraft polyurethane topcoat (MIL-PRF-85285) and Army solvent-borne topcoat (MIL-PRF-53039)
c: NSS = Neutral salt spray testing (ASTM B117)
d: Adhesion testing (ASTM D 3359)
e: PATTI adhesion (pneumatic adhesion tensile test instrument, ASTM D 4541)
AA = aluminum alloy
psi = pounds per square inch

The “best” term means that the BAM-PPV pretreatment layer incorporated into a full military coating (primer + topcoat) passed the military specification for that test, whereas the “worst” means it fails completely not meeting the minimum military specification for that test. Thus, the best–performing full military coating system using BAM-PPV as the pretreatment layer coating on aluminum alloys were field tested by each of the services (Navy, Army and Air Force [AF]). The summation of the field tests conducted by AF, Army, and Navy are listed below:

- AF field test on C-5 cargo plane aluminum rear hatch door using BAM-PPV as pretreatment with full military coating (non-chromium primer + topcoat) survived 1-year field test with no visual evidence of corrosion, delamination or loss of protective properties.
- Army field test on aluminum flag holder for the Bradley vehicle using BAM-PPV as pretreatment with full military coating (non-chromium primer + topcoat) survived 1-year field test with minor abrasion, minor loss of topcoat coating (BAM-PPV pretreatment coating intact) without any visual evidence of corrosion.
- Navy field test on aluminum support equipment using BAM-PPV as pretreatment with full military coating (non-chromium primer + topcoat) failed at 6 months of field tests, extensive delamination, cracking, and loss of coating was evident.

1.3 REGULATORY DRIVERS

The Occupational Safety and Health Agency (OSHA) have published a final standard for occupational exposure to Cr(VI) in the February 28, 2006, Federal Register. The standard covers occupational exposure to Cr(VI) due to the known carcinogenic nature of this compound and it is highly regulated by the Environmental Protection Agency (EPA) and OSHA [7-13]. OSHA has determined based upon the best scientific evidence that at the current permissible exposure limit (PEL) for Cr(VI), workers face a significant risk to their health. Therefore, a final rule establishes a PEL of 25 micrograms of Cr(VI) per cubic meter of air for aerospace painting (25 $\mu g/m^3$) as an 8-hour time weighted average (TWA) for all Cr(VI) compounds in the paint hangar. This ruling was based on extensive consideration of all comments and evidence submitted during this process. However, the PEL for the maintenance worker is still 5 $\mu g/m^3$. This standard must be met during painting by using protective personnel equipment (PPE).

As of January 24, 2013, the National Institute for Occupational Safety and Health (NIOSH) had posted a document entitled “Criteria for a Recommended Standard: Occupational Exposure to Hexavalent Chromium.” NIOSH reviewed the critical health effect studies of Cr(VI) compounds and updated its assessment of the potential health effects of occupational exposure to Cr(VI) compounds. The recommendation for the new PEL is 0.20 $\mu g/m^3$ for a workplace environment [7-11]. This recommendation by NIOSH was advisory only; NIOSH cannot issue a regulatory directive.

The European Union (EU) Registration, Evaluation, Authorization and Restriction of Chemicals (REACH) regulations (EC 1907/2006) were adopted in December 2006, and came into force June 2007. REACH was introduced because many thousands of chemicals are used in the EU, some in very large quantities and with increased risks to human health and to the environment. Cr(VI) is one of the many substances that are highly regulated by the EU, and is currently a substance of very high concern (SVHC).

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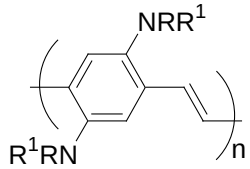
2.0 DEMONSTRATION TECHNOLOGY

2.1 TECHNOLOGY DESCRIPTION

A brief review is warranted in order to understand EAP compounds and their potential applications to Department of Defense (DoD) infrastructure and equipment. The Los Alamos National Laboratory (LANL) and Kennedy Space Center (KSC) investigators have demonstrated that doped EAPs, such as PANI coatings, inhibited corrosion on carbon steel [14]. Their approach was based on earlier work suggesting that the interfacial contact between the metal and a doped EAP would generate an electric field that would restrict the flow of electrons from the metal to an outside oxidizing species, thus preventing and/or reducing corrosion [15]. The LANL-KSC tests were conducted in a 3.5wt % NaCl/0.1 M HCl environment using 0.005 centimeter (cm) thick films of PANI doped with p-toluenesulfonic acid on carbon steel. The PANI primer was coated with an epoxy topcoat. The PANI/epoxy coating performed significantly better than the epoxy topcoat alone. These initial results were used by researchers at LANL-KSC to develop EAP coatings to resist the corrosive effects of acid vapor generated during space shuttle launches. The ground support equipment and structures at the KSC were susceptible to these severe environmental conditions. Marine outdoor exposure testing over 28 months have shown that PANI/epoxy coatings on carbon steel can survive a severe corrosive environment providing acceptable corrosion protection.

However, an examination of EAPs as an alternative to CCC pretreatments has not been thoroughly studied. The Naval Air Warfare Center Weapons Division (NAWCWD) has investigated BAM-PPV (Figure 1) as an alternative to CCC due to poly(para-phenylene vinylene)'s (PPV) known redox properties and tertiary (3^0) amine functionalities capable of corrosion inhibition with adhesive properties. BAM-PPV has shown strong adhesion to AA2024-T3 alloy in a simulated seawater immersion test (pH~8). Its ability to inhibit corrosion was demonstrated [16-21]. Constant current (galvanostatic) and constant potential (potentiostatic) methods were used to investigate the corrosion protection of BAM-PPV on AA2024-T3 coupons. Quantitative evidence was obtained from these results, which showed that corrosion inhibition was obtained without the loss of adhesion and no pH dependency was observed. These tests were run against control samples (non-coated AA2024-T3 coupon) and the BAM-PPV coated coupons outperformed the non-coated coupons. Visual inspection of the coupons showed significant pitting in the non-coated as compared to the coated (BAM-PPV) samples.



where: R= methyl and R1=hexyl

Figure 1. BAM-PPV structure.

2.1.1 Technology Chronology

Prior to initiation of the completed ESTCP project WP-200527, a SERDP program (PP-1148) was successfully completed over 4 years during FY00-04, and EAP polymers can repeatedly meet the minimum military specification requirement of MIL-DTL-5541 as alternatives to CCCs. This military specification requires 336 hours of corrosion inhibition in NSS without any evidence of corrosion, delamination, or blistering to be considered as a viable alternative to CCC. The accelerated weathering testing on BAM-PPV proved that it can meet and exceed this military requirement. The EAP coated panels were compared to trivalent chromium pretreatment (TCP) (Metalast TCP-HF) and CCC (Alodine 1200S) coated AA2024-T3 coupons. An alternative to CCC on aluminum alloys requires that the alternative pretreatment pass exposure to NSS for 336 hours without blistering, delamination, corrosion, or significant discoloration (Figure 2). All of these criteria have been met for BAM-PPV during the SERDP/Office of Naval Research (ONR) program. BAM-PPV polymers can be incorporated into military coatings, and in most cases, can perform as well as the CCC and TCP based military coating with non-chrome primers and topcoats (this usage of the term "incorporation" refers to having BAM-PPV as the pretreatment layer in full military coatings [epoxy primer layer + polyurethane topcoat layer]). In general, the alternatives to fully chromated systems do not meet the minimum requirement for neutral salt fog. However, the BAM-PPV pretreatment film is a potentially viable alternative to the currently approved pretreatment (TCP) coating system. BAM-PPV does not contain any heavy metals in the system (e.g., chromium: hexavalent or trivalent). This represents a significant improvement over heavy metal based coatings (e.g., TCP) that contain chromium. Trivalent chromium is not considered a carcinogen but with potential restrictions on the future use of chromium (in any form), a fully chromium-free coating will be more attractive to military installations as they seek to comply with future regulations. The best performing BAM-PPV coated with primer and topcoat onto AA2024-T3 coupons were used as the basis for transition to the ESTCP program.

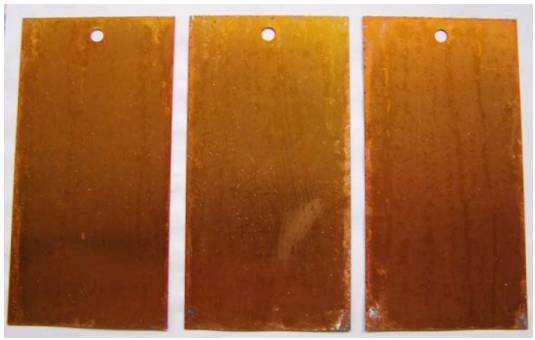


Figure 2. BAM-PPV on AA 2024-T3 panels at 336 hours NSS exposure.

2.1.2 Expected Applications

EAPs such as PANI, polythiophene, and polypyrrole coatings have demonstrated corrosion protection even when the coating is scratched and exposed to aqueous salts and hydrochloric acids. There have been numerous studies that support and demonstrate the idea that EAPs can inhibit corrosion. EAP based polymer coatings are robust materials that are environmentally benign. A comprehensive study of EAP coatings, including synthesis, scale-up, benign coating formulations, testing in accelerated weathering chambers and an examination of their corrosion protective

mechanisms has been investigated from previous SERDP and ONR studies. These novel EAPs are now potential candidates to replace CCC. In addition, these new EAP coatings have been incorporated into military coating systems using non-chromium primers and topcoats. Thus, EAP pretreatment coatings can provide the DoD community a replacement for CCC containing military coating systems and primers.

2.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

2.2.1 Advantages of BAM-PPV Pretreatment Coating

The advantages of using BAM-PPV as a new pretreatment coating will allow the elimination of Cr(VI) from the pretreatment coating process for metal alloys. Data available from FY06 shows CCC usage generating 5,182 lbs of hazardous waste (Table 2), which is an example of a military depot Cr(VI) usage. The data presented in Table 2 is from the Environmental Systems Allocation Database. The use of BAM-PPV will eliminate this hazardous waste stream. The current alternative, TCP, while non-carcinogenic is a chromium-based material. This material in the near future may be regulated by both EPA and OSHA due to its chromium-based formulation.

Table 2. Environmental systems allocation database.

MIL-DTL-81706 Chemical Conversion Materials for Coating Aluminum and Aluminum Alloys	
2006 Material Usage	
O&I Level Maintenance Usage	1,907 lbs
Depot Level Maintenance Usage	3,275 lbs
Total Usage	**5,182 lbs**

O&I = organizational and intermediate

Another advantage of this technology is that current paint equipment can be used. No special equipment would be necessary. However, one limitation of this technology could be the dilute solutions used. BAM-PPV has been prepared as a 1 weight % solution in solvents, such as Oxsol-100, xylenes, or limonene. Oxsol-100 is the most promising because it is a VOC-exempt solvent. This limitation is solubility of the BAM-PPV in Oxsol-100 requires multiple passes in order to achieve the proper thickness (~2 microns) to inhibit corrosion on aluminum alloys. Further discussion of this topic is found in section 2.2.2.

Another aspect that has been rigorously tested is its full shelf life. The studies have shown that the shelf life of BAM-PPV is very long (years). It can be stored for long periods of time without degradation. As a solution, it has a shelf-life of several months (6-10 months). In powder form, it is stable for years (≥ 4 years). Both NAWCWD and Wright Patterson Air Force Base (WPAFB) have examined the stability and processability of BAM-PPV powder and solution. The data supports the idea that BAM-PPV is stable and can be processed from powder after years of standing in a closed container.

2.2.2 Limitations of BAM-PPV Pretreatment Coating

The major limitation of using BAM-PPV as a pretreatment coating is the high number of passes (9) as compared to CCC (2). This high number of passes is required in order to produce the BAM-PPV coating with the proper thickness (2 microns). This requirement is necessary for BAM-PPV

pretreatment coating to exhibit corrosion-inhibiting properties, which, thereby increases costs for this material and application.

3.0 PERFORMANCE OBJECTIVES

The December 2000 Joint Test Protocol (JTP) developed by Naval Air Warfare Center Aircraft Division (NAWCAD) has been used as a guide for CCC replacements to evaluate the effectiveness of the BAM-PPV pretreatment coating [22]. Quantitative and qualitative data was collected and used to evaluate the BAM-PPV coating system's ability to replace the CCC corrosion/adhesion performance, as well as to identify environmental benefits, cost savings, and improvements to mission readiness. Performance objectives for this WP-200527 ESTCP project are included in Table 3, and acceptance/rejection criteria for these performance objectives are described in the table. The JTP was used as the guidance document for evaluating the performance of BAM-PPV with and without primer and topcoats for each service.

Table 3. Performance objectives.

Type of Performance Objective	Primary Performance Criteria	Expected Performance (Metric)	Actual Performance Objective Met?
(1) Reduce Cr(VI) in coating/quantitative	Reduce the use of chrome in a coating system	Eliminate the need for chrome in a pretreatment	Yes
(2) Corrosion resistance in NSS/quantitative	Corrosion resistance: NSS on unpainted substrate with pretreatment	336 hours with no visible sign of corrosion; lightening of coating is acceptable	Yes
(3) Corrosion resistance on scribed panels/quantitative	Corrosion resistance NSS on scribed, painted substrate	2,000 hours with no evidence of corrosion (minor surface corrosion in scribe permissible).	Pass with chromated primer: 4000 hours Pass with non-chrome primer: 2000 hours
(4) SO_2 corrosion resistance/quantitative	SO_2 salt fog on scribed, painted substrates	500 hours with no evidence of corrosion (minor surface corrosion in scribe permissible).	No, all panels failed
(5) Cyclic corrosion resistance/qualitative	Cyclic corrosion test on scribed, painted substrates	Equivalent or improved performance compared to controls.	Several panels showed acceptable performance
(6) Filiform corrosion resistance/quantitative	Filiform corrosion resistance	All filaments < 1/4"; Majority <1/8".	No, all panels failed
(7) ECR of EAP coated panels/quantitative	Electrical conductivity of unpainted, pretreated substrates	<5 milliohms/square-inch as coated. <10 milliohms/square-inch after 168 hours neutral salt fog exposure.	Several coupons pass
(8) Marine outdoor exposure testing qualitative/quantitative	Marine atmospheric outdoor test (Beach Test) exposure on scribed, painted substrates	Equivalent or improved performance compared to chromate controls	All panels failed at 6 months, except Cr(VI) controls
(9) Outdoor exposure testing qualitative/quantitative	Outdoor exposure tests	Equivalent or improved performance compared to chromate controls	BAM-PPV coated panels survived 24 months
(10) WTA/quantitative	WTA and water resistance of painted substrates	Rating of 4A or 5A.	Pass

ECR = electrical contact resistance
SO_2 = sulfur dioxide
WTA = wet tape adhesion

Table 3. Performance objectives (continued).

Type of Performance Objective	Primary Performance Criteria	Expected Performance (Metric)	Actual Performance Objective Met?
(11) Dry tape adhesion quantitative	Dry tape adhesion of painted substrates	Loss of two or more complete primer squares shall constitute failure (<3B).	Pass
(12) Adhesion testing during field studies/qualitative	In-service paint adhesion	Equivalent or improved paint adhesion compared to chromate controls	BAM-PPV coated hardware passed AF and Army field testing; BAM-PPV coated hardware failed Navy field testing
(13) Corrosion testing during field studies/qualitative	In-service corrosion	Equivalent or improved performance compared to chromate controls	BAM-PPV coated hardware passed AF and Army field testing; BAM-PPV coated hardware failed Navy field testing

The results documented in Table 3 shows that in several cases BAM-PPV passed the performance objectives listed. The reader is referred to the Joint Technical Report (JTR) published on-line at https://serdp-estcp.org to obtain complete information on which coating systems incorporating BAM-PPV as the pretreatment layer passed the performance objectives listed in Table 3.

As a brief summation, for the BAM-PPV pretreatment layer on aluminum alloys it passed the NSS military specification requirement of 336 hours. When incorporated into fully chromated systems (primer and APC topcoat), it survived 4000 hours NSS. Several non-Cr(VI) primers when incorporated with BAM-PPV pretreatment and APC topcoat layers survived 2000 hours NSS. Both NSS tests in which BAM-PPV either met or exceeded the mil spec of 2000 hours NSS is considered a pass. The results of the filiform and SO_2 testing with BAM-PPV as the pretreatment layer in full military coatings (Cr(VI) and non-Cr(VI) primers + topcoat) all failed these tests. These tests showed that BAM-PPV pretreatment coating layer with either non-Cr(VI) or Cr(VI) primer and topcoat failed to meet the minimum requirements for the mil spec. The field tests for both the Army and AF were successful (passed) with BAM-PPV as the pretreatment layer incorporated into a full military coating system (non-Cr(VI) primer + topcoat). The Navy field test of BAM-PPV pretreatment layer in a full military coating (non-Cr(VI) primer + topcoat) failed at 6 months.

4.0 SITES/PLATFORM DESCRIPTION

A demonstration plan was submitted to the ESTCP office on July 24, 2008. This plan was accepted on September 30, 2008. This demonstration plan listed all tests that will be conducted on non-critical military hardware/platforms and the criteria for pass/fail of the BAM-PPV coating. During Phase I of the ESTCP Program, laboratory tests were conducted by WPAFB, Army Research Laboratory (ARL) and NAWCWD/NAWCAD to evaluate BAM-PPV as a pretreatment coating without any primer and topcoat and incorporated into a full military coating system (primer + topcoat). After laboratory evaluations, the best performing system (full military coating) were then field tested by each service on non-critical military hardware.

4.1 TEST PLATFORM/FACILITIES

The demonstration platforms that were selected during Phase II were based on each service analyzing the laboratory and outdoor exposure, testing and determining a suitable platform for testing the BAM-PPV candidate. Thus, after full completion of the laboratory accelerated weathering, outdoor exposure, and toxicology testing, a down-selection of the best performing EAP pretreatment coating with Cr(VI)-free primers and topcoats was applied to non-critical military hardware for field testing.

4.1.1 Test Platforms/Facilities at WPAFB

The platform for field testing the BAM-PPV pretreatment was determined by WPAFB. The WPAFB testing facility provided an excellent opportunity to test the BAM-PPV material on the C-5 cargo plane. The unique characteristics and history of the 445th Aircraft Wing at WPAFB provided first rate testing facilities and performance evaluations on new alternative pretreatment coatings to CCC. The 445th Airlift Wing, located at WPAFB, is an operation wing of the AF Reserve. The C-5 is a long-range troop and cargo transport built by Lockheed-Georgia Company. The C-5 Galaxy provides the AF's strategic airlift capability. The C-5 cargo plane was chosen as an appropriate military aircraft for field testing the BAM-PPV pretreatment coating as an alternative to CCCs for several reasons:

- The size of the rear-hatch door provided adequate surface area such that multiple coating systems were tested in patches side-by-side for immediate performance comparison;
- The door was removable, and if a serious coating failure were noted, the door was removed and replaced easily with minimal interference using typical repair operations;
- At the time of the field test, the C-5 maintenance group was located at WPAFB and was immediately accessible to Air Force Research Laboratory (AFRL) Materials and Manufacturing Directorate personnel, so periodic checks and performance feedback was readily available;
- Because of the mission requirements of the C-5 cargo aircraft, flight performance of the system was ascertained from this test bed, which was immediately comparable to many other aircraft performance requirements; and
- BAM-PPV coating in several laboratory test systems showed comparable performance to the chromate controls and these systems were used as the coatings for the field studies.

4.1.2 Test Platforms/Facilities at ARL

The ARL chose the Bradley vehicle as the non-critical military hardware for field demonstration of the BAM-PPV pretreatment coating. Only non-critical parts of the Bradley vehicle were coated for the field demonstration. The headlight cover of the Bradley vehicle was selected for field demonstration of the BAM-PPV compound. Several Bradley vehicles were available at ARL, Maryland, and the headlight cover provided enough area to test the new coating in various environmental conditions. The reasons for selecting the headlight cover of the Bradley vehicle were as follows:

- The Bradley fighting vehicle was an ideal Army platform for assessing the performance of the BAM-PPV;
- The headlight cover was constructed of an aluminum alloy that provides the EAP a fair approximation of Army inventory; and
- The location of this vehicle at the Aberdeen Test Center (ATC) provides evaluators with several critical advantages over other locations.

4.1.3 Test Platform/Facilities at Fleet Readiness Centers (FRC)

In cooperation with NAWCAD, the Naval Air Systems Command (NAVAIR)-Lakehurst facility demonstrated EAP coatings (BAM-PPV) as replacements for CCC on support equipment. The demonstration locations for the Navy were the FRC Northwest (FRC-NW) and FRC Southeast (FRC-SE). FRC-NW serves as maintenance and repair facility for naval ground support equipment. FRC-NW has substantial expertise in the evaluation of new coating systems under other ESTCP and related evaluations. Service items from each location were used within the demanding and corrosive environment of Navy submarines and aircraft carriers present some of the largest opportunities for the evaluation of new coating systems. The components selected for the 12 month field service evaluations were the Navy's towbars and bomb hoists. These items were recommended based upon these reasons:

- High likelihood of field service evaluation (FSE) success;
- Material quantities reduced/eliminated (for chromium-based pretreatments);
- Potential reduction in labor costs required for EAP implementation;
- VOC, hazardous air pollutants (HAP), and hazardous waste reduction related to processing each component; and
- Demonstration effort was confined to ensure Naval Air Station Whidbey Island and the Naval Air Station Jacksonville to ensure real-world processing, testing, and potential implementation pathways of new EAP materials.

4.1.4 Test Platform/Facilities at National Aeronautics and Space Administration (NASA) - KSC

The NASA Beach Corrosion Test Facility was chosen for marine outdoor exposure testing for several reasons:

- Site's harsh marine conditions,
- High solar,
- High humidity,
- Salt spray,
- Rain, and
- Wind.

These conditions provided an ideal environment to measure the robustness of new coatings systems in an environment that can mimic real world sea environments. This facility is located approximately 150 feet from the Atlantic Ocean, and is approximately 1 mile south of the Space Shuttle launch sites. The facility includes an atmospheric exposure site, flowing seawater immersion tanks with spray-down capabilities, cathodic protection compatibility tank, weather station, on-site electrochemistry laboratory, monitoring station, and sample preparation and processing area. The beachfront laboratory has the capability to provide real-time data access to monitor corrosion experiments and surrounding weather conditions.

4.2 PRESENT OPERATIONS

For each facility listed below, the current operations associated with the military hardware, coating processes and methods to monitor the new EAP coating (BAM-PPV) during field testing are provided.

4.2.1 Present Operations at WPAFB

WPAFB houses the AFRL Materials and Manufacturing Directorate and the 445th Airlift Wing. Current laboratory operations for the AF have been performed by the Coatings Technology Integration Office (CTIO). CTIO serves as the AF's central resource for aircraft coating systems and their applications. CTIO primary objectives are pollution prevention and improved coating system performance through the integration and transition of environmentally acceptable materials and processes for aircraft refinishing. The facility holds a climate-controlled paint booth that can be controlled to allow paint application and curing over the full range of environmental conditions likely to be found in the field. The equipment brings climate-related problems (e.g., poor film-build, sagging) into the lab for controlled study and resolution. Adjacent to the large booth (10 feet x 14 feet x 9 feet) is an equally large climate-controlled prep area. This combination permits the AF to coat samples that range from very small to large sections (8 feet by 4 feet and larger). Equipment is available to immerse samples in alkaline cleaners, acid etches, and conversion coatings (either Cr(VI) or Cr(VI)-free). The equipment accommodates both hand- and spray-applied surface pretreatments. University of Dayton Research Institute (UDRI) contractor support for the CTIO, operate the facility and their organization is accredited to International Organization for Standardization (ISO) 17025 and Society of Automotive Engineers (SAE) AS5505 for the application, testing, and performance characterization of organic coatings. CTIO has developed a working relationship with the C-5 Systems Group and the 445th Airlift Wing to solve de-paint, coating application, and coating performance issues.

4.2.2 Present Operations at ARL

The ARL at Aberdeen Proving Ground (APG) has the capability to apply most of the coatings and pretreatments included in the chemical agent resistant coatings (CARC) application specification to smaller parts and test coupons. ATC has similar capabilities with the added ability to apply these coatings in-situ to systems. The removed components should pose no problem for either facility. Both components had a blasted surface with BAM-PPV pretreatment substituted for a conversion coating. This was followed by a standard CARC coating of MIL-P-53022 primer and MIL-DTL-64159 waterborne polyurethane in a color to match the vehicle. The inspections were on a phase schedule that coincides with that of the vehicle to which the parts are affixed. This was once every 3 weeks, which depended on the mechanical stability of the vehicle.

4.2.3 Present Operations at FRC-NW

At FRC-NW/Naval Air Station Whidbey Island and Intermediate Maintenance Facility/Naval Base Kitsap at Bangor, the substrate pretreatment for non-flight support components typically includes a conversion coating. CCCs are used for both zinc-plated parts as well as aluminum components, in order to prevent corrosion. For aluminum components, a high-solids epoxy primer coating would be applied to this (based on MIL-PRF-23377, MIL-P-53022, or MIL-P-53030), followed by a polyurethane topcoat (based on MIL-PRF-85285). Coating pretreatments must serve the following corrosion prevention functions: passivation of base aluminum; action as a barrier against moisture, oxygen, and other corrosive agents; electrochemical insulation; and protection against mechanical erosion. In addition, conversion coatings must provide other essential interfacial properties to complement the next coating layers. This includes an effective and continuous bonding site; chemical stability during the service life of coated products; insolubility, imperviousness, and flexibility. The ability to provide a wettable subsurface for paint application and maintaining adhesive integrity is also required.

Regular maintenance is typically performed at the squadron level at the FRC-NW. The regular maintenance cycle calls for inspections every 364 days. Only when there is the need for a major repair do the components actually get sent back to FRC-NW. Upon receipt of the equipment, the coating system would be stripped prior to repair. Once the component has been repaired and the coating system refurbished, FRC-NW would send the component off as needed. It may go to the supply shelf, or it may be returned to the aircraft in order to go back into service.

4.2.4 Present Operations at NASA-KSC

The NASA Beach Corrosion Test Facility has continued to operate for several decades as the premier marine outdoor exposure testing facility. The operating environment consisting of harsh marine conditions: solar, high humidity, salt spray, rain, and wind make it an ideal operating environment to monitor the effects of marine corrosion on various surfaces. These conditions provide a prime location to measure the robustness of new coatings systems that can mimic real world sea environments. The ability to obtain real-time data and to monitor corrosion experiments under harsh weather conditions is a noted feature of this facility. It continues to offer operating partnerships with industry, private, and government organizations to monitor corrosion in an outdoor marine environment.

4.3 SITE-RELATED PERMITS AND REGULATIONS

For each facility, no site-related permits or regulations allowing for field testing or marine outdoor exposure testing was required. The only basis for testing BAM-PPV coated panels on non-critical military components or marine outdoor exposure was the ability of the EAP to meet minimum corrosion/adhesion requirements set down in the JTP December 2000 [22].

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5.0 TEST DESIGN

During Phase I, laboratory experiments by each of the co-performers was undertaken to determine the corrosion/adhesion properties of BAM-PPV as a pretreatment coating. Also BAM-PPV was incorporated into full military coatings and subjected to a variety of accelerated weathering and adhesion tests. In addition, marine outdoor and outdoor exposure tests were performed at NASA-KSC and WPAFB, respectively. Toxicology tests were also investigated to determine lethal doses on experimental animals using BAM-PPV powder. The best performing military coating systems using BAM-PPV as the pretreatment were down selected for field testing during Phase II for this completed ESTCP program. The flow chart (Figure 3) shown below provides a review of the overall execution of Phases I and II.

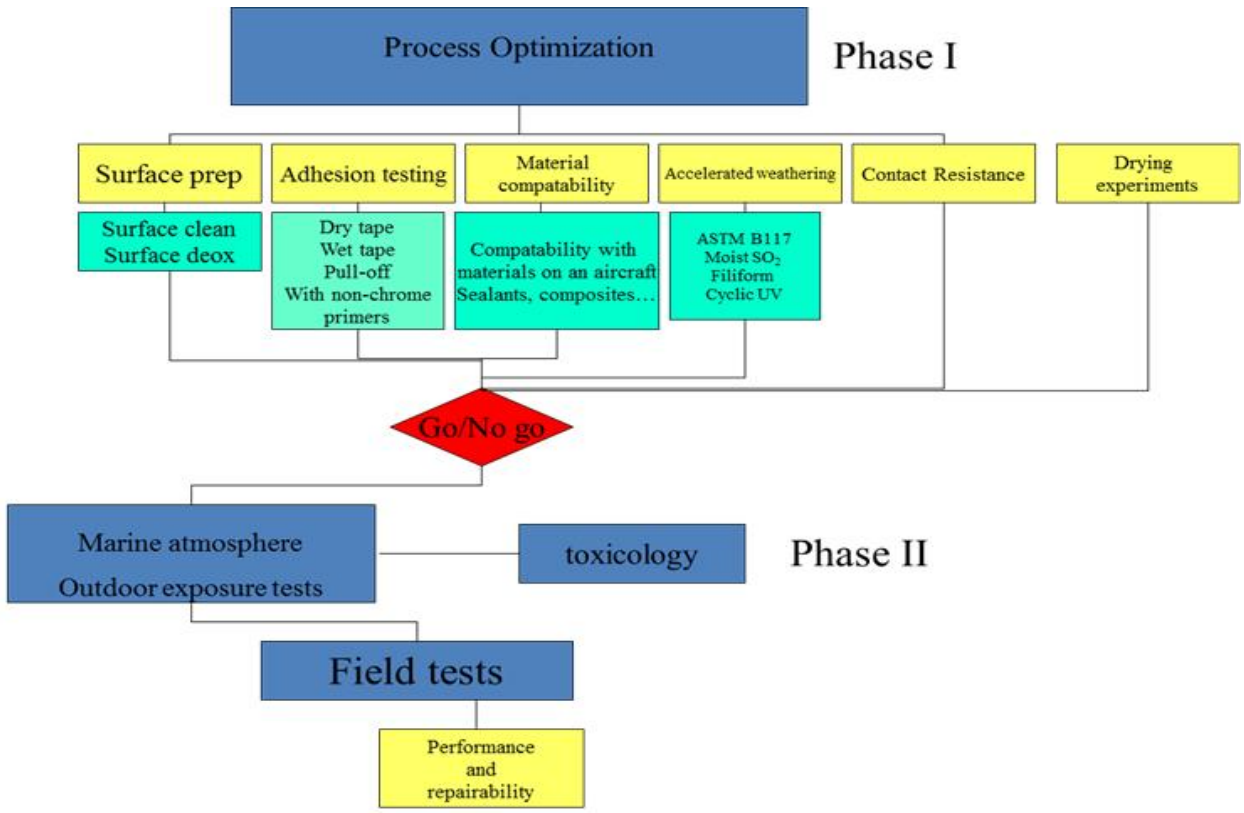

Figure 3. Flow chart for EAP testing and down-selection for field studies during phases I and II.

5.1 JTP TESTING OF BAM-PPV PRETREATMENT COATING

Table 4 lists all engineering and testing requirements identified for validating alternatives to CCCs that are common to all affected defense systems. Table 4 includes acceptance criteria and references, if any, used for developing the tests that are taken from the JTP developed by NAWCAD [22].

Table 4. Engineering and testing requirements.

Phase	Engineering Requirement	Test	JTP Section	Acceptance Criteria	References
I	Corrosion resistance	Neutral salt fog on unpainted substrate with pretreatment	3.1	• Class E: 7 days with no visible sign of corrosion whatsoever; spots and discoloration are acceptable; lightening of coating is acceptable. • Class B 1: 7 days with no visible sign of corrosion; lightening of coating is acceptable. • Class B 2: 14 days with no visible sign of corrosion; lightening of coating is acceptable.	ASTM B 117, ASTM D 714
I	Corrosion resistance	Neutral salt fog on scribed, painted substrate	3.2	• Class C: 3000 hours with no evidence of corrosion (minor surface corrosion in scribe permissible). • Dry scrape adhesion after exposure to corrosive environment.	ASTM B 117, ASTM D 714
I	Corrosion resistance	SO_2 salt fog on scribed painted substrates	3.3	• Class C: 500 hours with no evidence of corrosion (minor surface corrosion in scribe permissible). • Dry scrape adhesion after exposure to corrosive environment.	ASTM G 85, ASTM D 714
I	Corrosion resistance	Cyclic corrosion test on scribed, painted substrates	3.4	• Class C: Equivalent or improved performance compared to controls. • Dry scrape adhesion after exposure to corrosive environment.	GM 9540P
I	Corrosion resistance	Filiform corrosion resistance	3.5	All filaments ≤1/4"; Majority <1/8"	MIL-P-23377G and MIL-PRF-85582C
I	Corrosion resistance	Marine atmospheric test (beach test) exposure on scribed, painted substrates	3.6	Class C: Equivalent or improved performance compared to chromate controls.	KSC-STD-C-001D
II	Corrosion resistance	In-service corrosion	3.7	Equivalent or improved performance compared to chromate controls.	NA
I	Adhesion	WTA and water resistance of painted substrates	3.8	Rating of 4A or 5A.	Method: Modified Federal Test method Standard 141C. Rating: ASTM D3359 Method A. Test at 1, 4, and 7 days.
I	Adhesion	Dry tape adhesion and water resistance of painted substrates	3.9	Loss of two or more complete primer squares shall constitute failure.	Army CARC performance clause "Long Term CARC Adhesion" (ASTM D3359 Method B)

Table 4. Engineering and testing requirements (continued).

Phase	Engineering Requirement	Test	JTP Section	Acceptance Criteria	References
II	Adhesion	In service paint adhesion	3.10	Equivalent or improved paint adhesion compared to chromate controls.	NAVAIR 01-1A-509
I	Electrical resistance	Electrical conductivity of unpainted, pretreated substrated	3.11	• <5 milliohms/square-inch as coated. • <10 milliohms/square-inch after 168 hours neutral salt fog exposure.	MIL-C-81706
I	ESOH	Toxicology	3.12	Less toxic than MIL-C-81706 chromate conversion coating control per EPA Toxicity Categories (40 [CFR] 156.10)	40 CFR Parts 798, 158, 156, MIL-C-81706
II	Repairability	Repairability	3.13	Corrosion resistance, paint adhesion, and electrical contact resistance equal to or better than controls.	ASTM B 117, ASTM D 714, ASTM D3359, MIL-C-81706

CFR = Code of Federal Regulations
ESOH = Environmental Safety and Occupational Health
WTA = wet tape adhesion

FIELD AND REAL-WORLD TESTING OF BAM-PPV PRETREATMENT COATING

The following sections provides a description on the testing that was done on BAM-PPV pretreatment including outdoor, marine outdoor, and real-world field tests.

5.1.1 Outdoor Exposure Testing

Because accelerated testing can only give an estimate regarding corrosion resistance, degradation, and adhesion characteristics of a coating system, outdoor weathering was included in a battery of exposure tests to determine the effect natural weather patterns and environmental exposure would have on a coating system. These data along with accelerated corrosion and weathering data provide more detail to the anticipated performance of the EAP coating system prior to field testing. This test was performed on topcoated systems for AA2024-T3 substrates only. ASTM D 1014, *Standard Practice for Conducting Exterior Exposure Tests of Paints and Coatings on Metal Substrates*, was used for guidance to run the test and to evaluate the samples. Samples were scribed with an X-scribe (full size) prior to exposure. To prevent loss of the panel number during exposure, a label was applied to the backs of each sample prior to exposure. There were three replicates per coating system. Samples were rated and photographed every month for the first 6 months and then every 3 months thereafter until the end of the test.

5.1.2 Marine Outdoor Exposure Testing

The NASA Beach Corrosion Test Facility was used as the site for marine outdoor exposure testing. Full military X-scribe (full size) coatings are exposed to solar, high humidity, salt spray, rain, and wind. The beachfront laboratory has the capability to provide real-time data access to monitor corrosion experiments and surrounding weather conditions. Typical evaluations are similar to laboratory methods and the list is provided below following ASTM methods:

- Corrosion from the scribed surface (ASTM 1654);
- Degree of rusting on painted steel surface (ASTM D 610);
- Degree of blistering of paints (ASTM D 714);
- Color in CIE lab format (ASTM D 2244);
- Gloss (ASTM D 523); and
- Overview photo-documentation of the samples.

5.1.3 Field Testing of BAM-PPV Pretreatment Coating

Each service field tested the best performing full military coating down-selected from Phase I for a 1-year field test during Phase II.

5.1.4 Field Testing at WPAFB

The test components (C-5 cargo plane's rear hatch door) were monitored for 12 months in field service conditions, as determined by C-5 Systems Group and mission requirements. Because of the proximity of the 445th Airlift Wing to AFRL Materials and Manufacturing Directorate (AFRL/RX) operations, the preparation of the test articles was performed with direct assistance from AFRL. The C-5 rear hatch door was removed from the aircraft and transported to the CTIO facility a short distance away and coated there by AFRL personnel. The door was re-affixed to an operational aircraft and monitored for adhesion behavior, corrosion resistance, and color retention for 12 month time frame (flight hours = 299.7).

5.1.5 Field Testing at ARL

This specific piece of hardware (headlight cover on Bradley vehicle) was selected due to its non-critical military hardware status and ease of visual inspection and removal during maintenance cycles. The Bradley vehicle headlight cover was sand blasted prior to coating to achieve the appropriate surface roughness. Solutions were then applied onto the substrate using HVLP spray equipment, coated with MIL-DTL-53022 non-Cr(VI) primer, and top-coated with MIL-DTL-64159 (waterborne CARC polyurethane topcoat). The vehicle underwent field testing on the ARL outdoor weathering test track in Maryland and was exposed to rain, snow, sleet, sun, wind, coastal moisture, and humidity. Visual inspections for corrosion, adhesion, color change, gloss, chalking, cracking, peeling, and alligatoring were performed every 3 months during the 1-year field test experiment.

5.1.6 Field Testing at FRC-NW

Bomb hoists and towbars were pretreated with BAM-PPV coating using the following process whereby a solution of BAM-PPV dissolved in Oxsol-100 is then sprayed via HVLP onto the bomb hoists and towbars. Then the BAM-PPV is coated with a primer (MIL-PRF-23377N) and topcoated with MIL-PRF-85285. The parts were put into service and monitored monthly via visual inspection for corrosion, chipping, abrasion, and delamination of coating during normal operations.

6.0 PERFORMANCE ASSESSMENT

6.1 JTP LABORATORY TESTING FOR BAM-PPV PRETREATMENT COATING

The comprehensive result from laboratory studies using BAM-PPV pretreatment with and without primer and topcoat is fully documented in the JTR. This JTR documents all results of BAM-PPV including success and failures and provides information regarding why failures occurred and how to address them in future studies. Sections 6.1.1.1 - 6.1.1.1.5 from the JTR document the extensive laboratory studies performed on BAM-PPV pretreatment coatings.

6.1.1 Adhesion Testing for BAM-PPV Pretreatment Coating

The following sections describe the adhesion testing performed on BAM-PPV pretreatment coatings. The BAM-PPV pretreatment coating was tested in various combinations with primers and topcoats. Both qualitative and quantitative adhesion testing was performed on BAM-PPV coated coupons. The following adhesion tests were performed on BAM-PPV pretreatment coatings with and without primer and topcoat.

- ASTM D 3359, Method B, Crosshatch Adhesion (MIL-PRF-23377);
- Federal Test Method Standard 141D, Method 6301, WTA (MIL-PRF-23377, MIL-PRF-85285); and
- ASTM D 4541 PATTI, Pull-Off Adhesion.

The results from each of the above adhesion testing performed independently by the AF, Army and Navy showed that BAM-PPV pretreatment has adequate adhesion characteristics in several coating systems (pretreatment + primer + topcoat). The coating systems that had adequate adhesion consisted of BAM-PPV layer (with and without primer/topcoat) + epoxy primers (MIL-PRF-23377C or MIL-PRF-23377N) and polyurethane topcoats (MIL-PRF-85285 or MIL-DTL-64159).

6.1.2 Accelerated Weathering Testing for BAM-PPV Pretreatment Coating

The following tests were used to assess the performance of BAM-PPV as a pretreatment coating by the three services. BAM-PPV pretreatment coated coupons were evaluated against current chromated systems.

- NSS Testing (ASTM B 117)
- GM9540P (General Motors accelerated corrosion test)
- Xenon-Arc Accelerated Weathering Test
- Moist SO_2 Tests
- Filiform Corrosion Resistance of Organic Coating Testing

The AF tested BAM-PPV using NSS, GM9540P, and Xenon-Arc and the results are listed below:

- ASTM B117 NSS exposure testing verified that BAM-PPV and Prekote (control) pretreatment coating only on both AA2024-T3 and AA7075-T6 coupons did not pass 336 hours NSS exposure;

- ASTM B117 NSS exposure testing verified that BAM-PPV and Prekote (control) pretreatment coating only on both AA6061-T6 and AA5083-H116 passed the 336 hours NSS exposure testing;
- BAM-PPV as pretreatment coating with MIL-PRF-23377C or MIL-PRF-23377N with MIL-PRF-85285 or APC topcoat passed 2000 hours NSS;
- Xenon-Arc testing (500 hours) of BAM-PPV coating systems showed no change in)E greater than 1; and
- BAM-PPV military coating systems performed as well as the Prekote military system in GM9540P accelerated weathering tests.

The Army tested BAM-PPV pretreatment on both aluminum and steel alloys in NSS and found that BAM-PPV performs best when the metal surface is grit blasted prior to testing.

Both the NAWCWD and NAWCAD tested BAM-PPV with and without primer and topcoat in NSS, SO_2 and filiform chambers and the following conclusions can be made about BAM-PPV's performance:

- BAM-PPV passed $\geq$ 336 hours NSS exposure testing;
- SO_2 salt spray exposure resulted in BAM-PPV coatings failing at 500 hours, which did not meet the minimum requirement for passing; and
- Filiform testing resulted in BAM-PPV coatings failing.

6.1.3 Additional Testing for BAM-PPV Pretreatment Coating

Several additional tests were performed on BAM-PV pretreatment coatings to determine its robustness as compared to current AF and Navy pretreatment coatings. These additional tests were selected by each of the co-performing organizations according to their military coating requirements.

The AF examined the degree to which BAM-PPV pretreatment coating can perform as well as current coatings when exposed to the following tests:

- Pencil hardness (ASTM D 3363 pencil hardness [MIL-PRF-23377, MIL-PRF-85285]);
- Fluid resistance (hydraulic, lubricating oil, and JP-8 fluid resistance [MIL-PRF-83282, MIL-L-23699, MIL-PRF-23377, MIL-PRF-85285]);
- GE impact flexibility (ASTM D 6905 GE impact flexibility testing [MIL-PRF-23377, MIL-PRF-85285]);
- Repairability (repairability testing [T.O. 1-1-8, Table 3-2; MIL-R-81294; MIL-PRF-25134; and TT-R-2918]); and
- Storage and stability.

The results from WPAFB testing of BAM-PPV are listed below:

- BAM-PPV has an acceptable pencil hardness rating of HB at ambient conditions;
- No deficiencies in JP-8 fuel resistance was observed with BAM-PPV coating systems;
- Lubricating fluid resistance results of topcoated BAM-PPV systems showed no change in pencil hardness from room temperature results; and
- Impact flexibility showed that BAM-PPV coated systems performed as well as Alodine 1200 systems.

Full discussion of the above results is found in the JTR.

The NAWCAD also tested BAM-PPV pretreatment coatings for ECR testing. When tested in accordance with MIL-DTL-81706, the contact electrical resistance of aluminum alloy panels treated with class 3 materials under an applied electrode pressure of 200 psi shall be not greater than 5.0 milliohms psi as applied, and 10.0 milliohms psi after salt spray exposure. Individual readings not greater than 20% in excess of the specified maximums shall be acceptable, provided that the average of all readings does not exceed the specified maximum resistance. The ECR results for BAM-PPV are shown below with a full discussion provided in the JTR.

- ECR measurements for BAM-PPV gave satisfactory results. Several BAM-PPV panels passed the ECR mil spec before NSS exposure and after NSS.

6.1.4 Toxicology Testing of BAM-PPV Powder

The following tests were measured for BAM-PPV powder except acute inhalation toxicity/LC_{50} in rats due to the inability to process BAM-PPV powder to meet test specifications.

- Acute Oral Toxicity-Up and Down Procedure (UDP) Standard Protocol Number 1010-02
- Acute Dermal Toxicity/LD_{50} in Rabbits Standard Protocol Number 1100-02
- Acute Eye Irritation in Rabbits Standard Protocol 1200-02
- Acute Dermal Irritation in Rabbits Standard Protocol 1130-02
- Delayed Contact Dermal Sensitization Test-Buehler Standard Protocol Number 1160-03
- Acute Inhalation Toxicity/LC_{50} in Rats Standard Protocol Number 1300-02

The results are summarized below and a full discussion is found in the JTR.

- BAM-PPV is a non-toxic, non-hazardous material.
- BAM-PPV has an LD50 $\geq$2000 mg/kg for both acute dermal and acute oral toxicity.
- BAM-PPV is not a dermal irritant.
- BAM-PPV is not a sensitizer.
- BAM-PPV does not appear to be an acute inhalation material due to its difficulty in producing small particles that can enter the lungs.

- BAM-PPV conforms to EPA/OSHA standards.

6.2 FIELD AND REAL-WORLD TESTING FOR BAM-PPV PRETREATMENT COATING

6.2.1 Outdoor Exposure Testing

WPAFB conducted outdoor exposure testing on BAM-PPV pretreatment coating with full non-chromium and chromium military coating versus chromate controls for 24 months of exposure. BAM-PPCV survived 24 months of outdoor exposure without any loss of properties.

6.2.2 Marine Outdoor Exposure Testing

NASA-KSC conducted marine outdoor exposure testing on BAM-PPV with both non-chromated and chromate primers with topcoats. The results are summarized below:

- BAM-PPV failed the marine outdoor exposure testing;
- BAM-PPV showed signs of corrosion after several months of marine outdoor exposure with non-Cr(VI) epoxy primer and topcoat indicating that the BAM-PPV coated panels were failing this test;
- BAM-PPV showed improved performance (survived 9 months) with chromated primer and topcoat but did not survive a full year of testing thus failing this test; and
- Best performing systems were CCC + chromated or non-chromated primer + topcoat and TCP + chromated or non-chromated primer + topcoat, which passed this test by surviving 1-year of marine outdoor exposure.

6.2.3 Field Testing for BAM-PPV Pretreatment Coating

Field testing of BAM-PPV pretreatment on the C-5 cargo plane rear hatch door showed after 12 months (299.7 hours) no damage or corrosion. The results provided convincing evidence that BAM-PPV can survive AF mission environments using the NAWCWD's BAM-PPV as a non-chromium pretreatment coating (Table 5).

Table 5. Assessment of BAM-PPV field test on C-5 cargo aircraft rear hatch door.

Visual Inspection Test	Performance at 12 months
ASTM D 660 Degree of Checking of Exterior Paints	No Damage
ASTM D 661 Degree of Cracking of Exterior Paints	No Damage
ASTM D 662 Degree of Erosion of Exterior Paints	No Damage
ASTM D 714 Degree of Blistering of Paints	No Damage
ASTM D 772 Degree of Flaking of Exterior Paints	No Damage
ASTM D 1654 Evaluation of Painted Specimens Subjected to Corrosive Environments	No Damage
ASTM D 4214 Degree of Chalking of Exterior Paints	No Damage

For the ARL field tests, the Bradley vehicle headlight cover (AA2024-T3) was tested at the ATC. BAM-PPV was sprayed onto the substrate using HVLP spray equipment coated with MIL-DTL-53022 non-Cr(VI) primer and top coated with MIL-DTL-64159 (waterborne CARC polyurethane

topcoat) for a 1-year field test. The results are summarized in Table 6, which shows that BAM-PPV incorporated as the pretreatment layer with non-Cr(VI) epoxy primer and topcoat survived this test with minor corrosion damage to the entire coating.

Table 6. Assessment of BAM-PPV field test on headlight cover of Bradley vehicle.

Visual Inspection Test	Performance at 12 months
ASTM D 523 Gloss Measurements	No Damage
ASTM E 308 Color Measurements	No Damage
ASTM D 1654 Evaluation of Painted Specimens Subjected to Corrosive Environments	Limited corrosion damage to areas where all coatings were removed including BAM-PPV
ASTM D 4214 Degree of Chalking of Exterior Paints	No Damage

Field testing at the FRC-NW facilities using BAM-PPV coated bomb hoists and towbars were used as non-critical military hardware. The bomb hoists and towbars were pretreated via HVLP spray gun with BAM-PPV (coating thickness ~2 microns, dissolved in Oxsol-100), primed (MIL-PRF-23377N), and topcoated with MIL-PRF-85285. The parts were put into service and monitored monthly via visual inspection for corrosion, chipping, abrasion, and delamination of coating during normal operations. After 6 months of service, the BAM-PPV coated bomb hoists showed significant chipping and scratches as documented in Table 7 indicating complete failure of the BAM-PPV coating system. For a further discussion of the poor performance of BAM-PPV coated towbars and bomb hoists, refer to the JTR.

Table 7. Assessment of BAM-PPV field test on bomb hoists and towbars.

Visual Inspection Test	Performance at 12 months
ASTM D 660 Degree of Checking of Exterior Paints	Failure ≤6 months
ASTM D 1654 Evaluation of Painted Specimens Subjected to Corrosive Environments	Failure ≤6 months
ASTM D 4214 Degree of Chalking of Exterior Paints	Failure ≤6 months
ASTM 661 Degree of Cracking of Exterior Paints	Failure ≤6 months
ASTM 772 Degree of Flaking of Exterior Paints	Failure ≤6 months

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7.0 COST ASSESSMENT

7.1 COST MODEL

The costs associated with reducing Cr(VI) from current military hardware will be significant. By eliminating Cr(VI) from the pretreatment a cost saving in reduction of hazardous waste and compliance with current and future regulatory directives will ensure mission readiness and improve worker safety.

7.1.1 Performing Organization Example

As an example, the C-5 is about 10,000 square feet (sq. ft.) in surface area and that at least 80% of that must be chromate conversion coated. Removal of chromates from the conversion coating process will prevent the added costs of environmental testing and medical monitoring of employees, both of which are required for processes that have Cr(VI) levels above the action level of 2.5 $\mu g/m^3$.

There are several ways in which this ESTCP project will reduce cost and pollution.

- Using BAM-PPV as a new pretreatment coating will allow the elimination of Cr(VI) from the pretreatment coating process for metal alloys, which results in:
  - eliminating the chromated hazardous waste and the cost associated with the disposal, and
  - increasing worker safety and eliminating the cost of health monitoring the Cr(VI).
- Other advantages of this technology include:
  - no special equipment required, and
  - no detrimental effect to air quality due to use of exempt solvent.

By eliminating the CCC from current military applications at the depot level one can significantly reduce the costs associated with coating and re-coating non-critical equipment. These saving would result in reduction of hazardous disposal costs that continue to rise across the United States due to the most recent OSHA rules governing Cr(VI) PEL in operating areas. The application of the BAM-PPV solution onto non-critical equipment uses current spray equipment present at all major military depots. Oxsol-100 is the most promising solvent of choice because it is a VOC-exempt solvent. This makes solutions of BAM-PPV very attractive due to its solubility in a non-polluting solvent and easy application onto a variety of substrates.

7.1.2 Data Requirements

To document the anticipated cost savings, the Environmental Cost Analysis Methodology (ECAM) will be used to perform a cost/benefit analysis for the application of the BAM-PPV solution using Oxsol-100 solvent applied via spray technology on non-critical equipment at each military facility [23]. Both the baseline costs and the costs for the new process will be examined. An assumption is made that because an EAP solution is applied onto non-critical equipment using a VOC-exempt solvent, all CCC coatings are eliminated on these same non-critical equipment.

Table 8 will be used to track the costs associated with equipment, design, site preparation, permitting, installation, and training.

Table 8. Environmental activity costs.

Direct Environmental Activity Costs		Indirect Environmental Activity Costs	Other Costs
Start-up (innovative process only)	**Operation & Maintenance**		
Facility preparation, mobilization	Labor to operate equipment	Compliance audits	Overhead associated with process
Equipment design	Labor to manage hazardous waste	Document maintenance	Productivity/cycle time
Installation	Utilities	Environmental management plan development and maintenance	Worker injury claims and health costs
Training of operators	Hazardous waste disposal fees	Reporting requirements	
	Raw materials	Test/analyze waste	
	Process chemicals, nutrients	Medical exams (including loss of productive labor)	
	Consumables and supplies	Waste transportation (on and off-site)	
	Equipment maintenance	OSHA/EHS training	
	Training of operators		

7.1.3 Performing Organization

No outside organizations such as consultants or other federal agencies were used to track costs, or develop a cost/benefit analysis. All data was done in-house by each of the co-performers listed in Appendix A.

7.1.4 Assumptions Based on BAM-PPV Coating Process

The major assumption for the BAM-PPV coating process was the number of passes required to reach the minimum thickness of 2 microns. This number was nine passes, which provided a 2 micron thick film necessary for acceptable performance levels. The number of passes for BAM-PPV is considerably higher than currently used for CCCs. Therefore, this increases potential costs associated with implementing this technology.

A potential joint venture with Dr. Fredrik von Kieseritzky, CEO, Arubedo AB, Sigtunagatan 10, 113 22 Stockholm, Sweden (fvk@arubedo.com, 46 70 751 5353) and NAWCWD was initiated in December 2012. The research group under Dr. von Kieseritzky, is trying to develop a solvent system that will improve the solubility of BAM-PPV during coating processes. No Cooperative Research and Development Agreement (CRADA) has been signed between the two groups but the project team is pursuing potential funding from European sources.

7.1.5 Emissions Monitoring and Reporting for BAM-PPV Applications

Due to the fact that the solvent employed for all demonstrations was VOC-exempt (Oxsol-100), no emissions monitoring was required during the application of the BAM-PPV to non-critical military hardware. The solvent and BAM-PPV are both compliant with federal and state regulations.

7.1.6 Scale of Operations

Current operations for producing BAM-PPV are at the kilogram scale with scale-up to higher quantities feasible. An industrial partner must be obtained in order to scale-up to industrial levels but at this time the two issues preventing scale-up are control of molecular weight and reduction in the number of passes associated with coating BAM-PPV onto various substrates.

7.1.7 Life Cycle Costs Time Frame

It is reasonable to assume that many DoD assets are on a schedule for maintenance and recoat activities. These schedules vary based upon the asset (aircraft, vehicle, etc.) as well as the mission requirements. For the AF assessment, a typical legacy cargo aircraft has a life cycle of at least 20 more years. However, cost analyses have shown that the base periodic inspection workload does not increase with the age of the cargo aircraft during the 20-40 year lifespan [24]. With this in mind, the AF assessment will assume a life cycle on a legacy cargo aircraft for the next 20 years.

7.2 COST ANALYSIS AND COMPARISON

Once EAPs are approved for use by military organizations, the cost to implement within the AF should be minimal. This is because the EAP material can be applied via HVLP; the primary system utilized by AF, Navy, and Army maintenance operations. The need for extensive PPE, hazardous waste removal, employee monitoring, and other expenses associated with CCC do not exist with the EAP-based coating systems. Storage stability of EAPs will be the only issue that may deter the implementation of this system in place of CCC. Packaging and availability of the final product will need to be determined by an appropriate vendor (not available at this time) who will receive this technology.

As there does not seem to be costs associated with equipment change for application of the EAPs, the change in cost would be due to increased preparation time (mixing the EAP), change in application time, savings from hazardous waste disposal costs, and savings in depainting costs because EAPs are Cr(VI)-free.

7.2.1 EAP Primary Cost Element Categories

The cost drivers for the manufacture of BAM-PPV will be dependent on obtaining a manufacturer of the material. BAM-PPV has only been synthesized at the kilogram level by scientists at the NAWCWD, China Lake, California and through a Small Business Innovative Research (SBIR) contract (ONR sponsored) with Spectra Group Ltd, Toledo, Ohio. Multiple kilogram quantities have been prepared during the previous SERDP program and completed for this ESTCP program. The costs associated with preparing multiple kilogram quantities based on the synthetic process developed at NAWCWD is ~ $10.00/gram. The improvement in the synthesis of BAM-PPV by

Spectra Group Ltd will reduce the cost of manufacturing BAM-PPV. Recently, Spectra Group Ltd provided NAWCWD with costs on preparing the BAM-PPV polymer. Their costs for preparing the BAM-PPV polymer were estimated at $20/gram. Because the price drops the more you make, 500 grams would cost approximately $13.40/gram and for 10 kg it would be approximately $6.02/gram (see Table 9).

Table 9. Estimated cost of making BAM-PPV.

Amount of Scale Grams	Estimated Price/Gram
100	$20/gram
500	$13.40/gram
2,500	$8.98/gram
10,000	$6.02/gram

Both NAWCWD and Spectra Group Ltd used recovered solvents. Almost all the reactions can be done using the recovered solvent and reuse for the same reaction. Reactions at NAWCWD and Spectra Group Ltd. were done on a 10 and 22 liter scale, respectively, distilling the used solvent, and then using the recycled solvent for repeating the reaction. There were no ill effects from using recycled solvent during any of the synthetic steps used to make BAM-PPV. This process could be easily scaled-up to a manufacturing level and several manufacturers of specialty chemicals could use reactors that hold up to greater than 10,000 liters. The project team believes there would be no problems with doing any of the reactions to produce the BAM-PPV on a larger scale.

Therefore, the primary factors affecting cost for implementing this technology are the following:

- Control of molecular weight for BAM-PPV production (major);
- Improve solubility for HVLP application (major);
- Facility capital costs (minor);
- Start-up and operations and maintenance costs (minor);
- Equipment replacement costs (negligible); and
- Re-processing or re-application costs (negligible).

7.2.2 Facility Capital

The costs for facility capital are minor since most depots and maintenance sites use commercial-off-the-shelf HVLP spray equipment. These sites all have spray booths and this is where the majority of the application of BAM-PPV solutions will occur. BAM-PPV spraying does not require any new equipment rather standard HVLP are appropriate for delivering BAM-PPV solutions to the substrate.

7.2.3 Start-up and Operations & Maintenance

As BAM-PPV is a potential “drop-in” replacement for CCC, there should be no costs associated for equipment changes or operations/maintenance issues other than the present requirements associated with CCCs. For each of the military services at the depot level, there is no cost associated with start-up and operations since BAM-PPV can be used with existing equipment.

As an example, for the AF, there are no costs associated with the start-up for incorporation of the BAM-PPV material. The material is sprayed using HVLP equipment, which is standard at the Air Logistics Complexes. Additionally, mixing equipment, hazardous materials storage, and basic organic coating application and maintenance practices would not be altered by incorporation of BAM-PPV.

7.2.4 Equipment Replacement

There is no equipment replacement for applying BAM-PPV solutions onto various substrates. HVLP spray equipment is the current method used for coating substrates and equipment at various DoD depots and maintenance facilities.

7.2.5 ESOH and Cost Avoidance

The ESOH regulations do not apply to BAM-PPV due to its non-hazardous, non-toxic properties as determined by MB Research Laboratories. BAM-PPV has been found (see page 20 for details) and the JTR for a full explanation. Therefore, costs associated with ESOH compliance are avoided. Only PPE that are required during painting are needed.

7.2.6 Reprocessing/Reapplication

Reparability studies of BAM-PPV coated panels showed that BAM-PPV was easily removed and replaced with new BAM-PPV coating without any degradation of the coating during accelerated weathering and adhesion tests. These results are described and documented in the JTR. BAM-PPV does not have any issues regarding its removal and re-application onto various substrates.

AF and Army testing and field demonstration of the BAM-PPV material showed that the material can be repaired and reapplied where necessary following standard procedures in T.O. 1-1-8.

7.2.7 Hazardous Waste Storage and Disposal

Because BAM-PPV is a non-toxic, non-hazardous material and complies with both state and Federal regulations regarding disposal of non-hazardous waste, this material allows for significant reductions in costs associated with current chromate systems.

As a result of the new Cr(VI) OSHA regulations, these new standards will now cover occupational exposure to Cr(VI) for workers during an 8-hour TWA period. In order for the DoD to comply with these regulations, there will be an increase in disposal costs for Cr(VI) waste paint as a hazardous material. The costs associated for industry/government to comply with the new federal Cr(VI) PEL are summarized in Table 10. Table 10 provides a historical summary of the OSHA requests for information from the DoD and their response regarding compliance costs with reducing Cr(VI) exposure.

Table 10. Estimated compliance costs for general industry with new Cr(VI) guidelines.

Cost Category	10 µg/m^3	5 µg/m^3	1 µg/m^3	0.5 µg/m^3	0.25 µg/m^3
Engineering controls	$10,652,864	$14,475,735	$26,474,262	$52,467,526	$82,207,372
Initial exposure assessment	$15,250,335	$15,250,335	$15,250,335	$15,250,335	$15,250,335
Periodic monitoring	$24,605,517	$30,034,467	$60,305,070	$126,687,514	$161,729,092
Respirators	$29,448,797	$29,448,798	$35,361,768	$40,773,063	$56,907,196
Medical surveillance	$21,211,591	$13,230,302	$67,359,536	$62,126,618	$79,073,671
Communication of hazards	$21,211,591	$21,193,263	$21,881,436	$21,889,546	$21,892,346

The estimates shown below are considered general costs in complying with the 5 µg/m^3 requirement. Each of the affected weapons systems field-tested during this ESTCP demonstration program will have to implement this new guideline. Current alternative Cr(VI)-free primers have been developed by each service and the EAP coating under this ESTCP study does not contain Cr(VI). This allows for easy compliance with the new military Cr(VI)-free coating, whereby EAPs, specifically BAM-PPV, is not considered a hazardous material. Therefore, the DoD would not be required to dispose of BAM-PPV as a hazardous material, thereby, reducing costs.

7.2.8 Life Cycle Costs Comparison

For the AF cost comparison, data was utilized from the Defense Logistics Agency, which publishes the costs associated with pretreatments currently in use. According to the Defense Logistics Agency, the price per gallon of Prekote is $48.50 with coverage of 160 sq. ft. resulting in a cost of $0.30 per sq. ft. Prekote requires two applications using a scrub process, whereas BAM-PPV requires three cross coat applications using HVLP (up to nine applications) to achieve a robust coating. Therefore, the cost of application/manpower time for BAM-PPV would be approximately 1.5 times the amount of time needed for application of Prekote. Overall, the increased manpower cost and materials cost are a significant hurdle for implementation. If these costs could be reduced through cheaper manufacture and fewer applications of the material (fewer cross coats to generate a robust coating), then it is conceivable that the BAM-PPV material could be integrated into AF use. Table 11 provides a reasonable cost estimate for BAM-PPV and compares its cost to CCC and Prekote. The BAM-PPV costs are derived from Table 9 for producing BAM-PPV at the NAWCWD, China Lake, California. This includes both labor and materials costs to produce a gram of BAM-PPV powder. The labor costs associated with research scientists at the doctorate level adds significant costs to the production of BAM-PPV. At $20/gram of material to produce a 1 wt% BAM-PPV gallon solution in Oxsol-100 will cost $1,104.00. This is orders of magnitude more expensive than either CCC or Prekote. The coverage to coat a sq. ft. using CCC or Prekote gallon mix is significantly higher than BAM-PPV by a factor of >2.

Table 11. Costs comparison of BAM-PPV to CCC and Prekote pretreatments.

Pretreatment	Price($)/gallon	Coverage (sq. ft.)	$ per sq. ft.
CCC	32.37	400	0.08
Prekote	48.50	160	0.30
BAM-PPV	1,014.00	75.7	13.41

Additionally, the cost per sq. ft. ($ per sq. ft.) is also significantly higher than either CCC or Prekote. The costs of BAM-PPV could be reduced at the manufacturing level using less expensive labor and reduced materials cost. The reduction in hazardous waste disposal costs compared to CCC would provide a cost saving for implementing BAM-PPV usage at the depot level. If future regulations eliminate the use of Cr(VI) and trivalent chromium from the pretreatment layer and Cr(VI) from the primer layer, then BAM-PPV could potentially be an attractive alternative to these metals for use at the depots.

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8.0 IMPLEMENTATION ISSUES

8.1 IMPLEMENTATION STAKEHOLDERS

The implementation stakeholders are those who can approve new non-chromium pretreatments for DoD equipment and infrastructure:

- NAWCAD,
- ARL, and
- AFRL/Air Force Life Cycle Management Center.

8.1.1 EAP Acceptance Process

The acceptance of BAM-PPV by the DoD community as an alternative to CCCs requires an industrial partner who can control the molecular weight. A consistent batch-to-batch reproducibility is critical for DoD acceptance. Additionally, once the molecular weight issue is solved, the number of passes can be greatly reduced to compete on an equal level with CCC.

8.1.2 Impact of ESOH Regulations

The ESOH regulations do not apply to BAM-PPV due to its non-hazardous, non-toxic properties as determined by MB Research Laboratories. BAM-PPV has been found (see page 20 for details) and the JTR for a full explanation of the toxicology testing of BAM-PPV. The results are provided below as a brief synopsis:

- BAM-PPV is a non-toxic, non-hazardous material;
- BAM-PPV has an LD50 $\geq$2000 mg/kg for both acute dermal and acute oral toxicity;
- BAM-PPV is not a dermal irritant;
- BAM-PPV is not a sensitizer;
- BAM-PPV does not appear to be an acute inhalation material due to its difficulty in producing small particles that can enter the lungs; and
- BAM-PPV conforms to EPA/OSHA standards.

8.2 EAP PROCUREMENT

8.2.1 Process Equipment

There are no issues or requirements for process equipment in order to apply BAM-PPV. The current method of using HVLP is readily available and BAM-PPV solutions can be processed using this spray equipment.

8.2.2 Production and Scale-Up

Scale-up and industrial production is dependent on the two issues still impeding BAM-PPV acceptance by the DoD community. These two issues are: a) molecular weight control and

reproducibility, and b) reducing the number of passes during application to significantly reduce costs of producing BAM-PPV and to make it more cost competitive with both CCC and Prekote.

8.2.3 Proprietary and Intellectual Property Rights

Currently, all patents have expired and were not renewed by the Navy Patent office. Therefore, the DoD does not have any intellectual property rights on BAM-PPV materials/composition, processing, and its corrosion-inhibiting properties.

8.3 TECHNOLOGY TRANSFER EFFORTS

As was discussed in Section 7.1.5, efforts are underway to develop a joint CRADA agreement between the NAWCWD and Arubedo AB. A potential joint venture with Dr. Fredrik von Kieseritzky, CEO, Arubedo AB, Sigtunagatan 10, 113 22 Stockholm, Sweden (fvk@arubedo.com, 46 70 751 5353) and NAWCWD was initiated during December 2012. The research group under Dr. von Kieseritzky, is trying to develop a solvent system that will improve the solubility of BAM-PPV during coating processes. No CRADA have been signed between the two groups but the project team is pursuing potential funding from European sources. The main efforts are focusing on developing a mechanism by which funds can be transferred between the two groups in order to start writing joint proposals to Swedish Government funding agencies, the joint North Atlantic Treaty Organization-Sweden, and EU funding sources.

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APPENDIX A

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