ARL-TR-10137 ● JULY 2025

# Demonstrating Viability of Low-Volatile Organic Compound E-coat Primers for General Depot Use

by Daniel Pope, Brian Rearick, and David Walters

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# Demonstrating Viability of Low-Volatile Organic Compound E-coat Primers for General Depot Use

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Cationic electrocoat (e-coat) primers have revolutionized corrosion protection in the private sector. Automobiles that were manufactured 2–3 years before the invention of cationic e-coat primers were able to have their service life extended to over 10 years after cationic e-coat primers were applied to them. The objective of this project is to demonstrate the technical and economic viability of implementing cationic e-coats in depot applications.

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## Executive Summary

Cationic electrocoat (e-coat) primers have revolutionized corrosion protection in the private sector. The ability to apply a uniform, epoxy-based coating over every surface of intricate parts contributed significantly to extending the service life of automobile coating systems from 2–3 years prior to the invention of cationic e-coat primers, to over 10 years after the coating was applied. This excellent corrosion performance is standard even though cationic e-coats are hexavalent chromium (Cr [VI])-free, hazardous air pollutants (HAPs)-free, and contain low-to-no volatile organic compounds (VOCs).

The military recognizes the corrosion benefits of cationic e-coat and has issued MIL-DTL-0053084A[1] to document qualification criteria. This specification covers waterborne, cathodic epoxy e-coat primer formulated free of lead, Cr (VI), and HAPs. Primers conforming to the specification will meet solvent emission maximums of 144-g/L (1.2-lb/gal) VOC content and be compatible with Chemical Agent–Resistant Coating (CARC) topcoats. This primer is intended for use on properly cleaned and pretreated ferrous and nonferrous metal surfaces. Such primers are already qualified for use from multiple suppliers. E-coat is specified for protecting the Family of Medium Tactical Vehicles and is applied by original equipment manufacturers (OEMs) such as Oshkosh, AM General, and BAE Systems, as well as many small-parts suppliers to the defense industry.

Although the benefits of e-coat compared with spray-applied coatings are known, e-coat use by the DoD is currently limited to OEM purchases, precoated replacement parts, and via outsourcing. We assert that e-coat has not been adopted in the depots because of two key barriers:

1. The misconception that e-coat systems are only designed for industrial operations much larger than depot operations, and
2. The uncertainty that an e-coat system will provide an acceptable return on investment (ROI).

For all its merits, e-coat is only in use for military vehicles at the OEM level. In this demonstration, we show the potential benefits of implementing e-coat at depot facilities, particularly for ground vehicle parts. Activities included 1) obtaining and testing a variety of parts and panels coated with e-coat versus the current spray primer, 2) presenting test results along with cost modeling and "business case" to decision-makers, and 3) beginning discussion with depot-level stakeholders toward

[1] MIL-DTL-0053084A (MR). Detail specification primer, cathodic electrodeposition, chemical agent resistant. Army Research Laboratory (US); 2006 Aug 3.

implementation of appropriately scaled e-coat systems to meet their production needs.

The project team obtained ground vehicle parts, which are known to have corrosion problems, and which are difficult to paint by conventional spray methods due to complex geometry. These included both aluminum (Al) and steel parts such as underbody suspension members. Half were painted with existing spray processes and the other half were processed by PPG Industries, Inc. (PPG) with cationic e-coat technology. All parts and panels were topcoated with CARC topcoat. Testing included outdoor exposure at NASA Kennedy Space Center Beachside Atmospheric Corrosion Test Site in Florida and lab cyclic corrosion testing.

The e-coat process can be divided into four distinct sections:

- Pretreatment
- E-coat bath and ancillary equipment
- Post-rinses
- Bake oven

Parts are first cleaned and pretreated with a zirconium, trivalent chrome, or phosphate conversion coating to prepare the part for e-coating. Parts are dipped into a coating bath where DC is applied between the parts and a counter electrode. The charged coating is attracted through the electric field to the oppositely charged part and is deposited on the part until the film thickness provides enough insulation to cease electrical attraction. Parts are removed from the bath, rinsed to reclaim undeposited solids, and then baked to cure the deposited material. The process is represented in Figure ES-1.

The major advantages of the e-coat process include total coverage of parts that have complex shapes and interior surfaces with unsurpassed film uniformity; material transfer efficiencies known to be in the 95%–99% range; highly automated systems with excellent productivity and low operating costs; fast line speeds and high part racking densities; very low air and wastewater emissions that foster environmental compliance; and a totally enclosed system leading to a cleaner and safer paint application method.

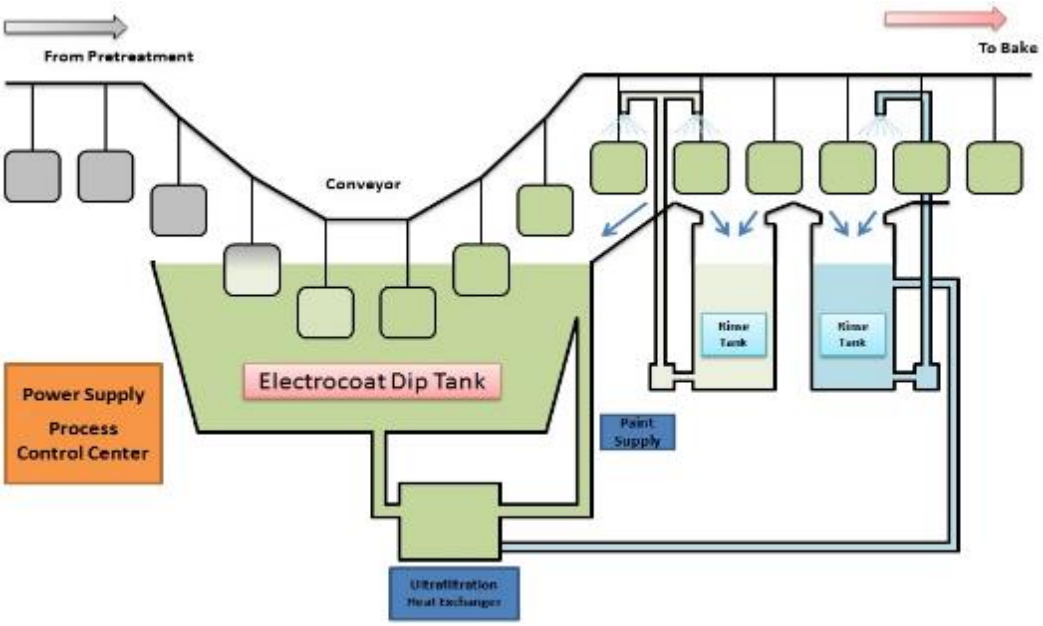


**Figure ES-1. Major components of a representative e-coat system.**

E-coat products can be anodic or cathodic, indicative of where coating deposition takes place. The process works on the principle of "opposites attract." Anodic e-coat involves the use of negatively charged paint particles that are deposited onto positively charged metal substrates. During the anodic process, a small amount of substrate dissolution occurs, resulting in metal ions (ferrous substrate) present in the paint film, which limit the corrosion performance properties of these systems. The main use of anodic e-coat is for products in interior or moderate exterior environments. Anodic coatings are economical systems and offer excellent color and gloss control.

Cathodic deposition, as employed in this program, uses positively charged paint particles that are attracted to a negatively charged part. This involves much less substrate dissolution and consequently offers substantially improved corrosion resistance for ferrous substrates. Cathodic coatings are high-performance coatings with excellent corrosion resistance and can be formulated for exterior durability.

As originally planned, the project would involve designing, fabricating, and installing a small-scale e-coat system at one of the partner organization sites. Parts normally coated with spray-applied coating systems would instead be coated with a MIL-DTL-0053084A-qualified e-coat primer and put in service on tactical vehicles or other equipment. A variety of roadblocks were presented that prevented the original planned activities. Instead, a test matrix was designed including steel and Al parts and panels, which were coated at either Aalberts Surface Technologies in Baltimore, Maryland, or PPG's Euclid, Ohio, facility. This revision to the plan

enabled direct comparison between e-coat and spray-applied epoxy primers, captured meaningful data on performance attributes of e-coat, and enabled both laboratory and outdoor exposure testing of all parts. While not as desirable as fielding an e-coat system in a depot environment, the revised plan provided better data that can be used to secure future buy-in and support of the technology.

To assess the ROI, the information gathered was reviewed with PPG's Industrial E-coat equipment group, which has expertise in translating part volume and coating usage into an estimate of the size and nature of e-coat system needed. This, along with any required peripheral equipment, was used to estimate the capital investment needed to ultimately stand up a complete process. PPG also utilized cost calculators to estimate the payback period of an e-coat system. These calculators use paint consumption numbers, the capital investment required, and the differences in efficiency, maintenance, and waste handling between e-coat and the spray process. Letterkenny Army Depot (LEAD) provided detailed paint consumption and workflow information to serve as a baseline for cost modeling. Multiple scenarios were modeled and potential savings were identified that ranged from 8% to 60% depending on capital costs and required labor resources. For example, assuming 10-year amortization of capital costs and no other changes to labor costs, an immediate savings of 8% is obtained for a facility like LEAD as compared with conventional spray-applied primers. Realistically, e-coat could reduce operating costs by reducing the number of shifts from two to one, and coupling this with complete payback of capital costs results in savings of 60% over existing procedures.

The primary goal of the project is to demonstrate the technical and economic advantages and benefits of using cationic e-coat primers in place of spray-applied primers for a wide variety of parts at Army depots. Technical benefits would include reduced VOC output, reduced paint usage, and the ability to efficiently coat complex geometries and recessed areas. Economic benefits would depend on site-specific system design and were assessed during each phase of project performance.

As potential demonstration sites, letters of support were obtained from Aniston Army Depot (ANAD), Red River Army Depot (RRAD), and LEAD. Our early efforts to move forward with the first phase of the project raised some concerns, which ultimately required significant modification to the original project plan.

The initial task of this project was to gather data on depot paint operations at ANAD and RRAD. Although representatives from both were active contributors to the proposal, we were unable to secure cooperation at the project's start. ANAD cited the inability to obtain capital for a system, regardless of the project outcome. Our contact at RRAD is no longer there. LEAD was also contacted and was supportive

of the technology but expects their part volume may be too small to justify a system. This response illustrates how firmly the barriers stated above are in place and reinforces the justification for this project.

Despite these issues, the project team desired to quantify the economic and environmental impact of an e-coat system for any given depot. The following strategies were considered as potential paths forward, which would enable successful completion of the project with minimal impact on original budget estimates.

1) Present the business case of e-coat to higher-ranking personnel at the U.S. Army Combat Capabilities Development Command (DEVCOM) Ground Vehicle Systems Center (GVSC) and the depot base commander (potential addition to travel budget). By addressing the perceived barriers at a high level, cooperation at the paint operations level should return.

    a. Industrial cost models and a similar program with the Air Force show very cost-positive results when replacing spray technology with e-coat, even when factoring in a capital investment.

    b. PPG acquired MetoKote Corporation with a high level of expertise in e-coat system design, fabrication, installation, and operation. They also have creative methods of capital amortization, which may address the capital investment concerns.

2) Expand depot site options (change project partners, potential budget change). Tobyhanna Army Depot (TAD) may be a good alternative site for this project. TAD has a more consistent stream of parts to coat than some other depots. They also provide services for a broader range of DoD customers. When initially contacted, TAD expressed interest but little knowledge of the e-coat process.

3) Host industrial e-coat line visits (potential addition to travel budget). Arranging for depot personnel to visit smaller industrial e-coat lines to see firsthand how a smaller operation is run was considered. This could have been combined with actual coating of depot-specific parts.

4) Expand stakeholder base. It is difficult to evaluate the economics of installing an e-coat primer line without an accurate estimate of part throughput at a depot. To this end, involving the broader Army community (including agencies such as GVSC and the U.S. Army Tank-Automotive and Armaments Command) was also considered.

5) External demonstrations. Validating the e-coat process for some subset of parts could be done without a depot demonstration. It may be possible to collect a variety of parts from a depot and perform the coating/demonstration at an industrial e-coat job shop. This would still require some level of depot participation, but not the same as the current statement of work.

6) Paper exercise only. To obtain the costs for small e-coat lines, PPG could move forward to generate a report on equipment and footprint for an example compact e-coat system.

7) Small-scale demo. An approach like the anodic Al primer demo completed by the Air Force under Environmental Security Technology Certification Program (ESTCP) project WP-201010[2] could be taken. This would involve a very small, portable (manual) coating setup that could easily be transported. We would coat parts to simply show Army depot personnel what the cationic deposition process looks like. This would not demonstrate automation but may build user interest.

8) Shift to anodic e-coat for Army aviation. Significant momentum has been generated for the use of anodic e-coat for Al substrates. ESTCP-supported activity for PPG's Aerocron primer has resulted in parts being flown on U.S. Coast Guard and Air Force assets. Army aviation usage could be facilitated with the funding, in addition to cationic e-coat for Army depots.

Ultimately, option five was chosen as the path forward for the project, which alleviated the demands of depot participation and logistical issues associated with design and installation of an e-coat system but allowed relevant parts to be coated and a compelling case to be made for e-coat in place of incumbent spray-applied primers. Figure E-2 shows the primer operations at the industrial toll-coater facility and e-coat at PPG's Euclid facility.

[2] PPG Industries Inc. Electrocoat process for non-chromate primers in DoD manufacturing. ASETSDefense 2012: Sustainable Surface Engineering for Aerospace and Defense Workshop; 2012 Aug 27–30; San Diego, CA. Accession No.: ADA601469. Project No.: WP-201010. 2012 Aug 29.

**Figure ES-2. Toll coating of MIL-DTL-53022 primer at Aalberts Surface Technologies (left) and e-coat at PPG's Euclid facility (right).**

# 1. Introduction

## 1.1 Background

Cationic electrocoat (e-coat) primers have revolutionized corrosion protection in the private sector. Automobiles that were manufactured 2–3 years before the invention of cationic e-coat primers were able to have their service life extended to over 10 years after cationic e-coat primers were applied to them. This excellent corrosion performance is standard even though cationic e-coats are hexavalent chromium (Cr [VI])-free, hazardous air pollutants (HAPs)-free, and contain low-to-no volatile organic compounds (VOCs).

The military recognizes the corrosion benefits of cationic e-coat and has issued MIL-DTL-0053084A[1] to document qualification criteria. This specification covers waterborne, cathodic epoxy e-coat primer formulated free of lead, Cr (VI), and HAPs. Primers conforming to the specification will meet solvent emission maximums of 144 g/L (1.2 lb/gal) VOC content and be compatible with Chemical Agent–Resistant Coating (CARC) topcoats. This primer is intended for use on properly cleaned and pretreated ferrous and nonferrous metal surfaces. Such primers are already qualified for use from multiple suppliers. E-coat is specified for protecting the Family of Medium Tactical Vehicles (FMTV) and is applied by original equipment manufacturers (OEMs) such as Oshkosh, AM General, and BAE Systems, as well as many small-parts suppliers to the defense industry.

Although the benefits of e-coat compared with spray-applied coatings are known, e-coat use by the DoD is currently limited to OEM purchases, precoated replacement parts, and outsourcing. We assert that e-coat has not been adopted in the depots because of two key barriers:

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## 1.2 Objective of the Demonstration

The objective of the demonstration is twofold. First, the project team wishes to demonstrate the superior performance of e-coat primers on relevant military ground vehicle parts. This will be readily apparent from the results of accelerated and atmospheric corrosion testing, which will show e-coat primers provide uniform coverage over complex geometries and enhanced corrosion-inhibition relative to incumbent spray-applied primers. Secondly, the project team desires to document economic feasibility and cost-savings afforded by e-coat primers. In addition to the process providing uniform coverage, it also offers near 100% transfer efficiency. These two features allow for increased mission readiness via decreased downtime for corrosion repairs.

The project team obtained ground vehicle parts that are known to have corrosion problems and are difficult to paint by conventional spray methods due to complex geometries. These included both aluminum (Al) and steel parts such as underbody suspension members. Half were painted with existing spray processes and the other half were processed by PPG with cationic e-coat technology. All were topcoated with CARC. Testing included outdoor exposure at NASA Kennedy Space Center (KSC) Beachside Atmospheric Corrosion Test Site in Florida and lab cyclic corrosion testing.

The DoD pursues pollution prevention programs to cost-effectively reduce pollution generation without adversely impacting mission readiness. The DoD has made great strides in making coatings more environmentally acceptable. For example, there are many Cr (VI)-free liquid primers qualified and available for use. One way to further reduce environmental impacts and improve readiness is to replace spray-applied primers with e-coat primers. Unfortunately, no DoD depot has installed or implemented an e-coat application system. This demonstration program seeks to overcome the barriers to installing e-coat systems and address the shortcomings of spray-applied primers.

The DoD has reduced VOCs by way of waterborne and high-solids primers, but these formulas still contain about 2.8-lb/gal VOCs. This is because solvents are required to ensure the primer viscosity is low enough to spray-apply. Additional solvent is typically added before application to further control spray viscosity. Unless the solvents are exempt, they push VOC emissions even higher.

Spray-applied coatings generate overspray waste. Spray-applied primers typically have a transfer efficiency of approximately 50%–70%, so at least roughly 30% of the coating and associated VOCs are lost as overspray or waste. Conversely, e-coat technology offers nearly 100% transfer efficiency from bath to part. Demonstrating the viability of low-to-no VOC e-coat primers for general depot use will enable

depots to reduce VOCs and paint waste while improving corrosion performance of complex parts.

The utility of e-coat primers is readily apparent on complex parts, which can be difficult to fully coat and protect with spray-applied coatings. Uncoated recessed areas corrode quickly, accelerating the repair cycle and increasing waste generated by stripping and repainting. For example, Aniston Army Depot (ANAD) refurbishes Armored Vehicle Launched Bridges (AVLBs) that have baffles and piping in the AVLB's hydraulic reservoir that spray-applied coatings cannot fully protect (Figure 1). A spray-painted reservoir would quickly corrode in a harsh operational environment. ANAD sent the reservoir to a shop in Mississippi to see if the e-coat would solve the issue.

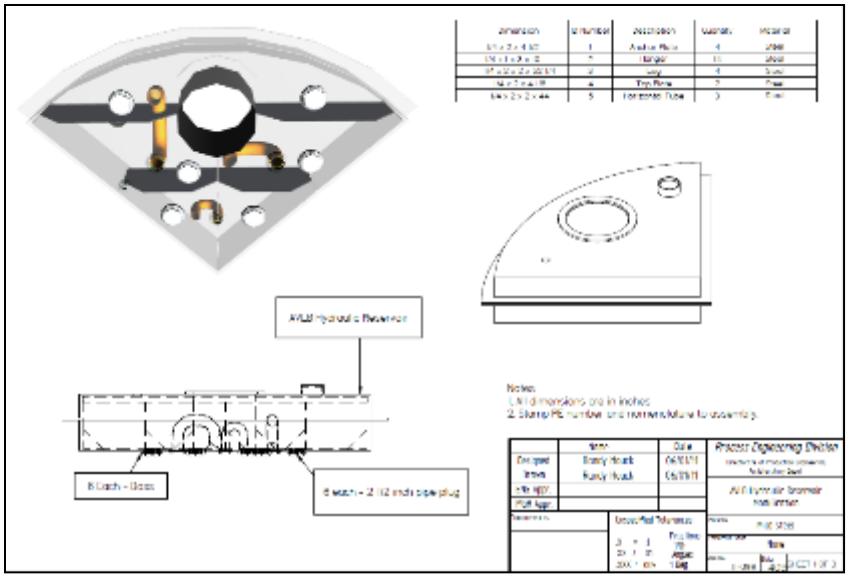


**Figure 1. Schematic and 3D drawing of an AVLB hydraulic reservoir. ANAD determined e-coat is the only coating technology that provides sufficient corrosion protection to this complex part.**

## 1.3 Regulatory Drivers

VOCs are defined as organic chemicals that photochemically react with nitrogen oxides to form ground-level ozone (smog). Sources of VOCs include gasoline-powered internal combustion engines, gasoline dispensing stations, industrial coating operations, printing shops, paints, and household chemicals, to name a few of the industrially relevant sources. The Clean Air Act (CAA) of 1970[2] led the Environmental Protection Agency (EPA) to establish the National Ambient Air Quality Standards,[3] and ground-level ozone is one of the six air pollutants on which the EPA focuses.

There are thousands of individual chemical species of VOCs that can react to form ozone. The regulatory definition of VOC has been published in the Code of Federal Regulations Part 51.100.[4] These regulations also identify those compounds determined to have negligible photochemical reactivity (VOC-exempt compounds). Coating formulations are regulated by federal, state, and local guidelines, which define the maximum allowable VOC for a given application (expressed in pounds/gallon or grams/liter). DoD specifications such as MIL-DTL-53022F[5] and MIL-DTL-53030C[6] will also prescribe VOC limits for various classes and types of coating materials.

Another method for controlling VOC emissions is limiting the total quantity of VOCs emitted from a facility for a unit of time. A threshold of more than 100 tons per year of one of the six major regulated pollutants (which includes VOCs) has been established, beyond which the facility will need to obtain a permit from the state under Title V of the CAA.[2] This requires a manager at the facility to keep records of the solvents emitting VOCs used and the amounts in which the solvents were used. If you go over the VOC limit, fines are assessed by the EPA. The fee is calculated based on the amount of VOC emissions over the limit: $0.0028/g, $1.27/lb, and $2,500/ton.

Significant progress in VOC reductions has been obtained at the federal level since 1990 when the CAA amendments were enacted.[3] At that time, the national average of ozone 8-h concentration level was 0.088 ppm, but at the time of this writing, levels have been further reduced to 0.068 ppm. Some states chose to adopt more rigorous regulations than federal requirements; for example, the California Air Resources Board[7] set VOC limits more restrictive than federal guidelines. Industrial coatings with a VOC limit of 450 g/L by federal regulations have a limit of 250 g/L in most of California, and only 100 g/L in the southern coastal region. Regulatory issues like these apply as much to DoD military installations as they do to commercial operations. Regional air-quality groups have been formed in other states as well, with as many as 17 unique requirements across the U.S.[8]

In addition to VOCs, the use of Cr (VI) compounds in coatings is also regulated. While these materials impart significant corrosion protection, they are also linked to cancer, and efforts have been underway for many years to identify nontoxic alternatives with equivalent performance. The Occupational Safety and Health Administration (OSHA) has established an 8-h time-weighted average (TWA) exposure limit of Cr (VI) to 5 $\mu g/m^3$ of air.[9] This is a considerable reduction from the previous permissible exposure limit (PEL) of 52 $\mu g/m^3$. OSHA's rationale is that the previous PEL still faces a significant health risk based on available evidence. In particular, the rulemaking relied on evidence of increased risk of lung cancer in workers exposed to Cr (VI). In addition, occupational exposure to Cr (VI)

may result in asthma and damage to the nasal epithelia and skin.[10] The final rule also contains additional provisions for worker protection, such as

- Requirements for exposure determination,
- Preferred exposure control methods, including a compliance alternative for a small sector for which the new PEL is infeasible,
- Respiratory protection,
- Protective clothing and equipment,
- Hygiene areas and practices,
- Medical surveillance,
- Record keeping, and
- Start-up dates that include 4 years for the implementation of engineering controls to meet the PEL.[10]

For bivalent (Cr [II]) and trivalent (Cr [III]) compounds, the PEL is an 8-h TWA of 500 µg/m³. For chromium (Cr) metal and insoluble compounds, the PEL is 1,000 µg/m³.[9]

The National Institute for Occupational Safety and Health (NIOSH) also has recommendations on exposure to Cr (VI) materials and has set a 10-h TWA exposure limit 1 µg/m³.[11] For Cr metal and Cr (II) and Cr (III) compounds, the recommended exposure limit is 500 µg/m³ as a 10-h TWA. Based on current evidence, NIOSH considers all Cr (VI) compounds potential occupational carcinogens.

Finally, the American Conference of Governmental Industrial Hygienists (ACGIH) adopted proposed changes to the threshold limit value (TLV) for Cr compounds in March of 2018.[12] The new TLV for inhalable Cr (VI) was set at 0.0002 mg/m$^3$, as well as a short-term exposure limit of 0.0005 mg/m$^3$. Additionally, Cr (VI) has been listed as a Category A1: Confirmed Human Carcinogen since 1990. The ACGIH states that respiratory sensitization and the likelihood of asthmatic responses in already sensitized individuals is minimized by this new TLV for Cr (VI) compounds.[12] The 2018 TLV did not distinguish between soluble and insoluble Cr (VI) and further included a new TLV of 0.003 mg/m$^3$ for inhalable, inorganic Cr (III) compounds.[12] The Cr (III) TLV is very significant, as Cr (III) compounds have been utilized as Cr (VI) alternatives in many corrosion-inhibiting pretreatment and primer compositions. While the ACGIH is a nonprofit, nongovernmental corporation, they believe their TLVs represent levels of exposure to which nearly every worker can be exposed throughout their working career without adverse health effects. These TLVs are not consensus standards nor does ACGIH consider economic or technical feasibility. Nonetheless, these highly restrictive levels are indicative of the direction of Cr regulatory bodies moving forward.

# 2. Demonstration Technology

E-coat is chromate-free, HAPs-free, has low-to-no VOCs, is applied in a dip process that eliminates overspray waste, and provides superior corrosion protection over parts with complex shapes. The uniform and complete barrier that e-coat provides (especially over complex parts) impacts part lifetime, repaint cycles, and the need for rework.

Replacing manual spray processes with an automated e-coat deposition system typically improves job quality and reduces waste. For example, coating thickness, coverage, and overspray are known to vary greatly from person to person in a spray operation. With e-coat, thickness and coverage are controlled by time and voltage settings and there is no overspray.

## 2.1 Technology Description

PPG has been supplying the automotive industry with corrosion-resistant cationic epoxy e-coat since 1976. Numerous advances have been made over the past 40 years, including removal of leaded pigments, better corrosion and chip resistance, development of ultrafiltration, UV durable e-coat products, high-edge e-coat products, and e-coat products for specific applications (e.g., frames, fasteners, and small parts). PPG has also developed new e-coat systems to process parts in bulk using barrel, belt, basket, and bandolier processes.

Cationic e-coat is an application method that provides a wide range of environmental, performance, and efficiency benefits over spray-applied coatings. Cationic e-coat primers are epoxy-based coatings that provide excellent corrosion protection over both steel and Al substrates. Cationic e-coat primers contain no Cr (VI), are HAPs-free, and typically contain less than 0.5-lb/gal VOCs compared with the 2.8 lb/gal of spray-applied primers. E-coat primers are thinned with water and are applied at a transfer efficiency of 95%–99%, so no additional VOCs are added or wasted during application as with spray-applied primers.

Unfortunately, cationic e-coat is not currently used in the depot setting. We conservatively estimate that each instance of switching from liquid, spray-applied primers to e-coat applied primers will reduce VOCs from primer application by at least 85%. Based on the volumes of primers typically used in Army and Marine depots, this could save approximately 400,000 lb of VOC/year. Using similar consumption volumes and assuming an e-coat transfer efficiency of over 95% compared with 50%–70%, we estimate that switching to e-coat primers would eliminate 19,000–33,000 gal of solid paint waste per year as well.

In the e-coat process, a part is immersed in a low-viscosity/low-solids, water-based, e-coat primer bath. An electric potential is applied so the e-coat primer coats all conductive surfaces of the part until the coating builds to a uniform thickness where the surface is no longer conductive. The coated part is cured in an oven and then is immediately ready to use. This unique application process yields parts with a uniform coating, even over very complex surfaces (Figure 2), frequently providing superior corrosion resistance compared with spray-applied coatings.

**Figure 2. E-coat fully protects the internal surfaces of complex parts that spray-applied coatings cannot (photos courtesy of PPG).**

The military recognizes the corrosion benefits of cationic e-coat. Cationic e-coat primers have revolutionized corrosion protection in the private sector. This excellent corrosion performance is standard even though cationic e-coats are Cr (VI)-free, HAPs-free, and contain low-to-no VOCs. The reason for the superior corrosion performance is corrosion mostly occurs at difficult-to-spray areas such as seams and crevices. There are military specifications for e-coat and a variety of e-coats from several suppliers are already qualified for use. U.S. Army Combat Capabilities Development Command (DEVCOM) Ground Vehicle Systems Center (GVSC) and PPG have worked through the DEVCOM Army Research Laboratory to validate and approve black cationic e-coat primers to MIL-DTL-0053084A.[1]

E-coat is a process in which electrically charged particles are deposited out of a water suspension to coat a conductive part. During the e-coat process, high-solid material is applied to a part at a certain film thickness, which is regulated by the amount of voltage applied. The deposition is self-limiting and slows down as the applied coating electrically insulates the part. E-coat solids deposit initially in the areas closest to the counter electrode and, as these areas become insulated to current, solids are forced into interior or hidden surfaces to provide complete coverage. This phenomenon, known as “throwpower,” is a critical aspect of the e-coat process.

### 2.1.1 The E-coat Process

The e-coat process can be divided into four distinct sections:

- Pretreatment
- E-coat bath and ancillary equipment
- Post-rinses
- Bake oven

Parts are first cleaned and pretreated with a variety of conversion coating pretreatments to prepare them for e-coating. This pretreatment process will often be conducted in an in-line operation immediately prior to e-coat. Parts are dipped into a coating bath where DC is applied between the parts and a "counter" electrode. The coating is attracted by the electric field to the part and is deposited on it. Parts are removed from the bath, rinsed to reclaim undeposited solids, and then baked to cure the deposited material. A simplified schematic of the process can be seen in Figure 3.

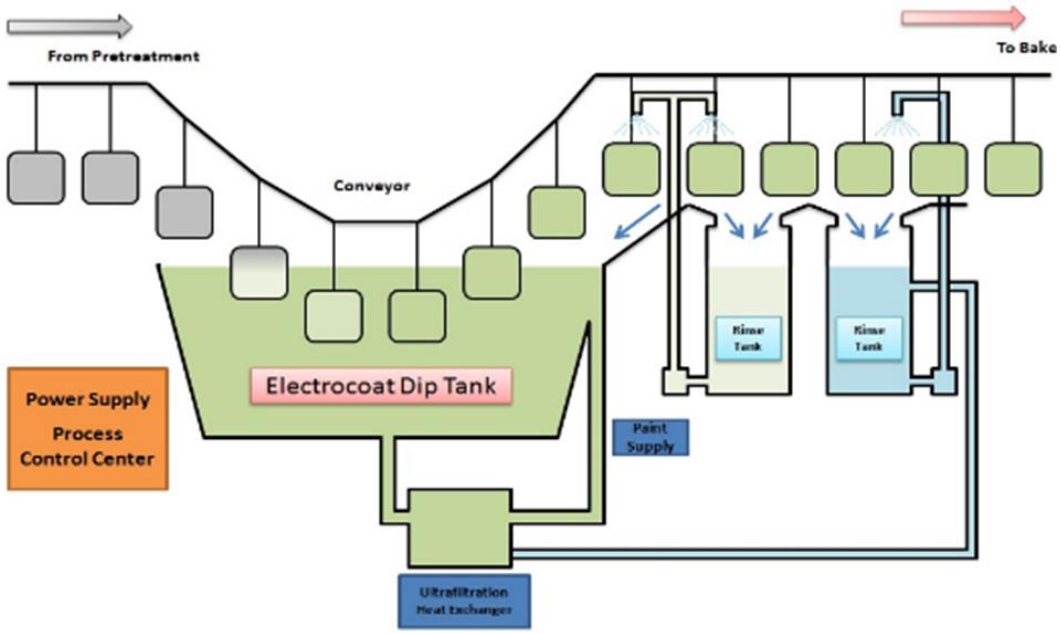



**Figure 3. E-coat coating process diagram.**

### 2.1.2 Anodic versus Cathodic E-coat

E-coat products can be anodic or cathodic, indicative of where coating deposition takes place. The process works on the principle of "opposites attract."

Anodic e-coat involves the use of negatively charged paint particles that are deposited onto positively charged metal substrates. During the anodic process, a small amount of substrate dissolution occurs, resulting in metal ions (ferrous substrate) present in the paint film, limiting the corrosion performance properties

of these systems. Their main use is for products in interior or moderate exterior environments. Anodic coatings are economical systems and offer excellent color and gloss control.

Cathodic deposition, where positively charged paint particles are attracted to a negatively charged part, involves much less substrate dissolution and consequently offers substantially improved corrosion resistance for ferrous substrates. Cathodic coatings are high-performance coatings with excellent corrosion resistance and can be formulated for exterior durability.

### 2.1.3 E-coat Product Types

Acrylics, epoxies, and hybrid formulations are available to match the desired quality, performance, cost, and environmental objectives that e-coat paint customers demand.

Both anodic and cathodic technologies can be based on epoxy polymers, known for their corrosion and chemical resistance. Cathodic epoxy e-coats are the benchmark in the industry for corrosion resistance. They are widely used in the automobile and automotive parts industries and provide superior salt spray, humidity, and cyclic corrosion resistance, but generally require a topcoat to protect their components from UV degradation. Anodic epoxy e-coats offer much lower cure temperature capability and some can be cured at less than 200 °F. The low-cure attributes of anodic epoxies make these e-coat products an excellent finish for castings, engines, and temperature-sensitive substrates like Al.

Acrylic polymers are known for their UV durability and color control. Cathodic acrylic e-coats are typically used in applications where both UV durability and corrosion protection on ferrous substrates (steel) are desired. These products are used as a one-coat finish in the agricultural, lawn and garden, appliance, and air-conditioning industries. Anodic acrylic e-coats offer a single-coat application used for both interior and exterior environments and are available in numerous colors and glosses. These products are used as a one-coat finish on toolboxes, air diffusers, hangers, and other indoor or mild exterior environments. Figure 4 highlights the overall benefits of e-coat systems.

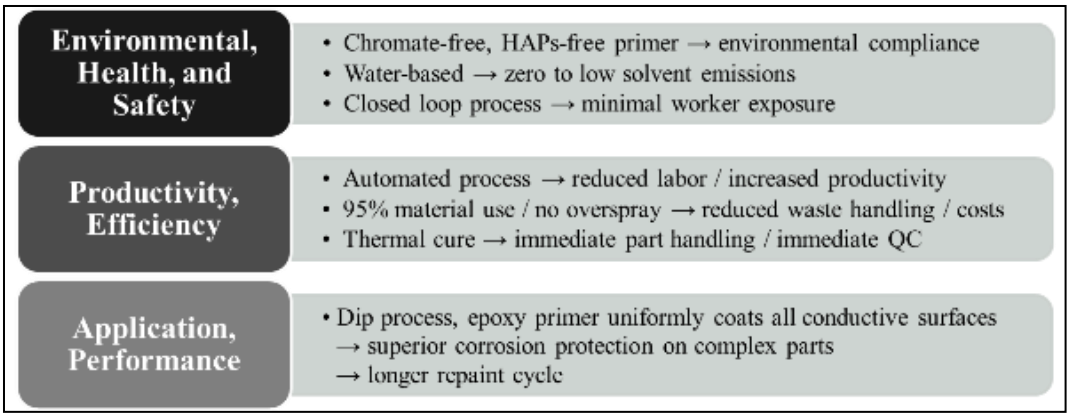



**Figure 4. The benefits of e-coat primers go beyond environmental impact and pollution prevention efforts. Productivity, efficiency, and corrosion performance benefits strongly influence decisions to invest in an e-coat system.**

## 2.2 Technology Development

A depot-viable cationic e-coat process is currently at Technology Readiness Level (TRL) 6; i.e., commercial e-coat systems have been implemented in relevant environments. The next step is to demonstrate a prototype system in an operational environment (TRL 7) so that an actual system can be implemented (TRL 8). The proposed path is like the U.S. Air Force's (USAF's) investigation into a depot-viable anionic e-coat process (anionic e-coat requires a lower cure temperature and is recommended for Al substrates only). The feasibility of implementing anionic e-coat systems in USAF depots is being demonstrated under Environmental Security Technology Certification Program (ESTCP) WP-201010[13] using the U.S. Coast Guard's (USCG's) system (Figure 5). Some parts have been fielded with performance exceeding the Cr (IV) controls in some instances. The proposed demonstration and validation project for cationic e-coat differs from the USAF project in that we must demonstrate technical and economic viability over a wider range of substrates, within the higher cure temperature constraint of cationic e-coat, and to a completely different end-user community.

Note that cationic e-coat primers themselves are at TRL 9; i.e., the primers are available and qualified to military specifications for military use. Coatings specific to this demonstration were initially tested and demonstrated to MIL-DTL-0053084A under contract W56HZV-09-C-0601 between GVSC and PPG and formally qualified to the same specification by ARL. This demonstration is not focused on further validating the coating; it is focused on validating the economics and technical viability of the e-coat process in-depot so that these high-performance, environmentally beneficial primers will be adopted.


**Figure 5. This anodic e-coat primer system recently installed at the USCG Aviation Logistics Center in Elizabeth City, North Carolina, was right-sized for the facility's operations after an extensive needs assessment (photo courtesy of PPG).**

## 2.3 Advantages and Limitations of the Technology

E-coat is known to be superior to spray coatings for preventing part corrosion over complex parts, and the potential environmental benefits are large. Unfortunately, e-coat use by the DoD is currently limited to OEM purchases, precoated replacement parts, and outsourcing. The misconception that e-coat systems are only designed for large industrial operations too large for depot use, and uncertainty that an e-coat system will provide an acceptable return on investment. Most people familiar with coatings operations have seen videos or pictures of large car bodies being coated in an automotive-scale e-coat tank. These are massive tanks, ranging from 50,000–100,000 gal, with large hoists that require a multimillion-dollar capital investment. E-coat is frequently associated with these huge systems that require very high part throughput to be economical and chemically stable over time. The association of e-coat with large size is a barrier to adoption by depots.

In 1994, the U.S. Army Tank-Automotive and Armaments Command asked the National Defense Center for Environmental Excellence (NDCEE) to facilitate the transition of e-coat to the DoD. In that study,[14] a 3,000-gal tank capable of coating 4- × 4- × 3-ft parts was installed at Concurrent Technologies Corporation and used to evaluate e-coat's cost-effectiveness and feasibility. The study determined that the minimum part volume threshold for cost-effective operation was significantly higher than the actual part volume experienced at any location. The report also indicated that every prior study on e-coat feasibility came to the same conclusion.[14] However, an important point is that the team did not suggest a smaller tank as an option. In the years since the NDCEE report, e-coat system manufacturers specializing in general industrial applications (as opposed to automotive-scale applications) are designing more standardized machines, suitable for installation in a wide range of facilities and tailored to maximize system efficiency.

One of the goals of this project is to raise awareness that smaller e-coat systems are now available for purchase. For example, the SlideRail Square Transfer Electrocoat line shown in Figure 6 processes part loads as large as 6 × 3.5 × 2.5 ft, with a tank size of approximately 1,400 gal. In 2011, MetoKote began offering their microKote system for sale or lease, which handles 1.5- × 3- ×1.5-ft parts through a 350-gal tank.[15] Finally, the microKote system at the USCG Aviation Logistics Center in Elizabeth City, North Carolina, is only a 135-gal system and is readily capable of coating a variety of parts and subassemblies and is now fielding parts.

**Figure 6. Parts progressing through an e-coat system at Blue Grass Plating in Richmond, Kentucky. The scale of an e-coat line must be matched to part size and throughput to minimize cost and footprint while maximizing bath stability (photo courtesy of Therma-Tron-X, Inc.).**

Lower throughput shops can still implement an efficient and cost-effective e-coat line so long as the system is appropriately sized. In this program, PPG will work with the depots to determine the right size for an in-depot e-coat system with consideration for the concerns that are outlined in the following paragraphs.

As e-coat tanks increase in size, there are three major concerns that need to be managed: cost, footprint, and bath stability. The first two concerns are obvious. Large parts require a large tank to fully immerse the part. The larger the tank size, the higher the tank cost and the larger the footprint in the coating facility. Furthermore, as tank size increases, larger ancillary equipment is also needed since a larger tank requires more pumping capacity, chiller capacity, ultrafiltration capacity, etc.

A potentially less obvious concern that increases with tank size is the matter of bath stability. An e-coat bath contains an e-coat primer product diluted and dispersed in water. Because the bath is a dynamic system that is continually replenished with new paint as parts are coated, the stability of the e-coat dispersion is extremely

important. Bath stability is maximized in a high-turnover system, where turnover is the average rate of deposition compared to the quantity of paint present in the bath. The higher the turnover, the more frequently the bath is replenished with fresh paint. When tank size is increased to process larger parts, the volume of the tank grows according to linear measurement *cubed*, while the surface area coated grows by linear measurement *squared*. Increasing the ratio of bath volume to surface area coated leads directly to a *lower turnover* system, which can negatively affect the stability of the bath. An unstable bath can cause appearance issues and require more frequent filter changes, driving up maintenance costs.

The key to implementing e-coat primers in military depots with an acceptable ROI is to right-size the system to manage the concerns just discussed. A depot should not install an e-coat system large enough to prime *every* steel or Al part coming through the facility. That approach would likely require a custom system, easily the size of most automotive systems, and result in a double negative—an extremely expensive machine handicapped by slow turnover. A depot should instead install a right-sized system that accommodates *most* (not all) of the parts processed in the facility. Using this approach, the DoD can install cost-effective e-coat systems, perhaps using standard industrial-scale designs that balance size, cost, efficiency, and utility.

## 3. Performance Objectives

An overview of performance requirements can be found in Table 1.

**Table 1. Performance objectives.**

| Performance objective | Data requirements | Success criteria | Results |
|---|---|---|---|
| **Quantitative performance objectives** | | | |
| Product testing<br>E-coat application properties | MIL-DTL-0053084A, Section 3.6.3, Application properties | Continuous film after baking, which conforms to the color, gloss, and performance properties. No mottling or color separation and free from craters or orange peel. | Pass |
| Product testing<br>Cure time | MIL-DTL-0053084A, Section 3.6.4, Cure time requirements | 30 MIBK solvent rubs with no film softening. | Pass |
| Product testing<br>Adhesion | ASTM D3359, method B | No removal from the surface of the cross-cut area, classification 5B.<br>Primer and the topcoat shall show less than 5% of the area affected, classification 4B. | Pass |
| Product testing<br>Cyclic salt spray resistance | 40 cycles of GMW14872<br>Control<br>Scribed<br>Chipped | 40 cycles of GMW14872 on chipped and undamaged “spangler” panels (multi-metal steel coupons fabricated to illustrate welds, fasteners, and edges where corrosion is particularly problematic), and chipped and scribed Al panels. | Pass |

**E-coat application properties:** Application properties are critical to providing a high-quality finish with desired cosmetic and protective properties. At a minimum, a continuous film is required after baking to ensure bare metal surfaces are uniformly covered and protected. E-coat's substrate protection is largely a result of the excellent barrier properties the coating provides; accordingly, any voids in coverage would compromise this feature. Cratering would be indicative of incompatible contaminants within the e-coat bath or an insufficiently clean substrate. The presence of craters could adversely affect both corrosion performance and appearance of the finished coated article. In addition, color and gloss within specifications assures the material has been formulated correctly and applied under appropriate process conditions. A key feature of e-coat is the uniform deposition across all surfaces being coated. Variations in color or gloss would be indicative of process or material issues, and film thickness measurements would be warranted to determine if significant differences in deposited film exist. Visual inspection and film thickness measurements are the primary metrics used to assess whether the objective was met or not. In the case of this demonstration, the e-coated films were observed to be smooth, defect-free, and of uniform film thickness across the entire coated surface.

**Cure time:** Section 3.6.4 of MIL-DTL-0053084A[1] identifies cure-time requirements for e-coat primers. In this case, the coated parts were cured at 375 °F for 30 min. Once cooled, methyl isobutyl ketone (MIBK) solvent rubs were performed with no film softening after 30 rubs. While this test is simple, it is also a strong indicator of whether the film is cured or not. Underbaking will result in partially unreacted coating materials, which are readily solvated by the MIBK. If insufficiently cured, problems might be expected with adhesion, corrosion resistance, and appearance. Parts and panels from this project showed no transfer of the coating to towel and no softening of the e-coat primer.

**Adhesion:** Adhesion was performed via method B in ASTM D3359[16] with no removal from the surface of the cross-cut area (classification 5B). Furthermore, primer and topcoat showed less than 5% of the area affected (classification 4B). Poor adhesion would be associated with early failure of the coating materials, the onset of corrosion, and the need for remedial repair operations.

**Cyclic salt spray resistance:** GMW14872 is a standard corrosion test method,[17] which more closely approximates real-world performance properties than other methods such as ASTM B117.[18] GMW14872 is performed to evaluate accelerated corrosion effects on assemblies and different components. A combination of cyclic conditions provides the right environment for this type of accelerated corrosion. It takes 24 h to complete one full cycle under these conditions, which include three

8-h stages: an ambient stage, which has frequent sprays of solution; a humid stage, which allows for a higher humidity; and a dry stage.

The GMW14872 solution is composed of sodium chloride (NaCl), calcium chloride ($CaCl_2$) and sodium bicarbonate ($NaHCO_3$) in concentrations as follows[17]:

- NaCl: 0.9%
- $CaCl_2$: 0.1%
- $NaHCO_3$: 0.075%

PPG conducted 40 cycles of GMW14872 on both steel and Al substrates, both undamaged and chipped, to create coating defects using a gravelometer.

# 4. Site/Platform Description

## 4.1 Test Platforms/Facilities

A total of five facilities were required to execute the revised program plan. These included PPG's Coatings Innovation Center (CIC) in Allison Park, Pennsylvania; PPG's Industrial Coatings Plant in Euclid, Ohio; Aalberts Surface Technologies in Baltimore, Maryland; Maryland Plating and Servicing, Inc., also in Baltimore; and finally, the NASA KSC Beachside Atmospheric Corrosion Test Site in Cape Canaveral, Florida. These five locations were used as no single performer was capable of processing all the parts used in the demonstration. In addition to these project co-performers, ARL personnel played a critical role in overall project management and coordination and had experience with several toll coaters who were considered for participation in the program. Figure 7 shows the specific roles and responsibilities for each performer.

ARL is the Army's corporate research laboratory, strategically placed under the Army Futures Command, and is the Army's sole fundamental research laboratory focused on cutting-edge scientific discovery, technological innovation, and transition of knowledge products that offer incredible potential to improve the Army's chances of surviving and winning any future conflicts. ARL holds responsibilities as the commodity manager for the CARC system and the preparation for all related military specifications. This put ARL in a unique position to develop and implement new coatings and requirements under the CARC system, which is required by Army Regulation 750–1, Army materiel maintenance policy,[19] to be used on all tactical and related support equipment.

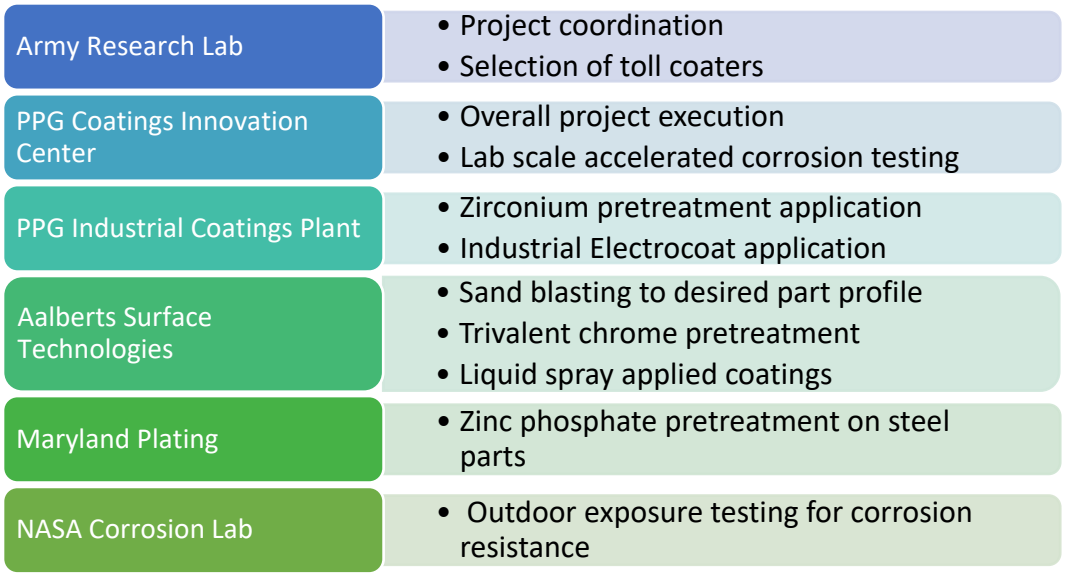



**Figure 7. Roles and responsibilities for project team.**

Pittsburgh-based PPG is a global supplier of paints, coatings, optical products, specialty materials, chemicals, glass, and fiberglass. The company has more than 140 manufacturing facilities and equity affiliates and operates in more than 60 countries. Sales in 2019 were $15.4 billion. PPG is one of the world's largest coating manufacturers serving automotive, industrial, aerospace, and consumer markets. PPG is also a leading manufacturer of aircraft transparencies, flat and fabricated glass, continuous-strand fiberglass, specialty chemicals, and architectural coatings.

Since PPG's first foray into coatings in 1900, the company has a long history of novel product development, with much of it focused on environmentally friendly technologies such as reduced-VOC coatings and Cr (IV)-free coatings for corrosion control. Since 1971, PPG has been granted about 1,700 US patents in the coatings arena, with over 650 since 2012.

The Allison Park CIC site was founded in 1974 and performs novel material development and formulation on the scale of microquantities up to 5 gal. Researchers at CIC collaborate with product engineers at the Springdale, Pennsylvania, development center, which is the largest pilot-production plant in the coatings industry.

PPG designs and manufactures most of the resins used in its products and therefore has the synthetic resources to manufacture and tailor materials for optimum properties. PPG's coatings research facility is a fully equipped chemical synthesis and coating facility, which employs about 300 full-time scientists and support staff. Analytical techniques available at this facility include IR, Raman, UV-visible and

mass spectrometry as well as gas chromatography, gel permeation chromatography, and numerous wet chemical analysis techniques. Surface analysis techniques include scanning electron microscopy, X-ray fluorescence, and time-of-flight secondary ion mass spectrometry. Synthesis capabilities include conventional condensation and free radical polymerizations as well as high-pressure polymerizations and continuous feed reactors. Application technology available at this facility includes airless, air-assisted airless, and high-volume, low-pressure (HVLP) spray equipment as well as electrostatic application equipment. An onsite training facility allows for coating application on full-sized automobiles. A variable temperature and humidity room allows control of environmental conditions during coating application and cure.

PPG's Euclid, Ohio industrial coatings plant produces pretreatment and specialty products including alkaline and acid cleaners and zinc (Zn) phosphates. The plant began operations in the 1940s. In 1997, PPG acquired the Man-Gill pretreatment business as an extension to its existing pretreatment technologies. Since the acquisition, various PPG pretreatment operations have consolidated; thus, the PPG Euclid business now includes products for the container and packaging industries, appliance, fasteners, and the general industrial market, as well as drawing compounds and lubricants for metalworking. With each consolidation of the pretreatment business, the Euclid facility underwent significant expansion to improve processes for pretreatment production. The facility now has 10-, 15-, 34-, 150-, and 225-gal tanks to service major customers including John Deere, Whirlpool, Harley Davidson, Springco, Bobcat, Ameristar, Curtis, and Almond.

Aalberts Surface Technologies was founded in 1975 as an Al precision extrusion company. Today they are an international innovator that engineers mission-critical technologies for ground-breaking industries and operates in more than 50 countries around the world. All branches of the military, as well as their primary contractors, recognize Aalberts Surface Technologies as the qualified leader in the application of high-performance coating systems. Aalberts Surface Technologies maintains an extensive library of military finishes, specifications, and qualified procedures. This enables them to routinely meet the highest quality-assurance standards and military specifications. As an added advantage, Aalberts Surface Technologies has the production capabilities to provide fast turnaround on both prototype and production runs. Aalberts Surface Technologies has substantial experience applying CARC, radar absorbing material coatings, chromate conversion coatings, tactical advantage coatings, fire and thermal protection coatings, and electromagnetic interference/RF interference shielding coatings. Aalberts Surface Technologies also offers metalizing, silk-screening, stenciling, custom packaging, detailed masking, and more.

Maryland Plating and Anodizing Service offers a portfolio of surface-prep technologies including clear and black sulfuric acid anodize, passivate nitric acid, gold and clear irridite, clear and gold chromate, and Zn and manganese phosphate.

NASA Corrosion Laboratory's long-term atmospheric testing area is located at latitude 28.7° N, longitude 80.6° W and 150 ft from the mean high-tide line of the Atlantic Ocean. The site includes 900 linear ft of front-row coastal exposure space. The testing area has a designated area for samples that need to be facing southward for when more direct UV exposure is needed. Although most specimens are more standard sizes of 4 × 6, 3 × 6, or 3 × 10 inches, test coupons of all sizes and configurations can be accepted since their custom-built stands and racks are easily modified. Most coupons are oriented at a 30° angle with respect to the horizontal, although alternative orientations are available. The test site also has an area for full-sized test articles. Most experiments can be performed in either a completely exposed, semi-exposed, or sheltered configuration. Both power and data connections are available to power test articles and record onboard data instrumentation outputs. Over the years, thousands of coated test panels, stress corrosion cracking specimens, nonmetallic materials, and commercially produced products have been evaluated in the high-salt, high-humidity, and high-UV Florida seacoast environment. Results from these evaluations have helped NASA KSC find new materials and processes that increase the safety and reliability of our launch structures and ground-support equipment.

Since single corrosion rate and chloride-concentration values are mere snapshots in a particular period, NASA KSC began higher fidelity measurements of corrosion rates and chloride concentration in 2010. The corrosion rate and chloride concentration of the beachside atmospheric test site are monitored to determine the range of corrosion rates and chloride levels at the site, rather than depend on a single value. The data is then evaluated for weighted mean values and seasonal corrosion rates and chloride concentrations. The corrosion rate and chloride concentration at the NASA KSC Beachside Atmospheric Corrosion Test Site are highest in the winter months due to the high number of wetness events brought about by the condensation in the morning and lower overall temperatures that leave the samples wet for a longer period. In the summer months, the temperatures are so high that condensation and precipitation tend to evaporate much faster, causing an overall lower corrosion rate. Data that is collected at this site are available, including weather, corrosion rate, and chloride concentration.[20]

## 4.2 Present Operations

The proposed cationic e-coat immersion coatings are intended to replace existing spray coating operations at depots such as Letterkenny Army Depot (LEAD),

ANAD, the Marine Corps Logistics Base in Albany, Georgia, or other DoD facilities that repair and recoat large volumes of parts and tactical vehicles. These facilities routinely spray-apply primers and topcoats using handheld HVLP spray guns that, in the hands of an experienced sprayer, can deliver transfer efficiencies around 60%. However, the proposed e-coat coatings offer transfer efficiencies of well over 95% when properly maintained. LEAD reported spraying about 1,000 gal of MIL-DTL-53022 primer over the calendar year 2023.

E-coat systems are often considered to be appropriate only when large volume tanks can be employed. However, the USCG recently installed a small modular e-coat system that demonstrated e-coat systems can be customized for specific applications where site limitations might prevent large scale implementation.

### 4.3 Site-Related Permits and Regulations

Regulations in no way hindered the execution of this project and no permits were required. Future implementation would require site surveys and an analysis of space, power, and water availability prior to adoption.

## 5. Test Design

Parts and panels selected for performance testing are shown in Figure 8. Steel panels and parts selected for performance testing are hot-rolled steel “spangler” panels and steel High Mobility Multipurpose Wheeled Vehicle (HMMWV) lower control arms. The “spangler” panels are custom fabricated to simulate welds, fasteners, recessed areas, and edges where corrosion on an actual vehicle might be expected to originate. Al panels and parts selected for performance testing are 6061 Al panels and HMMWV Al brackets.


**Figure 8. Al and steel testing panels and parts.**

All substrates were grit-blasted at Aalberts Surface Technologies in Baltimore, Maryland. Some of these parts and panels were then shipped to PPG's Euclid, Ohio facility for application of zirconium (Zr) pretreatments and e-coat primer. Some of the Zr-treated parts were returned to Aalberts Surface Technologies for application of MIL-DTL-53022 primer and CARC topcoat. Some of the parts and panels remained at Aalberts Surface Technologies for application of Cr (IV) pretreatment or shipped to a third-party coater (Maryland Plating and Services, Inc.) for the Zn phosphate application. All the pretreated parts eventually ended up back at Aalberts Surface Technologies for final applications of the MIL-DTL-64159 topcoat. The extensive back-and-forth between multiple facilities was necessary to obtain the desired coating stacks for comparison and was managed through a very tight time schedule to ensure appropriate timing between coating applications. At the conclusion of sample preparation, steel and Al were prepared with two different pretreatments per substrate. This enabled a performance comparison between MIL-DTL-53022A Type IV primer versus MIL-DTL-0053084A cationic e-coat. All parts and panels were topcoated with tan CARC (MIL-DTL-53039).

## 5.1 Description

The purpose of this project was to process steel spangler panels, 6061 Al 4- × 12-inch panels, Al brackets (HMMWV brackets) and steel control arms

(HMMWV lower control arms). The panels and parts were treated with either Zircobond 4200 or Xbond 4000. Some of the parts were pretreated at Aalberts Surface Technologies in Baltimore, Maryland with Cr (VI) pretreatment or Zn phosphate. The testing matrix presented in Table 2 is color-coded to illustrate which coating applications were performed at which locations.

**Table 2. Sample matrix.**

| Substrate | (blasted) Pretreatment | Primer | Topcoat | Extras | NASA | Part # | Total |
|---|---|---|---|---|---|---|---|
| Aluminum Bracket | HCP | Type IV | Tan CARC | 1 | 2 | 1-3 | 12 |
| | | Ecoat | | 1 | 2 | 4-6 | |
| | Zirconium | Type IV | | 1 | 2 | 7-9 | |
| | | Ecoat | | 1 | 2 | 10-12 | |
| Steel HMMWV Control Arm | Zinc Phos | Type IV | Tan CARC | 1 | 2 | 1-3 | 12 |
| | | Ecoat | | 1 | 2 | 4-6 | |
| | Zirconium | Type IV | | 1 | 2 | 7-9 | |
| | | Ecoat | | 1 | 2 | 10-12 | |

| Substrate | (blasted) Pretreatment | Primer | Topcoat | Extras | XH Adhesion | Chipped (1pt. GMW14872 | Undamaged GMW14872 | Scribed GMW14872 | NASA | Part # | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 6061 Aluminum Panel (McMaster-Carr) | HCP | Type IV | Tan CARC | 1 | 1 | 3 | | 3 | 3 | 1-11 | 44 |
| | | Ecoat | | 1 | 1 | 3 | | 3 | 3 | 12-22 | |
| | Zirconium | Type IV | | 1 | 1 | 3 | | 3 | 3 | 23-33 | |
| | | Ecoat | | 1 | 1 | 3 | | 3 | 3 | 34-44 | |
| HRS Weld Panel (Spangler) | Zinc Phos | Type IV | Tan CARC | 1 | 1 | 3 | 3 | | 3 | 1-11 | 44 |
| | | Ecoat | | 1 | 1 | 3 | 3 | | 3 | 12-22 | |
| | Zirconium | Type IV | | 1 | 1 | 3 | 3 | | 3 | 23-33 | |
| | | Ecoat | | 1 | 1 | 3 | 3 | | 3 | 34-44 | |

Aalberts, Inc
PPG Euclid, OH
Maryland Plating and Services, Inc.

## 5.2 Process Data

Three Al brackets, 11 Al panels, 3 steel control arms, and 11 steel spangler panels went through Xbond 4000DM/DR immersion pretreatment as follows:

- Clean: Ultrax 98D, 4%/volume, 140 °F, 240 s
- Rinse: Overflowing ambient city water, 60 s
- Rinse: Overflowing ambient city water, 60 s
- Pretreat: Xbond 4000DM/DR, 80 °F, 120 s, Zr: 200 ppm, pH: 4.7
- Rinse: Overflowing ambient city water, 60 s
- Rinse: Overflowing ambient deionized (DI) water, 60 s
- Dry: Oven, 5 min at 300 °F

Three Al brackets, 11 Al panels, 3 steel control arms, and 11 steel spangler panels went through Zircobond 4200DM/DR immersion pretreatment as follows:

- Clean: Ultrax 98D, 4%/volume, 140 °F, 240 s
- Rinse: Overflowing ambient city water, 60 s
- Rinse: Overflowing ambient city water, 60 s
- Pretreat: Zircobond 4200DM/DR, 80 °F, 120 s,
- Zr: 200 ppm, Cu: 18 ppm, pH: 4.7
- Rinse: Overflowing ambient city water, 60 s

- Rinse: Overflowing ambient DI water, 60 s
- Dry: Oven, 5 min at 300 °F

Six Al brackets, 12 hexavalent containing conversion coating (HCP)-pretreated Al panels, and 22 steel spangler panels were e-coated with P6000HE, 3 panels or parts at a time, as follows:

- Paint: P6000HE
- Application: 300 V, 3 A for 120 s at a bath temperature of 92–93 °F
- Rinse: DI water, 30 s
- Cure: 30 min at 375 °F metal temperature
- Film build: Al brackets: 1.02–1.12 mils, Mμ = 1.05 ± 0.0 mils
    - Al panels: 0.95–1.28 mils, Mμ = 1.09 ± 0.1 mils
    - Spangler panels: 1.52–1.68 mils, Mμ = 1.57 ± 0.0 mils

Twelve Zircobond pretreated Al panels were e-coated, three panels at a time, as follows:

- Paint: P6000HE
- Application: 310 V, 3 A for 120 s at a bath temperature of 92–93 °F
- Rinse: DI water, 30 s
- Cure: 30 min at 375 °F metal temperature
- Film build: 0.99–1.13 mils, Mμ = 1.07 ± 0.0 mils

Six control arms were e-coated, one at a time, as follows:

- Paint: P6000HE
- Application: 20 A for 180 s at a bath temperature of 92–93 °F
    - Parts #5 at 350 V, #6 at 300 V, and #4, #10–12 at 280 V
- Rinse: DI water, 30 s
- Cure: 30 min at 375 °F metal temperature
- Film build: #5: 2.30 mils
    - #6: 1.75 mils
    - #4, #10–12: 1.70–1.91 mils, Mμ = 1.78 ± 0.1 mils

Three-quarters of the coated Al and steel panels were tested in accordance with GMW14872[17] for 40 cycles. A third of that were chipped with 1 pt of gravel, a third were scribed, and the other third were left undamaged. The rest of the Al and steel panels went to NASA KSC Beachside Atmospheric Corrosion Test Site in Florida. All the Al brackets and steel control arm parts went to NASA KSC Beachside Atmospheric Corrosion Test Site in Florida as well.

## 6. Performance Assessment

The coated parts and panels were all inspected and coating thicknesses were measured and recorded (

Table 3. Average coating thickness of the parts and panels.

| Substrate | (blasted) Pretreatment | Primer | Topcoat | Ecoat (mils) | Total Stack (mils) |
|---|---|---|---|---|---|
| Aluminum Bracket | HCP | Type IV | Tan CARC | | 6.02 ± 0.32 |
| | | Ecoat | | 1.06 ± 0.06 | 4.27 ± 0.44 |
| | Zirconium | Type IV | | | 6.99 ± 0.28 |
| | | Ecoat | | 1.04 ± 0.01 | 4.53 ± 0.37 |
| Steel HMMWV Control Arm | Zinc Phos | Type IV | Tan CARC | | 4.69 ± 0.19 |
| | | Ecoat | | 1.65 ± 0.14 | 4.535 ± 0.18 |
| | Zirconium | Type IV | | | 5.42 ± 0.33 |
| | | Ecoat | | 1.78 ± 0.11 | 4.22 ± 0.22 |

| Substrate | (blasted) Pretreatment | Primer | Topcoat | Ecoat (mils) | Total Stack (mils) |
|---|---|---|---|---|---|
| 6061 Aluminum Panel (McMaster-Carr) | HCP | Type IV | Tan CARC | | 6.27 ± 0.55 |
| | | Ecoat | | 1.09 ± 0.13 | 4.56 ± 0.80 |
| | Zirconium | Type IV | | | 7.44 ± 0.69 |
| | | Ecoat | | 1.07 ± 0.04 | 4.48 ± 0.38 |
| HRS Weld Panel (Spangler) | Zinc Phos | Type IV | Tan CARC | | 6.06 ± 0.61 |
| | | Ecoat | | 1.58 ± 0.05 | 4.54 ± 0.29 |
| | Zirconium | Type IV | | | 6.74 ± 0.38 |
| | | Ecoat | | 1.56 ± 0.03 | 4.17 ± 0.17 |

). Overall, parts and panels primed with e-coat have a thinner coating stack than those coated with Type IV primer.

**Table 3. Average coating thickness of the parts and panels.**


| Substrate | (blasted) Pretreatment | Primer | Topcoat | Ecoat (mils) | Total Stack (mils) |
|---|---|---|---|---|---|
| Aluminum Bracket | HCP | Type IV | Tan CARC | | 6.02 ± 0.32 |
| | | Ecoat | | 1.06 ± 0.06 | 4.27 ± 0.44 |
| | Zirconium | Type IV | | | 6.99 ± 0.28 |
| | | Ecoat | | 1.04 ± 0.01 | 4.53 ± 0.37 |
| Steel HMMWV Control Arm | Zinc Phos | Type IV | Tan CARC | | 4.69 ± 0.19 |
| | | Ecoat | | 1.65 ± 0.14 | 4.535 ± 0.18 |
| | Zirconium | Type IV | | | 5.42 ± 0.33 |
| | | Ecoat | | 1.78 ± 0.11 | 4.22 ± 0.22 |

| Substrate | (blasted) Pretreatment | Primer | Topcoat | Ecoat (mils) | Total Stack (mils) |
|---|---|---|---|---|---|
| 6061 Aluminum Panel (McMaster-Carr) | HCP | Type IV | Tan CARC | | 6.27 ± 0.55 |
| | | Ecoat | | 1.09 ± 0.13 | 4.56 ± 0.80 |
| | Zirconium | Type IV | | | 7.44 ± 0.69 |
| | | Ecoat | | 1.07 ± 0.04 | 4.48 ± 0.38 |
| HRS Weld Panel (Spangler) | Zinc Phos | Type IV | Tan CARC | | 6.06 ± 0.61 |
| | | Ecoat | | 1.58 ± 0.05 | 4.54 ± 0.29 |
| | Zirconium | Type IV | | | 6.74 ± 0.38 |
| | | Ecoat | | 1.56 ± 0.03 | 4.17 ± 0.17 |


Forty cycles of GMW14872[17] on chipped and undamaged spangler panels, and chipped and scribed Al panels, are shown in Figures 9 and 10. E-coat produced less

red corrosion product (spangler panels) and white corrosion product (Al panels) than those coated with the Type IV primer. In addition, the MIL-DTL-53022F Type IV primer shows extensive corrosion around welds and the marking number that had been cut in the spangler panel. Conversely, the e-coated panels show reduced chip corrosion and excellent appearance around welds and marking numbers.

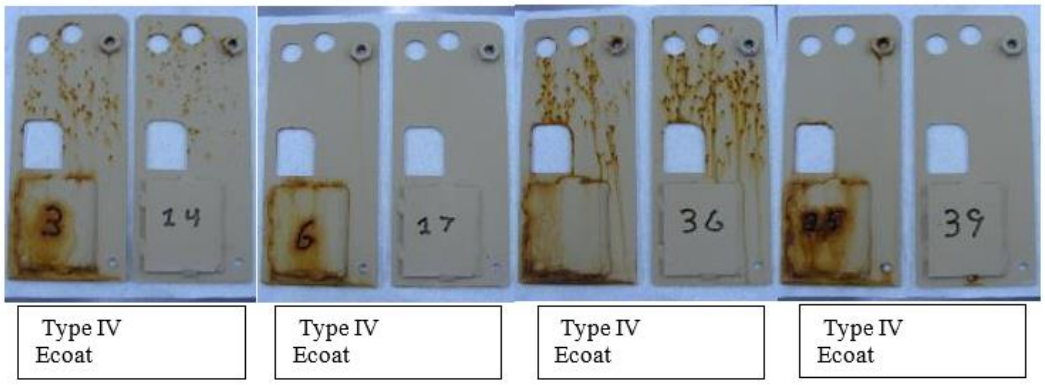



**Figure 3. Steel spangler panels Type IV vs. e-coat primer (GMW14872).**

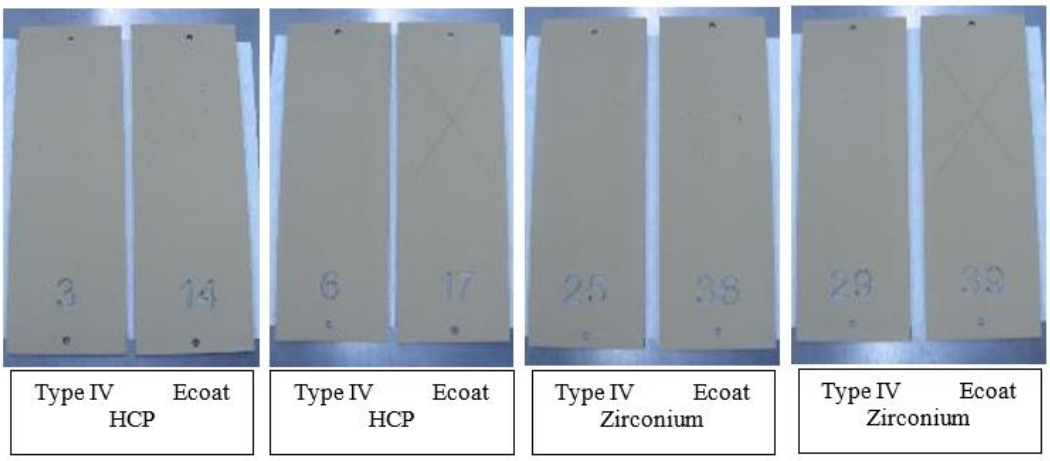



**Figure 4. Al panels Type IV vs. e-coat primer (GMW14872).**

Corrosion results after 8 months and 1 week of exposure at NASA Beachside Atmospheric Testing Facility are tabulated for spangler panels (Table 4) and steel part control arms (Table 5). Welded areas, bushing, and holes continue to be the corrosion sites for the control arms as well as the spangler panels. Control arms and spangler panels that received an e-coat primer have less corrosion between welded panels, cutout areas, and nuts than those coated with a Type IV primer.

**Table 4. Spangler panels average ASTM D610 and ASTM D714 ratings and observations.**

| ARL PPG Spangler Panels<br>Eight Month and 1 Week Evaluation (1/3/2020) | | | |
|---|---|---|---|
| Coating | ASTM D610 | ASTM D714 | Notes: |
| HCP/Type IV | 10 | 10 | Red bleeding between welded panels, corrosion on cutout, holes and nut. |
| HCP/Ecoat | 10 | 10 | Very slight corrosion between panels, cutout, nut and holes. |
| Zirconium/Type IV | 10 | 10 | Red bleeding between welded panels, corrosion on cutout, holes and nut. |

**Table 5. Control arms average ASTM 1654 method A ratings and observations.**

| ARL PPG Control Arms<br>Eight Month and 1 Week Evaluation (1/3/2020) | | |
|---|---|---|
| Coating | ASTM 1654 Method A | Notes: |
| Zinc Phos./Type IV | 5.5 | Corrosion at holes, bushing, and welded areas |
| Zinc Phos./Ecoat | 5.5 | Slight corrosion at holes, bushing and welded areas |
| Zirconium/Type IV | 6 | Corrosion at holes, bushing, and welded areas |
| Zirconium/Ecoat | 7 | Slight at holes, bushing, and welded areas |

After 8 months and 1 week of exposure at NASA Beachside Atmospheric Testing Facility, blisters have developed on some of the Al panels. Average corrosion ratings and observations are tabulated in Tables 6 and 7. One of the HCP/e-coat Al panels developed a small blister and all the Zr pretreated panels, with either Type IV or e-coat primers, developed blisters. The blisters on the Al panels were significantly smaller on the panels with e-coat compared with those coated with Type IV primer. None of the Al brackets have blisters on them.

**Table 6. Al panels average ASTM 1654 method A and ASTM 610 method B ratings and observations.**

| ARL PPG Aluminum Panels<br>Eight Month and 1 Week Evaluation (1/3/2020) | | | |
|---|---|---|---|
| Coating | ASTM 1654 Method A | ASTM 1654 Method B | Notes: |
| HCP/Type IV | 10 | 10 | White products in scribe |
| HCP/Ecoat | 9.3 | 10 | Dark products in scribe, one panel has a small blister |
| Zirconium/Type IV | 5.3 | 10 | White products in scribe, blisters |
| Zirconium/Ecoat | 8.3 | 10 | Dark products in scribe, small blisters |

**Table 7. Al brackets average ASTM 1654 method A and ASTM 610 method B ratings and observations.**

| ARL PPG 3" x 3" Aluminum Brackets<br>Eight Month and 1 Week Evaluation (1/3/2020) | | | |
|---|---|---|---|
| Coating | ASTM 1654 Method A | ASTM 1654 Method B | Notes: |
| HCP/Type IV | 10 | 10 | White products in scribe |
| HCP/Ecoat | 10 | 10 | Dark products in scribe |
| Zirconium/Type IV | 10 | 10 | White products in scribe |
| Zirconium/Ecoat | 10 | 10 | Dark products in scribe |

Figures 11 and 12 show final results for the control arms compared with the appearance at initial installation at NASA Beachside Atmospheric Testing Facility. As noted in earlier examinations, corrosion products are forming at threaded areas, the scribed region, and along edges. Closer examination of the interior surfaces also shows corrosion products, as seen in Figure 13. In each case, this corrosion is significantly worse for the spray applied MIL-DTL-53022F Type IV primed parts than the e-coated parts. Similar images are captured for the spangler panels that experienced atmospheric exposure during the same period. These panels are shown in Figure 14. In each case, the Zn phosphate-treated parts are exhibiting modestly better performance than the same coating stack with Zr oxide as the pretreatment.

These observations are consistent with industrial experience with e-coated parts and assemblies and are illustrative of the superior protection provided by the e-coat primer. This is particularly true of interior surfaces, which are nearly impossible to protect using conventional spray-applied coatings.

| Part # | (Blasted) pretreatment | Primer | Month 0 | Month 13 |
|---|---|---|---|---|

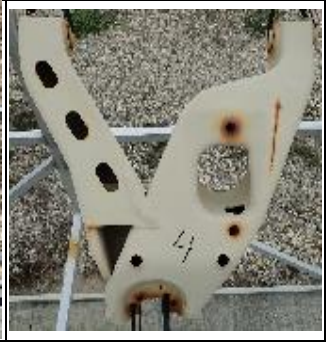
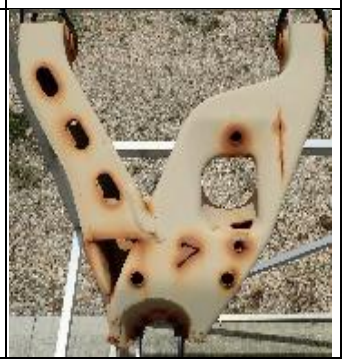
| | | | | |
|---|---|---|---|---|
| 1 | Zn phosphate | 53022 Type IV |  |  |
| 4 | Zn phosphate | E-coat |  |  |

**Figure 5. Comparison of Zn phosphate pretreated parts with either MIL-DTL-53022 Type IV or e-coat primer after 13-month exposure.**

| Part # | (Blasted) pretreatment | Primer | Month 0 | Month 13 |
|---|---|---|---|---|
| 7 | Zr<br>Xbond 4000 | 53022 Type IV |  |  |

| | | | | |
|---|---|---|---|---|
| 10 | Zr Zircobond4200 | E-coat |  |  |

**Figure 6. Comparison of Zr oxide pretreated parts with either MIL-DTL-53022 Type IV or e-coat primer after 13-month exposure.**

| Part # | (Blasted) pretreatment | Primer | Month 13 interior view |
|---|---|---|---|
| 1 | Zn phosphate | 53022 Type IV |  |
| 4 | Zn phosphate | E-coat |  |

**Figure 7. Interior view of control arms 1 and 4 showing corrosion products forming with the MIL-DTL-53022 Type IV primer after 13-month exposure but not the e-coat primed part.**

| Part # | (blasted) Pretreatment | Primer | Month 0 Exposure | Month 13 exposure |
|---|---|---|---|---|
| 10 | Zinc Phosphate | 53022 type 4 |   |   |
| 21 | Zinc Phosphate | Electrocoat |   |   |
| 29 | Zirconium | 53022 type 4 |   |   |
| 43 | Zirconium | Electrocoat |   |   |

**Figure 8. Spangler panels as initially installed for exposure and after 13 months at NASA Beachside Atmospheric Testing Facility.**

# 7. Cost Assessment

The proposed e-coat system is expected to result in significant cost and environmental benefits relative to the baseline materials and processes. However, there will potentially be significant costs involved in implementation of the proposed technology at each facility where the proposed technology has the potential to be deployed.

Detailing information for the cost assessment will ultimately be based upon a location-by-location assessment. For this program, LEAD was used as a baseline and larger volume depots were modeled to assess the cost savings possible when higher throughput or reduced number of shifts were possible.

## 7.1 Cost Model

Actual paint consumption for LEAD was obtained, which was used to approximate square footage surface area coated per year. LEAD provided the volume per month for both Zn-rich primer and MIL-DTL-53022F primer (Table 8). Zn phosphate is typically applied directly to metal with a mid-coat of 53022 primer on top of it. Since applying e-coat directly to a Zn-rich primed substrate is not usually performed, the volume of epoxy primer used as a sealer over Zn-rich primer was removed from the total volume estimate for MIL-DTL-53022F primer.

**Table 8. LEAD primer consumption data.**

| Gallons of Zinc-rich Primer (MIL-PRF-32550) Used, 01-Jan-2020 Through 31-Dec-2020 | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Source | Paint Booth | Bldg. | January | Feb. | March | April | May | June | July | August | Sept. | October | Nov. | Dec. | Total |
| 108 | 61 | 350 | 22 | 10 | 34 | 14 | 15 | 15 | 4 | 6 | 2 | - | - | - | 122 |
| 126 | 4298 | 370 | 7 | 3 | 2 | 3 | 4 | 4 | 4 | 6 | 1 | - | - | - | 34 |
| 200 | 4757 | 370 | 9 | 10 | 12 | 18 | 22 | 16 | 10 | 4 | 6 | - | - | - | 107 |
| Total | | | 38 | 23 | 48 | 35 | 41 | 35 | 18 | 16 | 31.75 | 31.75 | 31.75 | 31.75 | 381 |
| **Gallons of Epoxy Primer (MIL-DTL-53022, Type IV) Used, 01-Jan-2020 Through 31-Dec-2020** | | | | | | | | | | | | | | | |
| Source | Paint Booth | Bldg. | January | February | March | April | May | June | July | August | September | October | November | December | Total |
| 108 | 61 | 350 | 40 | 21 | 29 | 25 | 24 | 23 | 4 | 16 | 3 | - | - | - | 185 |
| 126 | 4298 | 370 | 13 | 11 | 10 | 13 | 12 | 11 | 11 | 10 | 1 | - | - | - | 92 |
| 200 | 4757 | 370 | 18 | 13 | 21 | 30 | 28 | 29 | 28 | 7 | 8 | - | - | - | 182 |
| Total | | | 71 | 45 | 60 | 68 | 64 | 63 | 43 | 33 | 55.875 | 55.875 | 55.875 | 55.875 | 670.5 |

**Assumptions/Corrections**

Full data to August was availble, full year volume assumed average consumption for remainder of year
Assume 1/3 of Zinc Rich Volume = amount of epoxy primer applied over zinc rich = 126.99
Assume amount of epoxy on steel without zinc rich = total - amount used with zinc rich = 543.51
Assume surface area covered equals epoxy x 496 sq. ft/gallon = 269,580 sq. ft.

The cost–benefit analysis (CBA) assesses the impact of inserting the e-coat process versus the current process for those parts that also require the use of spray booths for topcoating. To provide a thorough CBA of replacing the baseline technology with the proposed technology, costs for the baseline materials and processes versus proposed materials and processes were determined. These costs allowed for estimated cost savings to be calculated if the proposed technology replaces the baseline technology.

As a basis for performing this CBA, PPG has an established process for performing a comprehensive cost comparison between a new e-coat and an existing coating operation. PPG has an extensive history of providing analyses of this type for e-coat, other liquid coatings, and powder coatings, enabling each user to select the most cost-effective and best-performing coating system for its unique needs.

This model considers the following factors:

- Comparative coating cost per square foot of coated surface, which involves
    - Cost per liquid gallon
    - Volume solids of each coating
    - Required dry film thickness required by each coating technology
    - Transfer efficiency of each coating technology
- Comparative cost of pretreatment per square foot of coated surface
- Comparative cost of waste stream treatment required for each coating technology
- Capital cost of installation required to conduct coating operations, to the extent that the physical installations are different
- Comparative daily/weekly/yearly hours of operation to coat a given square footage of parts
- Labor requirements required for staffing operations for each technology
- Comparative utility (natural gas/electric) cost requirements (curing ovens, temperature and agitation control of application system)

These costs are annualized and then used to determine an applied cost per square foot of coated substrate to provide the best possible comparison between e-coat and either an existing system or an alternative proposed new system.

The cost model noted above is focused on installation and operating costs. These numbers can be clearly documented and will provide the most tangible basis for evaluating the feasibility of installing an e-coat system into an overall coating operation. Additional factors, which may be relevant in some instances, can be used to augment the standard cost comparison. These factors may include:

- Additional (or reduced) time introduced to the total coating process (process disruption cost).
- Additional (or reduced) pretreatment or coating steps/layers required by alternative technology.
- Additional (or reduced) rework required by alternative technology, if not captured in labor cost above.
- Additional (or reduced) waste or health/personal protection equipment requirements for rework.

## 7.2 Cost Analysis and Comparison

As described in Section 7.1, the factors for the cost model can be characterized simply by three main categories, as represented in Figure 15. By evaluating the material costs, operational costs, and utilities, we can see the impact of changes to these variables.

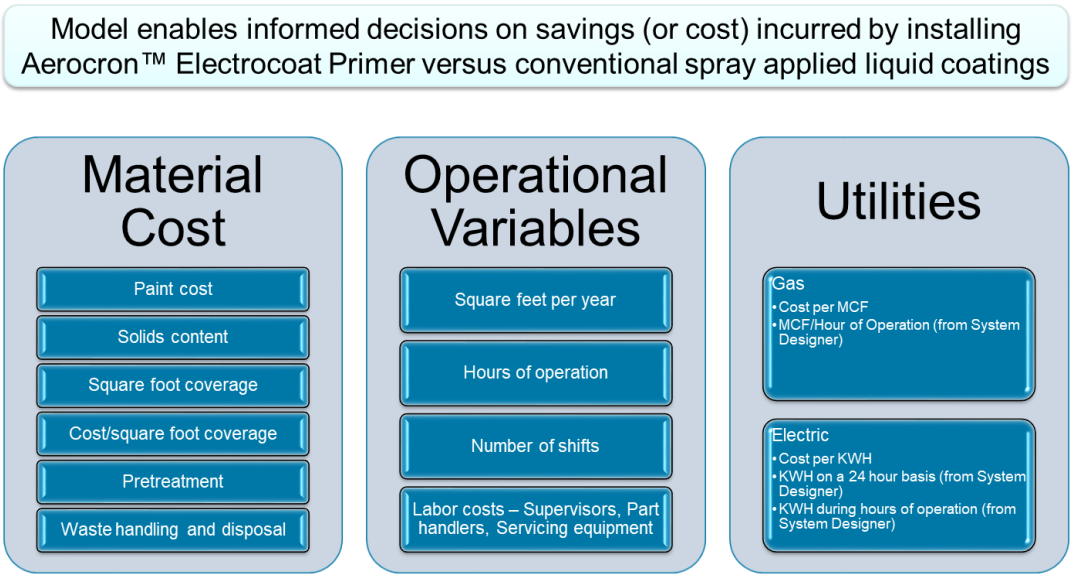



**Figure 9. Cost model inputs.**

A detailed breakdown is shown in Table 9. The model allows for versatility in changing multiple factors to determine their influence on costs. Inputs highlighted in yellow allow for adjustment based upon changing operational factors. For example, film thickness in spray application is directly impacted by the artisan's abilities and the complexity of the part. Achieving nominal film thickness and coverage in the recessed areas of complex parts with deep recesses creates a greater potential for having higher film build in non-recessed areas, thus increasing the overall average film thickness of the part. This directly relates to material usage and finished part weight. Another example would be the number of shifts per day;

it may require additional shifts to keep up with the workload for spray application. This directly impacts the number of hours per year and labor costs.

**Table 9. Cost model.**

| | E-Coat | Liquid Primer |
|---|---|---|
| **Aerocron® Paints** | | |
| Cost $/gal cationic electrocoat | $28.00 | |
| **Liquid Primer** | | |
| Cost $/gal LP | | $40.14 |
| Vol. Sol. % LP | | 48.0% |
| Cost per Blended Gallon | $28.00 | $40.14 |
| SF Coverage @1.0 mils | 598 | 744 |
| Cost/SF @1.0 mils | $0.05 | $0.05 |
| DFT (mils) | 0.8 | 1.5 |
| SF Coverage at DFT | 748 | 496 |
| Cost /SF @ DFT | $0.037 | $0.081 |
| Transfer Efficiency | 95% | 40% |
| Applied Cost/SF | 0.039 | 0.202 |
| **Ware Surface Area** | | |
| SF being Painted | 269,000 | 269,000 |
| **Capital Costs** | | |
| Price of the System | **$2,000,000** | |
| **Hours of Operation** | | |
| Hours/Shift | 8 | 8 |
| Shifts/Day | 2 | 2 |
| Days/Week | 5 | 5 |
| Weeks/Year | 50 | 50 |
| Hours/Year | 4000 | 4000 |
| **Labor** | | |
| Qty of Supervisors per Shift | 1 | 1 |
| Supervisor Hourly Rate | $25.00 | $25.00 |
| Qty of Line Operators per Shift | 1 | |
| Line Operator Hourly Rate | $20.00 | |
| Qty of Loaders/Unloaders per Shift | 2 | 2 |
| Loaders/Unloaders Hourly Rate | $16.00 | $16.00 |
| Qty of Painters per Shift | | 3 |
| Painter's Hourly Rate | | $20.00 |
| **Utilities** | | |
| ***Gas*** | | |
| Cost per MCF | $5.04 | $5.04 |
| MCF/Hour of Operation (from System Designer) | 20 | 25 |
| ***Electric*** | | |
| Cost per KWH | $0.05 | $0.05 |
| KWH on a 24 hour basis (from System Designer) | 10 | |
| KWH during hours of operation (from System Designe | 100 | 60 |

There are a few things to point out about the cost model. The first advantage e-coat has is the cost per gallon (~$28.00/gal) is significantly less than the spray-applied primer at $40.14/gal. However, square foot coverage is less for e-coat than the spray-applied primer, making cost per square foot at the same film thickness essentially the same. E-coat primer is typically applied at a much lower film

thickness (0.8 vs. 1.5 mils) so overall cost per square foot becomes about half the cost of spray-applied primer. This is a generous assumption for spray-applied primers because complex-shaped parts will typically require more than 1.5 mils to have at least some protection in recessed areas. Next, transfer efficiency comes into the model. E-coat can easily achieve 95% transfer efficiency whereas spray-applied primers are typically closer to 40%, especially for complex parts. This yields significant savings for applied cost per square foot of coverage. We assume slightly fewer labor resources are needed to operate the e-coat line, and we also assume a higher cost of energy due to operation of the bath and ultrafilters. Using these basic parameters, a range of scenarios were modeled to illustrate savings or costs relative to existing liquid spray-applied primers. While the initial assumptions show essentially a break-even cost savings of only 1% by utilizing the e-coat process, this is only one example of the possible operating scenarios for implementation at LEAD or a similar depot. The following examples (Scenarios 1, 2, and 3) provide the assumptions utilized in the model as well as the overall breakdown of costs between e-coat and liquid spray application. Tables 10–13 show cost savings from 14%–56%.

### 7.2.1 Scenario 1 Assumptions

- Annual square footage processed: 269,000
- Two shifts per day, four full-time labor equivalents
- Capital costs: e-coat equipment included at $2M amortized over 10 years (this is an estimate only and final cost would need to be verified based upon actual equipment, which could be higher or lower depending on design and installation)
- No change in current pretreatment

**Table 10. Cost model scenario 1.**

| | E-Coat Dollars | Liquid Dollars | E-Coat Percentage | Liquid Percentage |
|---|---|---|---|---|
| Paint Costs + other additives | $10,607 | $54,424 | 1.3% | 5.7% |
| Surface Treatment | $0 | $0 | 0.0% | 0.0% |
| Waste Treatment | $0 | $0 | 0.0% | 0.0% |
| Capital Costs (per year cost over 10 year period) | $0 | $0 | 0.0% | 0.0% |
| Labor | $388,000 | $388,000 | 46.8% | 40.4% |
| Utilities | $429,712 | $516,928 | 51.9% | 53.9% |
| | | | | |
| **Total Annual Costs/Year** | **$828,318** | **$959,352** | (131,033) | Difference |
| | | | 14% | E-Coat Savings |
| **Applied Costs/SF** | **3.08** | **3.57** | | |

Scenario 1 assumes an e-coat system replaces spray-applied primer but all other variables are held the same. No changes to the number or type of labor resources, number of shifts, or square footage of parts painted. Cost savings are estimated to be about 14%, even with amortized capital costs. This scenario would be representative of a situation where the e-coat line is newly installed and the workforce is still learning the details of safe and efficient operation.

### 7.2.2 Scenario 2 Assumptions

- Annual square footage processed: 269,000
- One shift per day, e-coat enables higher throughput
- Capital costs: e-coat equipment included at $2M amortized over 10 years (this is an estimate only and final cost would need to be verified based upon actual equipment, which could be higher or lower depending on design and installation)
- No change in current pretreatment

**Table 11. Cost model scenario 2.**

| | E-Coat Dollars | Liquid Dollars | E-Coat Percentage | Liquid Percentage |
|---|---|---|---|---|
| Paint Costs + other additives | $10,607 | $54,424 | 1.7% | 5.7% |
| Surface Treatment | $0 | $0 | 0.0% | 0.0% |
| Waste Treatment | $0 | $0 | 0.0% | 0.0% |
| Capital Costs (per year cost over 10 year period) | $200,000 | $0 | 32.2% | 0.0% |
| Labor | $194,000 | $388,000 | 31.2% | 40.4% |
| Utilities | $217,252 | $516,928 | 34.9% | 53.9% |
| | | | | |
| **Total Annual Costs/Year** | **$621,858** | **$959,352** | (337,493) | Difference |
| | | | 35% | E-Coat Savings |
| **Applied Costs/SF** | **2.31** | **3.57** | | |

Scenario 2 assumes the line has been in operation for some period of time, labor resources are fully trained, and efficiencies exist such that the same volume of parts are processed but the work can be completed in one shift as opposed to two. Here, even with amortized capital costs, savings reach 35%.

### 7.2.3 Scenario 3 Assumptions

- Annual square footage processed: 269,000
- One shift per day
- No capital costs (after e-coat equipment amortization)
- No change in current pretreatment

**Table 12. Cost model scenario 3.**

| | E-Coat Dollars | Liquid Dollars | E-Coat Percentage | Liquid Percentage |
|---|---|---|---|---|
| Paint Costs + other additives | $10,607 | $54,424 | 2.5% | 5.7% |
| Surface Treatment | $0 | $0 | 0.0% | 0.0% |
| Waste Treatment | $0 | $0 | 0.0% | 0.0% |
| Capital Costs (per year cost over 10 year period) | $0 | $0 | 0.0% | 0.0% |
| Labor | $194,000 | $388,000 | 46.0% | 40.4% |
| Utilities | $217,252 | $516,928 | 51.5% | 53.9% |
| | | | | |
| **Total Annual Costs/Year** | **$421,858** | **$959,352** | (537,493) | Difference |
| | | | 56% | E-Coat Savings |
| **Applied Costs/SF** | **1.57** | **3.57** | | |

Scenario 3 assumes the line has been in operation for a while, staff is fully trained, and the capital costs have been fully paid for. Here, savings jump to 56%, relative to the same volume of parts being coated with spray-applied primer.

### 7.2.4 Scenario 4 Assumptions

- Annual square footage processed: 538,000
- Two shifts per day for e-coat, three shifts for spray-applied
- No capital costs (after e-coat equipment amortization)
- No change in current pretreatment

**Table 13. Cost model scenario 4.**

| | E-Coat Dollars | Liquid Dollars | E-Coat Percentage | Liquid Percentage |
|---|---|---|---|---|
| Paint Costs + other additives | $21,213 | $108,847 | 2.5% | 7.4% |
| Surface Treatment | $0 | $0 | 0.0% | 0.0% |
| Waste Treatment | $0 | $0 | 0.0% | 0.0% |
| Capital Costs (per year cost over 10 year period) | $0 | $0 | 0.0% | 0.0% |
| Labor | $388,000 | $582,000 | 46.2% | 39.7% |
| Utilities | $429,712 | $775,392 | 51.2% | 52.9% |
| | | | | |
| Total Annual Costs/Year | $838,925 | $1,466,239 | (627,314) | Difference |
| | | | 43% | E-Coat Savings |
| Applied Costs/SF | 1.56 | 2.73 | | |

A final model is illustrated as Scenario 4. In this case, the e-coat line has been operating successfully and the volume of processed parts has doubled to 538,000 sq-ft/year. To spray-apply this volume might easily require an additional shift of painters and support staff, whereas the e-coat system is able to complete the work in two shifts. Capital costs have been paid down, and a 43% savings is realized, relative to spray application.

## 8. Conclusion

Implementing new coating technology in the military is challenging, especially new coating technology that also requires new application equipment. Implementation of a cationic e-coat in depot operations may benefit from similar work that is in progress to implement anionic e-coat in military aviation applications. The initial target for the transfer of anodic e-coat primers is the USAF for use on aviation assets. Adoption begins by developing strong support at the Materials and Manufacturing Directorate at Wright–Patterson Air Force Base (AFB) through extensive testing, demonstration, and development of a CBA. This first step was achieved through ESTCP program WP-201010 in conjunction with Bill Hoogsteden of the Air Force Research Laboratory.[13] However, once positive CBA and USAF support were in hand, significantly more time and effort were required to overcome the remaining barriers to implementation.

To aid in the transition of ESTCP programs into use, a funding program titled Innovative Technology Transfer Approaches was developed by ESTCP in 2015. This program was targeted at finding innovative ways to improve the adoption rate of new technologies that have demonstrated success through the demonstration/validation phase. PPG was granted a program titled “Cross-

Functional Training Workshops and Site Assessments for Non-Chromate, Anodic Electrocoat Primer Transfer (15 T2-013/WP-201568T2)."

WP-201568T2 was executed to improve upon the current transfer approach by streamlining communications and bringing together cross-functional teams to more effectively address implementation concerns. Workshops were scheduled at Hill, Robins, Tinker, and Wright Patterson AFBs. These workshops served to assemble various stakeholders in one room and ensure all parties received a consistent message. Stakeholders in coating performance, coating application, corrosion control, environmental compliance, and supply-chain logistics interacted to more fully address the many questions that arose. The cross-functional nature of this approach ensures that both the coating specifiers and coating implementers have confidence that the diverse risks of transition have been addressed. In addition, these cross-functional workshops were invaluable to PPG to gain a clearer picture of how the various stakeholders interrelate and how each will be involved in the actual implementation.

The workshops consisted of classroom instruction on the technology and field evaluation status, and, in the case of Robins, Tinker, and Wright Patterson AFBs, a live demonstration of the application method was conducted. The classroom portion of the program was also conducted at Hill AFB but, in place of the live demonstration, a training video was shown to the workshop attendees. Feedback from the workshops was positive and a collection of questions and answers regarding the technology were addressed, furthering the exchange of knowledge. Additionally, feedback received from the workshops indicated that, while the video was a good educational tool, the live demonstration was more effective as questions could be asked regarding equipment and operation in a live setting.

This program was an excellent example of bringing all the required stakeholders together to advance new technology and an approach that could be duplicated in the Army depot community for the cationic e-coat technology. In place of AFB participation, a similar program for ground vehicle applications would include stakeholders from Red River Army Depot (RRAD), ANAD, and LEAD. As in the anionic e-coat Technology Transfer program, execution could center around a combination of classroom instruction, hands on demonstration, question-and-answer sessions, and focused site-specific implementation issues.

In fact, at the time of proposal, preparation letters of support were obtained from ANAD, RRAD, and LEAD. This indicated an openness to technology and a perceived notion that performance and cost advantages were feasible. However, concerns were quickly raised soon after project execution that will need to be addressed to successfully implement the technology. Specifically, ANAD cited the inability to obtain capital to install a permanent e-coat tank and associated

equipment. A short-term demonstration of the technology is viewed as being of limited value unless a plan is in place for permanent installation. In the case of ANAD, stakeholders believe the volume of parts is sufficient to warrant an e-coat system but available funds for engineering, fabrication, installation, and training are roadblocks to implementation. In the case of LEAD, the major objection was the belief that ultimately the volume of their paint operations is too low to justify the investment. As our cost modeling has shown, this may not be the case since actual paint consumption data from LEAD was used in the analysis. Furthermore, given the tragic accident at LEAD in 2018, drivers for adoption of a water-based coating solution may be much greater.[4] These responses illustrate how firmly the barriers stated above are in place and reinforce the justification for this project.

Several options exist to address these implementation issues. First, PPG acquired MetoKote Corporation in 2016, which was incorporated as part of their coating services business, which applies coatings to customers' manufactured parts and assembled products. It operates onsite coatings services within several customer manufacturing locations as well as at regional service centers throughout the U.S., Canada, Mexico, the U.K., Germany, Hungary, and the Czech Republic. Customers ship parts to PPG service centers, where they are treated to enhance paint adhesion and painted with e-coat, powder, or liquid coatings technologies. Coated parts are then shipped to the customer's next stage of assembly. PPG coats an average of more than 1.5 million parts per day. This model is used by customers to achieve the benefits of e-coat coatings without the capital expense or logistical issues of installing their own e-coat line. Such a model could be explored for multiple depots to address their concerns regarding capital expense. Furthermore, the approach could be explored as a stopgap measure while creative methods of capital amortization are explored.

As an alternative to ANAD, RRAD, and LEAD, Tobyhanna Army Depot (TAD) should be considered for future implementation discussions. TAD has a more consistent stream of parts to coat than some other depots. They also provide services for a broader range of DoD customers. When initially contacted, TAD expressed interest but little knowledge of the e-coat process. At a minimum, in the event of a Technology Transition program like the previous anionic e-coat program, TAD would be an additional stakeholder to engage.

This program has produced abundant evidence of both performance and cost benefits to the use of e-coat primers. While capital expenditures remain a barrier to adoption, several approaches are possible to continue to build the value proposition with stakeholders or to implement on a limited scale without the logistical and financial burden of installing a line at the depot.

## 9. References


1. MIL-DTL-0053084A (MR). Detail specification primer, cathodic electrodeposition, chemical agent resistant. Army Research Laboratory (US); 2006 Aug 3.
2. Clean Air Act of 1970, Pub L No. 117-286, 69 Stat 322 (2022 Dec 27).
3. Clean Air Act of 1970, Pub L No 101-549, 104 Stat 2399 (1990 Nov 15). https://www.govinfo.gov/content/pkg/STATUTE-104/pdf/STATUTE-104-Pg2399.pdf
4. Protection of Environment, definitions, CFR Sect 51.100 (2024 Nov 21).
5. MIL-DTL-53022F. Detail specification primer, epoxy coating, corrosion inhibiting lead and chromate free. DEVCOM Army Research Laboratory (US); 2019 Dec 1.
6. MIL-DTL-53030C. Detail specification primer coating, epoxy, water based, lead and chromate free. Army Research Laboratory (US); 2010 May 19.
7. California Air Resources Board. Consumer products program. California Air Resources Board; c2025. https://ww2.arb.ca.gov/our-work/programs/consumer-products-program/about
8. Lattanzio RK. Clean Air Act: a summary of the act and its major requirements. Congress.gov; 2022 Sep 13. https://www.congress.gov/crs-product/RL30853
9. Hexavalent chromium. OSHA 3373-10 2009. Department of Labor (US); 2009. https://www.osha.gov/sites/default/files/publications/OSHA-3373-hexavalent-chromium.pdf
10. Document issue for 2006-07-28. Office of the Federal Register (US); 2006 July 28. https://www.federalregister.gov/documents/2006/07/28
11. What are the standards and regulations for chromium exposure? Agency for Toxic Substances and Disease Registry, Center for Disease Control (US); 2023 May 25. https://archive.cdc.gov/www_atsdr_cdc_gov/csem/chromium/standards_and_regulations.html
12. Hexavalent chromium. Defense Health Agency–Public Health (US); 2024 Jan 24. https://ph.health.mil/topics/workplacehealth/ih/Pages/Cr6.aspx
13. PPG Industries Inc. Electrocoat process for non-chromate primers in DoD manufacturing. ASETSDefense 2012: Sustainable Surface Engineering for Aerospace and Defense Workshop; 2012 Aug 27–30; San Diego, CA.

14. Electrocoating. Pollution Prevention Infohouse. 2003 Apr. https://p2infohouse.org/ref/38/37017.htm

15. MetoKote Corporation. MetoKote Corporation introduces MikroKote--the small-footprint, big-savings e-coating system. PR Newswire, 2010 Nov 2. https://www.prnewswire.com/news-releases/metokote-corporation-introduces-mikrokote----the-small-footprint-big-savings-e-coating-system-106520618.html

16. ASTM D3359-23. Standard test methods for rating adhesion by tape test. ASTM International; 2023 Mar 7.

17. GMW14872. Cyclic corrosion laboratory test. General Motors Worldwide; 2013.

18. ASTM B117-16. Standard practice for operating salt spray (fog) apparatus. ASTM International; 2016.

19. Headquarters, Department of the Army. Army materiel maintenance policy. Headquarters, Department of the Army; 2023 Mar 2. Army Regulation 750–1. https://armypubs.army.mil/epubs/DR_pubs/DR_a/ARN32929-AR_750-1-000-WEB-1.pdf

20. Atmospheric site data. National Aeronautics and Space Administration (US); 2023 July 31. https://public.ksc.nasa.gov/corrosion/atmospheric-site-data/

## List of Symbols, Abbreviations, and Acronyms

| | |
|---|---|
| 3D | three-dimensional |
| ACGIH | American Conference of Governmental Industrial Hygienists |
| AFB | Air Force Base |
| Al | aluminum |
| ANAD | Aniston Army Depot |
| ARL | Army Research Laboratory |
| AVLB | Armored Vehicle Launched Bridge |
| CAA | Clean Air Act |
| $CaCl_2$ | calcium chloride |
| CARC | Chemical Agent–Resistant Coating |
| CBA | cost–benefit analysis |
| CIC | Coatings Innovation Center |
| Cr | chromium |
| Cr (II) | bivalent chromium |
| Cr (III) | trivalent chromium |
| Cr (VI) | hexavalent chromium |
| DC | direct current |
| DEVCOM | U.S. Army Combat Capabilities Development Command |
| DI | deionized |
| DoD | Department of Defense |
| e-coat | electrocoat |
| EPA | Environmental Protection Agency |
| ESTCP | Environmental Security Technology Certification Program |
| FMTV | Family of Medium Tactical Vehicles |
| GVSC | Ground Vehicle Systems Center |

| | |
|---|---|
| HAP | hazardous air pollutant |
| HCP | hexavalent containing conversion coating |
| HMMWV | High Mobility Multipurpose Wheeled Vehicle |
| HVLP | high-volume, low-pressure |
| IR | infrared |
| KSC | Kennedy Space Center |
| LEAD | Letterkenny Army Depot |
| MIBK | methyl isobutyl ketone |
| NaCl | sodium chloride |
| $NaHCO_3$ | sodium bicarbonate |
| NASA | National Aeronautics and Space Administration |
| NDCEE | National Defense Center for Environmental Excellence |
| OEM | original equipment manufacturer |
| OSHA | Occupational Safety and Health Administration |
| PEL | permissible exposure limit |
| PPG | PPG Industries, Inc. |
| RF | radio frequency |
| ROI | return on investment |
| RRAD | Red River Army Depot |
| TAD | Tobyhanna Army Depot |
| TLV | threshold limit value |
| TRL | Technology Readiness Level |
| TWA | time-weighted average |
| USAF | U.S. Air Force |
| USCG | U.S. Coast Guard |
| UV | ultraviolet |
| VOC | volatile organic compound |

| | |
|---|---|
| Zn | zinc |
| Zr | zirconium |

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