ESTCP
Cost and Performance Report

(WP-200614)

Low Temperature Cure Powder Coatings

May 2013

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ACRONYMS AND ABBREVIATIONS

AFB	Air Force Base
AFCEC	U.S. Air Force Civil Engineer Center
AFMC	Air Force Materiel Command
ASTM	American Society for Testing Materials
CAA	Clean Air Act
CBA	cost benefit analysis
CCC	chromate conversion coating
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CFR	Code of Federal Regulations
COTS	commercial-off-the-shelf
CTIO	Coatings Technology Integration Office
CVCM	collected volatile condensable material
DoD	U.S. Department of Defense
DOI	distinctness of image
ECAM	Environmental cost analysis methodology
EEF	environmental equipment and facilities
EPCRA	Emergency Planning and Community Right-to-know Act
EQP	Engineering Qualification Plan
ESOH	Environmental, Safety, and Occupational Health
ESTCP	Environmental Security Technology Certification Program
FED-STD	Federal Standard
FRCE	Fleet Readiness Center East
FRCNW	Fleet Readiness Center Northwest
FRCSE	Fleet Readiness Center Southeast
FRCSW	Fleet Readiness Center Southwest
FSE	field service evaluation
GM	General Motors
GSE	ground support equipment
HAP	hazardous air pollutant
IRR	internal rate of return
JTP	Joint Test Protocol
JTR	Joint Test Report
LCC	life cycle costs
LTCPC	low temperature cure powder coating
MEK	methyl ethyl ketone
MIBK	methyl isobutyl ketone

MIL-PRF	Military Performance Specification
MSDS	Material Safety Data Sheet
N/A	not applicable
NAS	Naval Air Station
NASA	National Aeronautics and Space Administration
NAVAIR	Naval Air Systems Command
NDCEE	National Defense Center for Energy and the Environment
NESHAP	National Emissions Standards for Hazardous Air Pollutants
NIOSH	National Institute for Occupational Safety and Health
NPV	net present value
N/R	not reported
O&M	operations and maintenance
OMB	Office of Management and Budget
OO-ALC	Ogden Air Logistics Center
OSHA	Occupational Safety & Health Administration
PC	powder coating
PEL	permissible exposure limit
PPE	personal protective equipment
QPD	qualified product database
RCRA	Resource Conservation and Recovery Act
RED	Reregistration Eligibility Decision
SAIC	Science Applications International Corporation
SERDP	Strategic Environmental Research and Development Program
SOP	Standard Operating Procedures
TCLP	toxicity characteristic leaching procedure
TGIC	triglycidyl isocyanurate
TO	technical order
TML	total mass loss
TRI	toxics release inventory
USAF	United States Air Force
USEPA	U. S. Environmental Protection Agency
USN	United States Navy
UV	ultraviolet
VOC	volatile organic compound
Wt%	weight percentage

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- Naval Air Systems Command, Patuxent River, MD
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- Oklahoma City Air Logistics Center, Tinker AFB, OK
- Warner Robins Air Logistics Center (WR-ALC), Robins AFB, GA

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EXECUTIVE SUMMARY

BACKGROUND

The ESTCP project WP-200614 completed the work associated with transitioning the Low Temperature Cure Powder Coating (PC) (LTCPC) into use at U. S. Department of Defense (DoD) maintenance facilities. This project accomplished the following major milestones: (1) conduct additional testing and evaluation of the candidate material to more thoroughly characterize performance (beyond the testing and substrates used in the previous Strategic Environmental Research and Development Program [SERDP] project PP-1268) utilizing a Joint Test Protocol (JTP); (2) demonstrate the improvements in the coating process and the superior operational performance of the PC on aircraft components and ground support equipment; (3) validate the environmental benefits associated with the LTCPC on aircraft components and ground support equipment; (4) quantify the cost, logistics, and performance parameters of baseline coating methods for Air Force and Navy logistics centers and demonstrate the cost-savings potential for transitioning to LTCPC; and (5) coordinate and facilitate technology transition of the low temperature process into governing documents (e.g., MIL-PRF-24712 and coatings related technical orders) and actual depot operations.

OBJECTIVES OF THE DEMONSTRATION

The performance objectives for the LTCPC program are summarized below.

Table 1. Summary of LTCPC performance objectives.

Performance Objective	Demonstration Results
Quantitative Performance Objectives	
Product Testing (JTP):	
• Color	• Not reported (N/R)
• Gloss	• N/R
• Neutral salt fog corrosion resistance	
o 2024-T3 aluminum	• Inconclusive
o 6061-T6 aluminum	• Passed criteria
o AZ31B magnesium	• Passed criteria
o 4130 steel	• Passed criteria
• Sulfur dioxide (SO_2) corrosion resistance	
o 2024-T3 aluminum	• Failed criteria
o 6061-T6 aluminum	• Inconclusive
o 4130 steel	• Passed criteria
• Cyclic corrosion resistance	• Passed criteria
• Filiform corrosion resistance	• Passed criteria
• Cross-cut adhesion by tape	• Passed criteria
• Impact flexibility	• Passed criteria
• Fluids resistance	• Passed criteria
• Low temperature flexibility	• Passed criteria

Table 1. Summary of LTCPC performance objectives (continued).

Performance Objective	Demonstration Results
Quantitative Performance Objectives (continued)	
Field Service Evaluation: • Color • Gloss • Film thickness • Corrosion	 • Inconclusive • Inconclusive • Not applicable (N/A) • Passed criteria
Reduction of hexavalent chromium use	• Passed objective
Reduction of hazardous waste generated	• Passed objective
Reduction of processing time requirements	• Passed objective
Qualitative Performance Objectives	
Product Testing (JTP): • Coating appearance • Strippability	 • Passed criteria • N/A
Field Service Evaluation: • Coating appearance • Adhesion • Fluids resistance • Humidity resistance • Abrasion resistance • Low temperature flexibility	 • Passed criteria • Passed criteria • Passed visual inspections • Passed visual inspections • Passed visual inspections • Passed criteria
Reduction of volatile organic compound (VOC)/ hazardous air pollutant (HAP) emissions	• Passed objective
Reduction of rework activities	• Inconclusive
Reduction of worker exposures	• Passed objective

DEMONSTRATION RESULTS

A combination of laboratory test results and actual field evaluations confirmed the suitability of LTCPC as a direct replacement for several wet coating systems that are currently in use on DoD aircraft and ground support equipment components. LTCPC demonstration results support the current stakeholder efforts directed at implementing this technology at DoD maintenance facilities.

IMPLEMENTATION ISSUES

Although this coating material will not be used initially on a wide scale basis, Air Force and Navy acceptance will increase LTCPC usage through the modification of specifications and technical orders regarding approved coatings. This will facilitate adoption of the process by other services and original equipment manufacturers. In addition to the previously identified military uses for LTCPCs, technology transition opportunities exist within general aviation and other industries looking to reduce existing powder cure energy requirements or to apply uniform, high-performance coatings to temperature-sensitive substrates.

1.0 INTRODUCTION

1.1 BACKGROUND

The use of traditional coating systems formulated with volatile organic compounds (VOC) and hazardous air pollutants (HAP) presents the U. S. Department of Defense (DoD) with a significant burden for environmental compliance, permitting, tracking, storage, operations, disposal, and reporting requirements. Handling and disposal of toxic hazardous waste associated with these coatings is extremely costly, time consuming, and presents risk to human health and the environment. Senior officials have recognized the increasing environmental demands placed on DoD facilities and have shown continued interest and support of demonstration/validation efforts which reduce dependence on traditional coating systems.

Powder coating (PC) is a technology that virtually eliminates the hazardous waste streams associated with conventional painting techniques. These waste streams include air emissions, contaminated booth filters, unused admixed paints and cleaning solvents. PC also greatly reduces employee exposure and liabilities associated with liquid coating use. The PC process distributes a small-particulate mixture of resin and pigment onto a substrate, which is then hardened at high temperature inside a curing oven. Advantages over conventional spray painting include greater durability, improved corrosion resistance; and elimination of drips, runs, and bubbles.

PCs currently in use have a range of applications within the automotive, aerospace, construction, and consumer products industries; however, certain applications are limited due to the process requirements of PC. Some components cannot withstand the high temperatures required for curing of the PC without degradation. Within the DoD, temperature-sensitive components made of aluminum and magnesium are used extensively on weapons systems due to their durability and low weight. These substrates cannot withstand the high temperature cure (up to 400 °F) necessary for PCs.

A low temperature cure technology would offer the DoD a VOC and HAP-free material coating system that does not compromise substrate material properties. A candidate material was identified under Strategic Environmental Research and Development Program (SERDP) project PP-1268 “120 °C (250 °F) Cure, Durable, Corrosion Protection Powder Coatings for Temperature Sensitive Substrates.” This low temperature cure PC (LTCPC) material was produced by Crosslink Powder Coatings, Inc. and designated White 595B-17925, with product number 6191-61003. The LTCPC has the potential to eliminate a significant amount of the toxic and hazardous materials currently being used on the targeted components and equipment without compromising structural integrity.

1.2 OBJECTIVES OF THE DEMONSTRATION

Each of the following objectives for the LTCPC program was met:

1. Conduct additional testing and evaluation of the candidate material to more thoroughly characterize performance (beyond the testing and substrates used in the related SERDP project) utilizing a Joint Test Protocol (JTP).

2. Demonstrate the improvements in the coating process and the superior operational performance of the LTCPC on aircraft components and ground support equipment.
3. Validate the environmental benefits associated with the use of LTCPC on aircraft components and ground support equipment.
4. Quantify the cost, logistics, and performance parameters of baseline coating methods for Air Force and Navy logistics centers and demonstrate the cost-savings potential for transitioning to LTCPC.
5. Coordinate and facilitate technology transition of the low temperature process into governing documents (e.g., military performance specification [MIL-PRF]-24712 and coatings related Technical Orders) and actual depot operations.

1.3 REGULATORY DRIVERS

The current use of solvent-based chromated primers and topcoat compounds poses risks in the form of fines for non-compliance to federal, state, and local regulations. Fines may be imposed for violations related to the Clean Air and Clean Water Acts, National Emissions Standards for Hazardous Air Pollutants (NESHAP), Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), and Resource Conservation and Recovery Act (RCRA). Senior officials have recognized the increased environmental demands placed on DoD facilities and have shown continued interest and support of demonstration/validation efforts to reduce dependence on traditional coating systems.

VOCs are defined within Title 40 of the Code of Federal Regulations (CFR) [40 CFR 51.100(s)]. Typically, state or local agencies only regulate VOC emissions for sources residing within ozone non-attainment areas, new facility construction, or major modifications to existing facilities (American Solvents Council, 2005). HAPs are defined by the 1990 Clean Air Act (CAA) Amendments [Section 112(a)]. Environmental Protection Agency (EPA)-regulated major sources, as defined by the CAA Amendments, encompass stationary sources nationwide that annually emit or have the potential to emit at least 10 tons of a single HAP or 25 tons of any combination of HAPs. DoD rework and repair facilities commonly fall within this category.

Conventional paints include solvents, such as methyl ethyl ketone (MEK) and methyl isobutyl ketone (MIBK), which help dissolve or disperse the various paint components and ensure the desired consistency for application. The coatings release the majority of VOCs and HAPs during application of primers, and topcoats. Residual VOC/HAP releases continue as the coating system proceeds to full cure, and to a smaller extent throughout the coating's lifespan. DoD coating applications are currently subject to NESHAP for Aerospace Manufacturing and Rework Facilities [40 CFR Part 63, Subpart GG]. In respect to solvent-based coatings, the NESHAP standards for primer and topcoat application operations [40 CFR 63.745] define the maximum allowable HAP and VOC content for both uncontrolled and controlled applications at aerospace rework facilities. These environmental constraints are of particular concern to defense facilities residing within non-attainment regions subject to fines for non-compliance.

The implementation of the OSHA Final Rule designating the permissible exposure limit (PEL) for hexavalent chromium is a significant driver for the use of non-chromium containing coatings.

The employer must demonstrate that they have controls capable of keeping the Occupational Safety & Health Administration (OSHA) 8-hour time weighted average to below 5.0 µg/m^3. The advantage of the LTCPC is that it replaces chromium use by eliminating chromium containing primers such as MIL-PRF-23377.

The LTCPC material has the ability to significantly mitigate the contributions to VOCs and HAPs for the solvent-based coating applications it replaces. It can also reduce the utilization of hexavalent chromium, by eliminating the primer process. This can all be accomplished without contributing to any new foreseen regulatory drivers.

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2.0 DEMONSTRATION TECHNOLOGY

2.1 LTCPC DESCRIPTION

2.1.1 Low Temperature Cure Mechanisms

The temperature at which a thermosetting resin cures is a function of the cross-linker's chemical composition and cure rate is dependent upon the associated heat of reaction. To achieve a desired low cure temperature of 120°C, resin systems are selected that have a compatible curing point at or below this constraint while also fulfilling the desired material characteristics. Required heats of reaction can be decreased through the addition of low-concentration reaction catalysts (< 1.0 weight percentage [wt %]) that greatly enhance the reaction at the desired cure temperature. To a lesser extent compatible corrosion inhibitor compounds can impact the observed cure rate for powders.

2.1.2 Material Properties

For LTCPCs there were several required physical properties defined within the JTP. These requirements included a final coating thickness range, a minimum product shelf life, and finished surface quality as measured by a distinctness of image (DOI) wavescan. In addition to required physical properties, there were several material performance requirements a LTCPC candidate needed to meet. Performance with respect to the mechanical properties of coating adhesion, flexibility, impact resistance, and hardness needed to be satisfactory. The coating needed to display excellent corrosion resistance, to be evaluated by salt fog exposure, SO_2 exposure, cyclic corrosion for scribed substrates, and filiform corrosion testing. In addition, a LTCPC needed to show a level of resistance to commonly used chemicals, such as MEK. The initial SERDP effort was designed to produce a low temperature cure powder that exhibited these properties, which was validated through the JTP and demonstration.

2.1.3 Material Application

Ease of application is dramatically improved for PCs versus multistage primer/topcoat systems. Electrostatic spray was used for the purposes of this demonstration.

In 1993, the EPA published a Reregistration Eligibility Decision (RED) document (EPA-738-F-93-019) on barium metaborate. The EPA determined that barium metaborate should be in Toxicity Category III for oral, inhalation, and eye irritation. However, the EPA assessed the risk as minimal. The EPA has indicated that standard personal protective equipment (PPE) including a dust mask is all that is required. The Material Safety Data Sheet (MSDS) for the LTCPC lists the PEL for this material at $5 mg/m^3$, and recommends long-sleeved shirt, full-length trousers, impervious gloves, safety glasses with side shields, and a National Institute for Occupational Safety and Health (NIOSH) approved dust respirator. Bioenvironmental personnel at Hill Air Force Base (AFB) have reviewed barium metaborate and have concurred with the assessment.

Figure 1 is an illustration of the steps required for electrostatic spraying. In electrostatic spraying, an electrical charge is applied to the dry powder particles while the component to be painted is electrically grounded. The charged powder and grounded workpiece create an electrostatic field that pulls the paint particles to the workpiece. The coating deposited on the workpiece retains its charge, which holds the powder to the workpiece. The coated workpiece is then placed in a curing oven, where the paint particles are melted onto the surface and the charge is dissipated.

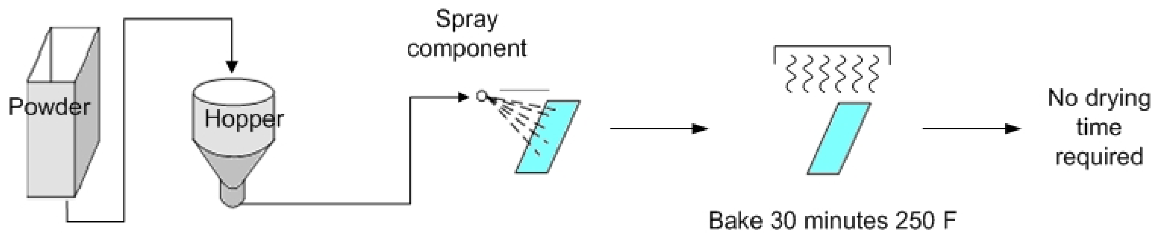

Figure 1. Process illustration of coating process.

2.1.4 Disposal

Accumulation of PC waste is made possible through localized waste stream collection and separation from any carrier material. PC disposal is then accomplished by means of bulk storage container removal by contracted waste management carriers. Most PCs are not defined as hazardous waste, and as such, do not require the level of documentation, reporting, and disposal costs normally associated with more conventional solvent-based coating systems. Avoidance of these disposal restrictions presents the potential for significant cost savings over the life cycle of identified service components. These savings were explored in greater detail later as part of the overall Environmental Security Technology Certification Program (ESTCP) program.

Recently the use of barium-containing compounds within coatings has raised concerns regarding appropriate characterization of worker exposure and risk. Testing based on EPA standards has proven that the level of barium metaborate present within the formulated LTCPC does not constitute a hazardous waste characteristic. As such, both the uncured and cured powder can be disposed of using methods for non-hazardous waste.

2.2 ADVANTAGES AND LIMITATIONS OF LTCPC

The main advantages of LTCPCs include the elimination of HAP and VOC content, as well as improved durability and corrosion resistance. Powders offer superior coating properties, thereby providing an inherent advantage that primers do not. Additionally, PCs are easier to prepare and apply in an application environment as there is no thinning, catalyst addition, mixing, or pot life issues with which to be concerned.

A current limitation of PCs resides in the allowable humidity range for the application of powders, as humid conditions commonly promote clumping and degrade powder adherence to substrates. Also, complex shapes often create difficulties in achieving adequate coverage over all part areas as a result of Faraday Cage effects. The inability to cover large items effectively and size limitations imposed on qualified parts due to the curing oven’s physical dimensions comprise two additional drawbacks of PC technology. Technology innovations such as Ultraviolet (UV) curable powders, which are not constrained by physical oven size due to their cure mechanism, may soon mature and compliment LTCPC by accommodating larger parts.

3.0 PERFORMANCE OBJECTIVES

There were a number of performance objectives evaluated over the course of this project. During the first phase of this demonstration/validation the LTCPC was subject to both qualitative and quantitative product testing, which validated the results of earlier SERDP testing. For the second phase of this project, both services conducted field service evaluations after reviewing the results of LTCPC laboratory-scale testing.

Table 2. LTCPC performance objectives.

Performance Objective	Data Requirements	Success Criteria	Results
Quantitative Performance Objectives			
Product Testing			
Color	MIL-PRF-85285D FED-STD-595B ASTM D 2244	ΔE <1 from Federal Standard	N/R
Gloss	MIL-PRF-85285D FED-STD-595B ASTM D 523 (60°)	≥90 gloss units (gloss coatings) 15≤ χ ≤45 gloss units (semi-gloss coatings)	N/R
Neutral salt fog corrosion resistance	MIL-PRF-23377J ASTM B 117 ASTM D 1654	No blistering or undercutting from the scribe after 2000 hours	**Inconclusive:** 2024-T3 Al **Passed criteria:** 6061-T6 Al; AZ31B Mg; 4130 Steel
Sulfur dioxide (SO_2) corrosion resistance	ASTM G 85, Annex A4 ASTM D 1654, Procedure A, Method 1	No blistering or lifting after 500 hours	**Failed criteria:** 2024-T3 Al **Inconclusive:** 6061-T6 Al **Passed criteria:** 4130 Steel
Cyclic corrosion resistance	GM 9540P GM 4465P ASTM D 1654 ASTM D 714 ASTM D 610	No significant blistering, lifting, or softening of coating after 80 test cycles	Passed criteria
Filiform corrosion resistance	MIL-PRF-23377J ASTM D 2803 ASTM D 1654	≤0.25 inch filaments from the scribe	Passed criteria
Cross-cut adhesion by tape	MIL-PRF-32239 FED-STD-141D, Method 6301.3 ASTM D 3359, Test Method B	4B or better rating	Passed criteria
Impact flexibility	MIL-PRF-85285D ASTM D 6905	5% or better elongation/area increase (Type II)	Passed criteria
Fluids resistance	MIL-PRF-85285D	No blistering or loss of adhesion	Passed criteria
Low temperature flexibility	MIL-PRF-85285D ASTM D 522, Test Method B	No cracking over 1 inch mandrel @ -60 °F	Passed criteria

Table 2. LTCPC performance objectives (continued).

Performance Objective	Data Requirements	Success Criteria	Results
Quantitative Performance Objectives (continued)			
Field Service Evaluation			
Color	FED-STD-595B ASTM D 2244	Utilization of initial color swatches to determine amount of color change versus time	Inconclusive
Gloss	FED-STD-595B ASTM D 523 (60°)	Determination of initial gloss and any change in gloss vs. time, especially for components exposed to outdoor conditions of sunlight, wind, and rain	Inconclusive
Film thickness	ASTM D 7091 ≥6 unique points	N/A - record and report	N/A
Corrosion	ASTM D 1654 Identify coating corrosion failures	No significant blistering, undercutting, or pitting of coating	Passed criteria
Reduction of Hexavalent Chromium Use	Volume of: • Chromated primer usage	Elimination of chromate utilized by current process wet primer	Passed objective
Reduction of Hazardous Waste Generated	Volume of: • Raw materials usage • Air emissions filter use • Disposable PPE usage • Single-use supply use • Organic coatings waste • Spent cleaning solvent • Removed coatings	Elimination of hazardous waste generated by the current wet process	Passed objective
Reduction of Processing Time Requirements	Tracking of processing time in demonstration	Reduction of processing time required for current wet process	Passed objective

Qualitative Performance Objectives			
Product Testing			
Coating appearance	MIL-PRF-85285D	No visible coating or surface defects; Absence of micro-cracks at 10x mag	Passed criteria
Strippability	TO 1-1-8 AF Engr Qual Plan CLG-LP-043 Revision 0	N/A - record and report	N/A
Field Service Evaluation			
Coating appearance	Inspection of the coating for presence of visible surface defects	Uniform smooth surface free from common surface defects Minimal to no orange peel shall be evident	Passed criteria
Adhesion	Determine adhesion after exposure to ops environments	No visible lifting or flaking of coating	Passed criteria
Fluids resistance	Document occurrences of operational fluid exposures to coating	No visible coating defects when and if encountered in the field	Passed visual inspections
Humidity resistance	Document coating performance after long-term ops exposures to high humidity	No visible defects or loss of adhesion when/if encountered in the field	Passed visual inspections
Abrasion resistance	Document occurrences of coating abrasions during operational use	Resistance to abrasion that equals/exceeds the baseline when/if encountered in the field	Passed visual inspections
Low temperature flexibility	Inspection of the coating for presence of visible coating failure	No visible cracking of the coating after exposure to low temperatures	Passed criteria
Reduction of VOC/HAP Emissions	Volume of: • Raw materials usage • Cleaning solvent usage	VOC/HAP reductions from current process	Passed objective
Reduction of Rework Activities	Feedback from field technicians during demonstration	Reduced number of “no pass” component coating jobs currently experienced at the depot facilities from current process	Inconclusive
Reduction of Worker Exposures	Track usage reductions in solvent-containing and chromated materials related to coating operations	Minimize worker exposure to VOCs, HAPs, and hexavalent chrome	Passed objective

AF Engr Qual Plan = Air Force Engineer Quality Plan
MIL-PRF = Military Performance Specification
FED-STD = Federal Standard
ASTM = American Society for Testing Materials
N/R = Not reported
N/A = Not applicable
GM = General Motors
TO = Technical Order

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4.0 SITES/PLATFORM DESCRIPTION

4.1 TEST PLATFORMS/FACILITIES

At the completion of qualification testing, full-scale field demonstration/field service evaluations (FSE) were accomplished. Field demonstrations spanned a minimum 12-month period, starting with the application of the LTCPC onto candidate parts. Navy components were powder coated at Fleet Readiness Center Northwest (FRCNW) or Fleet Readiness Center Southwest (FRCSW); while Air Force components were powder coated at Ogden Air Logistics Center (OO-ALC) prior to installation onto each weapons system.

4.1.1 FRCNW, Naval Air Station (NAS) Whidbey Island, Washington

FRCNW provides intermediate and depot level aviation maintenance, component repair, and logistics support to the Fleet both locally and around the world. FRCNW provides a full range of aircraft avionics, armament, and electrical systems component repair that includes: J52 engine and component repair/build-up; T56-A-14 engine and component repair/build-up; flight control surface structural repair; P-3, EA-6B, and MH-60 aircraft tire/wheel repair; as well as aircraft ground support equipment (GSE) repair Fleet Readiness Center Northwest, 2009).

4.1.2 FRCSW, NAS North Island, California

FRCSW is the lead facility nationwide performing overhaul, repair, and modification of the F/A-18 Hornet, including the E/F model Super Hornet. In addition to maintaining F/A-18 Hornets, FRCSW returns E-2 Hawkeyes, C-2 Greyhounds, multi-use S-3 Vikings, as well as H-60 Seahawk and AH-1/UH-1 helicopters to the fleet while providing over 60,000 aircraft component parts. FRCSW's component program boasts repair capability for over 35,000 unique components used on Navy and Marine frontline tactical and support aircraft for use by the depot's own programs and as critical parts for the Navy-wide supply system. Common avionics and support equipment are serviced by the depot as well (North Island Naval Air Station Fact Sheet, 2005).

4.1.3 OO-ALC, Hill AFB, Utah

OO-ALC operates as one of Air Force Materiel Command's (AFMC) three depot maintenance facilities, with engineering, sustainment, and logistics management for United States Air Force (USAF) weapon systems including all F-16 fighters, Air Force and Marine Corps C-130 Hercules, as well as A-10 Thunderbolts. OO-ALC is the organization responsible for the management, overhaul, and repair of all types of landing gear, wheels, brakes, and tires. Additionally, maintenance activities associated with various USAF avionic, hydraulic, pneudraulic, and radar components, as well as instruments, gas turbine engines, power equipment systems, and special purpose vehicles occur at OO-ALC (Ogden Air Logistics Center, 2009).

4.2 PRESENT OPERATIONS

Coatings currently in use on various non-flight critical components and ground support equipment are typically based on a layered coatings approach. These coatings begin with substrate pretreatment, usually including a conversion coating (either a phosphate-type treatment for steel or a chromated conversion coating for aluminum) to which a high-solids epoxy primer coating is applied (based on MIL-PRF-23377, MIL-P-53022, or MIL-P-53030), followed by a polyurethane topcoat (based on MIL-PRF-85285). Both the primer and topcoat are generally spray-applied. The conversion coating contributes to adhesion of subsequent coatings and provides limited corrosion resistance due to the hexavalent chromium content. The epoxy primer improves adhesion of the topcoat and offers excellent corrosion and chemical resistance while the topcoat typically provides the final finish color and appearance. The solvent-based coating process flow is illustrated in Figure 2 while the resultant coating system is illustrated in Figure 3.

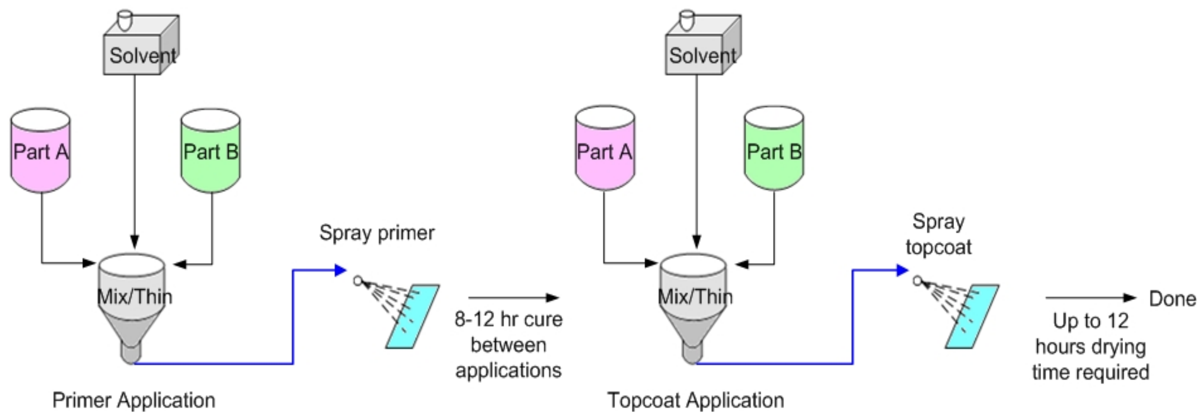

Figure 2. Conventional solvent-based coating process.

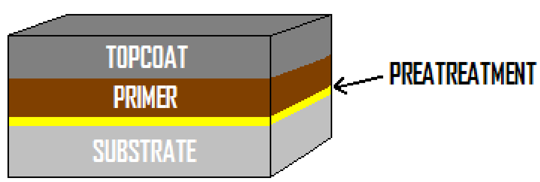

Figure 3. Typical coating stack-up.

Wet paint operations require the user to measure a quantity of paint for the task, combine the paint with appropriate components, mix to spray, and then apply. The user then must wait 8 to 12 hours before the next coat can be applied. Thus, significant labor costs can accumulate when multiple coating layers are required.

Operational procedures common to wet coatings that are potentially impacted by LTCPC use include: (1) storage and shelf life, (2) paint systems, (3) paint equipment, (4) general maintenance requirements for paint spray equipment, (5) preparation of surfaces for painting, (6) health and safety precautions, and (7) application methods, procedures, and paint equipment. The environmental impacts of the solvent-based paint process result from the VOC and HAP contents and from the hexavalent chromium used as a corrosion inhibitor in most primers currently used.

4.3 SITE-RELATED PERMITS AND REGULATIONS

PCs release very little, if any, VOCs and HAPs during application and curing. Additionally, the volume of solvent use associated with traditional wet coatings application and clean-up will be avoided, thereby reducing the overall amount of hazardous waste generated. Therefore, the demonstration of LTCPC will not result in any additional permitting or regulation beyond what is currently in place at each location.

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5.0 TEST DESIGN

5.1 JTP TESTING

5.1.1 Performance Testing Summary

Tables 3 and 4 summarize the common and extended performance testing conducted under the JTP and the subsequent JTP addendum.

Table 3. Common performance and testing requirements.

Engineering Requirement	Test	JTP Section	Acceptance Criteria	References
Critical detailed evaluation of coating appearance and integrity	Coating appearance and quality	4.1	Visible coating or surface defects. Presence of micro-cracks observable at 10X magnification. Gloss and color retention.	MIL-PRF-85285D, FED-STD-595B, ASTM D 2244, ASTM D 523
Acceptable performance in aggressive salt water fog atmosphere	Neutral salt fog corrosion resistance	4.2	Degree of blistering, lifting, and/or substrate corrosion after 2000 hours	MIL-PRF-23377J, ASTM B 117, ASTM D 1654
Acceptable performance after exposure to varying/ cycling environments of salt fog, humidity and heat	Cyclic corrosion resistance	4.4	Degree of blistering, lifting, and/or substrate corrosion after 80 cycles	GM 9540P, GM 4465P, ASTM D 1654, ASTM D 610, ASTM D 714
Performance of coating system in an environment suitable for the formation of filiform corrosion	Filiform corrosion resistance	4.5	Measurement of corrosion filaments from scribe lines	MIL-PRF-23377J, ASTM D 1654, ASTM D 2803
Determine adequacy of intercoat and surface adhesion of organic coating	Cross-cut adhesion by tape	4.6	Adhesion classification based on ASTM scale	MIL-PRF-32239, FED-STD-141D Method 6301.3, ASTM D 3359 Test Method B
Performance of coating when subjected to impact, and deformation of substrate	Impact flexibility	4.7	Type II – 5%	MIL-PRF-85285D 4.6.7.1, ASTM D 6905
Determine the ability to remove the LTCPC from various substrates	Strippability	4.8	Determination of coating strip rate and removal damage appraisal*****	AF TO 1-1-8 AF EQP, CTIO Lab Proc. CLG-LP-043
Performance of coating when subjected to commonly encountered service fluids	Fluids resistance	JTR Appendix A.4	Visible coating or surface defects or failure modes after fluid immersion	MIL-PRF-85285D
Performance of coating when subjected to incidental material impact	Chipping resistance	JTR Appendix A.5	Chipping resistance classification based on ASTM scale*****	ASTM D 3170
Performance of coating when subjected to low temperatures	Low temperature flexibility	JTR Appendix A.6	Presence of surface cracking or failures observable with unaided eye	MIL-PRF-85285D, ASTM D 522 Test Method B

* Evaluation only, not considered part of the Pass/Fail criteria.
EQP = Engineering Qualification Plan JTR = Joint Test Report CTIO = Coatings Technology Integration Office

Table 4. Extended performance and testing requirements.

Engineering Requirement	Test	JTP Section	Acceptance Criteria	References	Org Req Test
Acceptable performance in acidic corrosive environment	SO_2 corrosion resistance	4.3	Degree of blistering, lifting, and/or substrate corrosion after 500 hours.	ASTM G 85 Annex A4, ASTM D 1654 Proc A Mthd 1	USN
Acceptable performance in aggressive salt water fog atmosphere	Neutral salt fog corrosion resistance on 7075 Al	JTR Appendix A.1	Degree of blistering, lifting, and/or substrate corrosion after 2000 hours*****	MIL-PRF-23377J, ASTM B 117, ASTM D 1654	NASA
Performance of coating when subjected to space-based temperature extremes	NASA extreme temperature flexibility	JTR Appendix A.2	Presence of surface cracking or failures observable with unaided eye*****	ASTM D 522 Test Method A	NASA
Vacuum stability of coating for use in spaceport applications	NASA outgassing	JTR Appendix A.3	Measurement of percentage total mass loss and collected volatile condensable material*****	ASTM E 595, NASA-STD-6001, SP-R-0022A Addendum 1	NASA

* Evaluation only, not considered part of the Pass/Fail criteria.
NASA = Naval Aeronautics and Space Administration USN = United States Navy

Test coupons were comprised of steel, aluminum, and magnesium alloys commonly utilized within aircraft and GSE applications. More detailed information, such as test procedures and the rationale for inclusion, is documented within Section 5 of the LTCPC project's publicly-available ESTCP Final Report.

5.2 FIELD AND REAL-WORLD TESTING

5.2.1 FSE Measurement and Monitoring

Initial color, gloss, and film thickness measurements were documented for each component prior to installation or return to inventory. Stakeholders assessed LTCPC performance during the FSE via periodic measurement of the color, gloss, and film thickness for each article. For most FSE components a standard time interval of one every six months is expected to provide adequate performance data for the FSE. When necessary, coating measurements were taken as frequently as possible where the geographical deployment or operational tempo of a component weren't accommodated by the standard time interval. Stakeholders recorded final color, gloss, and film thickness measurements at the completion of each component's FSE period.

5.2.1.1 <u>Color</u>

Color measurements were taken from separate locations across each component's coated surface. During initial color readings the approximate locations of each measurement were documented on drawings by the observer, with the intention of attempting to record all subsequent color measurements from the same general areas. During the FSE, evaluators utilized a BYK-Gardner color meter for all color measurements.

5.2.1.2 Gloss

Gloss readings were taken from the same color measurement locations across each component's coated surface. During field inspection observers attempted to record all subsequent gloss measurements from the same general areas. During the FSE, evaluators used a BYK-Gardner gloss meter for all gloss measurements.

5.2.1.3 Film Thickness

Film thickness measurements were also taken from the same color measurement locations across each component's coated surface. During field inspection observers attempted to record all subsequent film thickness measurements from the same general areas. During the FSE, evaluators utilized a film gauge that was capable of handling both ferrous and non-ferrous metallic substrates for all film thickness measurements.

5.2.1.4 Surface Appearance

Over the course of the FSE, project stakeholders or field technicians completed qualitative inspections of each LTCPC surface for the appearance of any visible (unassisted eye) coating defects such as delamination, bubbling, or corrosion filaments. Initial color, gloss, and film thickness measurements were documented for each component prior to installation or return to inventory. LTCPC performance during the FSE was assessed via periodic measurement of the color, gloss, and film thickness for each article. For most FSE components a standard time interval of one every six months was expected to provide adequate performance data for the FSE. When necessary, coating measurements were taken as frequently as possible in those instances where the geographical deployment or operational tempo of a component weren't accommodated by the standard time interval. Final color, gloss, and film thickness measurements were recorded at the completion of each component's FSE period.

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6.0 PERFORMANCE ASSESSMENT

6.1 JTP TESTING

6.1.1 Assumptions and Deviations

Detailed information related to the assumptions and deviations that comprised LTCPC testing is documented within Final Report, section 6.1.1.

6.1.2 Initial JTP

Section 6.1.2 of the LTCPC Final Report provides comprehensive test matrices and results in tabular format. Photographs of the test coupons following laboratory tests are also provided.

6.1.2.1 Coating Appearance and Quality

Several substrate/coating system combinations were used for the evaluation of coating appearance and quality. No major deviations from the expected appearance metrics were noted for the LTCPC panels.

6.1.2.2 Neutral Salt Fog Corrosion Resistance

Neutral salt fog testing was performed on 2024 and 6061 aluminum, steel and magnesium substrates. For neutral salt fog corrosion resistance, results demonstrated that most coupons met the program's corrosion resistance requirement for exposure to salt spray environments.

All of the Alodined aluminum coupons (both LTCPC and conventional wet coating) passed inspection after 2000 hours of exposure inside the salt fog corrosion chamber. Non-pretreated aluminum coupons generally failed to meet the corrosion resistance criteria as defined within the JTP, exhibiting unacceptable blistering of the coatings near the scribed areas. However, on a relative basis, the non-pretreated LTCPC coupons displayed less blistering than the similar non-pretreated controls. These test results demonstrate the need for a chromate conversion coating (CCC) or comparable pretreatment process to be in place for aluminum substrates regardless of the coating stack-up used. Testing also demonstrated that LTCPC performance on Dow 7-treated, LTCPC coated magnesium coupons paralleled the performance of controls covered with conventional coating systems. Both the LTCPC and control-coated steel specimens failed to meet ideal performance requirements even with a manganese phosphate pretreatment; however, LTCPC's performance was equivalent to the control stack-up. As with the other two substrates, steel LTCPC coupons displayed a level of corrosion resistance similar to that shown by the conventional wet coating.

6.1.2.3 SO_2 Corrosion Resistance

The Navy's Patuxent River facility completed 500 hours of SO_2 corrosion resistance testing on 2024 and 6061 aluminum and 4130 steel. SO_2 corrosion resistance test results confirmed that LTCPC performs in a similar fashion as the baseline coating stack-ups when prepared and tested in a production-like environment.

Evaluation of the selected aluminum coupons resulted in acceptable SO_2 corrosion resistance (as defined by the JTP) for only the Alodined 2024-T3 LTCPC and control-coated coupons. All remaining aluminum specimens suffered major blistering near the scribed regions. Stakeholder discussion produced a consensus that poor surface pretreatment was likely to blame for the test failures of low copper content aluminum alloys while the 2024-T3 specimens passed. From a comparative standpoint, the LTCPC-coated Al coupons for each group matched the performance of the baseline coatings. For the 4130 steel substrate, all specimens passed 500 hours of SO_2 exposure. Side-by-side comparison of the steel test coupons reveals that LTCPC's resistance to SO_2-based corrosion equals that of the control stack-up.

6.1.2.4 Cyclic Corrosion Resistance

Cyclic corrosion resistance testing was performed on multiple substrate/coating system combinations. Overall cyclic corrosion resistance test results confirmed that LTCPC performs in a similar fashion as the baseline coating stack-ups when prepared and tested in a production-like environment.

The Alodined 2024-T3 Alclad coupons outperformed the baseline MIL-PRF-85285 aluminum counterparts, while non-pretreated Alclad coupons exhibited equivalent corrosion resistance with regards to the scribed and unscribed area creepage/failure ratings. On average the LTCPC coupons survived exposure to cyclic corrosion for a longer period of time before displaying the first signs of adhesion loss. Mean time to noticeable adhesion loss for the three Alodined LTCPC specimens was 1046 hours and 336 hours for the set of non-pretreated LTCPC coupons. The trio of aluminum controls had a mean time to noticeable adhesion loss of 384 hours, which is reasonably equivalent to the average of the non-pretreated LTCPC coupons. Also LTCPC on manganese phosphate treated steel coupons responded to cyclic corrosion in a manner similar to that of the comparable baseline primer and topcoat combination. Ratings and post-test photographs revealed the levels of blistering and red rust for the steel controls were as pronounced as the LTCPC coupons.

6.1.2.5 Filiform Corrosion Resistance

In the initial round of filiform testing, no conventional wet coating coupons were submitted as controls. This was problematic as the LTCPC performance did not meet specification requirements (performance comparable or better than controls would have been considered acceptable). A second set of LTCPC coated clad aluminum panels were prepared, in conjunction with conventional wet coating stack-up control coupons. Results of the retest revealed that both LTCPC and the control stack-up provided acceptable resistance. From a comparative standpoint LTCPC performed as well as the control coating stack-up with regards to filiform corrosion resistance. Individually, two of the LTCPC coupons passed with acceptable test results while a third coupon was marginal (maximum filament length exceeded by 1/32") as defined within the JTP. The three control coupons produced very similar test results, limiting maximum filament length to 1/16" for each article.

6.1.2.6 Cross-Cut Adhesion by Tape

Cross-cut adhesion by tape testing was performed on several substrate/coating system combinations. Cross-cut adhesion test results for LTCPC coupons equaled those of the control coating stack-ups. All but three of the prepared aluminum, steel, and magnesium specimens met the acceptance criteria for intercoat and surface adhesion as defined within the LTCPC JTP. Test results revealed the following unacceptable adhesion ratings: 1B for the untreated, bare 2024-T3 coupon coated with LTCPC; 0B for the untreated 2024-T3 Alclad coupon coated with only a MIL-PRF-85285 topcoat; and 3B for the untreated AZ31B coupon coated with LTCPC. Each of these coupons did not receive surface pretreatment prior to coating application, which likely contributed to their failure as measured by cross-cut adhesion standards. Also, one statistical outlier appears within the reported test results. The failure (2B rating) of an untreated 4130 coupon coated with LTCPC appears to be indicative of a poor surface pretreatment.

6.1.2.7 Impact Flexibility

Impact flexibility testing was performed on 2024 0-Temper aluminum coupons. Overall impact flexibility test results confirmed that both the LTCPC and control coating coupons met the acceptability criteria of 5% elongation per area increase defined within the JTP. From a comparative standpoint, the control stack-ups demonstrated greater average impact flexibility (47%) as defined by this method than the LTCPC specimens (8%).

6.1.2.8 Strippability

Strippability was evaluated for informational purposes only, as previous research indicated that the LTCPC could be removed with methylene chloride based strippers. The evaluation performed at Hill AFB under the current project looked at a benign benzyl alcohol peroxide stripper and a plastic media blast removal method. A comparative study of LTCPC and control coating removal using a non-methylene chloride stripper (benzyl alcohol peroxide) confirmed the product’s acceptability. Reported efficiencies for the chemical stripper used on each of the prepared aluminum and steel specimens followed the guidelines provided within the JTP. The benyzl alcohol peroxide’s ability to remove 100% of the LTCPC from each substrate met the defined efficiency measures for chemical strippability. With regards to mechanical strippability, Type V plastic and GPX media blasting adequately removed LTCPC from each substrate well within the study’s 90 minute time limit.

6.1.3 JTP Addendum

6.1.3.1 Neutral Salt Fog Corrosion Resistance on 7075 Aluminum

Three coupons were submitted for salt fog corrosion resistance testing. Of the three, one showed significant blistering of the coating after 1104 hours of exposure. The other two showed blistering at the completion of the 2000 hour test. These failures indicate that the LTCPC, as applied in this study, may not be ideal for use on 7075 aluminum components.

6.1.3.2 NASA Extreme Temperature Flexibility

NASA's Kennedy Space Center conducted extreme temperature flexibility testing of the following substrate/coating system combinations. These tests confirmed stakeholder assumptions that LTCPC would fail to meet flexibility requirements at extremely low temperature due to the coating's overall chemistry. PCs, such as LTCPC, are comprised of polyester backbones, which cure to form thermoset plastics. By design thermoset plastics are more structurally rigid than thermoplastics and therefore suffer from brittleness at extremely low temperatures. NASA's laboratory confirmed this behavior by testing three coupons at minus 250°F, which resulted in disbondment of each LTCPC layer from the 2024-T3 substrates. In contrast to the extreme low temperature results, all three LTCPC coupons successfully passed NASA's testing requirement for extreme high temperature (+350°F) flexibility.

6.1.3.3 NASA Outgassing

Outgas tests conducted at Boeing's Huntington Beach, California facility failed to provide stakeholders with any useful information regarding LTCPC performance. Each of the eight foil samples exceeded the maximum allowable percentages for collected volatile condensable material (CVCM) and total mass loss (TML). The reported CVCM values of 0.30 – 0.76% were well outside the range expected for PCs. Calculated values for TML were also unexpectedly high. These test results led stakeholders to review the sample preparation procedures used and identified improper handling as the contributing factor. Boeing's interest in LTCPC (for potential space applications) hinged on the coating's ability to pass both the extreme temperature flexibility and outgassing tests. Therefore, Boeing engineers were not interested in preparing a second set of foil specimens once LTCPC failed the extreme low temperature flexibility test.

6.1.3.4 Fluids Resistance

Stakeholders conducted fluids resistance testing for several substrate/coating system combinations. Overall fluids resistance test results for LTCPC coupons proved to be acceptable as defined within Final Report, section 5.1.4.4. Each of the prepared aluminum 2024-T3 specimens met the acceptance criteria for resistance to immersion in common operational fluids by exhibiting no signs of blistering, softening, or other coating defects.

6.1.3.5 Chipping Resistance

Chipping resistance testing occurred for two substrate/coating system combinations. Chipping resistance tests confirm that LTCPC performance equals or exceeds the results observed for the selected baseline stack-up. The 2024-T3 LTCPC specimens exhibited lower coating damage than the controls measured as a percentage of the coating's surface. Surface damage percentages measured for the coupons ranged from 0.56 – 0.74%. In comparison the controls permitted between 1.04 – 1.42% of the surface to be damaged by chipping. The LTCPC chip ratings were better than or equal to those reported for the control coupons.

6.1.3.6 Low Temperature Flexibility

Laboratory test results confirm that LTCPC exhibits acceptable low temperature flexibility as measured by the requirements of MIL-PRF-85285. Each control coupon and all but one of the

LTCPC specimens passed low temperature flexibility at -60°F. Stakeholder analysis of the failed test coupon identified adhesion failure due to inconsistent coverage of the chromate pretreatment as the most likely source of cracking within the coating.

6.2 FIELD AND REAL-WORLD TESTING

6.2.1 Assumptions and Deviations

Detailed information related to the assumptions and deviations that comprised LTCPC testing is documented within Final Report, section 6.2.1.

6.2.2 FSE Measurement and Monitoring

Measurements were reported by FSE evaluators over the course of each item's 12-month service evaluation. Section 6.2.2 of the LTCPC Final Report provides comprehensive FSE measurement matrices in tabular format. Photographs of the FSE components before and after exposure are also provided within Section 6.2.3 of the Final Report.

6.2.2.1 Color

For color, recorded changes in ΔE values varied for each FSE component but generally proved to be inconclusive in nature. From an overall standpoint it is difficult to determine the significance of the magnitude of each change in the absence of required controls, which would eliminate the possibility of changes due to instrument drift. Field evaluators encountered less than ideal conditions during the course of taking color readings. Regardless, the project stakeholders and users agreed reported color changes were within the range of acceptability.

6.2.2.2 Gloss

Recorded specular gloss values varied for each FSE component but generally proved to be inconclusive in nature. Conditions for taking gloss measurements were not optimum. However, both LTCPC team members and the FSE field personnel found the reported values to be acceptable.

6.2.2.3 Film Thickness

From an overall standpoint, variations in average dry film thickness documented from the initial through third inspections suggests that a level of difficulty exists with taking measurements from the same component locations over time. In a few cases, evaluators documented small reductions in the average dry film thickness from the initial through third inspections, suggesting that LTCPC experienced partial shrinkage over the period of environmental exposure. Still, project stakeholders have confirmed that LTCPC film thickness remained within the range of acceptability.

6.2.2.4 Surface Appearance

Stakeholders evaluated the surface appearance of the LTCPC with unaided eyes for visible coating or surface defects. There were no noteworthy surface appearance deficiencies reported during the course of each component's FSE period, outside of the normal level of wear and tear.

7.0 COST ASSESSMENT

7.1 COST MODEL

7.1.1 Description

LTCPC stakeholders utilized the Environmental Cost Analysis Methodology (ECAM)SM approach to determine both the direct process costs as well as the costs associated with indirect environmental activities for both the baseline and LTCPC processes. The ECAM Level I strives to identify the direct costs (conventional and environmental) associated with both the baseline and proposed technologies, while an ECAM Level II seeks to establish the costs of additional environmental activities supporting the process under consideration, which are usually performed for the entire facility (National Defense Center for Energy and Environment, 1999).

7.1.2 Data Requirements

For the initial Level I analysis, facility personnel provided the National Defense Center for Energy and the Environment (NDCEE) with estimates of the direct costs during the development of the ESTCP project proposal. Where necessary, NDCEE later verified the cost data through phone interviews with project stakeholders. The Level I analysis focused on:

- Equipment purchases
- Process consumables
- Utilities
- Process labor
- PPE
- Waste stream

A copy of the Level I cost benefit analysis (CBA) report, entitled “Final Type A Cost Benefit Analysis of Low Temperature Cure Powder Coating,” can be obtained from Mr. Andy Del Collo, Office of the Chief of Naval Operations, Environmental Readiness Division, in Arlington, Virginia.

For the Level II analysis, project stakeholders accomplished data collection related to environmental activities by means of a comprehensive questionnaire that took into consideration the resources and drivers associated with each activity. This questionnaire was built from a list of suggested questions provided within Appendix B-4 of the ECAM Handbook and expanded upon, when necessary, in order to capture all potential environmental activities costs. The primary areas of focus for the questionnaire included:

- Operating and maintaining equipment and facilities
- Providing and administering training
- Obtaining and maintaining permits
- Supporting facility operations
- Developing and maintaining documentation

A copy of the baseline and LTCPC questionnaire resides within Appendix B of the LTCPC ECAM Level II CBA report, entitled “Cost Benefit Analysis of Indirect Environmental Activities for Validation of Low Temperature Cure Powder Coating, WP-200614.”

7.1.3 Performing Organization

LTCPC stakeholders directed individuals from NDCEE to provide assistance in gathering process data related to the ECAM Level I CBA, which estimated the start-up and direct process costs associated with transitioning from a wet paint process to LTCPC.

ECAM methodology was also used when Science Applications International Corporation (SAIC) performed the subsequent Level II analysis to examine LTCPC's impact on indirect environmental activity costs.

7.1.4 Assumptions

Table 5. Level I ECAM assumptions.

Recurring equipment costs for baseline process were estimated
Rework will remain constant
The number of parts to be painted (surface area) for each facility will remain constant for the time period of this analysis
Based on data gathered at several of the facilities, a primer thickness of 1 mil and two topcoats of 2 mil each are assumed to be the baseline at each facility
For the low temperature cure PC, it is assumed no primer is needed
A ratio of solvent (used for equipment cleaning, surface preparation, and viscosity reduction) to total coating was estimated
No major equipment will need replacement for any application method within the CBA time frame
All surveyed facilities are in compliance with all affected regulatory permits; so transitioning to the alternatives will not eliminate fines
Purchase of an electric heat driven curing oven
Labor and material requirements are derived from a surface area estimate of 1476 square feet per year with a component tempo of 308 parts per year (based upon the original list of components identified by LTCPC stakeholders at the beginning of this project)
Curing oven electricity use constitutes no less than 50% of the total calculated for the LTCPC process

Table 6. Level II ECAM assumptions.

Surface preparation of substrates is identical for both processes
Primer is only applied to the substrate when using wet paint (i.e., no primer is applied under LTCPC)
Five painters are required for the baseline wet paint or PC shop
The PPE item “heavy duty blast suit” is replaced twice per year
Two contractors are utilized for O&M of EEF
60 man-hours are shared between the four military members assigned to O&M of EEF
30 man-hours are shared between the two contractors utilized for O&M of EEF
The current contractor charges a fully burdened rate of $100 per hour for O&M of EEF
One GS-11 level civilian is assigned wet paint school instructor duties
One contractor is responsible for one-day PC instructor duties
The contractor charges a fully burdened rate of $100 per hour for PC instructor duties
The average Navy painter possesses an enlisted rank of E-3
Five painters complete annual refresher training
The annual refresher training is an self-paced course that requires no instructor to complete
One GS-9 level civilian is responsible for in-house training material (courseware) development
40 man-hours are allocated for developing Standard Operating Procedures (SOP) training materials
A team of three GS-9 level and 2 GS-11 level civilians comprise the internal audit team

Table 6. Level II ECAM assumptions (continued).

One GS-9 or GS-11 level civilian is required to generate internal audit checklists and documentation (Note: Pay bands for GS-9 and GS-11 level civilians will be averaged to utilize a midrange value where only one civilian is assigned to a particular task)
One GS-9 or GS-11 level civilian is accountable for completing internal audit reports (Note: Pay bands for GS-9 and GS-11 level civilians will be averaged to utilize a midrange value where only one civilian is assigned to a particular task)
The overall time requirement to complete activities related to on-site hazardous material handling, transportation, and storage of wet painting waste is divided equally between the five individuals
A team of 10 civilians (five GS-9 level, three GS-11 level, and two GS-12 level) is required to complete various activities comprising the development and maintenance of facility documentation
The overall time requirement to complete activities comprising the development and maintenance of facility documentation is divided equally between each of the 10 individuals
Overall time requirements for various facility document development and maintenance activities are: • Prepare state reports - 40 hrs • Prepare toxic release inventory (TRI) reports - 40 hrs • Fill manifest forms - 8 hrs • Prepare container labels - 8 hrs • Prepare spill/release emergency plans - 12 hrs • Develop and maintain programs and procedures - 12 hrs • Develop and maintain strategic plans and budgets - 24 hrs • Perform internal industrial hygiene survey/report - 40 hrs • Oversee industrial hygiene audit by external agency - 24 hrs • Develop employee duties/responsibilities/procedures - 12 hrs • Prepare accident plans - 12 hrs • Create and maintain MSDS forms - 8 hrs • Prepare Emergency Planning and Community Right-to-know Act (EPCRA) reports - 40 hrs • Prepare supply orders - 12 hrs
The current contractor charges a fully burdened rate of $100 per hour for the execution of annual physicals and PPE fit-testing
The costs associated with annual physicals and fit-testing will be the same for FRCNW and OO-ALC
A composite locality payment rate, based upon the average of rates assigned to NAS Whidbey Island, NAS North Island, Hill AFB, and Warner-Robins AFB, will be used when estimating mean annual salaries for civilian employees
The PC facility will operate 250 days per year

Table 7. Financial metric assumptions.

LTCPC start-up activities are completed by the start of Q4, FY2011 (3 months to obligate funds; 6 months to install)
Three USAF Depots will implement LTCPC (Ogden, Oklahoma City, and Warner-Robins ALCs)
Four United States Navy (USN) facilities will implement LTCPC (FRCNW Whidbey Island, FRCSW North Island, Fleet Readiness Center Southeast (FRCSE) Jacksonville, and Fleet Readiness Center East (FRCE) Cherry Point)

7.1.4.1 Transfer Efficiencies

For the purposes of calculating cost savings, LTCPC was assigned a projected transfer efficiency of 95% (typical of PCs) compared to the 70% transfer efficiency associated with traditional liquid spray painting.

7.1.4.2 Emissions Monitoring and Reporting

The burden of emissions monitoring and reporting will be expressed as a percentage of each facility's total compliance costs based upon the number of waste streams contributing to the environmental burden.

7.1.4.3 Scale of Operations

The scale of operations for identified components exhibit a wide range of values. Estimates for depot throughputs are provided within Table 8. Overall, the components selected for this effort demonstrated and validated LTCPC for a wide range of temperature sensitive components.

Table 8. Expected scale of operations for targeted LTCPC components.

LTCPC Component	Component Coated Surface Area (in^2)	Estimated Depot Tempo (items/yr)	Total LTCPC Surface Area (ft^2)
F-15 A/C Mounted Accessory Drive	1321	476	4367
F-16 Accessory Drive Gearbox	690	308	1476
TF33 Engine 2nd Stage Stator	2000	24	333
Aero 12C Bomb Cart	2275	100	1580
NAN-4 Cart	8496	20	1180
Adjustable Length Tow Bar	7675	15	800
EA-6B Jammer Pod Rails	1757	80	976
EA-6B Jammer Pod Cradle	2232	80	1240
C-130 Landing Gear Doors	--	--	--
J52 Aft Engine Yoke	--	13	--
J52 Forward Engine Yoke	--	15	--
Engine Support Adapter	--	4	--
HLU-288 Bomb Hoist	2275	2	32

7.1.4.4 Life Cycle Costs (LCC) Time Frame

Unless otherwise noted, all LCC calculations are based upon an assumed operations and maintenance lifespan of 10 or 20 years. The appropriate reapplication period for LTCPC consideration is defined by the time elapsing between scheduled depot maintenance cycles for demonstration articles. For both the non-critical flight components and ground support equipment involved in this project, a typical depot cycle is approximately two years.

7.1.5 Cost Revisions

Table 9. ECAM Level I cost revisions and reasoning.

Man-hour estimates for the application of wet primer and topcoat onto components (*application time study completed to more precisely determine the requirement for a component using the baseline*)
Man-hour estimates for the application of LTCPC onto components (*application time study completed to more precisely determine the requirement for a component using the LTCPC process*)
Man-hour estimates for the management and handling of hazardous waste generated by the process (*an extensive application time study was completed in order to more precisely determine the man-hour requirement for a representative component*)
Civilian labor rate associated with each process' man-hour requirement (*facility stakeholders provided current estimates of their fully burdened labor rates*)
Quantity of masking required for the representative component (*facility stakeholders stated that the amount of masking required would remain constant when transitioning from wet coatings to LTCPC*)
Unit purchase cost of LTCPC material (*facility stakeholders provided current estimates for LTCPC cost taking volume purchase discounts into consideration*)

7.2 COST ANALYSIS AND COMPARISON

7.2.1 LTCPC Primary Cost Element Categories

7.2.1.1 Facility Capital

Facility capital encompasses initial costs associated with the acquisition of land and equipment, the construction or modification of buildings, as well as the support services associated with these expenditures. LTCPC facility capital costs include the purchase of any commercial-off-the-shelf (COTS) PC equipment such as an electrostatic powder gun, powder delivery and storage system, powder spray booth, or curing oven not currently in place at depot facilities.

7.2.1.2 Start-up and O&M

Start-up costs are defined as the various expenses, excluding facility capital, that are necessary to bring a new process into a production-ready state. Start-up costs related to LTCPC operations will be negligible, consisting mainly of initial operator checkout and setup. As the name implies, O&M costs include all of the expenses associated with ensuring the availability and reliability of process equipment during its use. Improved coating transfer efficiency lowers the volume of material required for coating a given surface area. Transitioning to PC will result in lower direct material costs than continuing to use solvent-based coatings. In addition, LTCPC labor hours are anticipated to decrease with the elimination of labor-intensive procedures such as the mixing and application of multi-component primers and topcoats. Utilities consumption has the potential to either increase or decrease based upon the coating process currently in use for each identified component.

7.2.1.3 Equipment Replacement

Equipment replacement encompasses the replacement of any limited lifespan components associated with the PC system. The magnitude of LTCPC equipment replacement is expected to remain unchanged relative to the baseline process' costs.

7.2.1.4 ESOH and Cost Avoidance

Changes made to a production line can positively or negatively impact the existing ESOH costs associated with the process. The immediate and potential impacts of proposed modifications must be considered across the expected lifespan of the process. PCs such as LTCPC are applied to components in solid form allowing for VOC and HAP-free application. Elimination of VOC and HAP emissions will slightly decrease the costs related to permitting, monitoring, and reporting requirements.

7.2.1.5 Reprocessing/Reapplication

There are no projected reprocessing costs since LTCPC will act as a direct replacement for the baseline coatings during each facility's typical material application schedule, which includes scheduled maintenance cycles. DoD stakeholders also require that the durability of any transitioned coating to be as good as the coating it is replacing, therefore periodic reapplication costs are not expected to increase.

7.2.1.6 Hazardous Waste Storage and Disposal

Each facility monitors current rates for the storage and disposal of hazardous waste associated with solvent based paints. As designed, LTCPC eliminates the production of hazardous waste streams during painting operations.

7.2.2 LCC Comparison

For the purposes of cost comparison, the baseline process consists of multi-layer paint systems utilizing wet primers and topcoats while the innovative replacement is the low temperature cure PC with no primer.

Table 10. Baseline process LCC by category.

ECAM LEVEL I				ECAM LEVEL II	
Direct Activity Costs				Indirect Environmental Activity Costs	
Start-Up		O&M			
Activity	Cost	Activity	Cost	Activity	Cost
SUNK COSTS UNDER CURRENT PROCESS		Wet primer applied to substrate	$1188	Maintenance of environmental equipment and facilities	$4804
		Wet topcoat applied to substrate	$2393	Development of in-house training materials	$1457
		Paint thinner used for primer and cleaning	$630	Fees to maintain permits	$500
		Filters for spray booth particulate matter	$3624	Labor for internal audit teams	$316
		Masking required for substrates	$294	Completion of audit reports	$644
		Required PPE	$27,095	Off-site waste treatment and disposal	$651
		Utilities (electricity for painting operations)	$205	Labor to handle, transport, and store hazardous waste on-site	$2875
		Labor for wet primer application	$69,564	Completion of miscellaneous documentation activities	$12,260
		Labor for wet topcoat application	$5814	Annual physicals and fit testing	$751
		Labor to containerize the process' hazardous waste	$19,125		
		Equipment maintenance	$1000		
		Periodic training of operators (new hires, refresher course)	$12,652		
		Total	**$143,584**	**Total**	**$24,258**

Table 11. LTCPC LCC by category.

ECAM LEVEL I				ECAM LEVEL II	
Direct Activity Costs				Indirect Environmental Activity Costs	
Start-Up		O&M			
Activity	Cost	Activity	Cost	Activity	Cost
Equipment purchase – PC system	$4895	PC applied to substrate	$281	Maintenance of environmental equipment and facilities	$4804
Equipment purchase – PC booth	$28,790	Masking required for substrates	$294	Development of in-house training materials	$1457
Equipment purchase – curing oven (Electric)	$50,925	Required PPE	$3825	Fees to maintain permits	$500
Equipment purchase – environmental controls system for PC Room	$20,995	Utilities (electricity for painting operations)	$328	Labor for internal audit teams	$316
Initial training of operators (PC)	$2002	Labor for powder application	$16,422	Completion of audit reports	$644
Development of internal audit checklists and documents	$80	Equipment maintenance	$1000	Off-site waste treatment and disposal	$185
		Periodic training of operators (new hires, refresher course)	$13,933	Completion of miscellaneous documentation activities	$10,581
				Annual physicals and fit testing	$751
Total	**$107,687**	**Total**	**$36,083**	**Total**	**$19,238**

Net present value (NPV) calculations used December 2008 Office of Management and Budget (OMB) discount rates of 2.4% and 2.9% based upon ECAM study periods of 10 and 20 years, respectively. These discount rates account for the time value of money and permit the estimation of LCC savings for a DoD facility implementation of LTCPC. Expected LCC savings are presented by funding source and study timeframe within Tables 12 through 15.

Table 12. LCC savings for LTCPC implementation – USAF, 20 years.

Fiscal Year	2006	2007	2008	2009	2010	2011	2012	2013 thru 2030	2031
Acct. Year	-5	-4	-3	-2	-1	0	1	2 thru 19	20
Benefits						$84K	$338K	$338K/year	$338K
Costs	$ -	$350K	$200K	$200K	$ -	$323K			

Present Benefits = $5,153,000
Present Costs = $1,145,000
LCC Savings = **$4,008,000**

Table 13. LCC savings for LTCPC implementation – USN, 20 years.

Fiscal Year	2006	2007	2008	2009	2010	2011	2012	2013 thru 2030	2031
Acct. Year	-5	-4	-3	-2	-1	0	1	2 thru 19	20
Benefits						$113K	$450K	$450K/year	$450K
Costs	$ -	$ -	$ -	$ -	$ -	$431K			

Present Benefits = $6,871,000
Present Costs = $431,000
LCC Savings = **$6,440,000**

Table 14. LCC savings for LTCPC implementation – USAF, 10 years

Fiscal Year	2006	2007	2008	2009	2010	2011	2012	2013 thru 2020	2021
Acct. Year	-5	-4	-3	-2	-1	0	1	2 thru 9	10
Benefits						$84K	$338K	$338K/year	$338K
Costs	$ -	$350K	$200K	$200K	$ -	$323K			

Present Benefits = $3,054,000
Present Costs = $1,132,000
LCC Savings = **$1,922,000**

Table 15. LCC savings for LTCPC implementation – USN, 10 years.

Fiscal Year	2006	2007	2008	2009	2010	2011	2012	2013 thru 2020	2021
Acct. Year	-5	-4	-3	-2	-1	0	1	2 thru 9	10
Benefits						$113K	$450K	$450K / year	$450K
Costs	$ -	$ -	$ -	$ -	$ -	$431K			

Present Benefits = $4,072,000
Present Costs = $431,000
LCC Savings = **$3,621 ,000**

7.2.3 LCC Assessment

Evaluation of LTCPC's LCC savings suggests that implementation will result in significant cost savings for both the USAF and USN over each of the study timeframes. NPV calculations suggest USAF savings of $1.9 million after utilizing LTCPC for 10 years and $4.0 million after 20 years. Likewise, NPV calculations identify approximately $3.6 million in savings for the USN over 10 years and $6.4 million over 20 years. All project expenditures as well as the expected annual cost savings for fiscal years 2011 through 2021 (or 2031) are identified in Tables 12 through 15.

A second commonly-used financial indicator is simple payback. By definition, simple payback doesn't take the time value of money into consideration but it provides decision makers with an easily calculated financial metric. As such, this metric is not affected by changes in discount rates associated with evaluating multiple time periods. An overall payback period of 3.4 years is projected for the process savings associated with transitioning LTCPC to the various Air Force and Navy primary maintenance facilities. Individually, the USAF and USN can anticipate payback periods of 3.2 and 1.0 years, respectively.

Another indicator utilized to evaluate the financial attractiveness of alternatives is the internal rate of return (IRR). The alternative under consideration is preferred in those instances where the alternative's IRR exceeds the accepted secondary investment strategy, which for the U.S. government is represented by the appropriate OMB discount rate. Overall IRRs for the LTCPC project over 10 and 20 years are 15.5% and 18.8%, respectively, while IRR estimates for ESTCP's investment in LTCPC are 25.4% and 26.7%. USAF IRRs are projected to be 17.9% over 10 years and 20.4% over 20 years. Lastly, it should be noted that the IRRs calculated for the USN, 141.4% for both timeframes, are much larger than the previous values due to the USN not contributing any LTCPC project funding.

Review of the CBA data reveals that the major cost drivers associated with traditional wet coatings are: (1) length of material cure times, (2) magnitude of generated hazardous waste, and (3) magnitude of required PPE purchases. These cost drivers increase both labor and material application costs while also raising the component's overall process flow time. In turn the increased process flow time negatively impacts repaired component delivery schedules that can indirectly reduce overall mission readiness.

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8.0 IMPLEMENTATION ISSUES

8.1 IMPLEMENTATION STAKEHOLDERS

Within the Navy, the following individuals and organizations with expansive implementation authority have been identified for the targeted components.

- Naval Air Systems Command (NAVAIR) GSE – David Piatkowski
- NAVAIR Aircraft – Kevin Kovaleski

In contrast, the Air Force assigns implementation authority to the individual weapon system level engineers at each program office.

8.2 LTCPC ACCEPTANCE PROCESS

Stakeholder acceptance of LTCPC as a viable replacement is based upon the results of laboratory and real-world material performance testing outlined within this final report. Technology implementation at depot facilities will occur once engineering approval have been granted to change the technical orders/manuals associated with this process and LTCPC has been added to an appropriate qualified product database (QPD).

During the FSE period, results from some of the LTCPC success criteria has such as color and gloss, were determined to be inconclusive based upon the reported values. However, after careful consideration of earlier laboratory results, project stakeholders anticipate there will be no impact to LTCPC implementation based upon these inconclusive results.

8.3 IMPACT OF ENVIRONMENTAL, SAFETY, AND OCCUPATIONAL HEALTH (ESOH) REGULATIONS

The LTCPC material contains a barium metaborate corrosion inhibitor package. Laboratory toxicity characteristic leaching procedure (TCLP) testing confirmed the leachable barium concentration is below the level requiring classification as a characteristic hazardous waste, so any unused and waste powder can be disposed of as ordinary waste.

PC of aircraft components is regulated under the Aerospace Manufacturing and Rework NESHAP (40 CFR 63, Subpart GG); however compliance will not be an issue due to the low VOC and HAP content of LTCPC. The USEPA is currently developing proposed rules for a Defense Land Systems and Miscellaneous Equipment NESHAP that would apply to defense items not applicable under Aerospace and Shipbuilding NESHAPs. As with the Aerospace NESHAP, future compliance is not expected to be a problem for the use of low temperature cure powder.

In addition to the presence of trace amounts of leachable barium in the uncured powder, the powder is ground to sufficiently fine particle size (average particle size is between 30 and 35 microns) that appropriate PPE will be required to avoid nuisance dust inhalation effects. This fine particle size also requires that precautions be taken (in the form of adequate air handling) to avoid a buildup of potentially explosive dust. Additionally, the PC crosslinker, triglycidyl isocyanurate (TGIC), is a toxic chemical. Therefore, inhalation exposure to LTCPC dust should be minimized to the largest extent possible for worker safety. However, these preventative measures are not atypical of routine precautions taken with any other PC material. Other than the current and potential NESHAPs mentioned the previous paragraph, there are no other known regulations that apply to PCs.

8.4 LTCPC PROCUREMENT

8.4.1 Process Equipment

Depot facilities wanting to utilize LTCPC would be required to purchase any COTS PC equipment such as an electrostatic powder gun, powder delivery and storage system, powder spray booth, and curing oven that is not currently in place. The technology associated with LTCPC has not been modified for the purposes of this demonstration.

8.4.2 Production and Scale-Up

Size-dependent costs associated with the construction and operations of convention curing ovens generate the only significant constraint to production and scale-up of this technology. Based upon localized inputs, each facility will need to determine the size (break-even point) at which the costs associated with an increase in oven capacity would outweigh the added benefits.

With respect to product manufacturing, economies of scale will reduce the per-pound cost once Air Force and Navy depot requirements for low temperature cure PCs are increased.

8.4.3 Technician Training/Transition from Wet Paint to Powder

Transition to and training for a powder process is relatively simple for a trained wet painter. In this study, a three-day class was provided that included the fundamental principles and hands on application of powder and coating of parts, all of the painters who were in the class were able to apply powder with a degree of expertise after the training and felt comfortable with the transition.

8.4.4 Repairability of PCs

PCs are easily repaired or touched up using the same techniques that are typically used for wet coatings, this includes feathering out and preparing the surface, the use of primer and a durable top coat that has been matched to the existing powder, thus field operations would be unaffected by the transition to powder.

8.4.5 Proprietary and Intellectual Property Rights

As designed, there are no proprietary or intellectual property rights associated with the LTCPC technology.

8.5 TECHNOLOGY TRANSFER EFFORTS

Although this coating material will not be used on a wide scale initially, Air Force and Navy acceptance will increase LTCPC usage through the modification of specifications and technical orders regarding approved coatings. This will facilitate adoption of the process by other services and original equipment manufacturers.

In addition to the previously identified military uses for LTCPCs, technology transition opportunities exist within general aviation and other industries looking to reduce existing powder cure energy requirements or to apply uniform, high-performance coatings to temperature-sensitive substrates. The technology associated with LTCPC has not been modified for the purposes of this demonstration. Therefore barring designation as a proprietary defense technology, there is no reason to believe that this SERDP and ESTCP-developed technology cannot be transitioned to the private sector.

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9.0 REFERENCES

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APPENDIX A

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