



# **COST AND PERFORMANCE REPORT**

## **Demonstration and Validation of LHE Zn-Ni Plating Process**

**ESTCP Project WP-201107**



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**Version 4**  
**October 2018**

**REPORT DOCUMENTATION PAGE**

*Form Approved  
OMB No. 0704-0188*

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<b>1. REPORT DATE (DD-MM-YYYY)</b> 31/10/2018			<b>2. REPORT TYPE</b> ESTCP Cost & Performance Report		<b>3. DATES COVERED (From - To)</b>	
<b>4. TITLE AND SUBTITLE</b> Demonstration/Validation of Zinc-Nickel as Replacement for Cadmium/Cyanide Plating Process for Air Force Landing Gears					<b>5a. CONTRACT NUMBER</b>	
					<b>5b. GRANT NUMBER</b>	
					<b>5c. PROGRAM ELEMENT NUMBER</b>	
<b>6. AUTHOR(S)</b> David Frederick: Hill AFB Lead Engineer, Material & Process  Craig Pessetto: ES3 Lead Engineer, Material & Process  Jeremy Hall: ES3 Project Engineer					<b>5d. PROJECT NUMBER</b> WP-201107	
					<b>5e. TASK NUMBER</b>	
					<b>5f. WORK UNIT NUMBER</b>	
<b>7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)</b> Hill AFB 6040 Gum Lane Bldg 1216 Rm 10 Hill AFB, UT 84056-5825					<b>8. PERFORMING ORGANIZATION REPORT NUMBER</b> WP-201107	
<b>9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)</b> Environmental Security Technology Certification Program 4800 Mark Center Drive, Suite 16F16 Alexandria, VA 22350-3605					<b>10. SPONSOR/MONITOR'S ACRONYM(S)</b> ESTCP	
					<b>11. SPONSOR/MONITOR'S REPORT NUMBER(S)</b> WP-201107	
<b>12. DISTRIBUTION/AVAILABILITY STATEMENT</b> DISTRIBUTION STATEMENT A. Approved for public release: distribution unlimited.						
<b>13. SUPPLEMENTARY NOTES</b>						
<b>14. ABSTRACT</b> The project objectives were met by installation of the full scale plating line at Hill Air Force Base (AFB) and validation of the performance of LHE Zn-Ni. After qualifying the plating tanks, landing gear were plated to perform a Performance Tracking Program (PTP) where LHE Zn-Ni plated components were installed and tested on aircrafts at select bases around the country. Bases with corrosive environmental conditions were selected, to simulate the most aggressive natural environment that would be experienced at any location worldwide. The selected bases include: McEntire Joint National Guard Base (JNGB), Barbers Point U.S. Coast Guard (USCG), New Orleans Naval Air Station (NAS) Louisiana, and Hickam AFB.						
<b>15. SUBJECT TERMS</b> Demonstration, Validation, Zinc-Nickel, Cadmium/Cyanide Plating, Air Force, Landing Gears						
<b>16. SECURITY CLASSIFICATION OF:</b>			<b>17. LIMITATION OF ABSTRACT</b>  UNCLASS	<b>18. NUMBER OF PAGES</b>  42	<b>19a. NAME OF RESPONSIBLE PERSON</b> David Frederick	
<b>a. REPORT</b>  UNCLASS	<b>b. ABSTRACT</b>  UNCLASS	<b>c. THIS PAGE</b>  UNCLASS			<b>19b. TELEPHONE NUMBER (Include area code)</b> 801-777-7352	

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## ACRONYMS AND ABBREVIATIONS

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AFB	Air Force Base
ANG	Air National Guard
ASTM	American Society for Testing and Materials
ATSDR	Agency for Toxic Substances and Disease Registry
Cd	Cadmium
CC	Conversion Coated
EDS	Energy Dispersive Spectroscopy
EPA	Environmental Protection Agency
FIB	Focused Ion Beam
FSE	Field Service Evaluation
HazMat	Hazardous Material
HE	Hydrogen Embrittlement
HSS	High Strength Steel
IAW	in accordance with
IVD	Ion Vapor Deposition
JNGB	Joint National Guard Base
LHE	Low Hydrogen Embrittlement
MLG	main landing gear
Mpy	Mils Per Year
mV	Millivolt
NaCl	sodium chloride
NAS	Naval Air Station
NCC	Non Conversion Coated
NFS	Notch Fracture Strength
Ni	Nickel
OCP	Open Circuit Potential
OSHA	Occupational Safety and Health Administration
PEL	Permissible Exposure Level
PTP	Performance Tracking Program
SCE	Saturated Calomel Electrode
SEM	Scanning Electron Microscope

USAF	U.S. Air Force
USCG	U.S. Coast Guard
XRF	X-ray Fluorescence
Zn	Zinc
ZRA	Zero Resistance Ammeter

## ACKNOWLEDGEMENTS

The team would like to thank the USAF project team at Hill Air Force Base:

Mr. David Frederick  
Mr. Ron Montgomery  
Mr. Chad Hogan  
Ms. Caroline LeClair  
Mr. Nate Hughes  
Ms. Debbie Hall  
Ms. Ruth Schaefer

The chemical suppliers for an alternative to cadmium, Dipsol of America:

Mr. Harry Willingmyre  
Mr. Tarek Nahlawi

The NASA Corrosion Technology Laboratory:

Mr. Kurt Kessel  
Mr. Jerry Curran

Boeing Research and Technology:

Mr. Stephen Gaydos  
Mr. Louie Tran

The ES3 project implementation team:

Mr. Doug Wisner  
Mr. Jeremy Hall  
Mr. Craig Pessetto  
Mr. Kelly Smith

And thanks to the funding sources for this effort:

ESTCP  
AFMC P2  
SBIR Phase II/ CPP  
309<sup>th</sup> CMXG

## EXECUTIVE SUMMARY

Cadmium (Cd) plating is used as a coating on High Strength Steel (HSS) landing gear alloys to prevent corrosion. The cadmium plating process uses three chemicals currently listed as hazardous materials by the Environmental Protection Agency (EPA), the Occupational Safety and Health Administration (OSHA), and the Agency for Toxic Substances and Disease Registry (ATSDR): cadmium, sodium cyanide, and hexavalent chrome. Cd is a known human carcinogen and a toxic heavy metal that can easily be leached; therefore, it poses both environmental and health concerns. Due to these concerns and other limitations of Cd plating, Low Hydrogen Embrittlement Zinc-Nickel (LHE Zn-Ni), which consists of a uniform zinc alloy containing 12-15% nickel, has been tested and qualified for use as a sacrificial coating to prevent corrosion to HSS alloys.

LHE Zn-Ni is applied through an electroplating process similar to that of Cd plating, except LHE Zn-Ni does not use sodium cyanide as a chelator in the process, or hexavalent chrome conversion coat, reducing the use of hazardous chemicals and hazardous waste. The main objective of this project was to implement a full-scale prototype LHE Zn-Ni plating line and demonstrate and validate that LHE Zn-Ni plating performs as well as or better than Cd plating in preventing corrosion that results from environmental conditions and operational use.

The project objectives were met by installation of the full scale plating line at Hill Air Force Base (AFB) and validation of the performance of LHE Zn-Ni. After qualifying the plating tanks, landing gear were plated to perform a Performance Tracking Program (PTP) where LHE Zn-Ni plated components were installed and tested on aircrafts at select bases around the country. Bases with corrosive environmental conditions were selected, to simulate the most aggressive natural environment that would be experienced at any location worldwide. The selected bases include: McEntire Joint National Guard Base (JNGB), Barbers Point U.S. Coast Guard (USCG), New Orleans Naval Air Station (NAS) Louisiana, and Hickam AFB.

During the installation of the prototype full-scale production line, existing equipment located at Hill AFB building 505 was demolished, removed, relocated and rebuilt to accommodate the prototype 3200-gallon LHE alkaline Zn-Ni production plating line. Upon final installation, the LHE Zn-Ni plating line chemical plating baths and processes were qualified by the following tests in accordance with U.S. Air Force (USAF) drawing 201027456: corrosion (American Society for Testing and Materials or ASTM B117), hydrogen embrittlement (ASTM F519) and adhesion (ASTM B571). Additional studies involving dezincification, hydrogen re-embrittlement, and LHE Zn-Ni stripping were also conducted. The installation of the 3200-gallon LHE Zn-Ni plating line in building 505 at Hill AFB was successful, and the 309 CMXG Production Group is currently plating landing gear components with LHE Zn-Ni.

Dezincification was studied with Boeing Research & Technology. It was found that accelerated or forced corrosion may start to cause dezincification, however corrosion rates closer to natural corrosion do not appear to have any impact on dezincification. Additional studies are suggested to verify these results and investigate true corrosion scenarios in the field.

Hydrogen re-embrittlement was performed using anodes for plating in both the LHE Zn-Ni solution and Cd solution. LHE Zn-Ni passed the saltwater immersion test while Cd failed in less than one hour. Inspection of the Cd-plated coupon under a microscope suggests that the notch may not have plated thick enough to protect the base material. Additional testing where the thickness of the notch plating is verified before testing is suggested.

Stripping chemical and procedure experiments were conducted for removing LHE Zn-Ni plating. Increasing the concentration of ammonium nitrate to 32 ounces per gallon of ammonium nitrate solution, which is currently used for stripping Cd, proved to be an acceptable method to remove the LHE Zn-Ni.

Landing gear components were plated with LHE Zn-Ni and sent to the select bases mentioned above where the performance tracking program (PTP) was performed over a 24-month period. Two LHE Zn-Ni plated components were installed, and two Cd plated components were installed opposite (LH/RH) to be used as a control during the PTP, on select aircraft. During the PTP three inspections occurred, one at the time of installation, and two more during the following 24 months. All components selected for the PTP passed visual inspections.

In conclusion, the installation of the LHE Zn-Ni plating line at Hill AFB was successful and is fully operational. The LHE Zn-Ni process has corrosion resistance that meets or exceeds that of Cd plating, and it can be used on all components where Cd plating is currently applied. Test results throughout the project show that LHE Zn-Ni plated landing gear comply with USAF performance objectives and meet current environmental objectives to reduce the purchase and use of hazardous chemicals, thereby reducing hazardous waste and pollution generation.

## **1.0 INTRODUCTION**

### **1.1 BACKGROUND**

Cadmium (Cd) plating is used as a coating on High Strength Steel (HSS) landing gear alloys to prevent corrosion. The cadmium plating process uses three chemicals currently listed as hazardous materials by the EPA, OSHA, and ATSDR: cadmium, sodium cyanide, and hexavalent chrome. Cd is a known human carcinogen and a toxic heavy metal that can easily be leached; therefore it poses both environmental and health concerns. Due to these concerns and other limitations of Cd plating, Low Hydrogen Embrittlement Zinc-Nickel (LHE Zn-Ni) has been tested and qualified for use as a sacrificial coating to prevent corrosion to HSS alloys.

LHE Zn-Ni is applied through an electroplating process similar to that of Cd plating, except LHE Zn-Ni does not use sodium cyanide as a chelator in the process, or hexavalent chrome conversion coat, reducing the use of hazardous chemicals and hazardous waste.

The installation of the 3200-gallon LHE Zn-Ni plating line in building 505 at Hill AFB was successful, and the 309 CMXG Production Group is currently plating landing gear components with LHE Zn-Ni. The LHE Zn-Ni plating line chemical plating baths and processes were qualified by the following tests in accordance with USAF drawing 201027456: corrosion (ASTM B117), hydrogen embrittlement (ASTM F519) and adhesion (ASTM B571). Various landing gear components were also plated and inspected to verify uniform plating from both the tank and conformal anodes fixtures.

Additional studies involving dezincification, hydrogen re-embrittlement and stripping LHE Zn-Ni from high strength steel (HSS) components were conducted. Boeing Research & Technology (BR&T) completed the dezincification study. Additional studies are suggested to validate the results of these tests discussed below.

### **1.1 OBJECTIVE OF THE DEMONSTRATION**

The main objective of this project was to demonstrate and validate a full-scale prototype LHE alkaline Zn-Ni production plating line to ensure operational robustness of the process, which has performed well in small-scale prototype production line tests. Scale-up testing is required to ensure that plating parameters such as current density, conformal anode requirements, bath agitation, plating bath stability, and coating uniformity are within specifications for landing gear parts in a full-scale production process line. Upon final installation, the prototype LHE Zn-Ni plating line was qualified in accordance with (IAW) USAF-DRW-201027456 prior to production plating. Additionally, quality conformance checks continue to be performed during plating runs of landing gear components.

Ultimately, the results of this project allow landing gear components to be plated with LHE alkaline Zn-Ni and to comply with USAF environmental objectives, as well as meet all performance requirements of the original designs.

Additional test objectives were completed to evaluate the properties of the LHE Zn-Ni coating, including dezincification using accelerated corrosion methods, re-embrittlement in 3.5% salt water of plated coupons using conformal anode fixturing for Cd and LHE Zn-Ni, and optimization testing using ammonium nitrate for stripping LHE Zn-Ni.

## 1.2 REGULATORY DRIVERS

Cd is identified as a hazardous substance under the Resource Conservation and Recovery Act, the Clean Water Act, and the Clean Air Act. OSHA’s National Institute for Occupational Safety and Health declared Cd to be immediately dangerous to life and health in 1996, and the ATSDR completed Cd’s toxicity profile in 1999. The OSHA standard Permissible Exposure Level (PEL) is a time-weighted average concentration that must not be exceeded during any eight-hour work shift of a 40-hour workweek. The standard sets a PEL of five micrograms of cadmium per cubic meter of air (5 µg/m<sup>3</sup>) for all Cd compounds, dust, and fumes.

Executive Order 12586 instructs Federal Agencies to minimize the use and requirement of extremely hazardous substances or toxic chemicals through the use of clean technologies and safe alternatives.

Executive Order 13423 instructs Federal Agencies to reduce their purchase and use of hazardous and toxic chemicals.

Secretary of the Air Force (SECAF) Memorandum dated September 18, 2007, instructs the U.S. Air Force to comply immediately with Executive Order 13423 and its implementing instructions.

Executive Order 13514 instructs Federal Agencies to reduce their purchase and use of hazardous and toxic chemicals and gives guidelines to implement source reduction to minimize waste and pollutant generation.

The European Commission Registration, Evaluation, Authorization and Restriction of Chemicals (REACH) drafted modifications to its current Cd guidelines further restricting its use.

**Table 1. Target Hazardous Material (HazMat) Summary**

Target HazMat	Current Process	Applications	Current Specifications	Affected Programs	Candidate Parts and Substrates
Cd	Cd Plating	Corrosion protection for aircraft landing gear components	Mil-STD-870 Mil-STD-1500 AMS-QQ-P-416 Affecting over 2500 Tech Orders	Air Force Landing Gear Maintenance	Multiple HSS components for F-15, F-16, KC-135, E-3, T-38, A-10, B-1, B-2, B-52, C-17, C-130, C-5 aircraft
Sodium Cyanide	Cd Plating	Chelator for keeping Cd in solution during plating	Mil-STD-870 Mil-STD-1500 AMS-QQ-P-416 Affecting over 2500 Tech Orders	Air Force Landing Gear Maintenance	As listed above
Hexavalent Chrome	Conversion Coating	Cd plate sealant	Mil-STD-870 Mil-STD-1500 AMS-QQ-P-416 Affecting over 2500 Tech Orders	Air Force Landing Gear Maintenance	As listed above

## **2.0 DEMONSTRATION TECHNOLOGY**

### **2.1 TECHNOLOGY DESCRIPTION**

LHE Zn-Ni is applied through an electroplating process and is a drop-in replacement for toxic Cd plating. The application process is similar to that of Cd, except that the LHE Zn-Ni plating bath does not use sodium cyanide as a chelator. LHE Zn-Ni is a plating process that meets the requirements for a non-embrittling process per ASTM F519. During qualification testing, LHE Zn-Ni performed as well as or better than the current Cd plating. The Dipsol IZ-C17+ LHE Zn-Ni process has excellent throwing power and uses a trivalent chromium conversion coating (Dipsol IZ-264). The coating consists of a uniform zinc alloy containing 12-18% nickel that self-heals minor scratches. A Class 1 (0.5-0.8 mils) Zn-Ni alloy plating is deposited in 20 minutes with a current density of 40 ASF. For information regarding qualifying LHE Zn-Ni material see the Source Control Document Drawing USAF 201027457, and for more details regarding the plating process see Specification Drawing USAF 201027456. The basic components of the prototype plating line are plating tanks, rectifiers, filters, anodes, carbonate removal chiller, and rinse tanks. A properly maintained plating bath has an indefinite life.

### **2.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY**

The LHE Zn-Ni process is a more environmentally acceptable alternative with excellent corrosion resistance that meets or exceeds that of Cd plating. It can be used on all components where Cd plating is currently applied. Since Cd is a known human carcinogen, the reduction or elimination at depot facilities nationwide is of great interest throughout the Department of Defense. Eliminating the potential for Cd to leach into soils and groundwater during aircraft maintenance wash-downs provides benefit to each squadron facility. In the maintenance lifecycle, Cd has to be stripped at each depot facility before the parts can be processed throughout the shop, exposing critical components to corrosion inside the facility with little or no protection. LHE Zn-Ni, on the other hand, can remain on critical components for protection during processing through depot facilities while posing no serious health risks to personnel.

In addition to current and future environmental risk considerations, the new LHE Zn-Ni process can potentially save on overall weapon system operational process costs not only from eliminating Cd plating, but also from the elimination of Ion Vapor Deposition (IVD) of aluminum. IVD aluminum is used as an alternative for Cd plating for limited landing gear components where practical. However, IVD has several significant disadvantages including high maintenance costs and part size limitations, so IVD aluminum coatings can never fully replace Cd. Once fully implemented, LHE Zn-Ni would free up an entire section of the landing gear facility currently dedicated to IVD operation. There are also significant cost savings to be realized by elimination of requirements for processing Cd/cyanide materials and wastewater streams.

Hill AFB currently plates nearly 10,000 primary parts per year with Cd. This does not include thousands of bushings, fasteners and small components.

### 3.0 PERFORMANCE OBJECTIVES

Performance objectives were evaluated as qualitative and quantitative. Tank qualification objectives include chemistry and coating testing. Performance testing objectives are Field Service Evaluation (FSE) and the impact to production time. Qualitative performance objectives include reduction of hazardous waste. Performance objectives for the study are summarized below in Table 2.

**Table 2. Performance Objectives**

<b>Performance Objective</b>	<b>Data Requirements</b>	<b>Success Criteria</b>	<b>Results</b>
<u>Tank Qualification</u>			
Corrosion Testing	USAF DWG 201027456	96 hours with no white corrosion products	Passed
Hydrogen Embrittlement	USAF DWG 201027456	200 hour pull test at 75% notch fracture strength (NFS)	Passed
Plating Uniformity	USAF DWG 201027456	plating 0.3-0.5 mil range	Passed
Plating Adhesion	USAF DWG 201027456	Pass 90–180-degree bend test	Passed
Finish Quality	USAF DWG 201027456	Pass visual examination	Passed
Composition	USAF DWG 201027456	X-Ray Fluorescence	Passed
Tank Chemical Analysis	USAF DWG 201027456	Bath chemistry aging	Passed
<u>Performance Testing</u>			
Field Service Evaluation (FSE)	Visual inspection for corrosion products	Negligible corrosion products observed	Passed - 1 year evaluation
Impact to Production Time	Tracking of production time in demonstration	Minimal increase versus cadmium process time	Passed
<b>Qualitative Performance Objectives</b>			
Reduction of hazardous waste generated (cadmium, cyanide, Hexavalent Chromium)	Raw materials usage	Reduction of future disposal of hazardous materials/exposure to personnel	Passed

## 4.0 SITE/PLATFORM DESCRIPTION

### 4.1 TEST PLATFORMS/FACILITIES

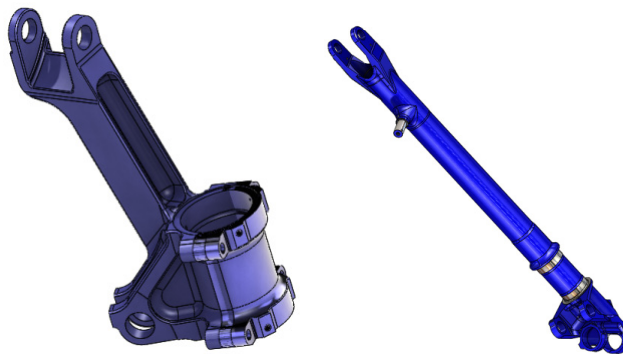
This project was divided into two phases. The first phase lasted approximately 18 months and entailed installation of the prototype line, establishing plating parameters and subsequently plating landing gear components. The second phase entailed a FSE following a PTP where LHE Zn-Ni plated landing gear components were installed on aircraft at selected air bases around the country. The second phase ran for approximately 24 months. Inspections conducted on fielded components determined the performance of the new coating in real world conditions.

<b>Zn-Ni Plating</b>	<b>1st Rinse</b>	<b>2nd Rinse</b>	<b>Acid Activator</b>	<b>Rinse</b>	<b>Conversion Coat</b>	<b>Hot Rinse</b>
Zn-Ni Dipsol Solution (PH12)	Deionized Water	Deionized Water	0.1% HCL Acid (PH 2)	Deionized Water	Trivalent Chrome (PH 4)	Deionized Water

**Figure 1. LHE Zn-Ni Prototype Plating Line Layout**

The location for the first phase of the project was Hill AFB Utah. Hill AFB is the primary landing gear maintenance facility for the Air Force. Work at the base includes maintenance for multiple weapons systems landing gear including the F-15, F-16, KC-135, E-3, T-38, A-10, B-1, B-2, B-52, C-130, and C-5 aircraft. For this project, landing gear components listed below were selected for LHE Zn-Ni plating.

- F-16 main landing gear (MLG) Collar
- F-16 MLG Tension Strut
- C-130 AFT Torque Strut
- C-130 FWD Torque Strut
- F-15 MLG Piston
- F-15 MLG Collar
- KC-135 Brake Equalizer Rod



**Figure 2. F-16 MLG Collar Assembly (Left) and F-16 MLG Tension Strut (Right)**

These components were selected because they are relatively easy to plate, they are accessible on aircraft for inspections, and they sustain more damage to their protective coatings due to location.

For the second phase of the project, parts were installed at bases with corrosive environments (i.e., located by salt water); McEntire JNG (F-16), Barbers Point US Coast Guard (C-130), New Orleans NAS Louisiana Air National Guard (ANG) (F-15), and Hickam AFB (KC-135). These bases were selected to closely simulate the most aggressive environment that would be experienced at any location worldwide.

## **4.2 PRESENT OPERATIONS**

Current plating operations for landing gear components at Hill AFB use electroplated Cd and IVD aluminum as sacrificial coatings to protect against corrosion. The Cd plating process uses three tanks: a plating tank and two counter-current rinse tanks. The plating solution is made up of cadmium oxide, sodium hydroxide and sodium cyanide. After Cd plating, high strength steel parts must be baked at 375°F for a minimum of 23 hours to remove hydrogen. After the bake, plated surfaces are re-activated in a dilute nitric acid solution, rinsed, and treated with a hexavalent chrome conversion coat. The rinse water from the Cd plating process is specially treated to first destroy the cyanide and then to remove Cd. The precipitated Cd must be disposed as hazardous material. Cd plating is used on nearly every steel part in landing gear. Once plated, the parts must be carefully handled to prevent contact between skin and cadmium plating.

IVD aluminum uses vacuum chambers to apply atomized aluminum on charged components. IVD aluminum application is limited to line of sight; consequently, internal bores, lugs and other surfaces require Cd plating for protection. Additionally, these chambers require a great deal of maintenance and are costly to run.

## **4.3 SITE-RELATED PERMITS AND REGULATIONS**

A notice of intent was submitted to the State of Utah for use of LHE Zn-Ni plating in January 2011. State approval for the air permit modification was given on June 28, 2011.

Wastewater discharge is regulated through the local publicly owned treatment works (POTW) North Davis Sewer District. A pretreatment permit is in place and all wastewater from the LHE Zn-Ni plating process will be treated at the Industrial Waste Treatment Plant (IWTP) prior to discharge.

## **5.0 TEST DESIGN**

### **5.1 PLATING LINE INSTALLATION AND QUALIFICATION**

The 309th CMXG identified an area in their overhaul facility to install the prototype full scale production tank. Site preparation for installation would include demolition and removal of the current equipment, re-establishing structural integrity of the area, and installation of the new LHE Zn-Ni plating tank and associated equipment.

#### **5.1.1 PROTOTYPE LHE ZN-NI PLATING LINE QUALIFICATION REQUIREMENTS**

All qualification testing was completed before operating the prototype LHE Zn-Ni plating line for full scale production. The following tests were used to verify operational compliance of the chemical solutions and their properties as plated on high strength steel:

- Hydrogen Embrittlement (ASTM F519)
- Coating Adhesion (ASTM B571)
- Corrosion (ASTM B117)
- Tank Chemical Composition
- Plating Uniformity
- Composition Finish Quality

### **5.2 ADDITIONAL TESTING**

Characteristics of the LHE Zn-Ni coating were researched and tested for dezincification using accelerated corrosion methods, re-embrittlement in 3.5% salt water of plated coupons using conformal anode fixturing for Cd and LHE Zn-Ni, and optimization testing using ammonium nitrate for stripping LHE Zn-Ni.

#### **5.2.1 DEZINCIFICATION CORROSION TESTING**

The objective of this testing was to determine if dezincification occurs on LHE Zn-Ni plating during exposure to saltwater corrosion environments, and if it does occur, does dezincification affect the corrosion resistance and/or sacrificial protection properties required by LHE Zn-Ni plating to protect high strength steel aircraft parts. Dezincification has been shown to occur in other combinations of Zn and other metals such as brass bushings. Testing included:

- Analyze the LHE Zn-Ni plating by measuring open circuit potential (OCP) and electrochemical corrosion rates in salt water and determine the composition of the LHE Zn-Ni plating with various analysis techniques.
- Corrode coupons via exposure in a salt fog chamber per ASTM B117, and perform electrochemically anodic polarization in a saltwater solution.
- Conduct analyses of LHE Zn-Ni plating on the test coupons after periodic exposure to corrosion environments. Analyze the LHE Zn-Ni plating by measuring OCP and electrochemical corrosion rates in salt water and analyze the composition of the LHE Zn-Ni plating by various analysis techniques.

- Continue exposure of LHE Zn-Ni plated test coupons to the corrosion environments and analyze the LHE Zn-Ni plating until effects of dezincification are fully understood.

### **5.2.2 DEZINCIFICATION TESTING CORROSION ENVIRONMENTS**

Eight of the test panels (four conversion coated and four non-conversion coated) were placed in the following corrosion environments (see note below for panel preparation):

- One conversion coated and one non-conversion coated Zn-Ni test panel in an ASTM B 117 salt spray chamber for four weeks.
- One conversion coated and one non-conversion coated Zn-Ni test panel in an ASTM G 85 SO<sub>2</sub> salt spray chamber for one week.
- Two conversion coated and two non-conversion coated Zn-Ni test panels in a 5% sodium chloride (NaCl) solution and adjust the anodic potential of the exposed test areas to produce a 10 mils per year (mpy) corrosion rate on the conversion coated test panels, and a 100 mpy corrosion rate on the non-conversion coated test panels.

After exposure to the corrosion environments, the conversion coated and non-conversion coated test panels were removed from each of the corrosion environments, rinsed in water, and dried. The following tests were then conducted:

- Measure zinc and nickel concentration on the test specimens by X-Ray Florescence (XRF).
- Measure OCP of the test specimens taken from the panels from the salt spray chamber and the accelerated corrosion test in 5% NaCl.

### **5.2.3 GALVANIC CORROSION AND LHE ZN-NI THROWING POWER**

Two LHE Zn-Ni test panels and one Cd control test panel were prepared with bare areas exposed for testing. Test panels were placed in ASTM B 117 salt spray for sufficient period of time to determine if dezincification is causing changes in sacrificial protection of LHE Zn-Ni on steel.

### **5.2.4 RE- EMBRITTLEMENT TESTING**

During previous re-embrittlement testing using LHE Zn-Ni and Cd, each test coupon was plated according to standard plating methods for each solution.

### **5.2.5 RESEARCH AND OPTIMIZATION OF LHE ZN-NI STRIPPING**

Hill AFB currently follows MIL-STD-871B, “Electro Chemical Stripping of Inorganic Finishes,” to strip Cd plating from HSS landing gear by using a solution of Ammonium Nitrate at a concentration of 16 ounces per gallon at a pH of 7. The stripping process takes approximately 75 minutes from start to finish, which includes part degreasing and rinsing, ammonium nitrate stripping using sodium hydroxide solution and 20% phosphoric acid solution, and rust stripping.

### **5.3 PERFORMANCE TRACKING PROGRAM**

The LHE Zn-Ni PTP validated the application of LHE Zn-Ni on landing gear components in an effort to replace Cd as a sacrificial protective coating. Subject aircraft had two LHE Zn-Ni plated components installed and opposite (LH/RH) cadmium plated components installed to be used as the control baseline. The corrosion of the two components was compared against each other. The subject aircraft were visually inspected for corrosion or corrosion products every year for two years. This allowed for three inspections, one at installation and two during the following years. Additional inspections may occur following the initial two years.

#### **5.3.1 PERFORMANCE TRACKING PROGRAM OBJECTIVE**

The objective was to demonstrate that LHE Zn-Ni plating performs as well as or better than Cd in corrosion prevention resulting from environmental conditions and operational use. High corrosive environments were chosen to show worst-case corrosion effects. Corrosion is most aggressive in hot, humid, and saltwater environments.

Tracking Procedure:

Components tracked through a two-year period were identified on the basis of:

- Air Force Base or National Guard Base
- Corrosive Environment
- Ease of access to component on aircraft
- Field level changeable
- Component environment/noted corrosion area
- Overhauled at Hill AFB

Visual inspection of the aircraft component occurred on a yearly basis to identify any corrosion or corrosion products. Components did not need to be disassembled to inspect the LHE Zn-Ni components. The following data was recorded and reported to the 417 Supply Chain Management Squadron (SCMS)/GUEA:

- Tail Number
- Component Noun
- Position of the component
- Serial number of component
- Date of Installation
- Notes on state of the component

LHE Zn-Ni plated components were marked “PTPZ” with a black stamp. Cd plated components were marked “PTPC” using a black stamp.

#### **5.3.2 FIELD CORROSION OBJECTIVE**

Three atmospheric site corrosion test facilities were identified as appropriate test sites for long term aerospace corrosion testing: National Aeronautics and Space Administration (NASA) Corrosion Technology Laboratory in Florida, Whidbey Island in Washington State, and El Segundo California. These three locations are exposed to oceanic costal environments.

At each location, both Cd and LHE Zn-Ni plated condemned landing gear components were placed on test stands that are exposed to atmospheric conditions. Cd test components were plated IAW MIL-STD-870. Zn-Ni test components were plated IAW USAF-DWG-20102746.

Two were painted to simulate real world landing gear components and two were left unpainted to simulate components that are damaged or directly exposed to the environment.

## 6.0 PERFORMANCE ASSESSMENT

### 6.1 PROTOTYPE LHE ZN-NI PLATING LINE QUALIFICATION

All qualification testing was completed prior to operating the prototype LHE Zn-Ni plating line for full-scale production. The following tests were used to verify operational compliance of the chemical solutions and their properties as plated on high strength steel:

- Hydrogen Embrittlement (ASTM F519) – 200 hr 75% NFS no failures.
- Coating Adhesion (ASTM B571) – Bend 180° and examine for peeling or flaking.
- Corrosion (ASTM B117) – 96 hours in salt fog with no white corrosion products.



**Figure 3. Hydrogen Embrittlement, Adhesion, and Corrosion Testing**

Additional metrics for tank chemistry were used for qualification of the new plating line setup:

- Tank Chemical Analysis – Tank solution makeup with lab analysis shown in Table 3.
- Plating Uniformity – XRF was used to measure thickness on a plated panel - Thickness 0.47-0.55 mil.
- Composition – XRF was used to check nickel composition in the plated coating - Nickel % 13.0-14.89%.
- Finish Quality – Visual inspection of the plated part finish showed uniform coating.

**Table 3. Startup Tank Chemical Analysis (5/16/13)**

IZ-C17+		
Parameter	Required Range	Measured Value
Zn (g/L)	7.0-9.0	6.75
Ni (g/L)	1.1-1.3	1.27
Zn/Ni Ratio	5.38-8.18	5.33
NaOH (g/L)	100 - 150	124.8
IZ-C17+B (g/L)	50-80	59.0
Na <sub>2</sub> CO <sub>3</sub> (g/L)	0-60	35.3



**Figure 4. Finish Quality**

## 6.2 DEZINCIFICATION CORROSION TESTING

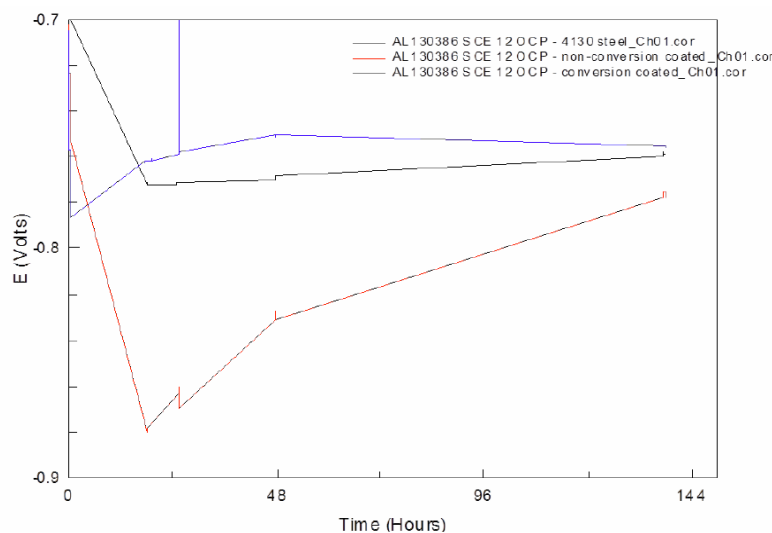
Two 4x6x0.040 Zn-Ni test specimens were analyzed using XRF to determine the concentration and thickness. The two LHE Zn-Ni test specimens were labeled NCC-2 (NCC = no conversion coating) and CC-2 (CC = conversion coated). The averages from the XRF analysis for zinc and nickel weight percentage and thickness (mils) are shown in Table 4.

**Table 4. XRF Analysis Data - Averages**

	Average % Zn	Average % Ni	Average Thickness (mils)
NCC-2 Front	84.43	15.57	0.42
NCC-2 Back	84.61	15.39	0.47
CC-2 Front	84.44	15.56	0.38
CC-2 Back	84.55	15.45	0.46

### 6.2.1 OPEN CIRCUIT POTENTIAL (OCP)

One each of the CC and NCC test panels were used measure OCP versus Saturated Calomel Electrode (SCE) in 5% NaCl solution. Periodic monitoring of the OCP for one to seven days obtained a steady state value for the OPC of -740 to -780 mV versus SCE. Bare 4130 steel was also measured to verify that LHE Zn-Ni plating OCP is anodic to steel OCP.



**Figure 5. OCP for Steel (Blue - Top Line), CC LHE Zn-Ni (Black - Middle Line) and NCC LHE Zn-Ni (Red - Bottom Line)**

## 6.2.2 POTENTIODYNAMIC POLARIZATION CURVES

One conversion coated test panel and one non-conversion coated test panel were used to prepare potentiodynamic anodic polarization curves in accordance with ASTM G5. Applying an anodic potential to create a current density of  $2 \times 10^{-5}$  A/cm<sup>2</sup> will represent a corrosion rate of 10 mpy. The non-conversion coated Zn-Ni scan showed that by applying an anodic potential to create a current density of  $2 \times 10^{-4}$  A/cm<sup>2</sup> will represent a corrosion rate of 100 mpy. These current densities were used to artificially corrode LHE Zn-Ni test specimens and determine if dezincification occurred.

## 6.2.3 DE-ZINCIFICATION AFTER SALT SPRAY CORROSION

Four Zn-Ni 4x6 inch test panels, two with conversion coating (CC-3 and CC-4) and two without conversion coating (NO CC-3 and NO CC-4), were masked to expose only half of the front side (a 3x4 inch area). CC-3 and NO-CC-3 were placed in an ASTM B 117 salt spray cabinet and were removed from the salt spray cabinet after four weeks exposure. CC-4 and NO-CC-4 were placed in an ASTM G 85 SO<sub>2</sub> salt spray cabinet and were removed from the salt spray cabinet after one week of exposure. XRF analyses could not be performed on the corroded side of these test panels.

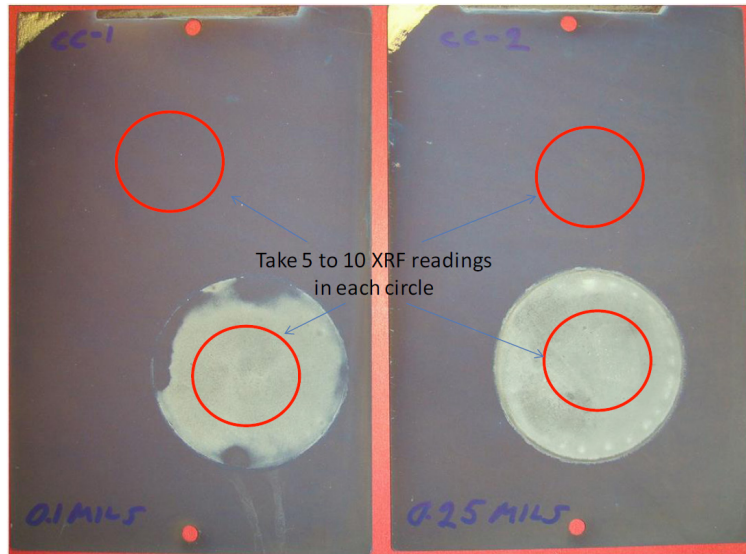


**Figure 6. Corroded and Un-corroded areas of LHE Zn-Ni Panes CC-3 (bottom) and NCC-3 (top) after Four Weeks in ASTM B117 Salt Spray**

## 6.2.4 DEZINCIFICATION AFTER ANODIC ETCHING

Four LHE Zn-Ni 4x6 inch test panels – two conversion coated (CC-1 and CC-2) and two with no conversion coating (NO-CC-1 and NO-CC-2) – were masked on the entire back side and front side, but an area 2 inches in diameter on front side was left unmasked.

Figure 7 shows pictures of CC-1 and CC-2 after 0.1 and 0.25 mils of LHE Zn-Ni were removed.

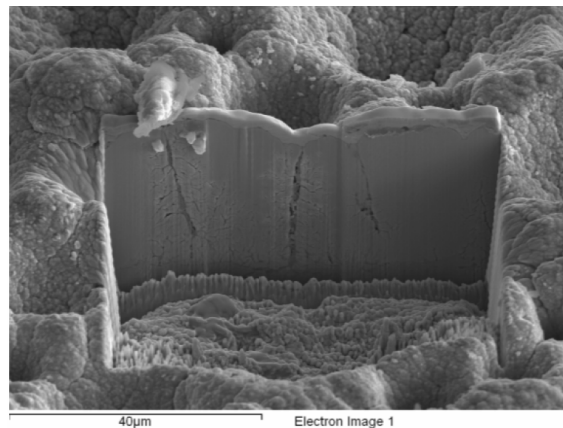


**Figure 7. LHE Zn-Ni Panels CC-1 and CC-2 After Anodic Etching**

CC-1, CC-2, NCC-1 and NCC-2 LHE Zn-Ni test specimens from the anodic etching test were analyzed using XRF to determine the concentration and thickness in microns.

### **6.2.5 DEZINCIFICATION ELECTROCHEMICAL AND SURFACE ANALYSIS**

Missouri University of Science and Technology received two test panels (one conversion coated and one non-conversion coated) to perform surface analysis of LHE Zn-Ni with Focused Ion Beam (FIB)/Scanning Electron Microscope (SEM)/Energy Dispersive Spectroscopy (EDS) equipment. Surface analyses were performed on as-received samples and again after samples were corroded by anodic dissolution to remove 0.04 mil (1 micron) of LHE Zn-Ni plating material to determine if dezincification occurred. There was Zn-Ni composition change with depth due to corrosion. There are no concentrations of either element, rather, a homogeneous structure of Zn and Ni.



**Figure 8. Conversion Coated (CC) Electron Beam Image (Corroded Area)**

Results from all of the scans show that there may be slight loss of percent weight of Zn during corrosion. The normalized percent weight of the samples is shown in Table 5. It is noted that the concentrations of Zn are higher than the correct concentrations of Ni. This is due to the fact that there was no standard for the EDS equipment to calibrate against. There can only be a comparison made from the un-corroded percent weight and the corroded percent weight.

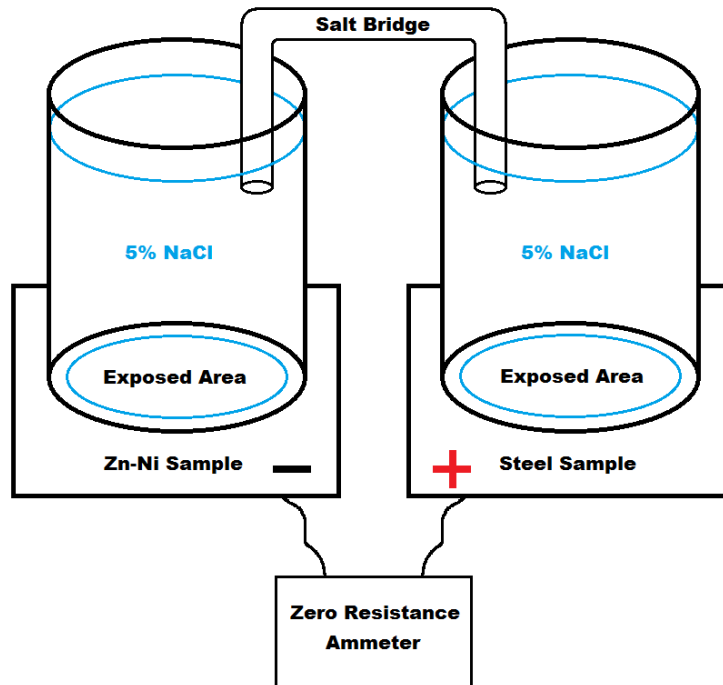
**Table 5. Percent Weight EDS Analysis**

	Un-corroded %wt	Corroded %wt
NCC-1		Zn (avg.) 65±3% Ni (avg.) 35±3%
CC-1	Zn (avg.) 70.3±0.2% Ni (avg.) 29.7±0.2%	Zn (avg.) 65±4% Ni (avg.) 35±4%

### 6.2.6 ZERO RESISTANCE AMMETER (ZRA) MEASUREMENTS

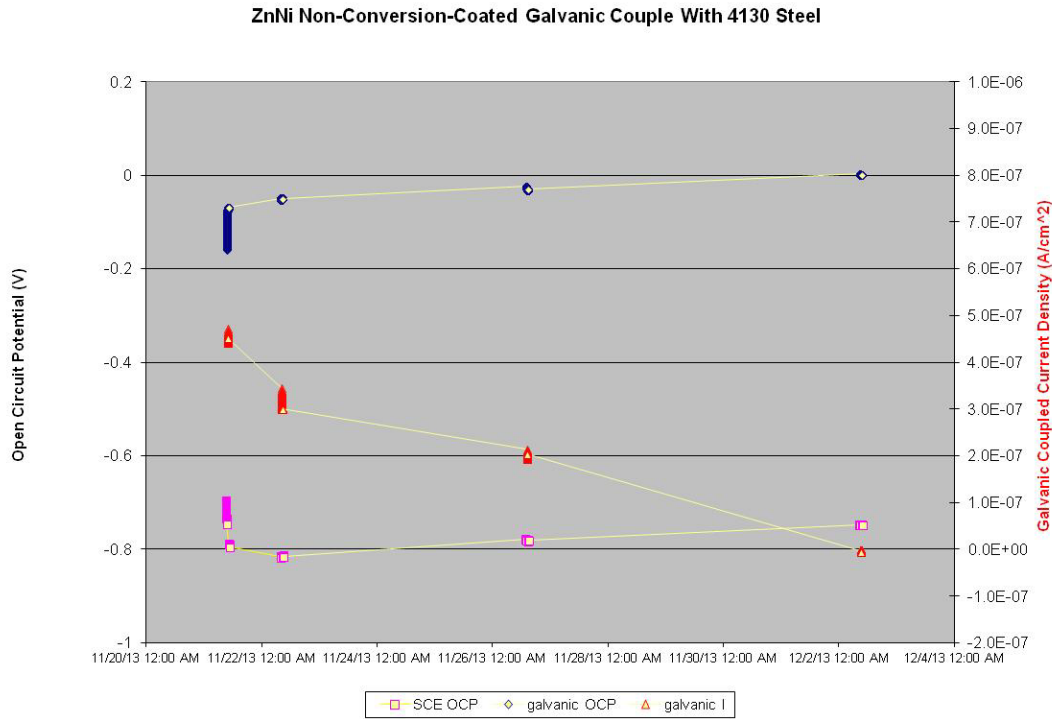
Two Zn-Ni test panels (one conversion coated and one non-conversion coated) were coupled to 1x6x0.04 inch bare steel strips (4130 alloy) in order to conduct galvanic corrosion tests in accordance with ASTM G 71. The test was conducted in 5% Na-Cl.

Galvanic current was measured while test panels were coupled and corrosion potentials of steel and LHE Zn-Ni test panels were measured uncoupled. The diagram below shows the laboratory set-up used to measure the galvanic current.



**Figure 9. ZRA Setup Diagram**

The data in Figure 10, show that Zn-Ni with CC had a steady OCP of -0.74 to -0.76 V versus SCE (steel is typically -0.6 to -0.7 V versus SCE) during the 10 day test, and the OCP for Zn-Ni when coupled to steel was -50 mV. The initial galvanic current flow between the Zn-Ni and bare steel was  $2.8 \times 10^{-7} \text{ A/cm}^2$  (Zn-Ni is anodic to the steel) but the galvanic current flow quickly dropped to zero, or slightly cathodic to the steel.

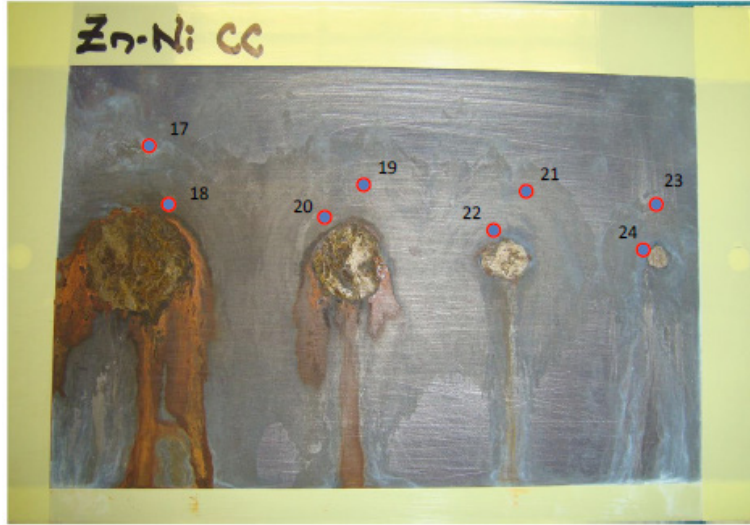


**Figure 10. ZRA of Zn-Ni NCC Coupled with 4130 Steel**

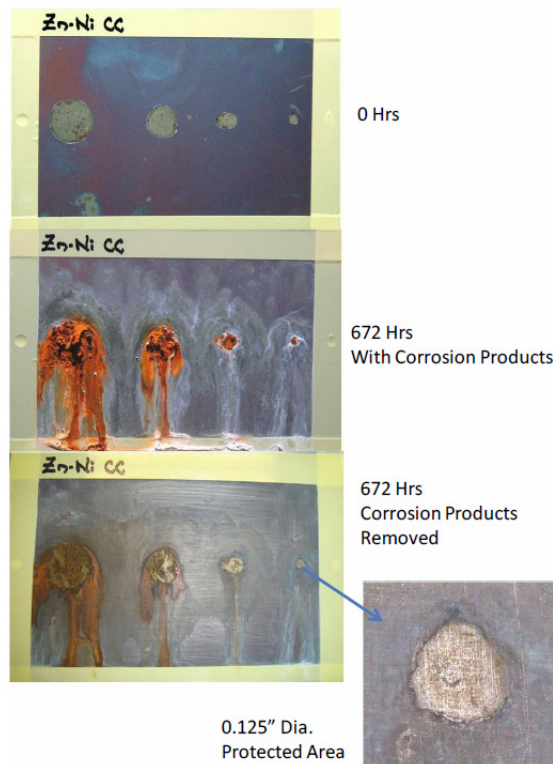
The data in Figure 10 show that Zn-Ni without CC had an initial OCP of -0.82 V versus SCE and then dropped to -0.75 V versus SCE after 10 days, and the OCP for Zn-Ni when coupled to steel was -80 mV. The initial galvanic current flow between the Zn-Ni and bare steel was  $4.5 \times 10^{-7} \text{ A/cm}^2$  (Zn-Ni is anodic to the steel) and then the galvanic current flow slowly dropped to zero or slightly cathodic to the steel after 10 days.

### 6.2.7 GALVANIC CORROSION AND LHE ZN-NI THROWING POWER

Plating materials were removed in four areas on three test panels: a LHE Zn-Ni plated test panel with conversion coating, a LHE Zn-Ni plated test panel with no conversion coating, and a Cd plated test panel. The three test panels were then placed in an ASTM B 117 salt spray cabinet for 672 hours and then removed. Heavy corrosion products were removed by scrubbing with water and then the cleaned corroded test panels were analyzed using XRF analysis to determine the percent weight Zn, both near the bare corroded areas and away from the bare corroded areas. Figure 11 shows the areas on the test panels where XRF analyses were taken. XRF analysis could not be performed on the Cd plated test panel, so that test panel was not analyzed.



**Figure 11. LHE Zn-Ni with Conversion Coat XRF Analysis Locations**



**Figure 12. LHE Zn-Ni Plated Test Panel with Conversion Coat**

LHE Zn-Ni and Cd sacrificial coatings have very poor throwing power and cannot protect large areas of bare steel. Zn concentrations near the bare corrosion areas and away from the bare corrosion areas for the non-conversion coated Zn-Ni test panel did not change significantly so dezincification did not occur. The results for the conversion coated Zn-Ni were inconclusive and additional testing is required.

### 6.3 RE-EMBRITTEMENT TESTING

Plating of both LHE Zn-Ni and Cd test coupons were both performed with a fixture to ensure uniform plating thickness across the coupon. Visual inspection showed plating in the notch area of both test groups.



**Figure 13. Cd (Left) and LHE Zn-Ni (Right) Plated Re-embrittlement Coupons**

Each coupon was loaded at 45% NFS in the test frame in a container with the 3.5% NaCl water solution per ASTM F519 testing procedures. Test results show all Cd plated test specimens failing in less than one hour. No LHE Zn-Ni plate coupons failed.

**Table 6. Hydrogen Re-embrittlement Test Results**

Coupon ID	Failed (Y/N)	Failure Time
Cd - 153	Y	0.2 hr
Cd - 143	Y	0.5 hr
Cd - 171	Y	0.7 hr
Cd - 134	Y	0.8 hr
Zn-Ni - 67	N	-
Zn-Ni - 167	N	-
Zn-Ni - 52	N	-
Zn-Ni - 83	N	-

### 6.4 RESEARCH AND OPTIMIZATION OF LHE ZN-NI STRIPPING

It is recommended that an agitated solution of ammonium nitrate solution at 32 ounces per gallon with a 7 pH is used to strip the LHE Zn-Ni plating off of HSS landing gear components. Sufficient process tank space must be provided to allow a minimum 30–60-minute immersion in the ammonium nitrate stripping solution.

## 6.5 PERFORMANCE TRACKING PROGRAM

The LHE Zn-Ni PTP validated the application of LHE Zn-Ni on landing gear components in an effort to replace Cd as a sacrificial protective coating. LHE Zn-Ni has been evaluated, tested and approved as a replacement for Cd. Testing has shown that LHE Zn-Ni performs as well as or better than Cd in corrosive environments.

Four aircraft (F-15, F-16, KC-135, and C-130) were selected as candidates to compare operational performance of LHE Zn-Ni with Cd. The subject aircraft had two LHE Zn-Ni plated components installed and opposite (LH/RH) cadmium plated components installed to be used as the control baseline. The corrosion of the two components was compared against each other.

Locations were selected due to their corrosive climates and operational mission conditions representative of the USAF fleet ensuring reliability and accuracy of the PTP data.

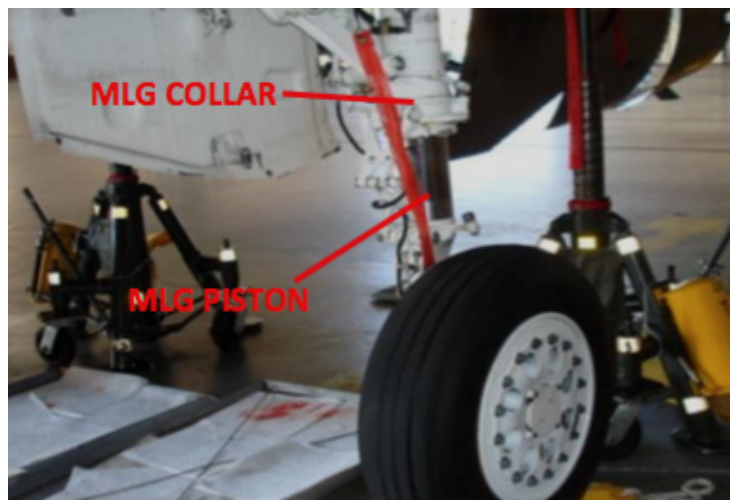
### 6.5.1 NEW ORLEANS NAVAL AIR STATION JOINT RESERVE BASE, LOUISIANA (F-15)

F-15 performance tracking was completed at the 159<sup>th</sup> Fighter Wing Louisiana ANG. The LHE Zn-Ni and Cd plated components were installed on Aircraft # 83-048 on October 30, 2014.

**Table 7. F-15 LHE Zn-Ni and Cd Components**

COMPONENT	P/N	NSN
MLG Collar (RH)	68A410733-2002	1620-00-338-6559
MLG Piston (RH)	68A410704-1012	1620-01-080-3407
MLG Collar (LH)	68A410733-2001	1620-00-344-0616
MLG Piston (LH)	68A410704-1101	1620-01-080-3404

Note: RH components are LHE Zn-Ni plated and LH components are Cd plated.



**Figure 14. F-15 MLG PTP Components**

### 6.5.2 JOINT BASE PEARL HARBOR-HICKAM – HAWAII (KC-135)

KC-135 performance tracking was completed at the 203nd Air Refueling Squadron at Joint Base Pearl Harbor-Hickam, Hawaii. The LHE Zn-Ni and Cd plated components were installed on Aircraft # 63-8030 on September 22, 2015.

**Table 8. KC-135 MLG PTP Components**

COMPONENT	P/N	NSN
MLG Brake Equalizer Rod (RH/LH)	65-1266-2	1620-00-658-7980

Note: RH components are LHE Zn-Ni plated and LH components are Cd plated.



**Figure 15. KC-135 MLG Components**

### 6.5.3 USCG AIR STATION BARBERS POINT – HAWAII (C-130)

C-130 performance tracking was completed at the USCG Air Station Barbers Point, Kapolei, Hawaii. LHE Zn-Ni and Cd plated components were installed on aircraft # 1716 on August 27, 2015. During overhaul at Hill AFB, PTP components were installed in the landing gear assemblies, after which the landing gear assemblies were installed on aircraft #1716.

**Table 9. C-130 MLG PTP Components**

COMPONENT	P/N	NSN
MLG Aft Torque Strut (RH/LH)	388066-1	1602-00-862-4059
MLG Fwd Torque Strut (RH/LH)	388065-1	1620-00-862-4058

Note: RH components are LHE Zn-Ni plated and LH components are Cd plated.



**Figure 16. C-130 PTP Components**

#### 6.5.4 MCENTIRE JOINT NATIONAL GUARD BASE – SOUTH CAROLINA (F-16)

F-16 performance tracking was completed at McEntire Joint National Guard Base in South Carolina. LHE Zn-Ni and Cd plated components were installed on Aircraft # 92-902 on December 16, 2014.

**Table 10. F-16 MLG PTP Components**

COMPONENT	P/N	NSN
MLG Tension Strut (RH/LH)	2007003-103	1602-01-252-1049
MLG Collar (LH)	2007307-105	1620-01-252-4036
MLG Collar (RH)	2007307-106	1620-01-252-4037

Note: RH components are LHE Zn-Ni plated and LH components are Cd plated.



**Figure 17. F-16 MLG PTP Components**

## 6.6 FIELD CORROSION EVALUATION

### 6.6.1 CORROSION TESTING FACILITIES

Boeing Research & Technology St. Louis coordinated placement of both Cd and LHE Zn-Ni plated parts for a side-by-side comparative study at each corrosion testing site.

### 6.6.2 NASA

Components were placed at the Kennedy Space Center/NASA atmospheric corrosion tests site on October 22, 2014, with interim inspections on July 13, 2015, August 26, 2015, May 24, 2016, and April 6, 2017. A summary of parts and inspection descriptions can be seen in Table 11. Test subjects are located approximately 250 feet from the Atlantic Ocean and 1.6 miles away from a launch pad used for space shuttle.

**Table 11. Florida Corrosion Test Summary**

<b>Test Component Installation Date: 10/22/2014</b>		
<b>Inspections</b>		
<b>Date</b>	<b>Part</b>	<b>Description</b>
7/13/2015 264 days exposure	Cd Drag Brace (Painted)	Slight Corrosion products visible
	Zn-Ni Drag Brace (Painted)	Visible rust/red corrosion products
	Cd Drag Brace	Slight white corrosion products
	Zn-Ni Drag Brace	Slight white corrosion products
	Cd Rotational Collar	Slight white corrosion products
	Zn-Ni Rotational Collar	Slight white corrosion products
8/26/2015 308 days exposure	Cd Drag Brace (Painted)	Slight Corrosion products visible
	Zn-Ni Drag Brace (Painted)	Visible rust/red corrosion products
	Cd Drag Brace	Slight white corrosion products
	Zn-Ni Drag Brace	White corrosion products
	Cd Rotational Collar	White corrosion products
	Zn-Ni Rotational Collar	White corrosion products
5/24/2016 580 days exposure	Cd Drag Brace (Painted)	Slight Corrosion products visible. Small amount of rust on bushing
	Zn-Ni Drag Brace (Painted)	Visible rust/red corrosion products
	Cd Drag Brace	Slight white corrosion products
	Zn-Ni Drag Brace	White corrosion products
	Cd Rotational Collar	White corrosion products
	Zn-Ni Rotational Collar	White corrosion products
4/6/2017 817 days exposure	Cd Drag Brace (Painted)	Slight Corrosion products visible. Small amount of rust on bushing
	Zn-Ni Drag Brace (Painted)	Large amounts of rust/red corrosion products
	Cd Drag Brace	Slight white corrosion products
	Zn-Ni Drag Brace	Moderate white corrosion products
	Cd Rotational Collar	Moderate white corrosion products
	Zn-Ni Rotational Collar	Moderate white corrosion products



**Figure 18. Corrosion Testing Components at NASA Atmospheric Corrosion Test Site Install (10/22/2014)**

### 6.6.3 EL SEGUNDO

Components were placed at the El Segundo atmospheric test site on November 3, 2014. Interim inspections were completed on November 4, 2015, and January 18, 2017. A summary of parts and inspection descriptions can be seen in Table 12. Parts were located on a Chevron refinery approximately 580 feet from the Pacific Ocean.

**Table 12. El Segundo Corrosion Test Summary**

<b>Test Component Installation Date: 11/3/2014</b>		
<b>Inspections</b>		
<b>Date</b>	<b>Part</b>	<b>Description</b>
11/4/2015 366 days exposure	Cd Drag Brace (Painted)	Slight corrosion products
	Zn-Ni Drag Brace (Painted)	Slight corrosion products
	Cd Drag Brace	Slight white corrosion products
	Zn-Ni Drag Brace	Slight white corrosion products
	Cd Rotational Collar	Slight white corrosion products
	Zn-Ni Rotational Collar	Slight white corrosion products
1/18/2017 807 days exposure	Cd Drag Brace (Painted)	Small amount of rust on bushing
	Zn-Ni Drag Brace (Painted)	Visible rust/red corrosion products
	Cd Drag Brace	Small amounts of white corrosion products
	Zn-Ni Drag Brace	White corrosion products, small amount of rust on bushing
	Cd Rotational Collar	
	Zn-Ni Rotational Collar	



**Figure 19. Corrosion Test Subjects on Installation (11/3/2014)**



**Figure 20. Corrosion Test Subjects on Installation (11/3/2014)**

#### **6.6.4 WHIDBEY ISLAND**

Components were placed at the Whidbey Island Corrosion Test Facility on May 15, 2014. Interim inspections occurred on May 13, 2015, and March 2, 2016. A summary of parts and inspection descriptions can be seen in Table 13. Parts were located at Ault Field Naval Air Station approximately 130 feet from Pacific Ocean waters and approximately 0.25 miles from aircraft runways.

**Table 13. Whidbey Island Corrosion Test Summary**

<b>Test Component Installation Date: 5/14/2014</b>		
<b>Inspections</b>		
<b>Date</b>	<b>Part</b>	<b>Description</b>
5/13/2015 364 days exposure	Cd Drag Brace (Painted)	Slight corrosion products
	Zn-Ni Drag Brace (Painted)	Slight corrosion products
	Cd Drag Brace	Moderate white corrosion products
	Zn-Ni Drag Brace	Moderate white corrosion products
	Cd Rotational Collar	Some red corrosion products/rust
	Zn-Ni Rotational Collar	Some white corrosion products
3/2/2016 667 days exposure	Cd Drag Brace (Painted)	Slight corrosion products
	Zn-Ni Drag Brace (Painted)	Slight corrosion products
	Cd Drag Brace	Moderate white corrosion products
	Zn-Ni Drag Brace	Moderate white corrosion products
	Cd Rotational Collar	Some white and red corrosion products/rust
	Zn-Ni Rotational Collar	Some white corrosion products



**Figure 21. Cd and Zn-Ni Plated Test Components at Whidbey Island on Installation (05/14/2014)**

## 6.7 PERFORMANCE ASSESSMENT FINAL CONCLUSIONS

The conclusions for this project are as follows:

- The installation of the LHE Zn-Ni Plating Line was successful and is fully operational. The chemical plating baths are in compliance and the process was qualified by testing corrosion (ASTM B117), hydrogen embrittlement (ASTM F519), and adhesion ASTM (B571) with successful results. Additionally, various landing gear parts were plated to verify uniform plating from the tank and fixturing.
- Dezincification was studied with Boeing Research & Technology. The team found that accelerated or forced corrosion may start to cause dezincification, however corrosion rates closer to actual corrosion in nature does not appear to have any impact on dezincification.
- Hydrogen re-embrittlement was performed using anodes for plating in both the LHE Zn-Ni solution and Cd solution. LHE Zn-Ni passed the saltwater immersion test while Cd failed in less than one hour.
- Stripping chemicals and procedures were experimented with for removing LHE Zn-Ni plating. Increasing the concentration of ammonium nitrate to 32 ounces per gallon ammonium nitrate solution, which is currently used for stripping Cd, proved to be an acceptable method to remove the LHE Zn-Ni.
- LHE Zn-Ni plated MLG components protected against corrosion as well as or better than Cd plated MLG components during the 2-year PTP. LHE Zn-Ni also appeared more robust in areas that had no paint or primer to protect the surface. Due to an F-16 brake fire, the test components were removed and condemned.
- The painted Zn-Ni drag braces located at Florida and California developed the most corrosion products, and they were the only painted test subjects to show any significant levels of rust. Painted test subjects located in Florida showed visible rust after only 264 days, whereas test subjects at Washington and California did not show any rust after 627 days (Washington) and 366 days (California). One painted component in California showed red rust after 807 days. Accelerated corrosion of test subjects at the Kennedy Space Center could potentially be from their proximity to the space shuttle launch pad. During launch, sulfur oxides are emitted into the surrounding environment, which could be affecting the test subjects. Accelerated corrosion of test subjects at the El Segundo facility could potentially be from their proximity to the oil refinery where it is located. There may be a reaction that is taking place between the Zn-Ni plating and the non-chrome primer used in the paint system that is causing the red rust in the painted parts where the unpainted parts are not affected the same way. The non-chrome paint system was qualified using aluminum samples and it was not tested and qualified on steel substrates. This phenomenon has only been displayed on the parts near emissions of sulfur oxides and has not been seen on aircraft components that have been installed and tracked for the PTP.

## 7.0 COST ASSESSMENT

### 7.1 COST MODEL

A standard cost basis analysis was developed on this project. A Work Break-down Structure (WBS) was used to analyze 1) facility capital cost; 2) start-up and operations and maintenance costs; 3) equipment replacement costs; 4) ESOH costs and cost avoidance; and 5) reprocessing or re-application costs.

Currently, as Hill AFB transitions workload from Cd plating to LHE Zn-Ni plating, both operations run simultaneously to meet the needs of the Air Force. Each part that is transitioned to LHE Zn-Ni plating must be prototyped through validation/verification for quality assurance. Hill AFB set a schedule to be fully transitioned from Cd to LHE Zn-Ni by December 2017. During the interim the cost savings cannot be realized and quantified until after Cd has been completely phased out of the overhaul facility.

**Table 14. Types of Costs by Category**

<b>Direct Environmental Activity Process Costs for LHE Zn-Ni</b>			
<b>Start-Up</b>		<b>Operation &amp; Maintenance</b>	
<b>Activity</b>	<b>\$</b>	<b>Activity</b>	<b>\$</b>
Equipment purchase/installation	1.3M	Labor to operate equipment	40k/year
Equipment design	500k	Manage hazardous waste	10k/year
Test and analyze waste streams	150k	Hazardous waste disposal fees	6k
Process chemicals	87k	Waste treatment	48k
		Process chemicals	8.7k
		Consumables and supplies	34k/year
		Equipment maintenance	5k
<b>Total Installation and Startup</b>	<b>2.037M</b>	<b>Total Yearly Operation Cost</b>	<b>151.7k/year</b>

One cost savings that was not taken into account during the initial Cost Benefit Analysis was the ability for LHE Zn-Ni to replace IVD aluminum. IVD aluminum was used as a corrosion preventative coating in areas where high temperature occurs on landing gear components, typically axles. This coating was used in place of Cd because Cd could melt at these higher temperatures and cause Solid Metal or Liquid Metal Embrittlement (SME or LME). LHE Zn-Ni has a higher melting temperature than Cd and could replace IVD in applications on the high heat areas of landing gear. Maintenance costs for the IVD equipment are approximately \$375,000 each year. These maintenance costs could be saved by eliminating this process and implementing LHE Zn-Ni.

## 7.2 COST ANALYSIS AND COMPARISON

Identification of the costs and benefits between using LHE Zn-Ni plating versus Cd plating are used in the following cost benefit analysis. The alternatives are to stay with the status quo of Cd plating and the alternative of LHE Zn-Ni plating. Hill AFB Depot is the largest user of Cd plating in the Air Force. Cd plating restrictions from the EPA are increasing to force reduction or replacement of Cd plating over the following years. LHE Zn-NI can be used in all locations that Cd is currently applied at Hill AFB and would be a direct drop in replacement. Personal exposure limits are set by OSHA and have a non-recurring cost that are required to be enacted to meet the current limits. The following requirements are non-recurring costs required to meet PELs.

**Table 15. Non-Recurring Cd Requirements**

<b>New Equipment:</b>	
Air Curtains (Zambonis)	\$250,000
Air Showers (17 total)	\$1,275,000
HEPA vacuums, Tables and Sanding Booths	\$760,000
<b>New Equipment Total</b>	<b>\$2,035,000</b>
<b>Process Facility Improvements:</b>	
Installation of Restrooms and Change Rooms	\$650,000
Lockers (225)	\$50,000
HVAC Upgrades	\$4,000,000
Isolation Walls and Transition Area Rooms (8)	\$1,200,000
Standardized Signs	\$10,000
<b>Process Facility Improvements Total</b>	<b>\$5,260,000</b>
<b>TOTAL</b>	<b>\$7,295,000</b>

**Table 16. Status Quo: Cadmium Plating**

	FY12	FY13	FY14	FY15	FY16	FY17-31	Total
Non-Recurring Costs:							
	\$7,295,000	\$0	\$0	\$0	\$0	\$0	\$7,295,000
<b>Total Non-Rec Costs</b>	<b>\$7,295,000</b>	<b>\$0</b>	<b>\$0</b>	<b>\$0</b>	<b>\$0</b>	<b>\$0</b>	<b>\$7,295,000</b>
Recurring Costs:							
Chemicals	\$16,925	\$16,925	\$16,925	\$16,925	\$16,925	\$253,879	\$338,506
Waste Water Treatment	\$79,945	\$79,945	\$79,945	\$79,945	\$79,945	\$1,199,178	\$275,400
Personnel Protective Equip.	\$33,570	\$33,570	\$33,570	\$33,570	\$33,570	\$503,550	\$671,400
Industrial Hygiene Services	\$3,200	\$3,200	\$3,200	\$3,200	\$3,200	\$48,000	\$64,000
<b>Total Recurring Costs</b>	<b>\$133,640</b>	<b>\$133,640</b>	<b>\$133,640</b>	<b>\$133,640</b>	<b>\$133,640</b>	<b>\$2,004,607</b>	<b>\$1,349,306</b>
<b>Total Costs</b>	<b>\$7,428,640</b>	<b>\$133,640</b>	<b>\$133,640</b>	<b>\$133,640</b>	<b>\$133,640</b>	<b>\$2,004,607</b>	<b>\$8,644,306</b>

**Table 17. Alternative: LHE Zn-Ni Plating**

	FY12	FY13	FY14	FY15	FY16	FY17-31	Total
Non-Recurring Costs:							
	\$1,300,000	\$0	\$0	\$0	\$0	\$0	\$1,300,000
<b>Total Non-Rec Costs</b>	<b>\$1,300,000</b>	<b>\$0</b>	<b>\$0</b>	<b>\$0</b>	<b>\$0</b>	<b>\$0</b>	<b>\$1,300,000</b>
Recurring Costs:							
Chemicals	\$103,925	\$22,240	\$18,855	\$15,470	\$12,085	\$365,400	\$537,976
Waste Water Treatment	\$79,945	\$63,956	\$47,967	\$31,978	\$15,989	\$0	\$239,836
Personnel Protective Equip.	\$33,570	\$33,570	\$33,570	\$33,570	\$33,570	\$503,550	\$671,400
Industrial Hygiene Services	\$3,200	\$2,560	\$1,920	\$1,280	\$640	\$0	\$9,600
<b>Total Recurring Costs</b>	<b>\$220,640</b>	<b>\$122,326</b>	<b>\$102,312</b>	<b>\$82,298</b>	<b>\$62,284</b>	<b>\$365,400</b>	<b>\$537,976</b>
<b>Total Cost</b>	<b>\$1,520,640</b>	<b>\$122,326</b>	<b>\$102,312</b>	<b>\$82,298</b>	<b>\$62,284</b>	<b>\$365,400</b>	<b>\$1,837,976</b>

An important consideration in determining which alternative to choose is an evaluation of the benefits that each alternative will yield. This analysis attempts to capture intangible factors that are neither monetary nor otherwise quantifiable. These benefits were judged on importance and each was assigned a rating for its ability to satisfy the desired benefit. The results were then used to compute a cost-to-benefit ratio, which is useful in comparing dollar cost to benefits achieved under each alternative. The following is a list of factors considered:

**Environmental:**

Fume release and the increasing possibility of collapse are serious environmental concerns. Violation of EPA regulations could result in heavy fines, imprisonment and work stoppage. Additionally, rebuilding the IVD equipment will allow more workload to be transferred from the existing Cd plating process, which has more environmental concerns than IVD.

**Safety:**

Employees exposed to Cd require Hazard Communication Training and Health Monitoring every 6 months for exposures at or above the action level of 2.5 µg/m<sup>3</sup> of Cd but below the PEL calculated as an 8-hour time weighted average (TWA). Monitoring every three months is required for exposures above the PEL.

**Change Rooms and Washing Facilities:**

The Cd standards include requirements for change rooms, washing facilities, and eating and drinking areas to minimize exposure to Cd.

**Monitoring and Maintenance:**

Monitoring and maintenance of the engineering controls to validate and maintain PELs below the OSHA action level.

**Record Keeping:**

Employers are required to maintain records of worker exposures (including air monitoring data, historical monitoring data and objective data) and medical surveillance records.

Each benefit category was assigned a weighted value from one to 10, with a larger value given to the benefits deemed most important to the Air Force. Scores were based on how well each alternative met each benefit criterion discussed above. Alternatives that do not meet the criteria are given a score of zero percent. Alternatives that provide an optimum solution are given a score of 100 percent. Other alternatives are given a relative score in between. A weighted benefit score is then calculated for each category and totaled for each alternative. The cost-to-benefit ratio is arrived at for each alternative based on the cost of the alternative divided by the benefit score. The alternative with the lower cost benefit ratio is the preferred alternative, as it has the lowest cost per benefit.

**Table 18. Benefit Matrix**

Benefits	Weight Points	Alt 1	Alt 1 Score	Alt 2	Alt 2 Score
Environmental	10	95%	9.50	95%	9.50
Safety	10	95%	9.50	95%	9.50
Change Rooms and Washing Facilities	8	95%	7.60	95%	7.60
Monitoring and Maintenance	7	85%	5.95	90%	6.30
Record Keeping	7	80%	5.60	95%	6.65
<b>Total Score</b>			<b>38.15</b>		<b>39.55</b>
<b>Net Total Cost</b>			<b>\$9,406,467</b>		<b>\$2,105,696</b>
<b>Cost/Benefit Ratio</b>			<b>\$246,565</b>		<b>\$53,241</b>
<p>Scale 100% Optimum Solution 0% Does Not Meet Objectives</p> <p>Weight Points 1 is least important, 10 is most important More than one benefit can have the same weight</p>					

## 8.0 IMPLEMENTATION ISSUES

Implementation of LHE Zn-Ni as a replacement for Cd is close to being a drop-in replacement for a plating process. Requirements for LHE Zn-Ni plating are similar to other electroplating processes and do not require any custom-built equipment for part processing. This technology follows traditional electroplating techniques and uses common commercial-off-the-shelf (COTS) equipment for the plating process. As with other plating process, conforming electroplating anodes may be required for uniform plating distribution.

The LHE Zn-Ni plating line installed at Hill AFB is a full production plating line. Hill AFB has been processing parts through the plating line since its completion in May 2013. The process is very similar to the Cd plating process that Hill AFB has been running for many years. Plating time and the plating amperage required are adjusted to meet the characteristics of the plating solution, and the process has been simplified by adding the conversion coat seal before the baking process instead of afterward as required by Cd. Brush plating technologies using Zn-Ni plating have been approved for use as touch-up in the field rather than only at the depot, as the chemistries are not hazardous as with Cd.

All HSS materials require a corrosion-preventative coating such as Cd or LHE Zn-Ni. Aircraft landing gear is typically designed with HSS so that it has sufficient strength required for aircraft, but also has reduced weight for fuel and space saving on aircraft. Any manufacturer or overhaul facility of aircraft landing gear requires electroplating services for a corrosion preventative electroplate. Many facilities have already installed this process, following the lead of Hill AFB. Additionally, many commercial aircraft manufacturing companies have written specifications governing the processing of their aircraft parts.