



FINAL REPORT

Demonstration and Validation of LHE Zn-Ni Plating Process

ESTCP Project WP-201107

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LIST OF ACRONYMS/ABBREVIATIONS

BR&T	Boeing Research and Technology
CC	Conversion Coated
EDS	Energy Dispersive Spectroscopy
EPA	Environmental Protection Agency
FIB	Focused Ion Beam
HE	Hydrogen Embrittlement
HSS	High Strength Steel
HVOF	High Velocity Oxygen Flame
LHE	Low Hydrogen Embrittlement
Mpy	Mils Per Year
mV	Milivolt
NCC	Non Conversion Coated
NFS	Notch Fracture Strength
OCP	Open Circuit Potential
PEL	Personal Exposure Limits
SCE	Saturated Calomel Electrode
SEM	Scanning Electron Microscope
XRF	X-ray Fluorescence
Zn-Ni	Zinc-Nickel
ZRA	Zero Resistance Ammeter

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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 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 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 good or better than Cd plating in corrosion prevention, resulting from environmental conditions and operational use.

The objectives of the project were met by installation of the full scale plating line at Hill 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 were selected with corrosive environmental conditions, to simulate the most aggressive natural environment that would be experienced at any location worldwide. The selected bases include: McEntire JNG, Barbers Point US Coast Guard, New Orleans 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 LHE 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 USAF drawing 201027456: corrosion (ASTM B117), hydrogen embrittlement (ASTM F519) and adhesion (ASTM B571). Additional studies involving de-zincification, hydrogen re-embrittlement, and LHE Zn-Ni stripping were also conducted. The installation of the 3200-gallon LHE zinc-nickel plating line in bldg. 505 at Hill AFB was successful and the 309 CMXG Production Group is currently LHE Zn-Ni plating landing gear components

De-zincification was studied with Boeing Research & Technology. It was found that accelerated or forced corrosion may start to cause de-zincification, however corrosion rates closer to natural corrosion does not appear to have any impact on de-zincification. 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 salt water immersion test while Cd

failed in less than 1 hour. Inspection of the Cd plated coupon under a microscope suggests that the notch may have not plated thick enough to protect the base material. Additional testing where the thickness of the notch plating is verified before testing is suggested.

Stripping chemicals and procedures were experimented with for removing LHE Zn-Ni plating. Increasing the concentration of ammonium nitrate to 32 oz/gallon 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 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 occur, first at 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 that Cd plating is currently applied to. 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

The installation of the 3200-gallon (Low Hydrogen Embrittlement) LHE zinc-nickel (LHE Zn-Ni) plating line in bldg. 505 at Hill AFB was successful and the 309 CMXG Production Group is currently LHE Zn-Ni plating landing gear components. 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 de-zincification, hydrogen re-embrittlement and stripping LHE Zn-Ni from high strength steel (HSS) components were conducted. Boeing Research & Technology (BR&T) completed the de-zincification study. They found that artificially accelerated corrosion or anodic etching may start to cause de-zincification, however traditional corrosion salt fog testing per ASTM B117, which is a closer representation of actual environment corrosion, does not appear to have any impact on de-zincification. Additional studies are suggested to validate these results.

Hydrogen re-embrittlement testing was performed per ASTM F519. The re-embrittlement test coupons were plated using conformal anodes fixtures for both the LHE Zn-Ni solution and cadmium (Cd) solutions. LHE Zn-Ni passed the salt water immersion test (150 hours without failure) while Cd failed in less than 1 hour. Inspection of the Cd plated coupon under a microscope suggests that the notch may have not plated thick enough to protect the base material.

Stripping chemicals and procedures were experimented with for removing LHE Zn-Ni plating from HSS coupons. Increasing the concentration of ammonium nitrate, which is currently used for stripping Cd, proved to be an acceptable method to remove the LHE Zn-Ni. Further testing is recommended to optimize the stripping process for production environments using higher concentrated ammonium nitrate solution.

1.2 OBJECTIVE OF THE DEMONSTRATION

The main objective of this project was to demonstrate and validate a full-scale prototype LHE alkaline LHE 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. 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 LHE Zn-Ni production plating line. Upon final installation, the prototype LHE Zn-Ni plating line was qualified 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 LHE Zn-Ni and 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. Additional testing included: de-zincification 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.

1.3 REGULATORY DRIVERS

Although the EPA has not established a reference concentration for Cd, it has classified cadmium as a Group B1, probable human carcinogen. Cd is identified as a hazardous substance under RCRA, the Clean Water Act, and the Clean Air Act. OSHA's National Institute for Occupational Safety and Health declared it to be immediately dangerous to life and health in 1996 and the Agency for Toxic Substances Disease Registry completed Cd's toxicity profile in 1999. The OSHA standard PEL is a time-weighted average concentration that must not be exceeded during any 8-hour work shift of a 40-hour workweek. The standard sets a PEL of 5 micrograms of cadmium per cubic meter of air ($5 \mu\text{g}/\text{m}^3$) for all Cd compounds, dust, and fumes.

Executive Order 12586 instructed 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 has instructed Federal Agencies to reduce their purchase and use of hazardous and toxic chemicals.

SECAF Memorandum dated 18 Sept 2007 from Michael Wynne instructs Air Force to comply immediately with Executive Order 13423 and it's implementing instructions.

Executive Order 13514 has instructed Federal Agencies to reduce their purchase and use of hazardous and toxic chemicals. It further 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. The Aerospace industry has not been granted any exemptions for use of Cd. Cd will continue to be listed with REACH and further efforts to reduce its use are called for.

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 landing gear 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) LHE 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. The plating bath if properly maintained has an indefinite life.

2.2 TECHNOLOGY DEVELOPEMENT

A chronological sequence of the development of the process is shown as follows:

- 1990 Automotive industry begins using LHE Zn-Ni plating for corrosion protection in lieu of galvanizing. Application restricted to low strength steel (<180 ksi).
- 1996 – 2000 WPAFB – ASC/ENVV
 - Evaluated IZ-260 In use at DoD Plating Facilities
 - Required Nickel Strike to be Non-Embrittling for HSS
- 2003-2005 C-17 Pollution Prevention
 - Developed IZ-C17 Alkaline LHE Zn-Ni for HSS
 - No Ni Strike and Non-Embrittling to High Strength Steels (HSS)
- 2002-2005 Boeing C-17 Program conducted initial evaluation of LHE Zn-Ni on HSS aircraft components.
- 2006-2007 C-17 Pollution Prevention
 - Conducted Qualification Tests for IZ-C17 LHE Zn-Ni
- 2007-2008 Boeing and ES3 conducted Phase I SBIR project to conduct preliminary qualification testing of LHE Zn-Ni coating on HSS components.
 - Evaluated IZ-C17 + LHE Zn-Ni Better Tank Life Than IZ-C17Also Compared TriCr CC with Hex Cr CC
- 2008-2010 Boeing and ES3 conducted Phase II SBIR project to perform qualification testing of LHE Zn-Ni coating on HSS components.
 - Installed Plating Tank with IZ-C17 +Zinc-Nickel at Hill AFBAlso installed IZ-264 Tri-Cr CC

- 2008-2010 ES3 – SBIR – Phase II
- 2009 ES3 Warner Robins – SBIR – Phase I
 - IZ-C17+LHE Zn-Ni Fasteners Feasibility Study
- 2011 LHE Zn-Ni process approved for use by OO-ALC/GHMW, (Landing Gear Product Group Manager).

Once successfully demonstrated the LHE Zn-Ni coating will be used on all Air Force HSS aircraft landing gear components. Other aircraft components currently plated with Cd, such as fasteners and bushings will also transition to LHE Zn-Ni. Other DoD services are closely watching the results of the Air Force study and may participate in the program as well.

Several phased studies have been conducted on the LHE Zn-Ni technology in advance of the joint ESTCP/P2 project. A Phase I Small Business Innovative Research (SBIR) study was conducted by ES3 in 2007-2008 to determine the hydrogen embrittlement, fatigue, and corrosion performance of an alkaline LHE Zn-Ni on HSS, and compare it to a Cd baseline. The results of the Phase I SBIR (ENGINEERING REPORT ER-9033-08-01) indicated that the alkaline LHE Zn-Ni performed very well and led to the award of a Phase II SBIR in 2008 to further investigate the LHE Zn-Ni coating.

Part of the technical objectives for the Phase II SBIR included the installation of a prototype LHE Zn-Ni tank. This tank was used to demonstrate plating full size landing gear components as well as test coupons for the qualification of the LHE Zn-Ni coating for use on HSS landing gear components. Approval of the LHE Zn-Ni coating was determined by passing the following qualification tests:

- Adhesion (ASTM B571).
- Hydrogen Embrittlement (ASTM F519).
- Re-embrittlement (ASTM F519 and USAF DWG 9825019).
- Liquid and Solid Metal Embrittlement (ASTM F519).
- Fatigue (ASTM E466).
- Corrosion (ASTM B117).
- SO₂ Corrosion (ASTM G 85).
- Brush Plating for repair of damaged LHE Zn-Ni coatings (ASTM B117, ASTM B571, and ASTM F519).

The Phase II study was successfully completed in December 2010. Test results indicate LHE Zn-Ni performed as well or better than Cd for most tests conducted. A final report with the details of the Phase II study was published by Engineering & Software Solutions Inc. (Engineering Report 2008007-01 Contract #FA8201-08-C-0054 Low Hydrogen Embrittlement (LHE) Zinc-Nickel SBIR Phase II 14 December 2010).

2.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

The LHE Zn-Ni process is a more environmentally acceptable alternative that has excellent corrosion resistance that meets or exceeds that of Cd plating. It can be used on

all components that Cd plating is currently applied to. Since Cd is a known human carcinogen the reduction or elimination at depot facilities nationwide is of great interest throughout DoD. There is also benefit to each squadron facility in the elimination of the potential for Cd to leach into soils and groundwater during aircraft maintenance wash-downs. In the maintenance lifecycle Cd also 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 practicable. However, it has several significant disadvantages including high maintenance costs and part size limitations. Hence, 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 Cd plates nearly 10,000 primary parts per year. This does not include thousands of bushings, fasteners and small components.

3.0 PERFORMANCE OBJECTIVES

Performance objectives were split into two groups to be evaluated, qualitative and quantitative. Quantitative objectives were separated into either tank qualification objectives or performance testing. Tank qualification objectives include: corrosion testing, hydrogen embrittlement testing, plating uniformity, plating adhesion, finish quality, and adhesion. Performance testing objectives are: FSE and the impact to production time. Qualitative performance objectives include: reduction of hazardous waste and ease of use. Performance objectives for the study are summarized below in Table 2.

Tank qualification testing performance objectives were evaluated IAW USAF DWG 201027456. Corrosion testing was considered successful if test subjects were able to sustain 96 hours after testing without any visible white corrosion products. Hydrogen embrittlement tests subjects had to sustain a 200 hour pull test at 75% notch fracture strength. Details of hydrogen embrittlement tests are outlined in USAF DWG 20102746 and ASTM F-519. Plating composition is to be determined by X-ray Fluorescence and shall be within the range of nickel and zinc percentages required by the chemistry being used (USAF DWG 20102746).

Plating thickness must fall within a range of 0.3-0.5 mils and shall be determined IAW USAF DWG 20102746. Plating adhesion tests must pass the 90-180 degree bend test. Coupons are bent and examined under magnification for lifting, crazing, and flaking. A visual inspection is conducted after the plating process to determine finish quality. The plating shall be smooth, continuous, adherent to the basis metal, and visually free from porosity, blisters, pits and other imperfections.

LHE Zn-Ni plated components were installed on aircraft to undergo FSE. Components were visually inspected for corrosion products over a two year period. FSE subjects are considered to pass if the inspector determines corrosion products, if any, are negligible. Reduction of hazardous chemicals and waste were monitored over the course of the project. If LHE Zn-Ni plating uses fewer hazardous chemicals and generates less hazardous waste than Cd plating, a reduction in hazardous waste is considered a success and passes criteria for the performance objective.

Table 2: Performance Objectives

Performance Objective	Data Requirements	Success Criteria	Results
Quantitative Performance Objectives			
<u>Tank Qualification Testing</u>			
Corrosion Testing	USAF DWG 201027456	Sustain 96 hours with no white corrosion products	Passed
Hydrogen Embrittlement Testing	USAF DWG 201027456	Sustain 200 hour pull test at 75% NFS	Passed
Plating Uniformity	USAF DWG 201027456	plating within 0.3-0.5mil range	Passed
Plating Adhesion	USAF DWG 201027456	Pass 90-180 deg bend test	Passed
Finish Quality	USAF DWG 201027456	Pass visual examination	Passed
Composition	USAF DWG 201027456	NDI X-Ray Fluorescence	Passed
Tank Chemical Analysis	USAF DWG 201027456	Bath chemistry aging	Passed
<u>Performance Testing</u>			
Field Service Evaluation	Visual inspection for corrosion products conducted by PI and ES3	Negligible corrosion products observed	Passed - 1 year evaluation
Impact to Production Time	Tracking of production time in demonstration	Minimal increase versus total cadmium process time	Passed
Qualitative Performance Objectives			
Reduction of hazardous waste generated (cadmium, cyanide, Hexavalent Chromium)	Raw materials usage	Reduction of future disposal of hazardous materials/exposure to personnel	Passed
Ease of Use	Feedback from field technician on usability of technology and time required during demonstration	Minimal training required/field plating repair	Unevaluated – No field repair has been required

4.0 SITES/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 Field Service Evaluation (FSE) following a Performance Tracking Program (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.

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 (plated portions in blue) and can be seen in Figures 1-4 below.

- F-16 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

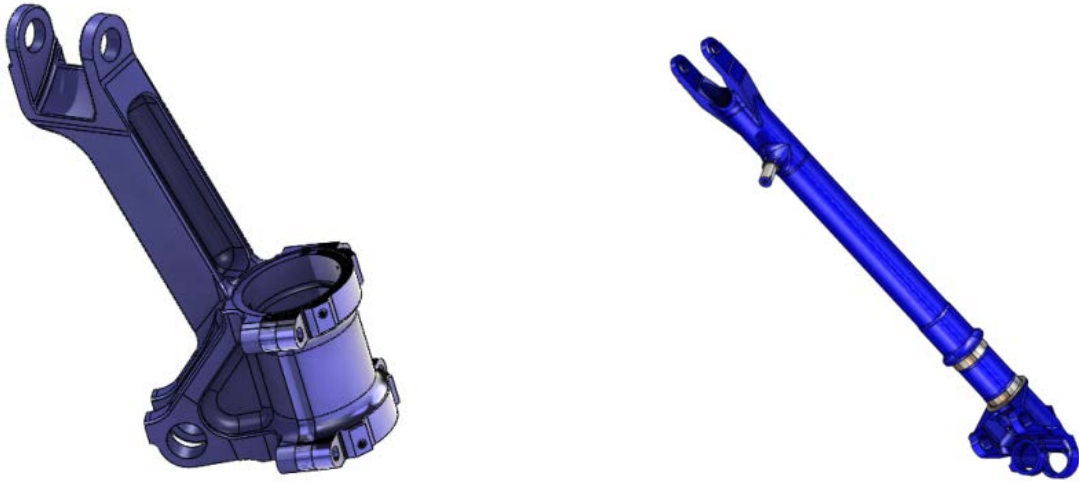


Figure 1: F-16 MLG Collar Assembly (Left) and F-16 MLG Tension Strut (Right)

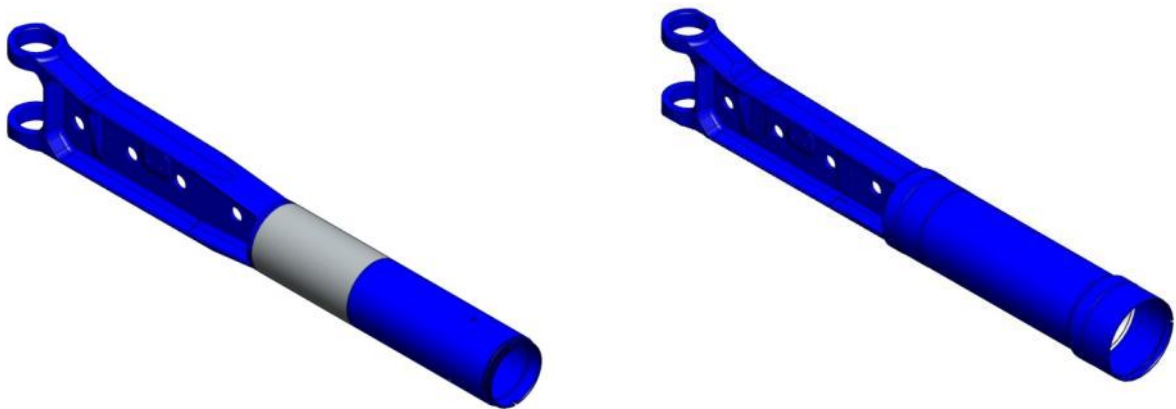


Figure 2: C-130 AFT Torque Strut (Left) and C-130 FWD Torque Strut (Right)

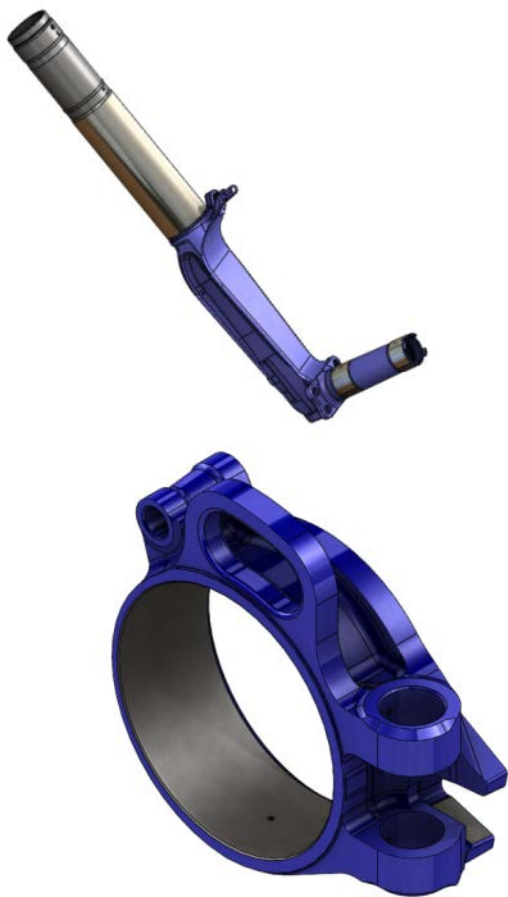


Figure 3: F-15 MLG Piston (Top) and F-15 MLG Collar (Bottom)



Figure 4: KC-135 Brake Equalizer Rod

These components were selected because they are relatively easy to plate, accessible on aircraft for inspections, and they sustain more damage to their protective coatings due to high take off and landing speeds, location and/or large cross sectional areas. There is excellent existing infrastructure for installing the prototype line at Hill along with significant stakeholder buy-in for the project.

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 ANG (F-15), and Hickam AFB (KC-135). These bases were selected to simulate closely the most aggressive environment that would be experienced at any location worldwide. Upon completion of the FSE, components were inspected and left on aircraft until removed for cause or sent in for depot overhaul. A successful test showed protection at least equivalent to that provided by Cd plating. A LHE Zn-Ni Performance Tracking Plan (PTP) was developed for each component and was coordinated and signed off by participating field unit(s), System Program Office(s) and OO-ALC/GHMWE before the FSE is conducted.

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. Balls of pure Cd metal are used as cathodes in the electroplating process. 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 of 2011. State approval for the air permit modification was given 28 June 2011.

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

5.0 TEST DESIGN

5.1 PLATING LINE INSTALLATION

The 309th CMXG identified an area in their overhaul facility in which the prototype full-scale production tank could be installed. Site preparation for installation included 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.

Making space available for the new plating tanks required removal of a large industrial oven (Figure 5), removal of the current chiller, and four tanks from the current Cd line were relocated to the area where the industrial oven was removed.



Figure 5: Industrial Oven Removal

Modification and removal of a section of the overhead trolley hoist system was required for both the ovens and the plating line to allow for a monorail hoist system (Figure 6).



Figure 6: Overhead Trolley Removal

5.1.2 SITE PREPARATION FOR RELOCATION AND INSTALLATION

Upon completion of the demolition and removal of the equipment, a survey of the structural members was completed and structural calculations were performed to determine any additional support structure required for the tank installation and overhead monorail. It was found that 14 footings were required to be re-established to ensure structural integrity of the plating line and monorail (Figure 7). Additional structural steel was required to raise the tanks to working level above floor.



Figure 7: Footing and Structure Re-Establishment

The overhead trolley support structure was modified to accommodate the monorail in accordance with the structural calculations. The monorail was installed.

A containment barrier was added in the basement of the building (Figure 8) to prevent the possibility of any acid leaks from mixing with any Cd waste water or leaks from the Cd plating line (mixture of acid solutions with Cd plating solutions will release cyanide gas which is very poisonous and dangerous to plating personnel).



Figure 8: Containment Barrier

5.1.3 IRIDITE TANK LINE RELOCATION

For waste stream containment purposes, the iridite tank line was relocated to the vacated oven space. Four tanks including all piping, electrical, and exhaust were moved to the newly established structure where the industrial oven had been removed (Figure 9).



Figure 9: Iridite Tank Line Relocation

5.1.4 PROTOTYPE LHE ZN-NI PLATING LINE INSTALLATION

The prototype LHE Zn-Ni plating line was installed at Hill AFB's overhaul facility located in bldg. 505 (Figure 10-Figure 12). The tanks were set in place and then all of the electrical, plumbing and air handling was installed along with the auxiliary equipment including pumps, filters, chiller, rectifiers and Carbolux. The auxiliary equipment is located below the tanks on an equipment platform. The tanks were filled with water after installation to verify no leaks were present. All equipment was turned on and verified operation for the system.



Figure 10: Prototype LHE Zn-Ni Plating Line Tank Installation



Figure 11: Auxiliary Equipment



Figure 12: Installed Prototype LHE Zn-Ni Plating Line

During all phases of demolition and installation, air quality was monitored for hazardous contaminants that may be liberated from construction activities. Four locations at the

work area had continuous sampling pumps, which were checked and tested periodically for Cd, chromium, lead, and asbestos that may have been liberated during construction phases. All samples taken were less than 1/5th of the PEL defined by OSHA. No additional clean up was required.

After successful demonstration of equipment operation and verification of no fluid leaks, the tanks were leached and prepared for chemical makeup. Following the Dipsol Technical Bulletin for LHE Zn-Ni the plating solution and conversion coat solution were mixed and chemical testing conducted to verify correct solution composition (Figure 13).



Figure 13: LHE Zn-Ni Plating

5.1.5 PROTOTYPE LHE ZN-NI PLATING LINE QUALIFICATION

REQUIREMENTS

Prior to operating the prototype LHE Zn-Ni plating line for full-scale production all qualification testing was completed. 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

5.1.6 ADDITIONAL TESTING

Additional testing of characteristics of the LHE Zn-Ni coating were researched and tested for de-zincification 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 DE-ZINCIFICATION CORROSION TESTING

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

BR&T- St. Louis, under the direction of Steve Gaydos, conducted the testing for the de-zincification studies. The following steps were conducted in order to determine if de-zincification occurs on LHE Zn-Ni plated steel test specimens:

- Procure or manufacture steel test coupons
- Plate test coupons per USAF drawing 201027456 using Dipsol IZ-C17+ LHE Zn-Ni
- 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 by various chemical surface analysis techniques (such as XRF, Auger, etc.)
- Corrode coupons via exposure in a salt fog chamber per ASTM B117 and electrochemically anodic polarization in a salt water 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 analyzing the composition of the LHE Zn-Ni plating by various chemical surface analysis techniques (such as XRF, Auger, etc).
- Continue exposure of LHE Zn-Ni plated test coupons to the corrosion environments and analyze the LHE Zn-Ni plating until effects of de-zincification are fully understood.
- Evaluate data and prepare a final report with recommendations for follow-on field tests

5.2.1 PREPARATION OF LHE ZN-NI TEST SPECIMENS

ES3 applied Dipsol IZ-C17+ LHE Zn-Ni plating in accordance with AF drawing 201027456 to 24 ea. 4130 steel test panels that were 4x6x0.040 inch. 12 of the test panels were conversion coated with Dipsol IZ-264 tri-Cr conversion coating and all of the plated test specimens were baked at 375°F for 24 hours and then shipped to BR&T – St. Louis for de-zincification testing.

5.2.2 DE-ZINCIFICATION TESTING CORROSION ENVIRONMENTS

8 of the test panels (4 conversion coated and 4 non-conversion coated) were placed in the following corrosion environments (see Note below for panel preparation):

- 1 conversion coated and 1 non-conversion coated LHE Zn-Ni test panel in an ASTM B 117 salt spray chamber for 4 weeks.
- 1 conversion coated and 1 non-conversion coated LHE Zn-Ni test panel in an ASTM G 85 SO₂ salt spray chamber for 1 week.
- 2 conversion coated and 2 non-conversion coated LHE Zn-Ni test panels in a 5% NaCl solution and adjust the anodic potential of the exposed test areas to produce a 10 mpy corrosion rate on the conversion coated test panels and 100 mpy corrosion rate on the non-conversion coated test panels.
- **NOTE:** Masking tape was applied to protect an area next to the corrosion area so that the masking could be removed later and the surface analyzed to compare corroded and non-corroded areas.

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, dried and then the following tests were conducted:

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

5.2.3 GALVANIC CORROSION AND LHE ZN-NI THROWING POWER

Two LHE Zn-Ni test panels (one conversion coated and one non-conversion coated), and one Cd control test panel were prepared as shown in Figure 14 below.

Test panels were placed in ASTM B 117 salt spray for sufficient period of time to determine if de-zincification is causing changes in sacrificial protection of LHE Zn-Ni on steel.

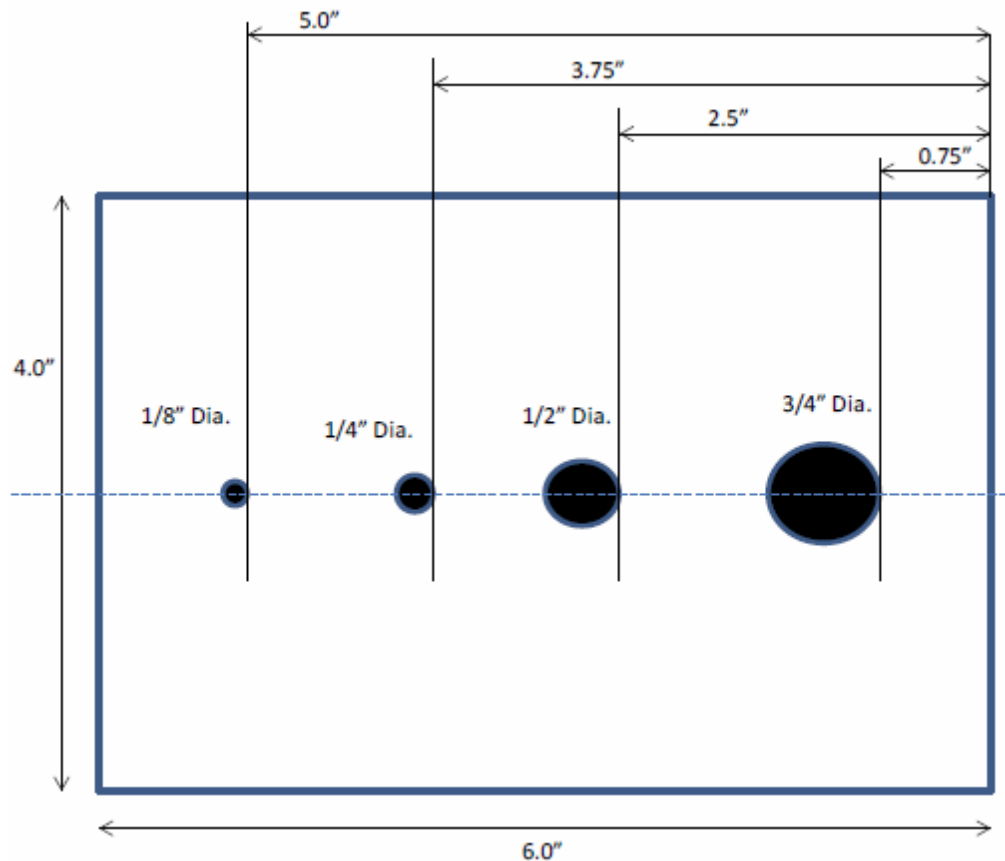


Figure 14: Galvanic Corrosion Test Panel (LHE Zn-Ni Removed in 4 Locations)

5.3 RESEARCH EVALUATE AND TEST RE-EMBRITTLEMENT PROTOCOLS

5.3.1 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. LHE Zn-Ni uses fixturing to ensure uniform plating thickness across the coupon. Cd has better throwing power during plating and does not require fixturing. Previous results have show that using fixturing with LHE Zn-Ni allows the coupon to pass ASTM F519F immersion test in 3.5% NaCl water solution where Cd could not pass this same test.

5.4 RESEARCH AND OPTIMIZATION OF LHE ZN-NI STRIPPING

PROCEDURES

Currently Hill AFB 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 oz/gal at a pH of 7. The stripping process takes approximately 75 minutes from start to finish, which includes part degreasing, rinsing, ammonium nitrate stripping (15 minutes), sodium hydroxide solution, 20% phosphoric acid solution and rust stripping. LHE Zn-Ni can also be removed using the same concentration of ammonium nitrate however, the time that is required for stripping the LHE Zn-Ni coating is increased significantly. Optimization of the ammonium nitrate concentration or other controls in the stripping solution may prove effective in reducing the stripping time to a reasonable time.

5.5 PERFORMANCE TRACKING PROGRAM

The Low Hydrogen Embrittlement Zinc-Nickel (LHE Zn-Ni) Performance Tracking Program (PTP) validated the application of LHE Zn-Ni on landing gear components in an effort to replace cadmium as a sacrificial protective coating. LHE Zn-Ni has been evaluated, tested and approved as a replacement for cadmium. Testing has shown that LHE Zn-Ni performs as good as or better than cadmium in corrosive environments. Subject aircraft had two LHE Zn-Ni plated components installed and an 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.

The selected location for the F-15 performance tracking is the 159th Fighter Wing Louisiana ANG. This location encompasses a corrosive climate and operational mission conditions representative of the USAF fleet ensuring reliability/accuracy of the PTP data. Subject aircraft participating in this effort were tracked for a two year period starting when the LHE Zn-Ni plated components were installed on the aircraft. This PTP monitored reliability and durability of the LHE Zn-Ni plating to ensure it met or exceeded design criteria. This PTP was managed and coordinated by AFMC 417 SCMS/GUEA.

5.5.1 PERFORMANCE TRACKING PROGRAM BACKGROUND

Cd plating is used as a sacrificial protective coating on high strength steel (HSS) landing gear alloys to prevent corrosion. The non-stainless HSS alloys (300M, 4340, 4330, etc.)

used in landing gear applications readily corrode if exposed to the environment without a sacrificial coating such as Cd, IVD aluminum, or LHE Zn-Ni. Therefore it is a design requirement that steel alloys used in landing gear be protected from corrosion attack via a sacrificial coating. Cd plating has been the choice for decades; however, it has known health concerns and is being banned from use in the aerospace industry. The EPA has identified cadmium as a particularly hazardous material.

Cd is an inherently toxic heavy metal poison that is quite easily leached, and therefore poses environmental and health problems throughout its life cycle. Not only does Cd pose environmental safety and health issues in the plating plant, but it can be leached (i.e. in aircraft landing gear wash-downs), and contaminate ground water simply by being exposed to cleaning solutions during normal service.

5.5.2 PERFORMANCE TRACKING PROGRAM OBJECTIVE

Demonstrate that LHE Zn-Ni plating performs as good 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 salt water environments.

Tracking Procedure:

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

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

In order to capture a “Zero Time” component comparison, the LHE Zn-Ni components (Table 3) and corresponding cadmium components were assembled into full MLG strut assemblies (Table 4). Having full assemblies installed helped in reducing FMC time at the 159th Fighter Wing. On aircraft locations of the LHE Zn-Ni components are shown in Figure 15.

Table 3: LHE Zn-Ni Components

Components	P/N	NSN
RH MLG Collar	68A410733-2002	1620-00-338-6559
RH MLG Piston	68A410704-1012	1620-01-080-3407

Table 4: MLG Strut Assemblies

Components	P/N	NSN
RH MLG Strut Assy	68A410501-1010	1620-01-448-4335LE
LH MLG Strut Assy	68A410501-1009	1620-01-448-1424LE



Figure 15: F-15 MLG Components

Visual inspection of the aircraft component occurred on a yearly basis to identify any corrosion or corrosion products. Struts did not need to be disassembled to inspect the LHE Zn-Ni components. The components were installed on Aircraft #82048. The following data was recorded and reported to the 417 SCMS/GUEA:

- Tail Number
- Component Noun
- Position of the component
- S/N of component
- Date of Installation

- Notes on state of the component

The 159th Fighter Wing created an IMDS inspection to track yearly compliancy.

LHE Zn-Ni plated components were marked PTPZ with a black stamp. Cd plated components were marked PTPC using a black stamp. The markings can be placed on the components prior to or after installation. During the PTP, corrosion or corrosion products and damages were recorded on the data sheet.

Evaluation Criteria:

- Corrosion or corrosion products identified during visual inspection.

5.6 FIELD CORROSION BACKGROUND

Low Hydrogen Embrittlement (LHE) zinc-nickel (LHE Zn-Ni) has been qualified as a replacement for cadmium (Cd) coatings on High Strength Steel (HSS) aircraft landing gear components to prevent corrosion. Hot, humid, salt-water environments are known to cause corrosion on HSS landing gear components, therefore corrosion from natural oceanic environments is a potential threat to metal plated HSS components. Qualification testing was accomplished via ASTM B-117, salt fog chamber corrosion testing. ASTM B-117 provides a controlled environment to produce relative corrosion resistance information for metal specimen and coated metal specimen exposed to the salt fog chamber.

5.6.1 FIELD CORROSION OBJECTIVE

Three atmospheric site corrosion test facilities were identified as appropriate test sites for long term aerospace corrosion testing: NASA Corrosion Technology Laboratory in Florida, Whidbey Island in Washington state, and El Segundo California. These three locations are exposed to oceanic coastal 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. Components were plated at Hill AFB Building 505 309 CMXG/EN. Cd test components were plated IAW MIL-STD-870. LHE Zn-Ni test components were plated IAW USAF-DWG-20102746.

Two C-5 rotational collars were plated with Cd or LHE Zn-Ni. Four F-15 lower drag bases were plated with either Cd or LHE Zn-Ni. 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 PLATING LINE INSTALLATION

6.1.1 PROTOTYPE LHE ZN-NI PLATING LINE QUALIFICATION

Prior to operating the prototype LHE Zn-Ni plating line for full-scale production all qualification testing was completed. 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 hrs in salt fog with no white corrosion products

All testing performed was shown to be in compliance with the requirements of the ASTM specifications.



Figure 16: Hydrogen Embrittlement



Figure 17: Plating Adhesion

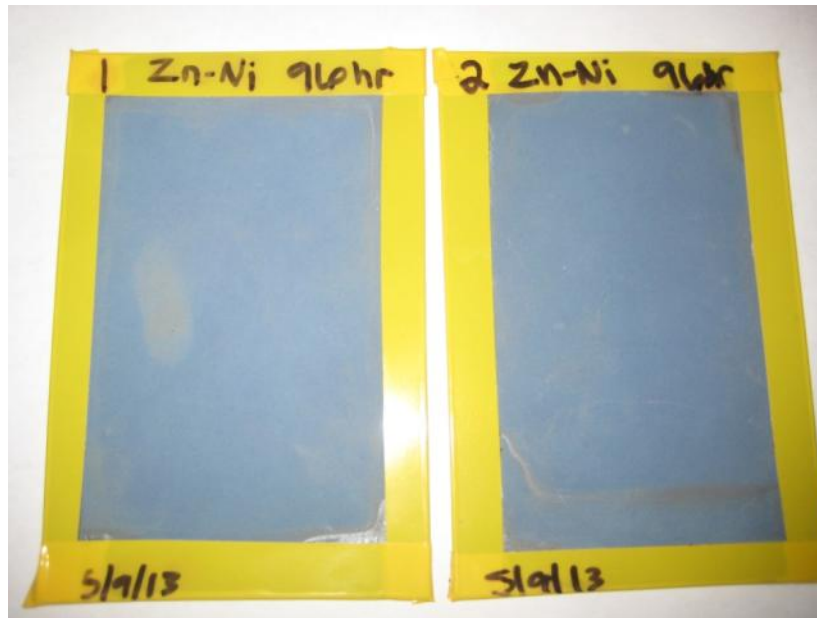


Figure 18: Corrosion Testing

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

- Tank Chemical Analysis – Dipsol verified tank solution makeup with lab analysis shown in Table 5.
- Plating Uniformity – Dipsol used XRF to measure thickness on a plated panel - Thickness 12-14 microns (0.47-0.55 mil)
- Composition – Dipsol used XRF 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 5 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
Cu (ppm)	< 1	< 1
Fe (ppm)	< 100	< 1
Co (ppm)	N/A	0
Total Cr (ppm)	<5	1.54
Na ₂ CO ₃ (g/L)	0-60	35.3



Figure 19: Finish Quality

6.1.2 DE-ZINCIFICATION CORROSION TESTING

6.1.2.1 XRF ANALYSIS OF LHE ZN-NI TEST SPECIMENS

2 each – 4x6x0.040 LHE Zn-Ni test specimens were sent to Dipsol of America (Livonia, MI) for XRF analysis to determine the concentration (in Wt. % of Zn and Ni) and thickness. The two LHE Zn-Ni test specimens were labeled NCC-2 (NCC = no conversion coating) and CC-2 (CC = conversion coated).

For each test panel, 11 locations were X-ray Fluorescence (XRF) analyzed on the front and back side as shown in Figure 20 and Figure 21. The XRF analysis data is shown in Table 6. The averages from the XRF analysis for zinc and nickel weight % and thickness (mils) are shown in Table 7. Composition is about 84.5% zinc and 15.5% Ni and XRF thickness averages to be 0.4 mils.

The plated test panels are representative of the LHE Zn-Ni plating operation outlined in USAF Drawing 201027456.

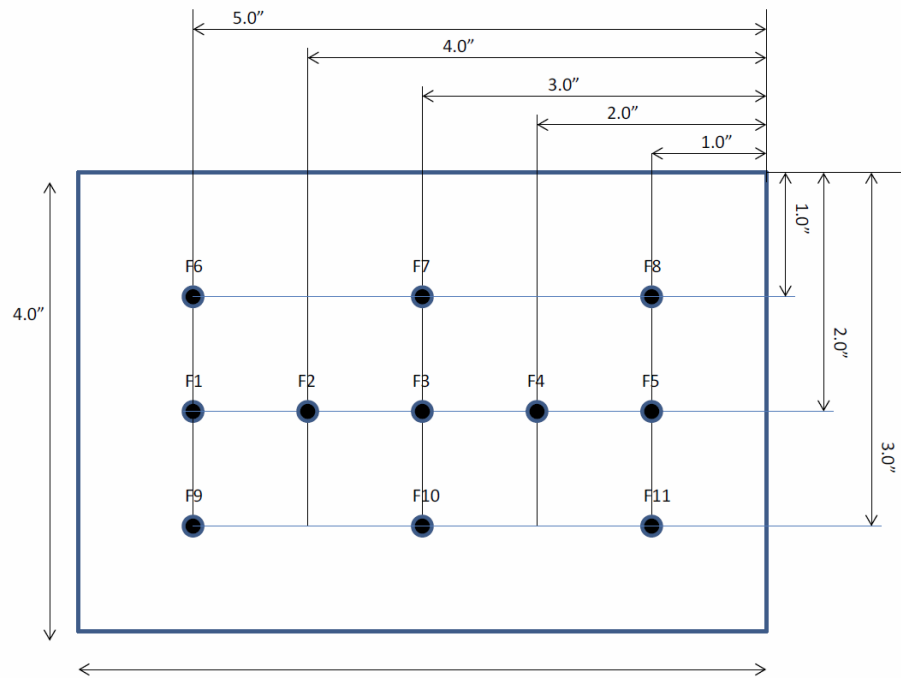


Figure 20: LHE Zn-Ni Test Panel - Showing Locations for XRF Analysis (Front)

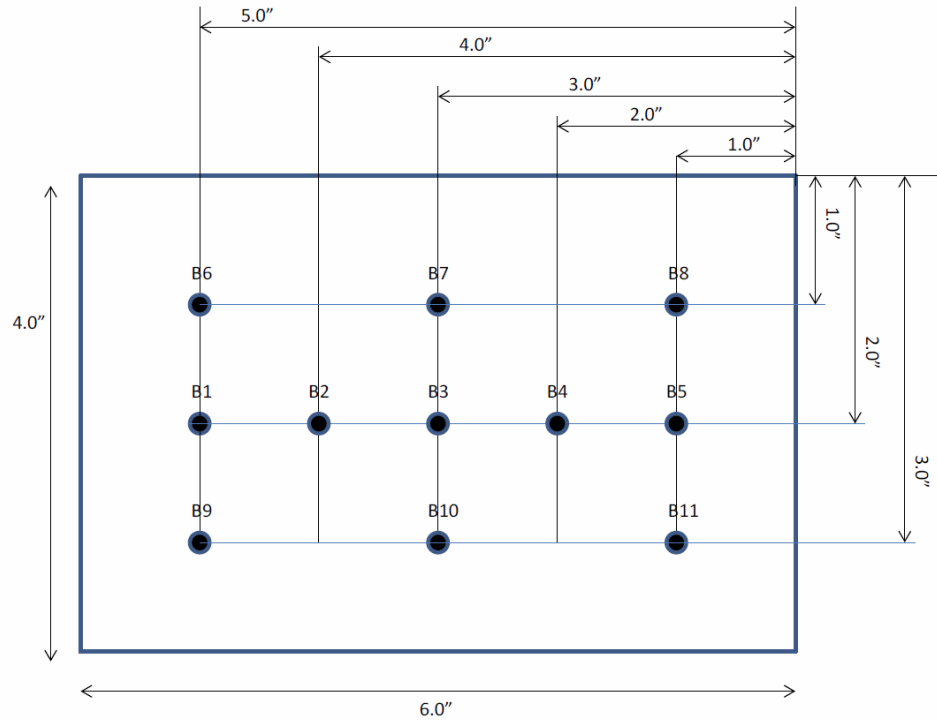


Figure 21: LHE Zn-Ni Test Panel - Showing Locations for XRF Analysis (Back)

Table 6: XRF Analysis Data

XRF Analysis				
Test Panel ID	Test Area	Thickness (mils)	Zn %	Ni %
NCC-2	F1	0.51	84.29	15.71
NCC-2	F2	0.42	84.40	15.60
NCC-2	F3	0.38	84.73	15.27
NCC-2	F4	0.36	84.78	15.22
NCC2	F5	0.32	84.27	15.73
NCC-2	F6	0.48	84.62	15.38
NCC-2	F7	0.34	84.34	15.66
NCC-2	F8	0.27	84.01	15.99
NCC-2	F9	0.59	83.97	16.03
NCC-2	F10	0.50	84.68	15.32
NCC-2	F11	0.44	84.62	15.38
NCC-2	B1	0.41	84.95	15.05

NCC-2	B2	0.41	84.59	15.41
NCC-2	B3	0.43	84.83	15.17
NCC-2	B4	0.46	84.78	15.22
NCC-2	B5	0.53	84.32	15.68
NCC-2	B6	0.39	84.74	15.26
NCC-2	B7	0.39	84.72	15.28
NCC-2	B8	0.52	84.72	15.28
NCC-2	B9	0.49	84.41	15.59
NCC-2	B10	0.51	84.36	15.64
NCC-2	B11	0.61	84.27	15.73
CC-2	F1	0.50	84.35	15.65
CC-2	F2	0.39	84.37	15.63
CC-2	F3	0.35	84.66	15.34
CC-2	F4	0.31	84.40	15.60
CC-2	F5	0.27	84.34	15.66
CC-2	F6	0.48	84.87	15.13
CC-2	F7	0.34	84.48	15.52
CC-2	F8	0.26	84.08	15.92
CC-2	F9	0.53	84.50	15.50
CC-2	F10	0.40	84.91	15.09
CC-2	F11	0.29	83.89	16.11
CC-2	B1	0.39	84.69	15.31
CC-2	B2	0.39	84.46	15.54
CC-2	B3	0.43	84.38	15.62
CC-2	B4	0.46	84.41	15.59
CC-2	B5	0.53	84.44	15.56
CC-2	B6	0.42	84.71	15.29
CC-2	B7	0.44	84.18	15.82
CC-2	B8	0.57	85.03	14.97
CC-2	B9	0.43	84.51	15.49
CC-2	B10	0.47	84.67	15.33
CC-2	B11	0.59	84.60	15.40

Table 7: 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

6.1.2.2 OPEN CIRCUIT POTENTIAL (OCP)

One each of the conversion coated and non-conversion coated test panels were used measure OCP vs. SCE (Saturated Calomel Electrode) in 5% NaCl solution. Periodic monitoring of the OCP for 1 to 7 days obtained a steady state value for the OPC of -740 to -780 mV vs SCE. This range is an acceptable value for LHE Zn-Ni with 15% Ni content. Bare 4130 steel was also measured to verify that LHE Zn-Ni plating OCP is anodic to steel OCP.

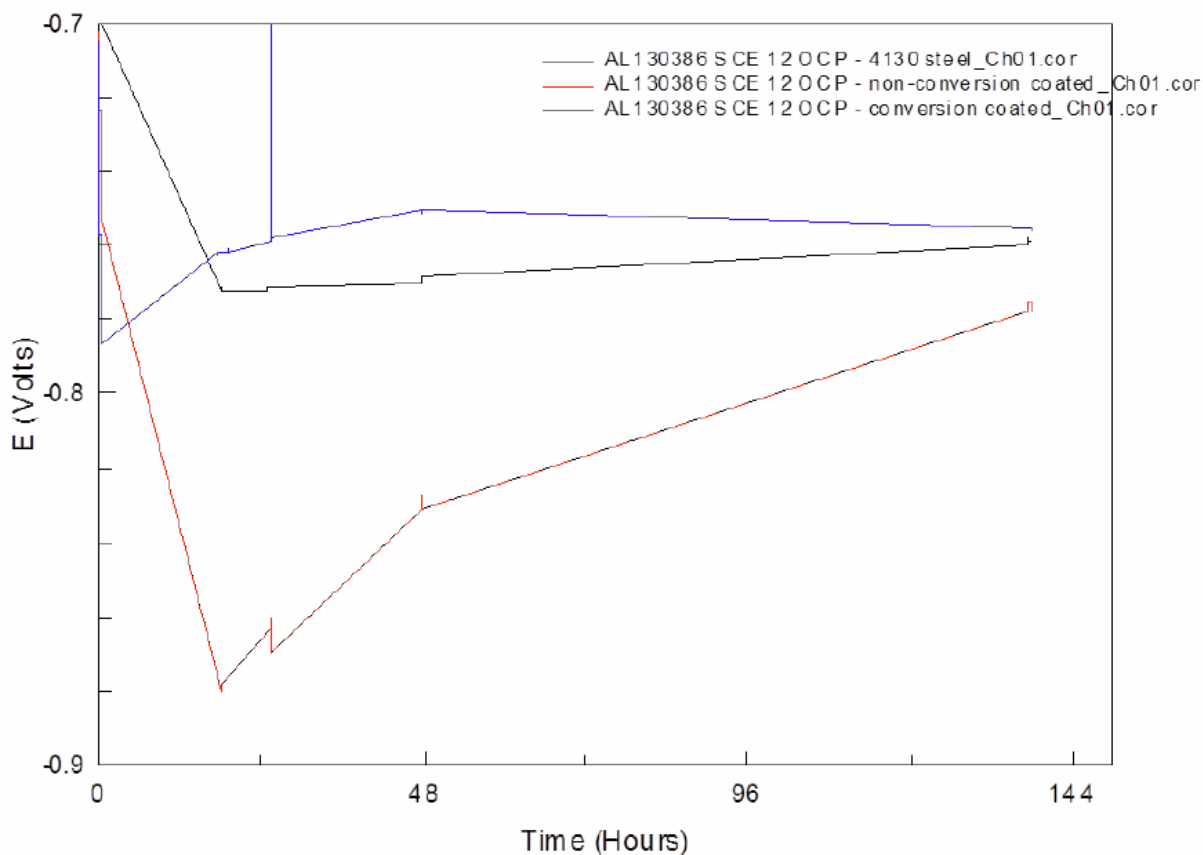


Figure 22: OCP for Steel (Blue - Top Line), CC LHE Zn-Ni (Black - Middle Line) and NCC LHE Zn-Ni (Red - Bottom Line)

6.1.2.3 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. The polarization curve was used to determine the anodic potential and current density to produce a corrosion rate of 10 mpy (mils per year) for the conversion coated test materials and 100 mpy for the non-conversion coated test materials. The potentiodynamic scans of the LHE Zn-Ni with conversion coating and with no conversion coating are shown in Figure 23.

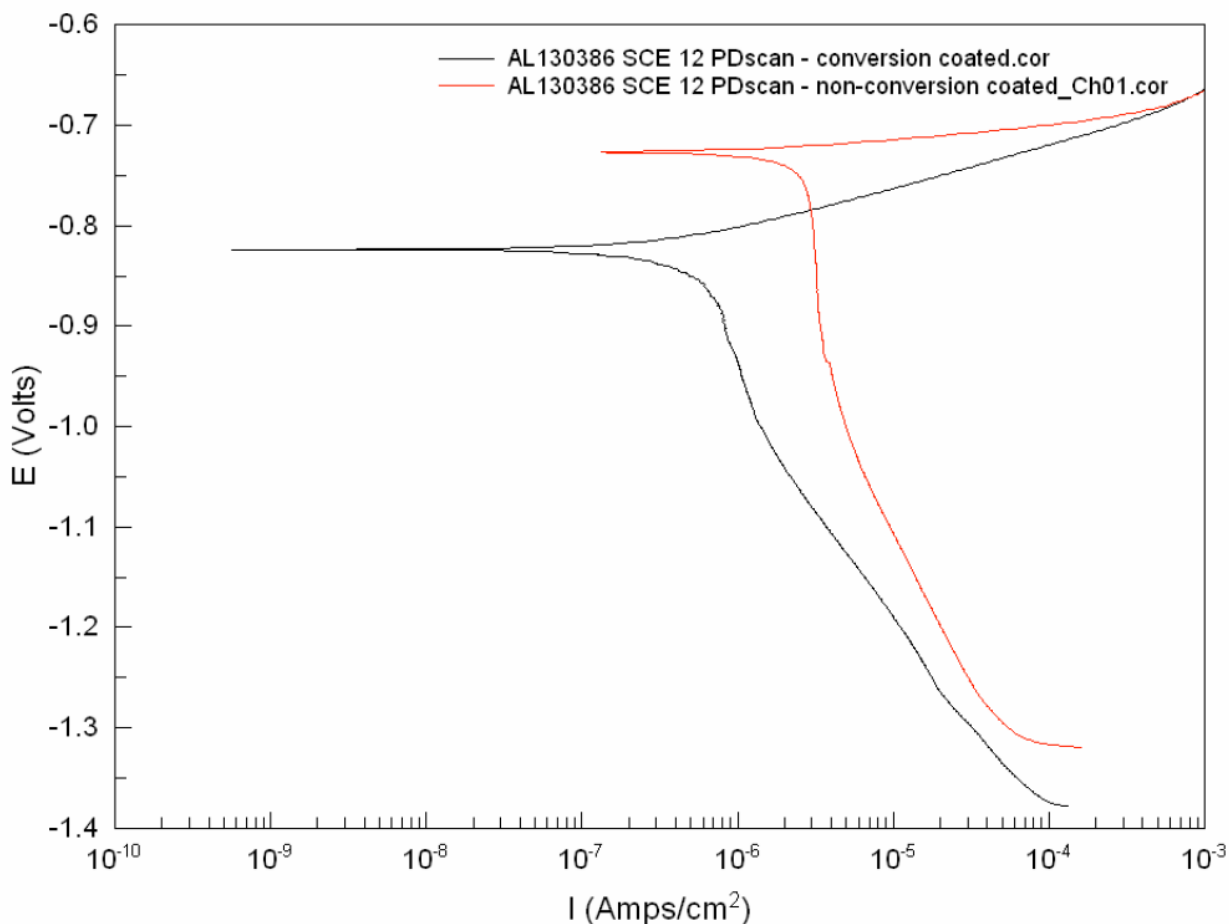


Figure 23: Potentiodynamic Scans of LHE Zn-Ni – CC (Black) and NCC (Red)

The potentiodynamic scan for the conversion coated LHE Zn-Ni showed that by applying an anodic potential to create a current density of 2×10^{-5} A/cm² represents a corrosion rate of 10 mpy. The non-conversion coated LHE Zn-Ni scan showed that by applying an anodic potential to create a current density of 2×10^{-4} A/cm² represents a corrosion rate of 100 mpy. These current densities were used in to artificially corrode LHE Zn-Ni test specimens and determine if de-zincification occurred.

6.1.2.4 DE-ZINCIFICATION AFTER SALT SPRAY CORROSION

Four LHE 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, with long side (6 inch) at bottom and masked side facing salt spray. CC-3 and NO-CC-3 were removed from the salt spray cabinet after four weeks exposure.

CC-4 and NO-CC-4 were placed in an ASTM G 85 SO₂ salt spray cabinet, with long side (6 inch) at bottom and masked side facing salt spray. CC-4 and NO-CC-4 were removed from the salt spray cabinet after one week of exposure.

Figure 24 shows pictures of NO-CC-3 and CC-3 after 4 weeks salt spray exposure. The maskant on NO-CC-3 had some leakage and the no corrosion area was very small but of sufficient size to perform XRF chemical analysis of the un-corroded LHE Zn-Ni plating. CC-4 and NO-CC-4 were severely corroded after one week in the ASTM G 85 SO₂ salt spray (see Figure 25) and XRF analyses could not be performed on the corroded side of these test panels.



Figure 24: Corroded and Un-corroded areas of LHE Zn-Ni Panes CC-3 (bottom) and NCC-3 (top) after 4 Weeks in ASTM B117 Salt Spray

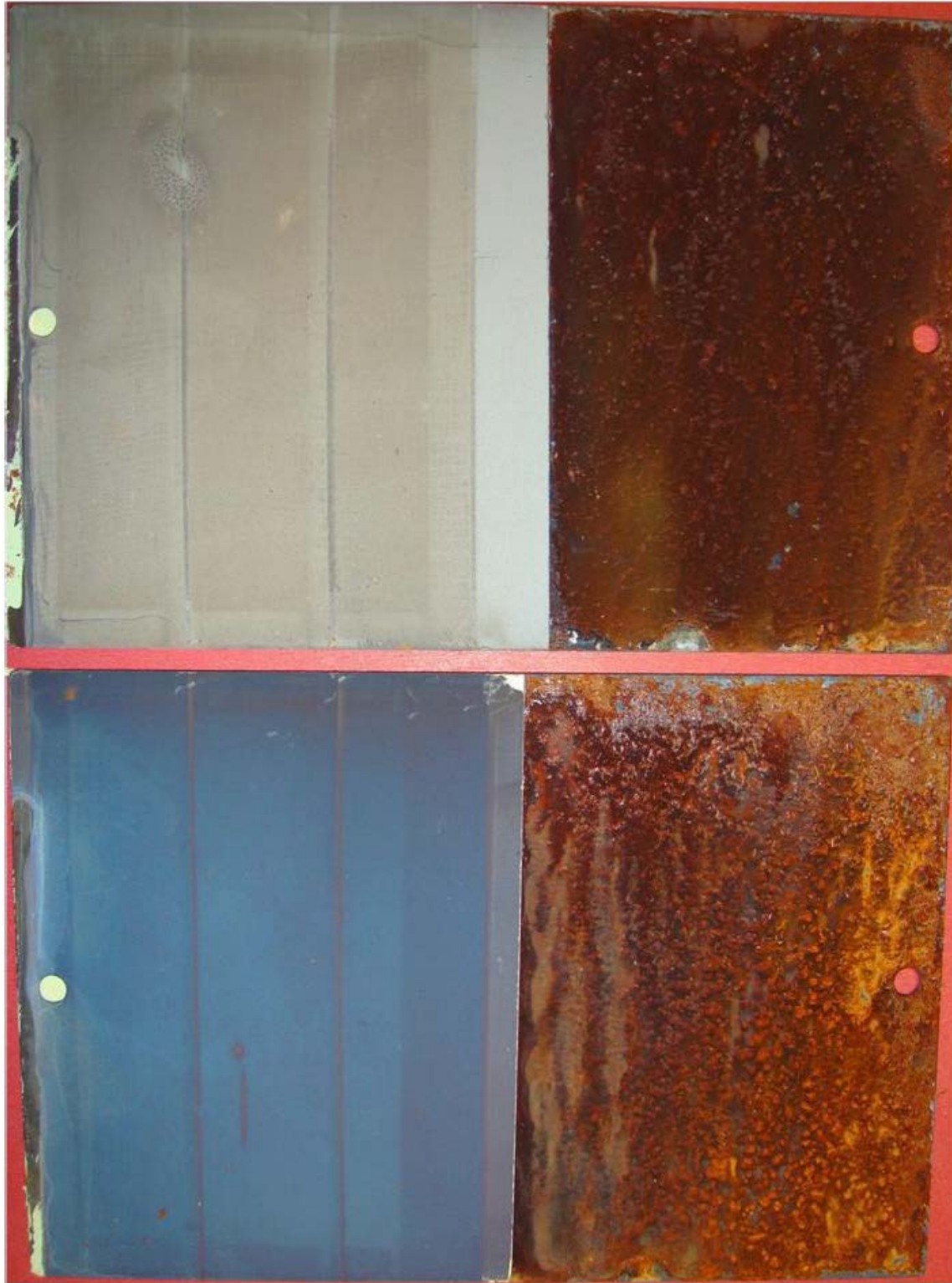


Figure 25: Corroded and Un-corroded areas LHE Zn-Ni Panels CC-4 (Bottom) and NCC-4 (Top) after 1 week in ASTM G85 SO₂ Salt Spray

CC-3 and NO-CC-3 LHE Zn-Ni test specimens from the ASTM B 117 salt spray exposure were sent to Dipsol of America (Livonia, MI) for XRF analysis to determine the concentration (in Wt. % of Zn) and thickness.

For each test panel, the areas where the XRF analysis took place are shown on the circled areas in Figure 24. The XRF analysis data is shown in Table 8 and Table 9

6.1.2.5 DE-ZINCIFICATION 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) had the entire back side and front side masked, but an area 2 inches in diameter on front side was left unmasked.

CC-1 and NO-CC-1 were placed in 3.5 % Na-Cl water solution and then anodically etched (using polarization data of 2×10^{-5} A/cm² from section 6.1.2.3 of this report) in order to remove 0.1 mils of LHE Zn-Ni.

CC-2 and NO-CC-2 were placed in 3.5 % Na-Cl water solution and then anodically etched (using polarization data of 2×10^{-5} A/cm² from 6.1.2.3 of this report) in order to remove 0.25 mils of LHE Zn-Ni.

Figure 26 shows pictures of NO-CC-1 and NO-CC-2 after 0.1 and 0.25 mils of LHE Zn-Ni were removed and Figure 27 shows pictures of CC-1 and CC-2 after 0.1 and 0.25 mils of LHE Zn-Ni were removed.

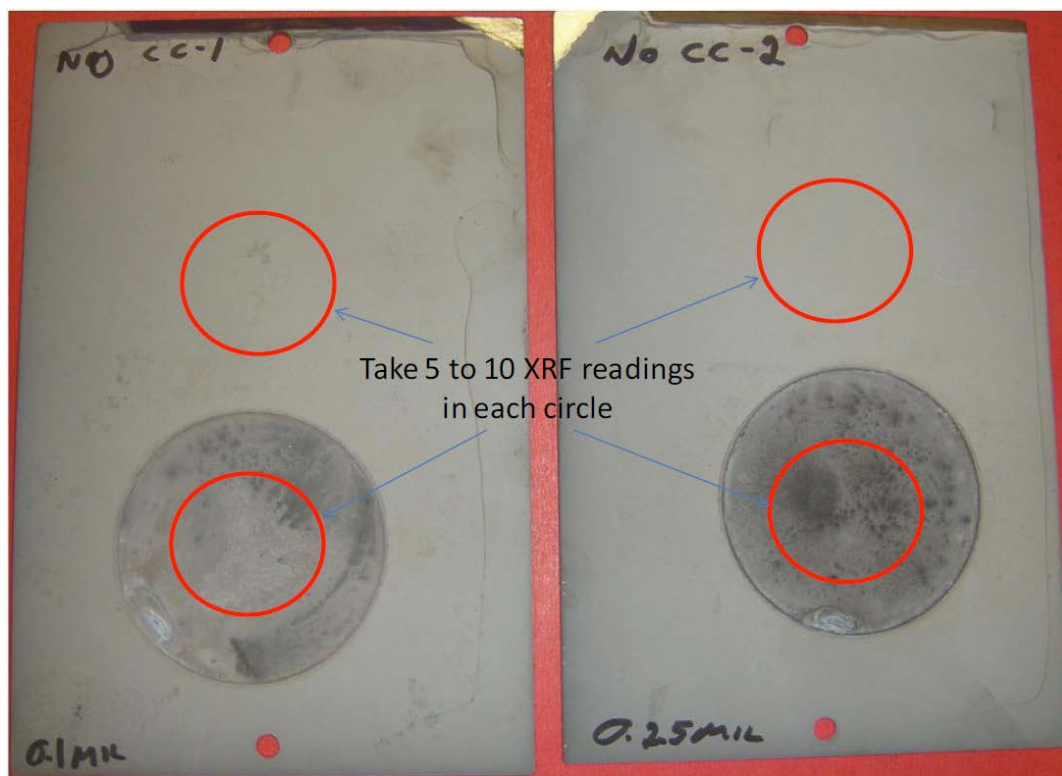


Figure 26: LHE Zn-Ni Panels NO-CC-1 and NO-CC-2 After Anodic Etching

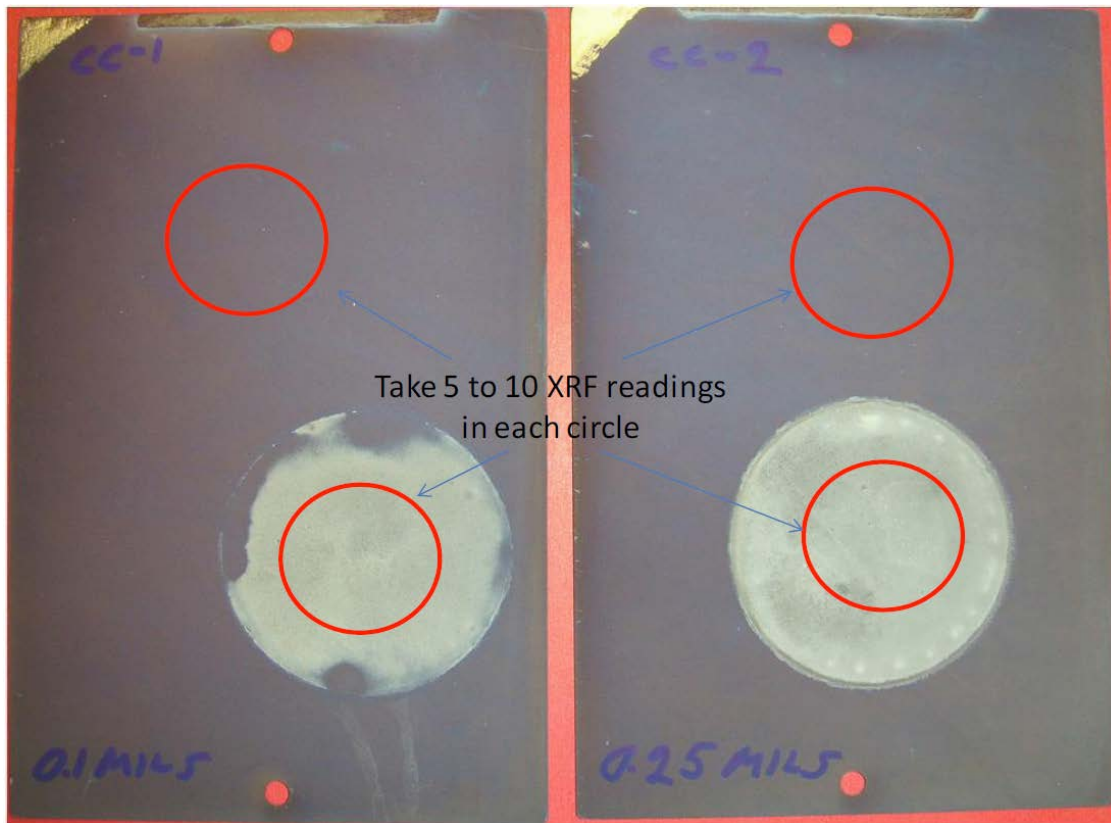


Figure 27: LHE Zn-Ni Panels CC-1 and CC-2 After Anodic Etching

CC-1, CC-2, NCC-1 and NCC-2 LHE Zn-Ni test specimens from the anodic etching test were sent to Dipsol of America (Livonia, MI) for XRF analysis to determine the concentration (in Wt. % of Zn) and thickness.

For each test panel, the areas where the XRF analysis took place are shown on the circled areas in Figure 26 and Figure 27. The XRF analysis data is shown in Table 8 and Table 9.

6.1.2.6 DE-ZINCIFICATION TESTING CORROSION ENVIRONMENTS XRF

CONCLUSION

The average and max-min values from the XRF analysis for zinc weight % and thickness (microns) for CC-3 and NO-CC-3 are shown in Table 8 and Table 9. Composition appears to be ~84.5% zinc for the CC-3 test panel (corroded and non-corroded areas) which is similar to the composition for the original test panels shown in Table 6, and composition appears to be ~84.5% zinc for the NO-CC-3 test panel (non-corroded area) which is similar to the composition for the original test panels shown in Table 6. However, the composition appears to be ~86.9% zinc for the NO-CC-3 test panel (corroded area) which is higher than the composition for the original test panels shown in Table 6. These results indicate that de-zincification did not occur on the LHE Zn-Ni when exposed to salt spray corrosion.

OCP measurements were made in salt water for the conversion coated (CC-3) and non-conversion coated (NO-CC-3) test specimens in the corroded and non-corroded areas to see if the OCP changed. OCP for CC-3 in the corroded and non-corroded areas was -750 mV and this is similar to OCP measurements for LHE Zn-Ni that were previously measured and shown in this report. However, OCP for NCC-3 in the non-corroded area was still -750 mV but in the corroded area the OCP increased to -680 mV.

Table 8: XRF Analysis of Test Panel CC-3 in Corrosion Areas CC-1, CC-2 and CC-3

	Corrosion Area					
	CC-1		CC-2		CC-3	
	Thickness (µm)	% Zn Codeposition	Thickness (µm)	% Zn Codeposition	Thickness (µm)	% Zn Codeposition
Point #1	7.66	76.87	6.13	68.99	12.38	84.38
Point #2	8.35	77.99	6.41	69.98	11.97	84.25
Point #3	6.78	76.37	6.02	69.76	13.86	84.19
Point #4	7.61	77.61	5.70	69.85	14.63	84.58
Point #5	8.44	78.57	6.23	68.93	11.54	84.69
Point #6	8.36	77.33	6.44	67.68	11.19	84.40
Point #7	7.52	76.70	6.17	69.30	13.54	84.41
Point #8	7.22	76.45	5.79	69.54	14.55	84.32
Point #9	7.31	77.56	7.64	71.30	12.66	84.57
Point #10	7.27	76.99	5.52	65.82	12.90	84.18
Mean	7.65	77.24	6.21	69.12	12.92	84.40
Max	8.44	78.57	7.64	71.30	14.63	84.69
Min	6.78	76.37	5.52	65.82	11.19	84.18
	No Corrosion Area					
	CC-1		CC-2		CC-3	
	Thickness	% Zn Codeposition	Thickness	% Zn Codeposition	Thickness	% Zn Codeposition
Point #1	9.31	84.61	10.86	84.47	11.42	84.76
Point #2	9.44	84.43	10.77	84.17	10.50	84.40
Point #3	9.50	84.37	10.82	84.63	12.16	83.99
Point #4	8.92	84.57	11.13	84.49	11.19	84.70
Point #5	9.75	84.68	10.55	84.09	11.04	84.01
Point #6	9.30	84.39	10.39	84.44	10.59	84.76
Point #7	8.83	84.06	12.46	84.43	10.86	84.68
Point #8	9.00	84.43	11.78	84.08	12.52	84.27
Point #9	9.24	84.45	10.97	84.10	12.41	84.53
Point #10	9.31	84.43	11.16	84.56	10.55	84.50
Mean	9.26	84.44	11.09	84.35	11.32	84.46
Max	9.75	84.68	12.46	84.63	12.52	84.76
Min	8.83	84.06	10.39	84.08	10.50	83.99

Table 9: XRF Analysis of Test Panel NCC-3 in Corrosion Areas NCC-1, NCC-2 and NCC-3

	Corrosion Area					
	No CC-1		No CC-2		No CC-3	
	Thickness (µm)	% Zn Codeposition	Thickness (µm)	% Zn Codeposition	Thickness (µm)	% Zn Codeposition
Point #1	6.94	76.45	4.82	67.38	11.95	86.85
Point #2	7.46	77.16	5.16	68.96	12.93	88.01
Point #3	6.92	77.46	4.49	66.31	12.48	86.96
Point #4	7.39	77.91	4.94	68.47	14.39	87.05
Point #5	7.18	77.44	4.97	68.32	9.52	84.94
Point #6	7.69	78.50	5.25	68.31	11.50	86.57
Point #7	7.43	77.19	5.04	68.34	11.17	86.61
Point #8	7.31	77.56	4.54	68.48	11.52	87.79
Point #9	7.50	78.90	4.97	68.94	14.82	87.29
Point #10	7.31	77.75	4.96	68.58	12.87	87.28
Mean	7.31	77.63	4.91	68.21	12.32	86.94
Max	7.69	78.90	5.25	68.96	14.82	88.01
Min	6.92	76.45	4.49	66.31	9.52	84.94
	No Corrosion Area					
	No CC-1		No CC-2		No CC-3	
	Thickness	% Zn Codeposition	Thickness	% Zn Codeposition	Thickness	% Zn Codeposition
Point #1	9.20	84.73	9.58	84.44	9.28	84.77
Point #2	9.41	84.44	9.71	84.46	9.15	84.64
Point #3	9.26	84.67	9.73	84.42	9.04	84.51
Point #4	9.20	84.74	9.34	84.35	8.76	84.15
Point #5	9.67	84.19	9.99	84.47	8.49	84.15
Point #6	9.82	84.80	9.89	84.49	8.60	84.15
Point #7	8.93	84.27	9.29	84.18	8.64	84.35
Point #8	9.55	84.62	9.64	84.35	8.83	84.27
Point #9	9.63	84.57	10.02	84.50	8.83	84.64
Point #10	9.47	84.50	9.97	84.22	9.78	84.41
Mean	9.41	84.55	9.72	84.39	8.94	84.40
Max	9.82	84.80	10.02	84.50	9.78	84.77
Min	8.93	84.19	9.29	84.18	8.49	84.15

The average, maximum, and minimum values from the XRF analysis for Zn weight % and thickness (microns) for CC-1, CC-2, NO-CC-1 and NO-CC-2 are shown in Table 8 and Table 9.

Zn composition for CC-1, CC-2, NO-CC1, and NO-CC2 in the non-corroded areas appears to be ~84.5%, which is similar to the composition for the original test panels shown in Table 6. However, the Zn concentration appears to drop for the corroded areas of test panels CC-1, CC-2, NCC-1 and NCC-2 and the Zn concentration for the 0.25 mil etched area, which is 68 to 69 wt. % Zn is lower than the Zn concentration for the 0.1 mil anodically etched area, which is ~ 77 wt. % Zn.

OCP measurements were made in salt water for the conversion coated (CC-1 and CC-2) and non-conversion coated (NO-CC-1 and NO-CC-2) test specimens in the corroded and non-corroded areas to see if the OCP changed. OCP for CC-1, CC-2, NO-CC-1 and NO-

CC-2 in the non-corroded areas and CC-1 and NO-CC-1 in the corroded areas was -740 to -790 mV and this is similar to OCP measurements for LHE Zn-Ni that were previously measured and shown in this report. However, OCP for CC-2 and NO-CC-2 in the corroded areas (which were anodically etched to remove 0.25 mils) were -540 to -580 mV.

Exposing the LHE Zn-Ni test panels to ASTM B 117 salt spray for 672 hours showed no change in the Zn concentration and no change in OCP measurements which indicated that de-zincification did not occur. However, artificially corroding the LHE Zn-Ni test panels by anodic etching to remove 0.1 and 0.25 mils did show a drop in the Zn concentration and in one case an increase in the OCP to -560 mV vs. SCE which suggests that de-zincification was occurring during anodic etching, which is not the same as natural corrosion in a salt spray exposure. There is a great deal of accelerated corrosion ASTM B 117 salt spray test data in industry and consequently, more weight should be given to its test results, which were that de-zincification did not happen. Additional testing should be conducted using anodic etching to determine how well the data correlates to corrosion in the environment.

6.1.2.7 DE-ZINCIFICATION ELECTROCHEMICAL AND SURFACE

ANALYSIS

Missouri University Science & 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 after samples were corroded by anodic dissolution to remove 0.04 mil (1 micron) of LHE Zn-Ni plating material to determine if de-zincification occurred.

The plating was cross sectioned using FIB in corroded and un-corroded regions of the samples along with EDS chemical analysis to determine the LHE Zn-Ni ratio in the cross-sectioned areas. This showed the LHE Zn-Ni composition change with depth due to corrosion. The EDS area scans shown in Figure 29 and Figure 30 show uniform stable distribution of Zn and Ni. There are no concentrations of either element rather a homogeneous structure of Zn and Ni.

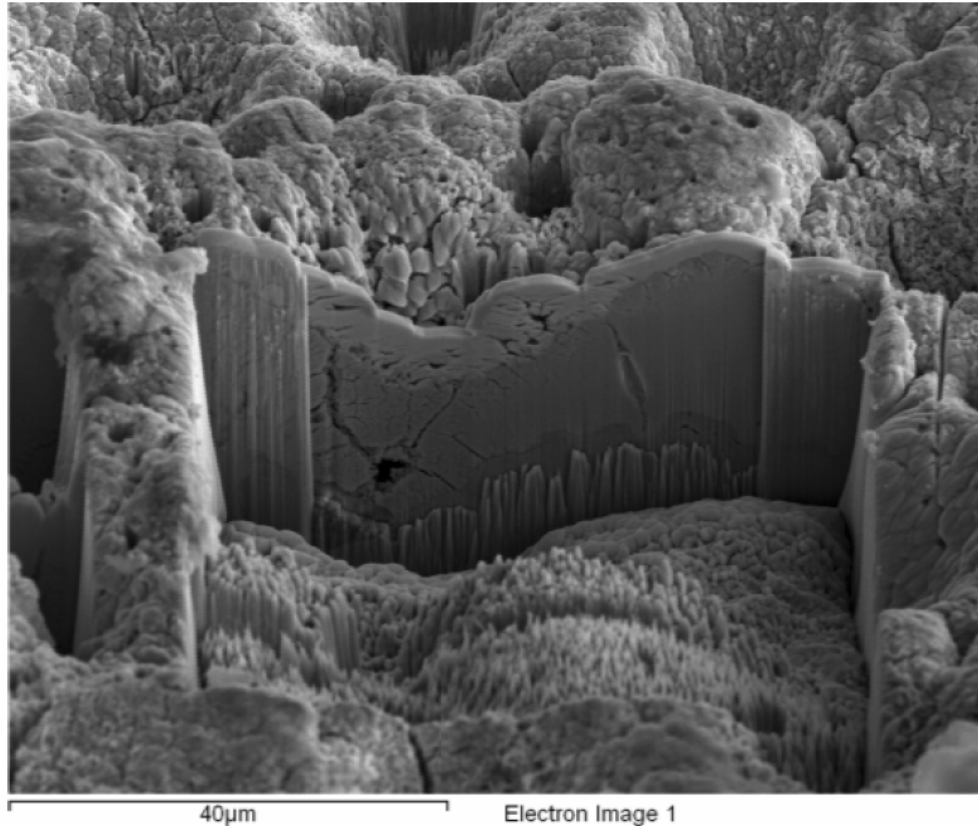


Figure 28: Non Conversion Coated (NCC) Electron Beam Image (Corroded Area)



Figure 29: Zn Concentration from NCC Area Scan

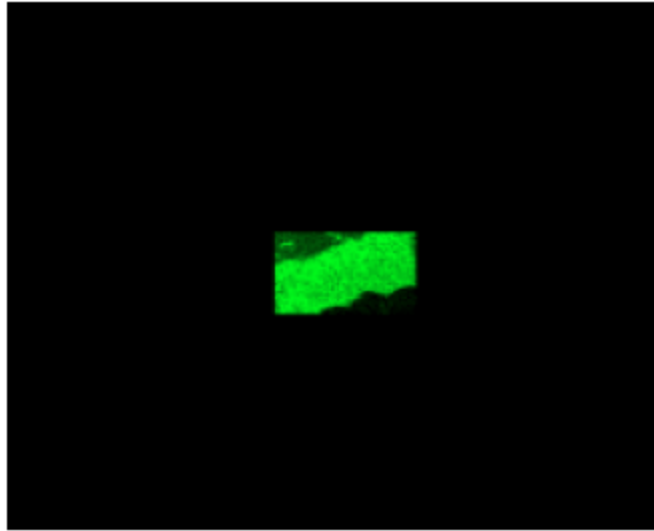


Figure 30: Ni Concentration from NCC Area Scan

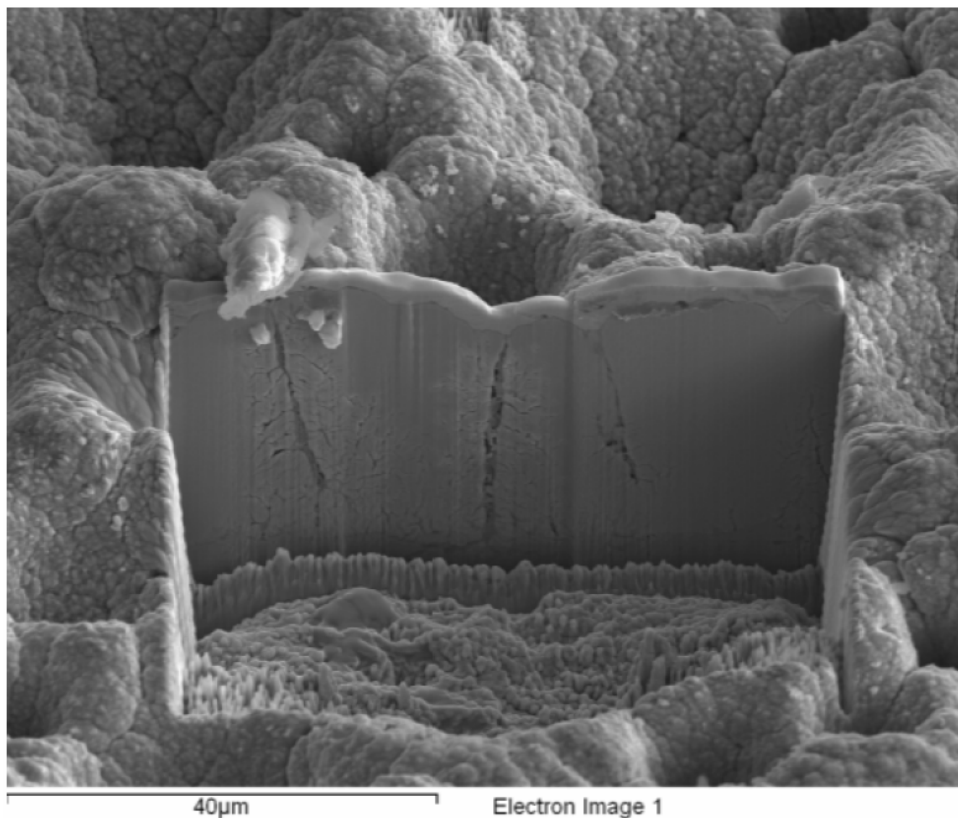


Figure 31: Conversion Coated (CC) Electron Beam Image (Corroded Area)

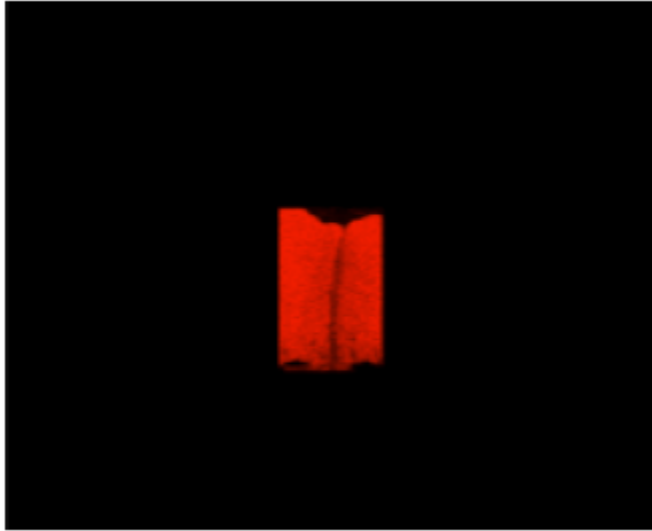


Figure 32: Zn Concentration from CC Area Scan

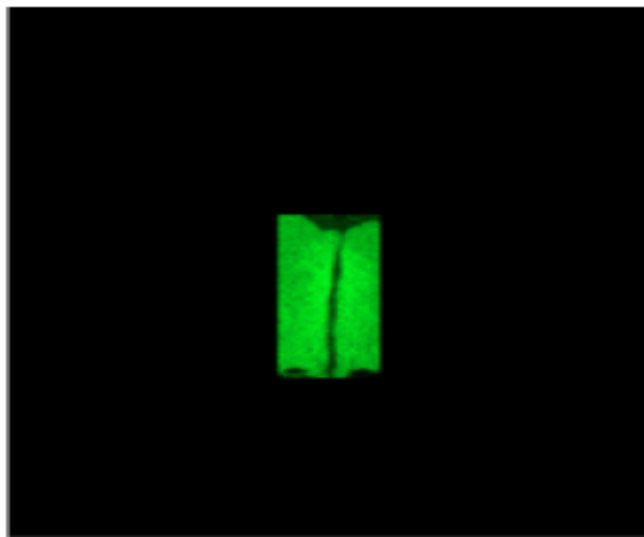


Figure 33: Ni Concentration from CC Area Scan

Results from all of the scans show that there may be slight loss of percent weight of Zn during corrosion and that the LHE Zn-Ni ratio may also be varying in depth, however there was a large fissure in the cross-section area that may have affected the results (see Figure 31 - Figure 33). The normalized percent weight of the samples are shown in Table 10. It is noted that the concentrations of Ni 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 %wt and the Corroded %wt.

Table 10: 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%

6.1.2.8 DE-ZINCIFICATION ELECTROCHEMICAL AND SURFACE

ANALYSIS CONCLUSION

Missouri University Science & Technology ran numerous electrochemical and surface analytical tests and their conclusions were as follows:

- At most, conversion coated LHE Zn-Ni loses a few wt% of Zn after corrosion.
- LHE Zn-Ni ratio of conversion coated LHE Zn-Ni could vary with depth after corrosion but is within the measurement error.
- There was no difference in the LHE Zn-Ni ratio between NCC-1 (no conversion coating) and CC-1 (with conversion coating) after corrosion.
- LHE Zn-Ni plating (15% Ni) is an alloy (gamma phase). No distinct phases of Zn or Zn rich areas could be found in the LHE Zn-Ni plating, and this would prevent de-zincification from readily occurring.

6.1.2.9 ZERO RESISTANCE AMMETER (ZRA) MEASUREMENTS

Two LHE Zn-Ni test panels (one conversion coated and one non-conversion coated) were coupled to 1x6x0.040" 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. Figure 34 shows the laboratory set-up used to measure the galvanic current with a zero resistance ammeter when bare steel and LHE Zn-Ni plated steel or coupled together.

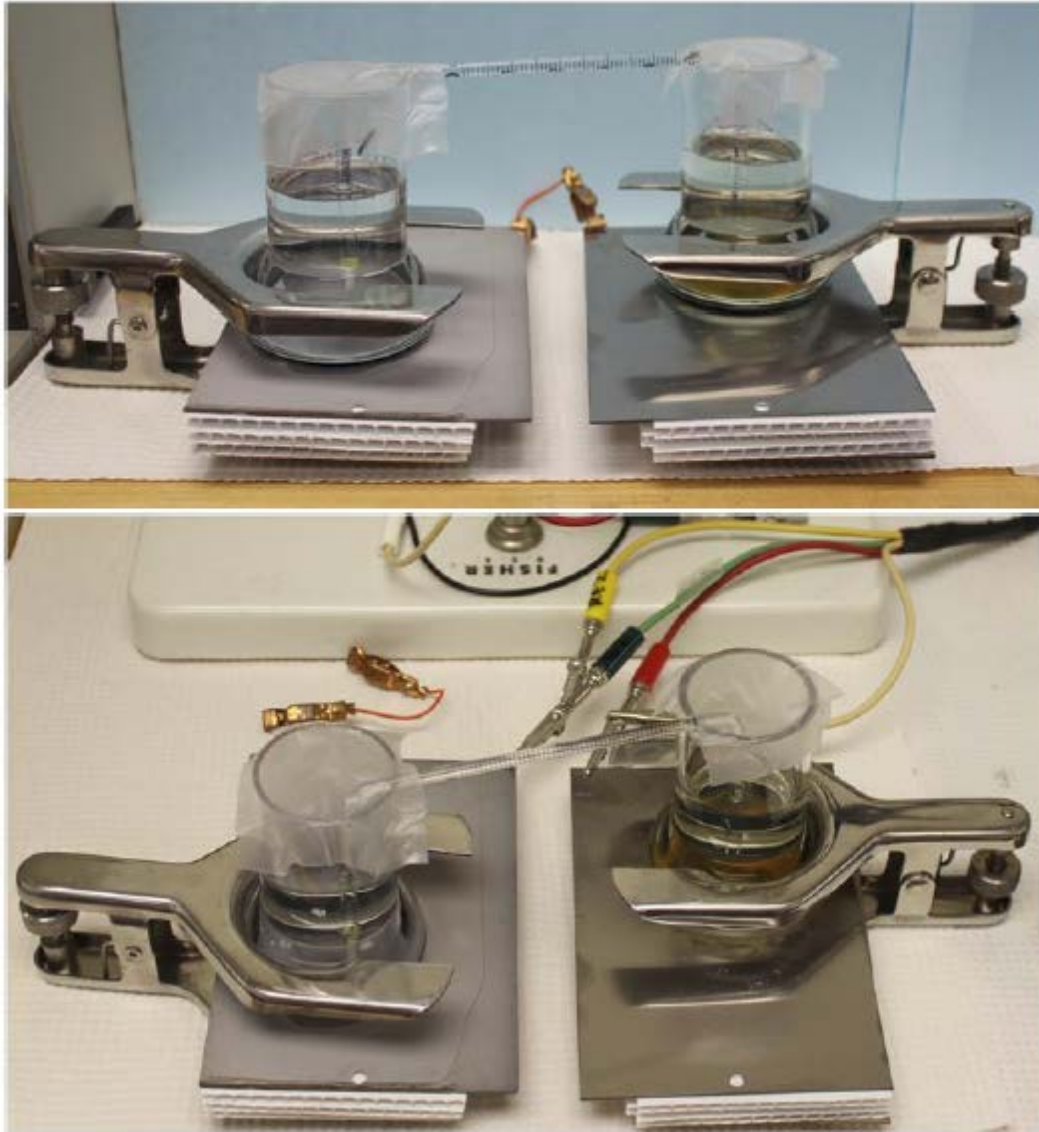


Figure 34: ZRA Test Set-up LHE Zn-Ni Panel (left) coupled with bare steel (right)

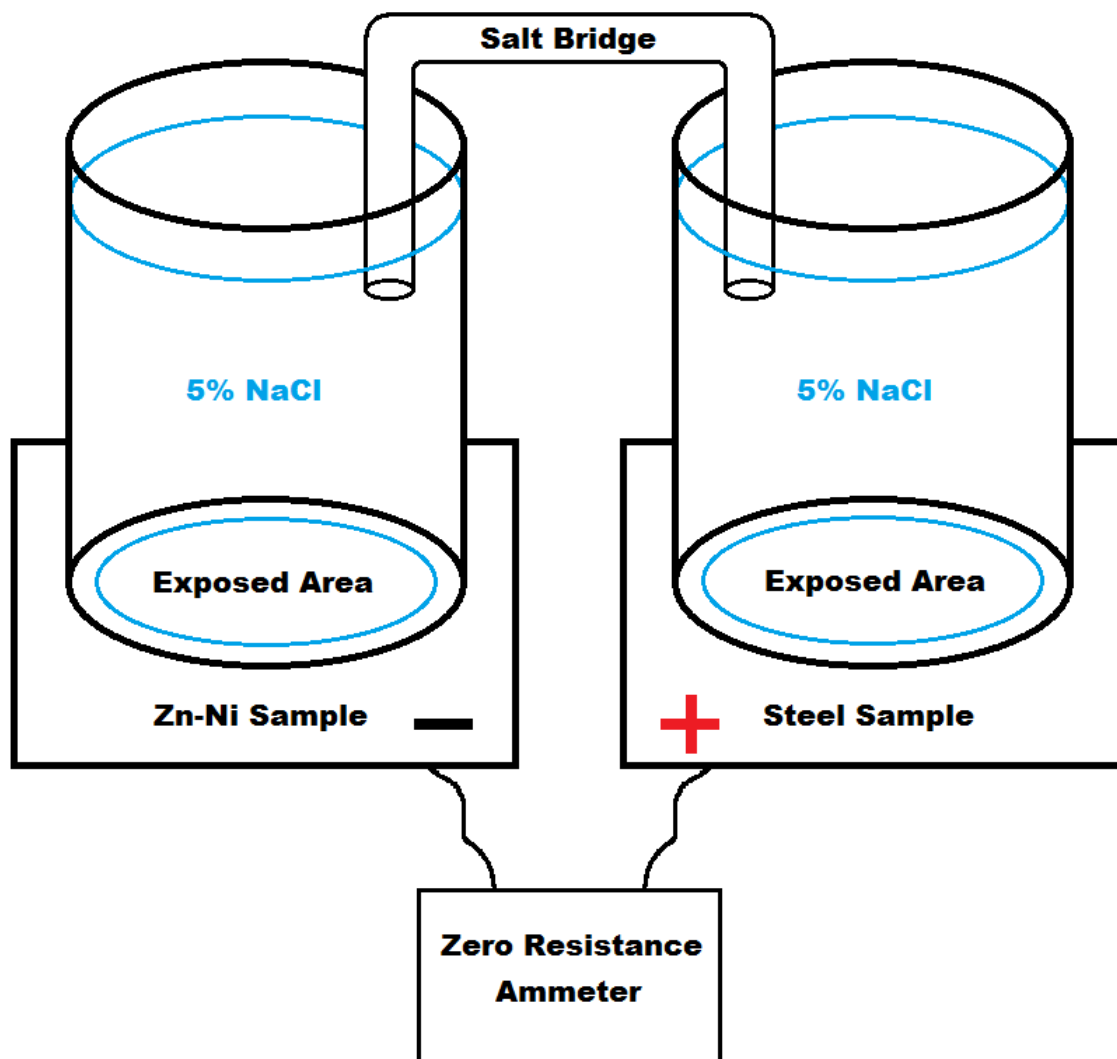


Figure 35: ZRA Setup Diagram

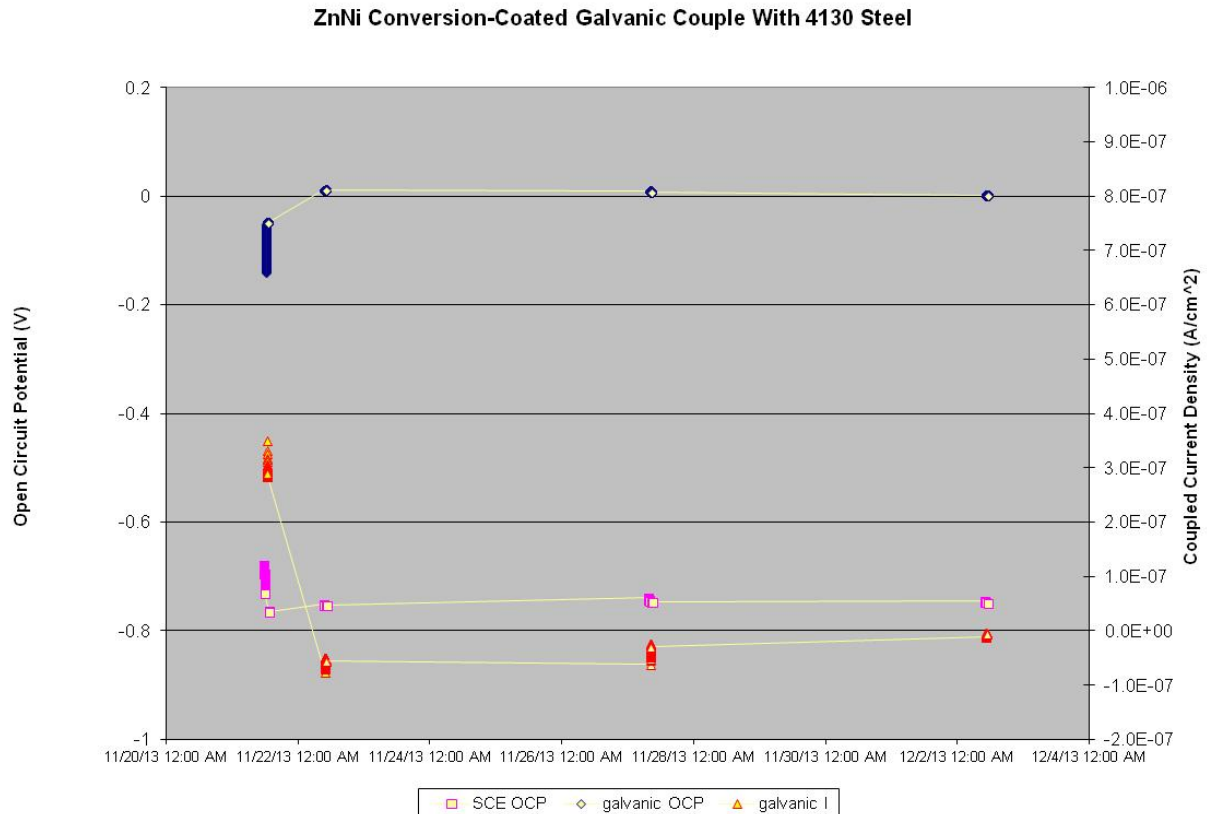


Figure 36: ZRA of LHE Zn-Ni CC Coupled with 4130 Steel

The data in Figure 36 shows that LHE Zn-Ni with CC had a very steady OCP (open circuit potential) of -0.74 to -0.76 V vs. SCE (steel is typically -0.6 to -0.7 V vs. SCE) during the 10 day test and the OCP for LHE Zn-Ni when coupled to steel was -0.050 V. The initial galvanic current flow between the LHE Zn-Ni and bare steel was 2.8×10^{-7} A/cm² (LHE Zn-Ni is anodic to the steel) but the galvanic current flow quickly dropped within one day to zero or slightly cathodic to the steel.

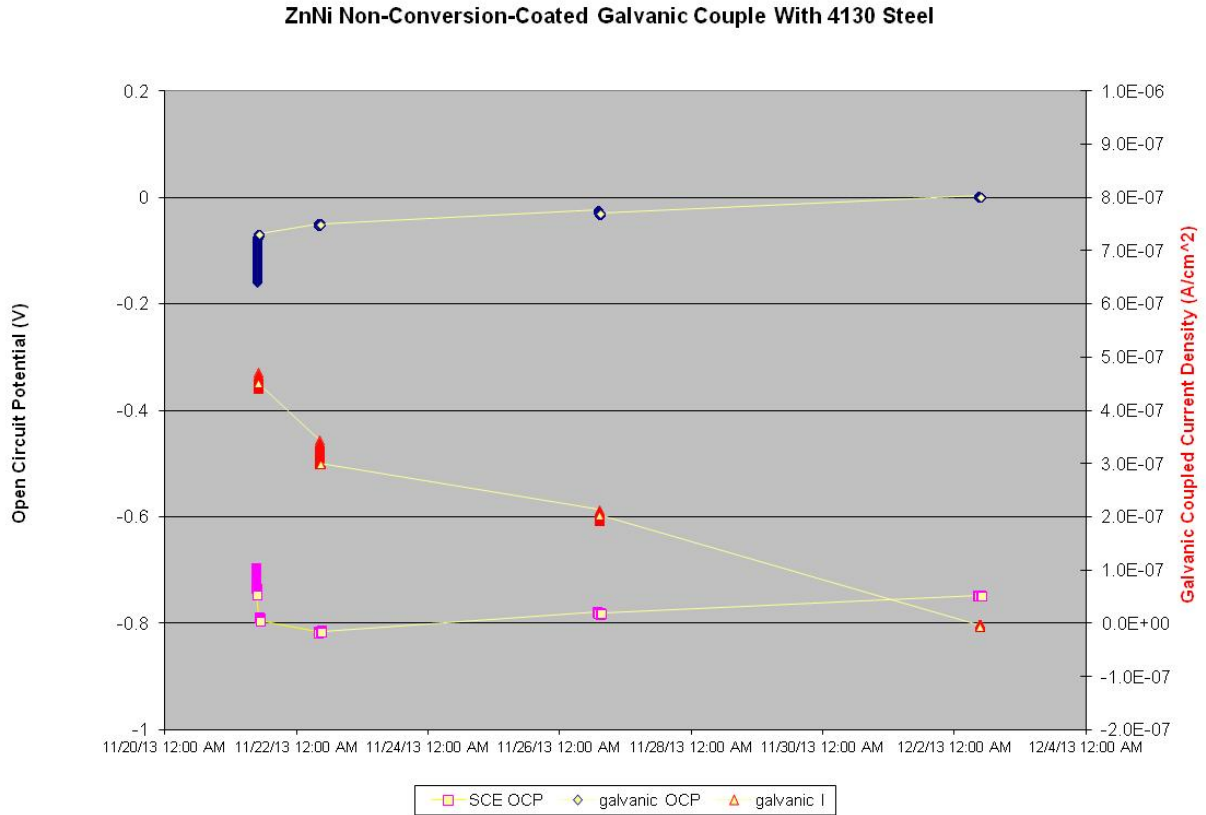


Figure 37: ZRA of LHE Zn-Ni NCC Coupled with 4130 Steel

The data Figure 37 shows that LHE Zn-Ni without CC had an initial OCP of -0.82 V vs. SCE and then it dropped to -0.75 V vs. SCE after 10 days and the OCP for LHE Zn-Ni when coupled to steel was -0.080 V. The initial galvanic current flow between the LHE Zn-Ni and bare steel was $4.5 \times 10^{-7} \text{ A/cm}^2$ (LHE 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.

6.1.2.10 ZERO RESISTANCE AMMETER (ZRA) MEASUREMENTS

CONCLUSION

Galvanic current measurements with the ZRA between conversion coated LHE Zn-Ni plated steel coupled to bare steel was $2.8 \times 10^{-7} \text{ A/cm}^2$ and between the non-conversion coated LHE Zn-Ni plated steel coupled to bare steel was $4.5 \times 10^{-7} \text{ A/cm}^2$.

In both cases the galvanic sacrificial protective current dropped to 0 or became slightly cathodic and after careful observations it appeared that the bare steel panel surface area was too large for the LHE Zn-Ni to protect and the steel quickly rusted in the salt water and this prevented flow of the galvanic current moving measurements out of the expected range.

6.1.2.11 GALVANIC CORROSION AND LHE ZN-NI THROWING POWER

LHE Zn-Ni plated test panel with conversion coating (identified as LHE Zn-Ni CC), LHE Zn-Ni plated test panel with no conversion coating (identified as LHE Zn-Ni) and a Cd plated test panel, had the plating materials removed in 4 areas on each test panel. The three test panels were then placed in an ASTM B 117 salt spray cabinet for 672 hours and then removed after 672 hours of salt spray exposure. Heavy corrosion products were removed by scrubbing with water and then the cleaned corroded test panels were sent to Dipsol of America for XRF analysis to determine the wt. % Zn near the bare corroded areas and away from the bare corroded areas. Figure 35 and Figure 36 show the areas on the test panels where XRF analyses were taken. Figure 37 - Figure 39 show the test panels before exposure to salt spray, after exposure to 672 hours of salt spray and after cleaning excess corrosion products. Dipsol could not perform XRF analysis on the Cd plated test panel, so that test panel was not analyzed.

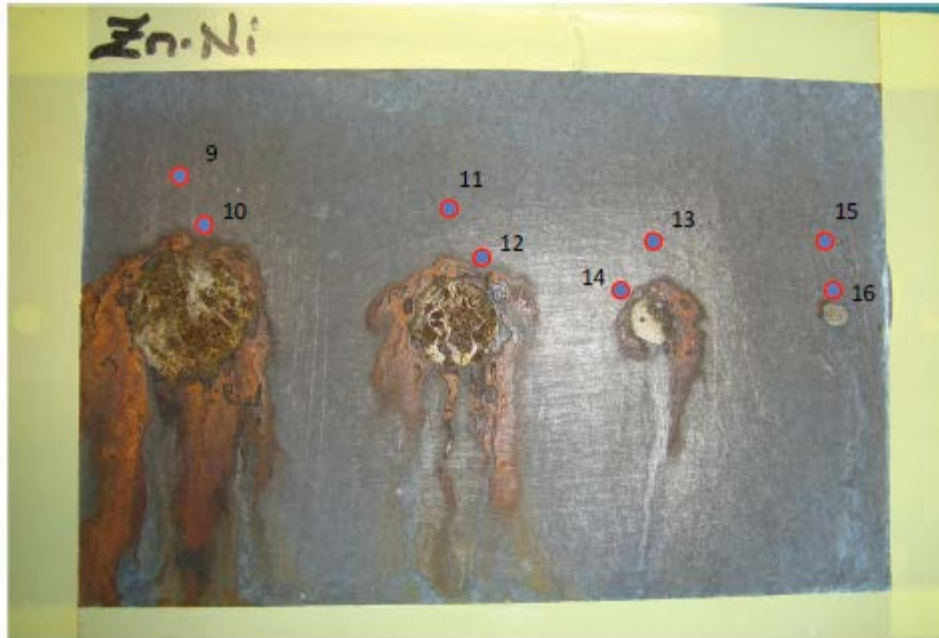


Figure 38: LHE Zn-Ni Plated No Conversion Coat XRF Analysis Locations



Figure 39: LHE Zn-Ni with Conversion Coat XRF Analysis Locations



Figure 40: Cd Plated Test Panel

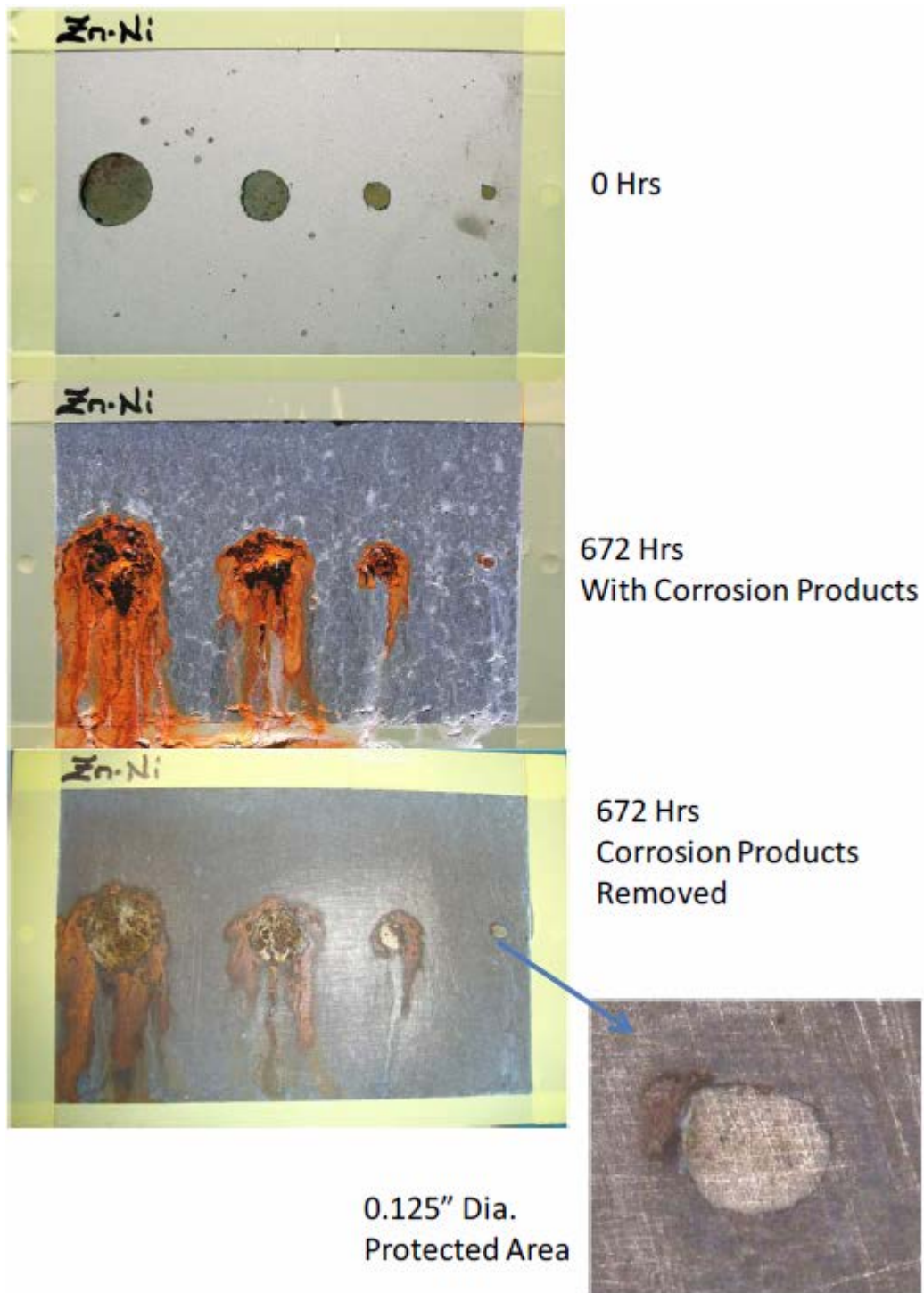


Figure 41: LHE Zn-Ni Plated Test Panel No Conversion Coat

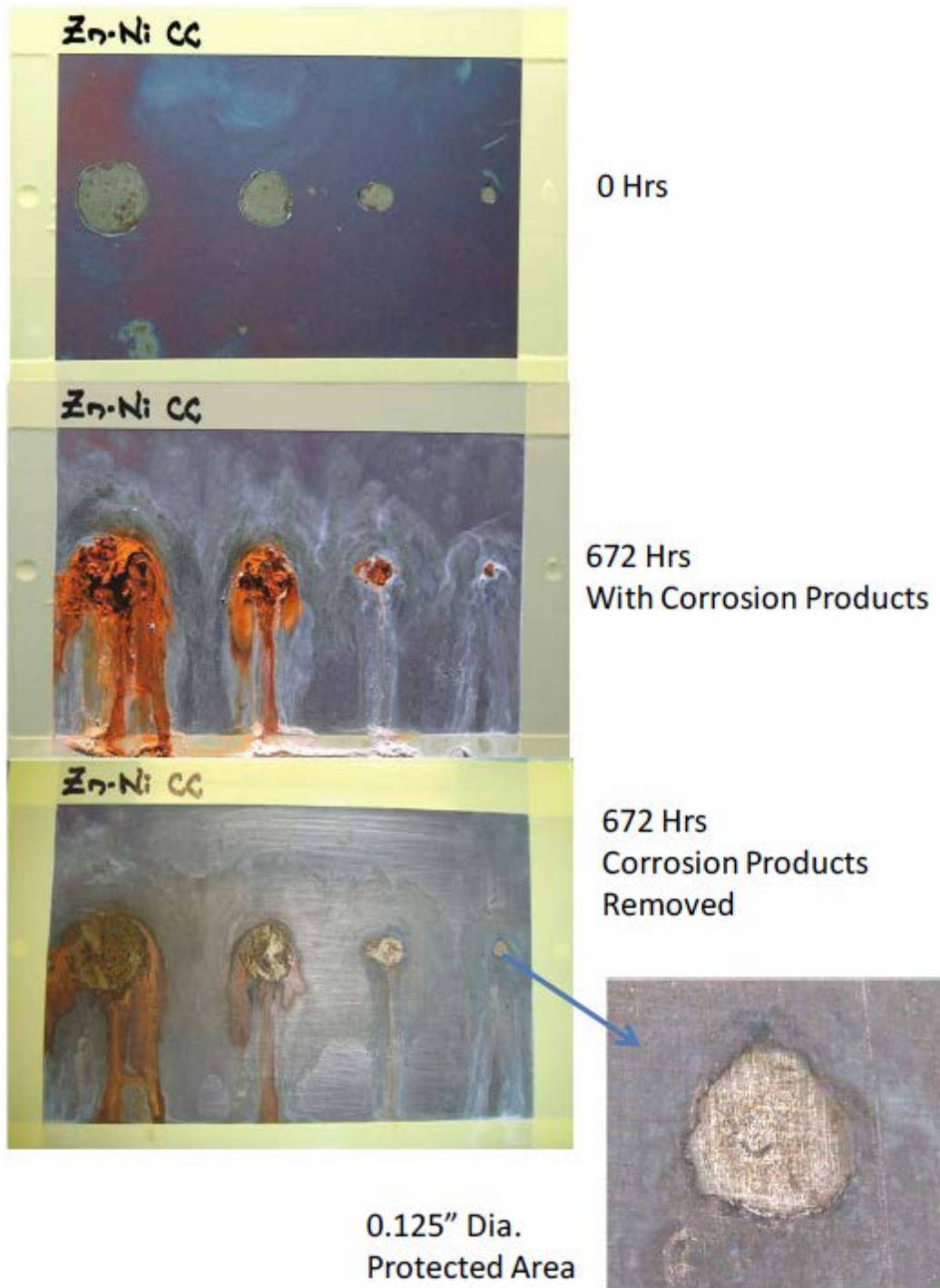


Figure 42: LHE Zn-Ni Plated Test Panel with Conversion Coat

6.1.2.12 GALVANIC CORROSION AND LHE ZN-NI THROWING POWER

CONCLUSION

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 LHE Zn-Ni test panel did not change significantly so de-zincification did not occur. The results for the conversion coated LHE Zn-Ni were inconclusive and additional testing is required.

Table 11: XRF Analysis of LHE Zn-Ni Panels. Odd numbered point IDs are locations away from the bare corroded area and even numbered Point IDs are location near the bare corroded area

No Conversion Coat Point ID	Thickness (μm)	% Zn	Conversion Coated Point ID	Thickness (μm)	% Zn
1	17.4	(Cd)	13	7.34	80.95
2	0.46	(Cd)	14	8.38	82.72
3	15.5	(Cd)	15	7.96	82.27
4	0.386	(Cd)	16	8.53	81.35
5	13.8	(Cd)	17	8.64	84.5
6	0.829	(Cd)	18	6.35	77.38
7	16	(Cd)	19	7.07	78.86
8	0.956	(Cd)	20	5.75	75.75
9	8.21	79.60	21	9.44	81.35
10	8.59	80.82	22	7.58	78.12
11	8.35	82.61	23	9.56	80.83
12	8.00	82.06	24	11.04	81.29

6.1.3 RESEARCH EVALUATE AND TEST RE-EMBRITTTLEMENT

PROTOCOLS

6.1.3.1 RE-EMBRITTTLEMENT 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 43: Cd Plated Re-embrittlement Coupons



Figure 44: LHE Zn-Ni Plated Re-embrittlement Coupons

Coupons were sent to Omega Research for testing. 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 in Table 12 show all Cd plated test specimen failing in less than one hour. No LHE Zn-Ni plate coupons failed.

Table 12: Hydrogen Re-embrittlement Test Results

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



Figure 45:Re-embrittlement Test Setup

Coupons were returned and cross-sectioned to measure plating in the root of the notch area. Plating on the LHE Zn-Ni coupons looked uniform through the notch. Plating on the Cd coupons was thin in the notch.

6.1.3.2 RE-EMBRITTLEMENT TESTING CONCLUSION

LHE Zn-Ni performed better than Cd, however upon microscopic inspection of the notch for the Cd coupon it was found that the plating in the root of the notch was very thin and may have not protected the base material from embrittlement in the salt water. It is suggested that additional coupons be plated and cross-sectioned before testing to identify proper plating in the notch.

6.1.4 RESEARCH AND OPTIMIZATION OF LHE ZN-NI STRIPPING

PROCEDURES

6.1.4.1 CHEMICAL TESTING AND RESULTS

During laboratory testing, it was determined that an agitated solution of ammonium nitrate at 16 oz/gallon in water would strip the LHE Zn-Ni deposit if the pH was adjusted

and maintained between 8 to 9. Unfortunately, ammonium gas is evolved out of solution if the pH is adjusted above 7 and swept out by the ventilation system. Additionally, agitation of the solution increases the loss of ammonium nitrate. The type of agitation, whether air or mechanical, makes little difference. It was determined that the reduction in useful life of a production ammonium nitrate stripping bath would likely be less than 1.5 months. Consequently, in production, pH would need to be monitored and adjusted continuously. It was also determined that agitation is critical in stripping internal diameters (IDs) and increasing the stripping speed of the solution.

Additional laboratory testing indicated that an ammonium nitrate solution at 32 oz/gallon without pH adjustment (pH 7) and using mechanical agitation adequately strips the LHE Zn-Ni coating in 30 to 60 minutes. The fact that the pH is not adjusted significantly reduces that amount of ammonium nitrate that is lost out of the stripping solution. Immersion in a 20% solution of phosphoric acid for up to 3 minutes following the ammonium nitrate process improves the stripping results. The stripping process takes approximately 90-120 minutes from start to finish, which includes part degreasing, rinsing, ammonium nitrate stripping (30-60 minutes), sodium hydroxide solution, 20% phosphoric acid solution and rust stripping.

It was also determined that inhibited sulfamic acid does not perform as well as phosphoric acid in cleaning up any residuals from the ammonium nitrate strip.

6.1.4.2 HYDROGEN EMBRITTLEMENT TESTING OF 32OZ/GALLON

AMMONIUM NITRATE STRIPPING SOLUTION

In order to ensure that the stripping solution of 32oz/gallon of ammonium nitrate do not cause hydrogen embrittlement failures of the HSS landing gear components, HE testing was conducted on the 32 oz/gallon ammonium nitrate solution. Eight specimens were LHE Zn-Ni plated to a thickness of 0.5 to 0.6 mils (0.0005 to 0.0006 inches) and conversion coated. The specimens were then baked at 375 degrees F for 23 hours. Six of these specimens were then stripped in the 32 oz/gallon ammonium nitrate solution for 60 minutes (the deposit appeared visually stripped in less than 30 minutes). They were not baked after strip.

Two specimens were not stripped to be used as control specimens in case of failure of one or more of the six stripped specimens. Four of the six stripped specimens were loaded in the embrittlement test instrument within one hour of removal from the strip solution. These four specimens passed 200 hours on test without failure. The remaining two stripped specimens and the two specimens that were not stripped were then placed on test. These also passed 200 hours without failure.

6.1.4.3 EFFECTS OF 32OZ/GALLON AMMONIUM NITRATE STRIPPING SOLUTION ON HVOF AND CHROMIUM PLATED SURFACES

The effect of the 32oz/gallon ammonium nitrate solution on HVOF (tungsten-cobalt-carbide) and chromium (Cr) plated surfaces was evaluated. Specimens coated with tungsten-cobalt-carbide and Cr were immersed in the strip solution for two hours. Only one side of a six sided specimen was coated. The rest of each specimen was bare steel. The surface of each deposit was examined under 10X magnification both before and after the immersion. There was no visible difference. There was some weight loss. However, this was attributed to attack on the bare steel surface of each specimen as evidenced by the rust red precipitate that formed in the strip solution. The weight loss calculates to a dimensional change of 0.07 mils (0.00007 inches) for the two hour immersion. Even though the weight loss indicates some attack on the steel, there is no visible etch pattern and no visible pitting.

6.1.4.4 LHE ZN-NI STRIPPING RECOMMENDATIONS

It is recommended that an agitated solution of ammonium nitrate solution at 32oz/gallon with a 7 pH is used to strip the LHE Zn-Ni plating from HSS landing gear components. Provide sufficient process tank space to allow a minimum 30-60 minute immersion in the ammonium nitrate stripping solution. 90 to 120 minutes would provide some margin to accommodate internal diameters. It is also recommend that the components be immersed in a 20% phosphoric acid bath (20 gallons of 85% phosphoric acid per 100 gallons of solution) for up to 3 minutes following the strip solution and rinse. Maintain the temperature on both solutions between 70°F and 80°F.

Again, the stripping process should take approximately 90-120 minutes from start to finish, which includes part degreasing, rinsing, ammonium nitrate stripping (30-60 minutes), sodium hydroxide solution, 20% phosphoric acid solution and rust stripping. Bake all parts for four hours minimum at 375 +/- 25 °F within four hours of the rust stripping process.

The use of low mineral content water (such as de-ionized water) is recommended for ammonium nitrate stripping solution makeup. If a sufficient volume of such water is not available for the initial makeup, tap water could be used. However, it is still recommend using low mineral content water to replace evaporation losses.

The ability to strip internal diameters (ID) depends on the amount of solution circulation in the ID, the greater the circulation, the faster the strip rate. Small diameters and parts with closed ends may need to be immersed for a longer period of time to complete stripping. Some amount of abrasive blast may be required following strip, especially on high current density areas where the deposit may be too thick to completely strip in the allotted time.

Run a strip rate test periodically to determine when additions need to be made or the solution discarded. A convenient test specimen is a 4 inch long by 3/8 inch diameter bolt with approximately 3 inches of unthreaded shank and 24 threads per inch. This specimen

fits the hydrogen embrittlement test specimen plating fixture and is convenient to weigh and plate.

Plate the specimen at 50 amps per square foot with approximately 0.4 grams of LHE Zn-Ni, conversion coat and bake. Plate entire specimen plated except the portion threaded into the fixture to a thickness of approximately 0.7 mils of deposit. Weigh the specimen before and after plate to allow the coating weight to be determined.

After the specimen has been baked, strip the specimen in a sample of the ammonium nitrate stripping solution. If the strip rate is not acceptable, determine if the solution is to be discarded or if additional ammonium nitrate can be added to restore stripping performance as follows:

- To a 500 milliliter sample of the strip solution, add 60 grams of ammonium nitrate (equivalent to an addition of 16 oz/gallon).
- Determine if the ammonium nitrate dissolves and that the solution is not too viscous.
- If acceptable, completely strip a minimum of three specimens to load the solution with additional LHE Zn-Ni. Following this, strip a single specimen for 60 minutes. NOTE: Four specimens in 500 milliliters of solution are approximately equivalent to three months of production in a 6000 gallon process solution.
- If the stripping rate is acceptable in the fortified solution, additional ammonium nitrate at 16 oz/gallon may be added to the process tank and processing continued. Otherwise discard the spent solution and remake.

It was determined that a 35% to 50% solution of hydrochloric acid (35 to 50 gallons of concentrated hydrochloric acid per 100 gallons of solution) with an added inhibitor (these tests used Henry Miller Activol 2105) strips the LHE Zn-Ni plating in several minutes (typically less than 5 minutes) with insignificant etch impact on the base metal steel. However, this solution also attacks any Cr plated surfaces. If there are sufficient parts to justify and if space allows, a separate tank with hydrochloric acid could be provided to strip parts that do not have any Cr plated surfaces. Additionally it was determined through limited testing that a 35% to 50% solution of hydrochloric acid has an insignificant impact on tungsten-cobalt-carbide.

More testing needs to be accomplished on Ni plated surfaces before a 35% to 50% solution of hydrochloric acid solution can be approved for use Ni plated landing gear components. Such testing should include the coating (HVOF or Ni) by itself and when combined with LHE Zn-Ni on the same specimen. Testing with LHE Zn-Ni and Cr plated surfaces indicates the addition of the Cr plated surfaces interferes with the inhibitor, resulting in more aggressive etch on both the Cr and the base metal steel. Testing would need to verify whether or not this same issue occurs with HVOF or nickel.

A note of caution: These tests were performed on freshly plated, conversion coated, and baked test specimens. Production parts arrive for overhaul with aged paint and primer that must be stripped. If any paint/primer residue remains embedded in the LHE Zn-Ni

coating, strippability will likely suffer. The only experience we currently have is with Cd. From this experience, it would appear to not be an issue.

The 32 oz/gallon ammonium nitrate solution can also be used to strip Cd. However, if it is used as a Cd strip solution, MIL-STD-871 needs to be changed since it currently specifies a 16oz/gallon solution. Since there is no reasonable test for the active ammonium nitrate concentration, any change should allow for additional ammonium nitrate to be added as necessary to maintain the stripping rate.

Success using the current Cd strip in conjunction with IVD strip has been achieved recently. Additional testing with this method and complex landing gear components is suggested.

6.1.5 PERFORMANCE TRACKING PROGRAM

The LHE Zn-Ni Performance Tracking Program (PTP) validated the application of LHE Zn-Ni on landing gear components in an effort to replace cadmium as a sacrificial protective coating. LHE Zn-Ni has been evaluated, tested and approved as a replacement for cadmium. Testing has shown that LHE Zn-Ni performs as well as or better than cadmium 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. Subject aircraft had two LHE Zn-Ni plated components installed and an 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.

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. The selected location for the F-15 performance tracking was the 159th Fighter Wing, New Orleans Naval Air Station Joint Reserve Base, Louisiana. The selected location for the F-16 performance tracking was McEntire Joint National Guard Base, South Carolina. The selected location for KC-135 performance tracking was the 203^d Air Refueling Squadron at Joint Base Pearl Harbor-Hickam, Hawaii. The selected location for C-130 performance tracking was USCG Air Station Barbers Point, Hawaii.

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

F-15 performance tracking was completed at the 159th Fighter Wing Louisiana ANG. The LHE Zn-Ni and Cd plated components were installed on Aircraft # 83-048 (**Figure 46**) on 30 October 2014.



Figure 46: F-15 LHE Zn-Ni PTP Aircraft #83-048

In order to capture a “Zero Time” component comparison, the LHE Zn-Ni and Cd components (Table 13) were assembled into full MLG strut assemblies (**Figure 47**). Cd plated components were installed on the LH MLG and LHE Zn-Ni plated components were installed on the RH MLG. Figure 2 shows the locations of F-15 MLG collars and pistons.

Table 13: F-15 LHE Zn-Ni and Cd Components

<u>COMPONENT</u>	<u>P/N</u>	<u>NSN</u>
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 47: F-15 MLG PTP Components

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

KC-135 performance tracking was completed at the 203d Air Refueling Squadron at Joint Base Pearl Harbor-Hickam, Hawaii. The LHE Zn-Ni and Cd plated components were installed on Aircraft # 63-8030 (Figure 3) on 22 September 2015. Cd plated components were installed on the LH MLG and LHE Zn-Ni plated components were installed on the RH MLG (Table 2). Figure 4, shows the locations of the KC-135 MLG brake equalizer rod.



Figure 48: KC-135 LHE Zn-Ni PTP Aircraft #63-8030

Table 14: KC-135 MLG PTP Components

<u>COMPONENT</u>	<u>P/N</u>	<u>NSN</u>
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 49: KC-135 MLG Components

6.1.5.3 USCG AIRS 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 (Figure 50) on 27 August 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.



Figure 50: C-130 LHE Zn-Ni PTP Aircraft #1716

In order to capture a Zero Time component comparison, Cd plated components were installed on the LH MLG, and LHE Zn-Ni plated components were installed on the RH MLG (Table 15). Figure 6 shows locations of C-130 MLG Components.

Table 15: C-130 MLG PTP Components

<u>COMPONENT</u>	<u>P/N</u>	<u>NSN</u>
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 51: C-130 PTP Components

6.1.5.4 MCENTIRE JOINT NATION 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 (Figure 52) on 16 December 2014.



Figure 52: F-16 LHE Zn-Ni PTP Aircraft #92-902

Table 16: F-16 MLG PTP Components

COMPONENT	P/N	NSN
MLG Tension Strut (RH/LH)	2007003-103	1602-01-252-1049
MLG Drag Brace (RH/LH)	2007304-101	1620-01-252-4090
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 53: F-16 MLG PTP Components

6.1.5.5 NEW ORLEANS NAVAL AIR STATION JOINT RESERVE BASE,

LOUISIANA (F-15) RESULTS

LHE Zn-Ni and Cd components were installed on aircraft # 83-048 on 30 October 2014. Annual visual inspections for corrosion and corrosion products were conducted on 28 October 2015 and 25 August 2016. The aircraft was transferred to Klamath Falls, OR where the final inspection took place 9 November 2016. LHE Zn-Ni components passed visual inspection on both occasions with no corrosion products visible. Paint and primer had both been chipped off of some plated components. The LHE Zn-Ni plating was still visible and intact, however the cadmium looked to be rubbed and worn. Figure 9 - Figure 16 are photos taken of the PTP MLG components during installation and inspection.



Figure 54: Installation of Cd Plated Component



Figure 55: F-15 MLG Cd Plated Component (8/25/2015)



Figure 56: F-15 MLG Cd Plated Component (8/25/2015)



Figure 57: F-15 MLG Cd Component (11/9/2016)



Figure 58: F-15 MLG Cd Component (11/9/2016)



Figure 59: Installation of LHE Zn-Ni Plated Component



Figure 60: LHE Zn-Ni Plated Component (8/25/2015)



Figure 61: LHE Zn-Ni Plated Component (8/25/2015)



Figure 62: LHE Zn-Ni Plated Component (11/9/2016)



Figure 63: LHE Zn-Ni Plated Component (11/9/2016)

6.1.5.6 JOINT BASE PEARL HARBOR-HICKAM – HAWAII (KC-135) RESULTS

LHE Zn-Ni and Cd components were installed on aircraft # 36-8030 on 22 September 2015. Annual visual inspections for corrosion and corrosion products were conducted on 29 June 2016, and 17 May 2017. LHE Zn-Ni components passed visual inspection on both occasions with no visible corrosion products similar to the cadmium components. Figure 64 - Figure 69 are photos taken of LHE Zn-Ni and Cd plated components during the visual inspections.



Figure 64: LHE Zn-Ni plated component (9/22/2015)



Figure 65: LHE Zn-Ni Plated Component (6/29/2016)

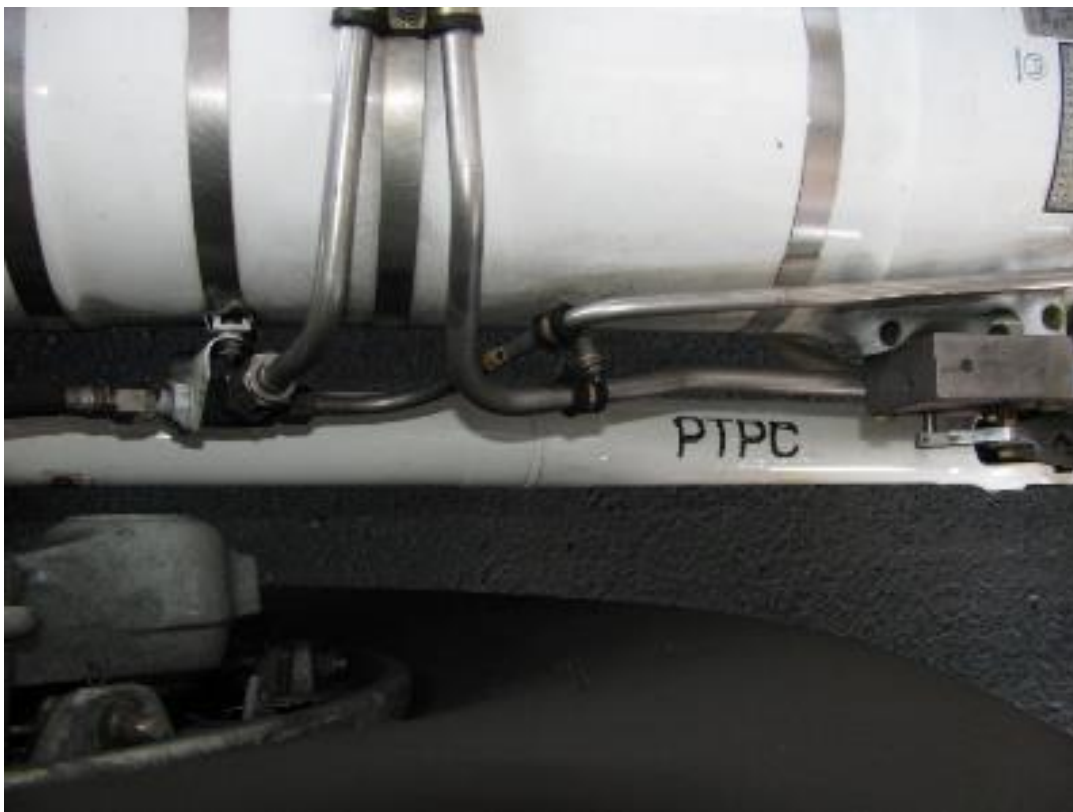


Figure 66: Cd Plated Component (9/22/2015)



Figure 67: Cd Plated Component (6/29/2016)



Figure 68: LHE Zn-Ni Plated Component (5/17/2017)



Figure 69: Cd Plated Component (5/17/2017)

6.1.5.7 BARBERS POINT US COAST GUARD AIR STATION – HAWAII (C-130)

RESULTS

LHE Zn-Ni and Cd components were installed on aircraft # 1716 on 27 August 2015. Annual visual inspections for corrosion and corrosion products were conducted on 23 September 2015, 28 June 2016, and 16 May 2017 LHE Zn-Ni components passed visual inspection on all occasions with no visible corrosion products similar to the cadmium components. Figure 70 - Figure 77 are photos taken of LHE Zn-Ni and Cd plated components during the visual inspections.



Figure 70: LHE Zn-Ni Plated Component (9/23/2015)



Figure 71: Cd Plated Component (9/23/2015)



Figure 72: LHE Zn-Ni Plated Component (6/28/2016)



Figure 73: Cd Plated Component (6/28/2016)



Figure 74: LHE Zn-Ni Plated Component (5/16/2017)



Figure 75: LHE Zn-Ni Plated Component (5/16/2017)



Figure 76: Cd Plated Component (5/16/2017)

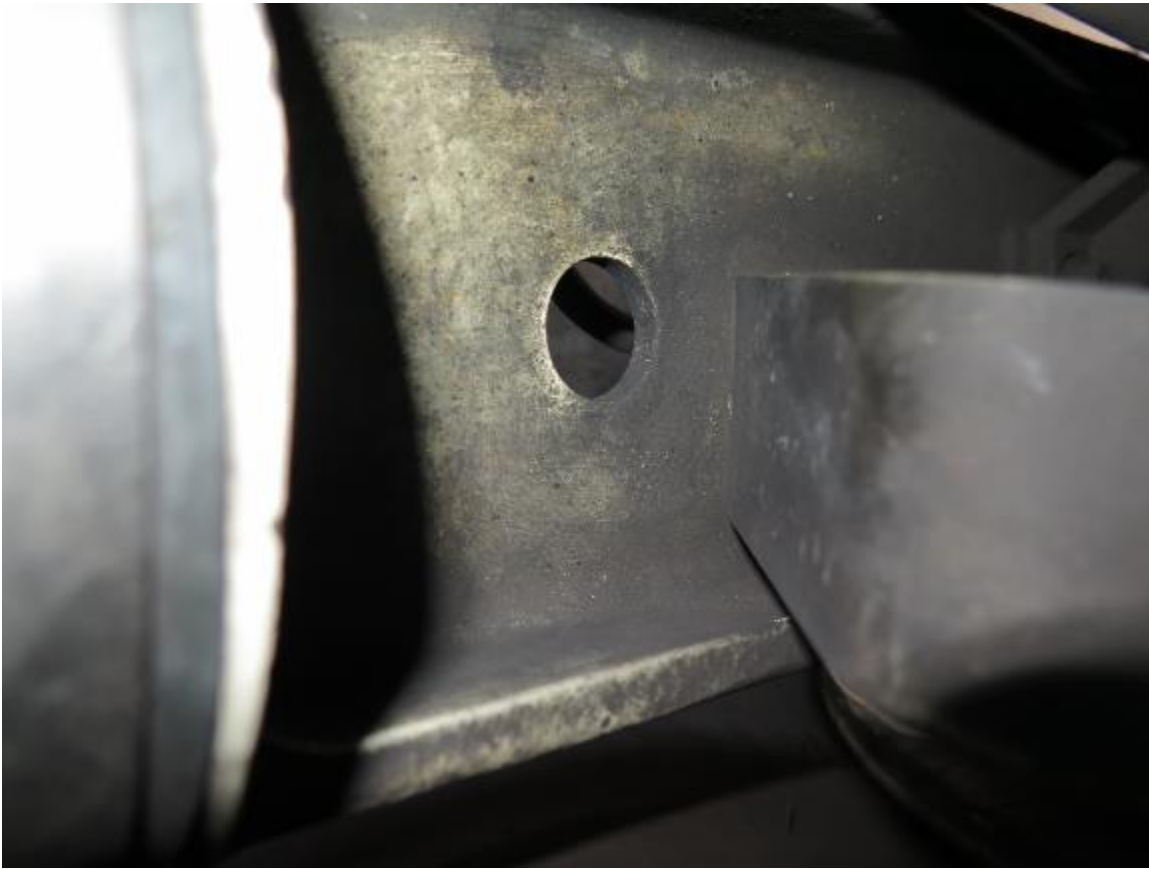


Figure 77: Cd Plated Component (5/16/2017)

6.1.5.8 MCENTIRE JOINT NATIONAL GUARD BASE – SOUTH CAROLINA

RESULTS

LHE Zn-Ni and Cd components were installed on aircraft # 92-902 on 16 December 2014. The first annual visual inspection occurred on 20 January 2015. A brake fire occurred before the second visual inspection and the components were removed and condemned. The condemned components were removed and shipped to ES3 where a visual inspection occurred on 16 April 2016. Prior to the brake fire, LHE Zn-Ni plated components passed visual inspections with no corrosion products similar to the cadmium components. LHE Zn-Ni appeared to be more robust in wear areas than cadmium. Figure 78 - Figure 86 are photos taken of LHE Zn-Ni and Cd plated components during the visual inspections.



Figure 78: LHE Zn-Ni and Cd plated components on installation (12/16/2014)



Figure 79: LHE Zn-Ni and Cd Plated Components (1/20/2015)



Figure 80: LHE Zn-Ni Component (1/20/2015)



Figure 81: LHE Zn-Ni Component (1/20/2015)



Figure 82: Cd Component (1/20/2015)



Figure 83: Brake Fire Inspection (4/16/2016)



Figure 84: LHE Zn-Ni Component Brake Fire Inspection (4/16/2016)



Figure 85: Cd Component Brake Fire Inspection (4/16/2016)



Figure 86: LHE Zn-Ni Component Brake Fire Inspection (4/16/2016)

6.1.6 FIELD CORROSION EVALUAION

6.1.6.1 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.

6.1.6.2 NASA

Components were placed at the Kennedy Space Center; NASA atmospheric corrosion tests site (Figure 87 - Figure 89) on 22 October 2014, with interim inspections on 13 July 2015, 26 August 2015, 24 May 2016, and 6 April 2017. A summary of parts and inspection descriptions can be seen in Table 5. Test subjects are located approximately 250 ft from the Atlantic Ocean and 1.6 miles away from a launch pad used for space shuttle. Photos from each inspection visit are located in the appendix.

Table 17: Florida Corrosion Test Summary

Test Component Installation Date: 10/22/2014		
Inspections		
Date	Part	Description
7/13/2015 264 days exposure	Cd Drag Brace (Painted)	Slight Corrosion products visible
	LHE Zn-Ni Drag Brace (Painted)	Visible rust/red corrosion products
	Cd Drag Brace	Slight white corrosion products
	LHE Zn-Ni Drag Brace	Slight white corrosion products
	Cd Rotational Collar	Slight white corrosion products
	LHE Zn-Ni Rotational Collar	Slight white corrosion products
8/26/2015 308 days exposure	Cd Drag Brace (Painted)	Slight Corrosion products visible
	LHE Zn-Ni Drag Brace (Painted)	Visible rust/red corrosion products
	Cd Drag Brace	Slight white corrosion products
	LHE Zn-Ni Drag Brace	White corrosion products
	Cd Rotational Collar	White corrosion products
	LHE 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
	LHE Zn-Ni Drag Brace (Painted)	Visible rust/red corrosion products
	Cd Drag Brace	Slight white corrosion products
	LHE Zn-Ni Drag Brace	White corrosion products
	Cd Rotational Collar	White corrosion products
	LHE 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
	LHE Zn-Ni Drag Brace (Painted)	Large amounts of rust/red corrosion products
	Cd Drag Brace	Slight white corrosion products
	LHE Zn-Ni Drag Brace	Moderate white corrosion products
	Cd Rotational Collar	Moderate white corrosion products
	LHE Zn-Ni Rotational Collar	Moderate white corrosion products



Figure 87: NASA Corrosion Site

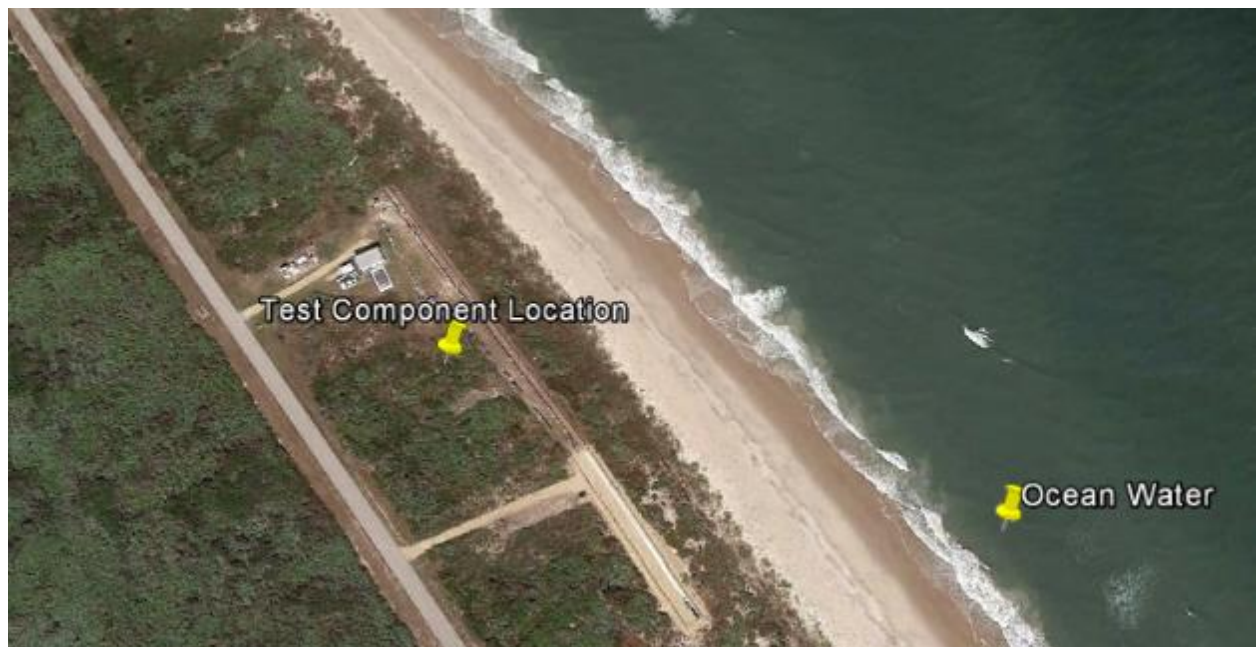


Figure 88: Google Earth Image of Part Location



Figure 89: Corrosion Testing Components at NASA Atmospheric Corrosion Test Site Install (10/22/2014)

6.1.6.3 EL SEGUNDO

Components were placed at the El Segundo atmospheric test site on 3 November 2014 (Figure 90 - Figure 93). Interim inspections were completed on 4 November 2015 and 18 January 2017. A summary of parts and inspection descriptions can be seen in Table 6. Parts were located on a Chevron refinery approximately 580 ft. from the Pacific Ocean. Photos from each inspection visit are located in the appendix.

Table 18: El Segundo Corrosion Test Summary

Test Component Installation Date: 11/3/2014		
Inspections		
Date	Part	Description
11/4/2015 366 days exposure	Cd Drag Brace (Painted)	Slight corrosion products
	LHE Zn-Ni Drag Brace (Painted)	Slight corrosion products
	Cd Drag Brace	Slight white corrosion products
	LHE Zn-Ni Drag Brace	Slight white corrosion products
	Cd Rotational Collar	Slight white corrosion products
	LHE Zn-Ni Rotational Collar	Slight white corrosion products
1/18/2017	Cd Drag Brace (Painted)	Small amount of rust on bushing

807 days exposure	LHE Zn-Ni Drag Brace (Painted)	Visible rust/red corrosion products
	Cd Drag Brace	Small amounts of white corrosion products
	LHE Zn-Ni Drag Brace	White corrosion products, small amount of rust on bushing
	Cd Rotational Collar	
	LHE Zn-Ni Rotational Collar	



Figure 90: El Segundo Corrosion Site

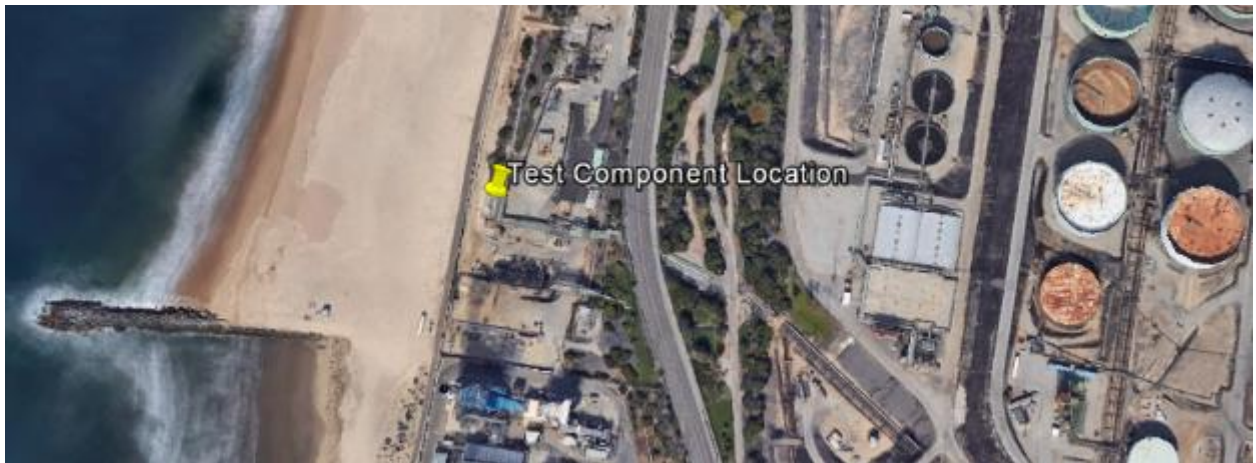


Figure 91: Google Earth Image of Test Component Location



**Figure 92: Corrosion Test Subjects on Installation LHE Zn-Ni Left, Cd Right
(11/3/2014)**



Figure 93: Corrosion Test Subjects on Installation (Cd, LHE Zn-Ni, Cd Painted, LHE Zn-Ni Painted) (11/3/2014)

6.1.6.4 WHIDBEY ISLAND

Components were placed at the Whidbey Island Corrosion Test Facility on 15 May 2014(Figure 94 & Figure 95). Interim inspections occurred on 13 May 2015 and 2 March 2016. A summary of parts and inspection descriptions can be seen in Table 7. Parts were located at Ault Field Naval Air Station approximately 130 ft from Pacific Ocean waters and approximately 0.25 miles from aircraft runways. Photos from each inspection visit are located in the appendix.

Table 19: Whidbey Island Corrosion Test Summary

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

3/2/2016 667 days exposure	LHE Zn-Ni Drag Brace (Painted)	Slight corrosion products
	Cd Drag Brace	Moderate white corrosion products
	LHE Zn-Ni Drag Brace	Moderate white corrosion products
	Cd Rotational Collar	Some white and red corrosion products/rust
	LHE Zn-Ni Rotational Collar	Some white corrosion products



Figure 94: Google Earth Image of Part Location



Figure 95: Cd and LHE Zn-Ni Plated Test Components at Whidbey Island on Installation (Top Left Cd Painted, Right LHE Zn-Ni Painted, Bottom Left Cd, Right LHE Zn-Ni) (05/14/2014)

6.1.6.5 KENNEDY SPCE CENTER, NASA PHOTOS

The first interim inspection visit occurred on 13 July 2015, 308 days after installation. The components were visually inspected and photographs were taken to document the condition.



Figure 96: LHE Zn-Ni Plated Drag Brace (7/13/2015)



Figure 97: Painted LHE Zn-Ni Plated Drag Brace (7/13/2015)



Figure 98: Cd Plated Drag Brace (7/13/2015)



Figure 99: Painted Cd Plated Drag Brace (7/13/2015)



Figure 100: Cd Plated Rotational Collar (7/13/2015)

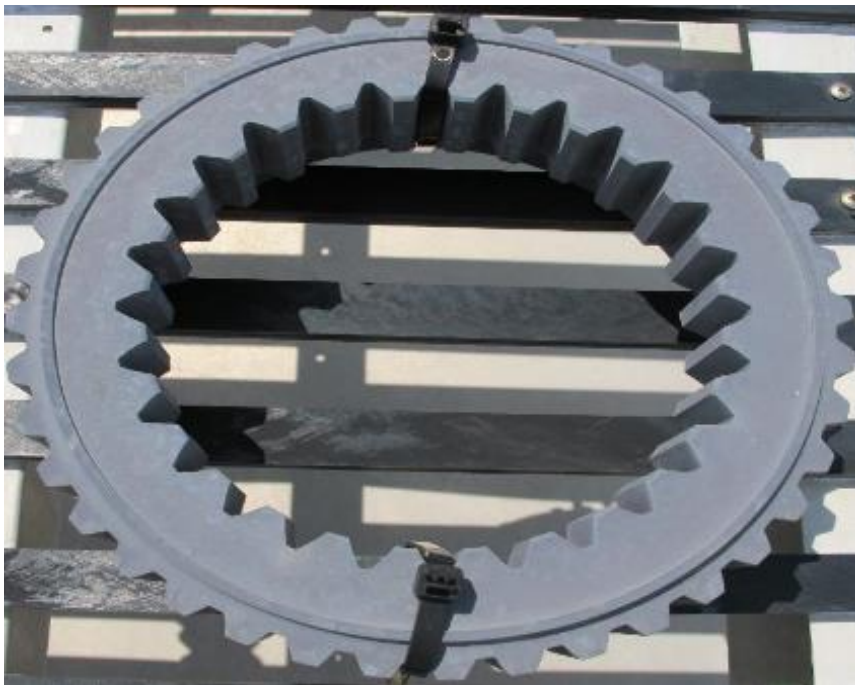


Figure 101: LHE Zn-Ni Plated Rotational Collar (7/13/2015)

An Interim site visit and inspection occurred on 26 August 2016 after 308 days of exposure. The components were visually inspected and photographs were taken to document the condition.



Figure 102: LHE Zn-Ni Plated Drag Brace (8/26/2015)



Figure 103: Painted LHE Zn-Ni Plated Drag Brace (8/26/2015)



Figure 104: LHE Zn-Ni Plated Drag Brace (8/26/2015)



Figure 105: Painted LHE Zn-Ni Plated Drag Brace (8/26/2015)



Figure 106: Cd Plated Drag Brace (8/26/2015)



Figure 107: Painted Cd Plated Drag Brace (8/26/2015)



Figure 108: Cd Plated Drag Brace (8/26/2015)



Figure 109: Painted Cd Plated Drag Brace (8/26/2015)



Figure 110: LHE Zn-Ni Plated Rotational Collar (8/26/2015)



Figure 111: Cd Plated Rotational Collar (8/26/2015)



Figure 112: LHE Zn-Ni Plated Rotational Collar (8/26/2015)



Figure 113: Cd Plated Rotational Collar (8/26/2015)

An Interim site visit and inspection occurred on 24 May 2016 after 580 days of exposure. The components were visually inspected and photographs were taken to document the condition.

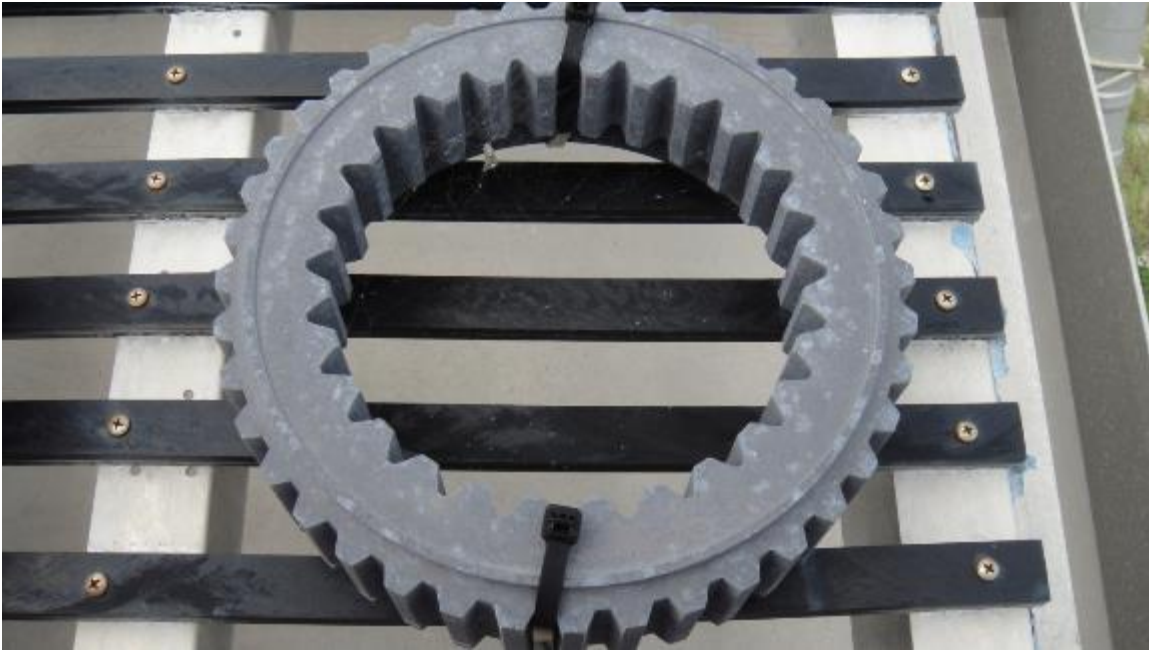


Figure 114: LHE Zn-Ni Plated Rotational Collar (8/26/2016)

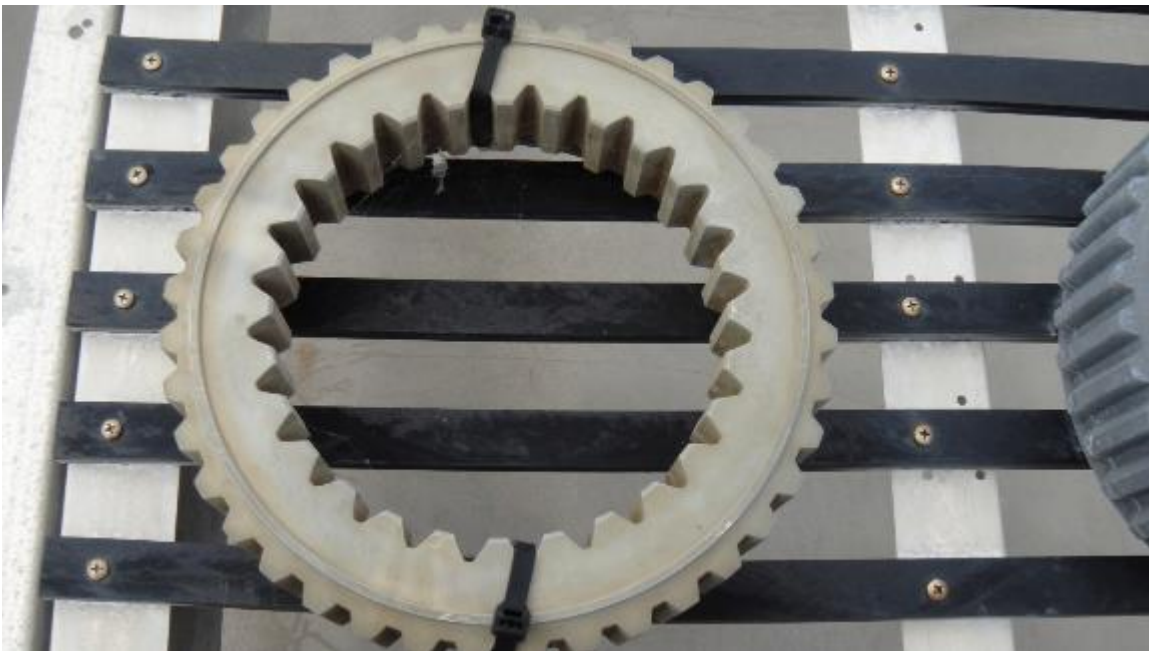


Figure 115: Cd Plated Rotational Collar (8/26/2016)



Figure 116: Cd Plated Drag Braces (8/26/2016)



Figure 117: LHE Zn-Ni Plated Drag Braces (8/26/2016)



Figure 118: LHE Zn-Ni Plated Drag Brace (8/26/2016)



Figure 119: Painted LHE Zn-Ni Plated Drag Brace (8/26/2016)



Figure 120: Cd Plated Drag Brace (8/26/2016)



Figure 121: Painted Cd Plated Drag Brace (8/26/2016)

An Interim site visit and inspection occurred on 6 April 2017, 817 days of exposure. The components were visually inspected and photographs were taken to document the condition.



Figure 122: Cd and LHE Zn-Ni Plated Drag Braces (4/6/2017)



Figure 123: LHE Zn-Ni Plated Drag Brace (4/6/2017)



Figure 124: Painted LHE Zn-Ni Plated Drag Brace (4/6/2017)



Figure 125: Cd Plated Drag Brace (4/6/2017)



Figure 126: Painted Cd Plated Drag Brace (4/6/2017)



Figure 127: Painted Cd Plated Drag Brace (4/6/2017)



Figure 128: Cd Plated Drag Brace (4/6/2017)



Figure 129: Painted LHE Zn-Ni Plated Drag Brace (4/6/2017)



Figure 130: LHE Zn-Ni Plated Drag Brace (4/6/2017)



Figure 131: Cd Plated Rotational Collar (4/6/2017)



Figure 132: Cd Plated Rotational Collar (4/6/2017)



Figure 133: LHE Zn-Ni Plated Rotational Collar (4/6/2017)



Figure 134: LHE Zn-Ni Plated Rotational Collar (4/6/2017)

6.1.6.6 EL SEGUNDO PHOTOS

The first Interim site visit and inspection occurred on 4 November 2015 after 366 days of exposure. The components were visually inspected and photographs were taken to document the condition.



Figure 135: El Segundo Corrosion Drag Braces (Cd Painted, LHE Zn-Ni Painted, Cd, LHE Zn-Ni) (11/4/2015)



Figure 136: Cd Plated Drag Brace (11/4/2015)



Figure 137: Cd (Far) and LHE Zn-Ni (Near) Painted Drag Braces (11/4/2015)



Figure 138: LHE Zn-Ni Plated Drag Brace (11/4/2015)



Figure 139: LHE Zn-Ni Plated Rotational Collar (11/4/2015)



Figure 140: Cd Plated Rotational Collar (11/4/2015)

An Interim site visit and inspection occurred on 18 January 2017 after 807 days of exposure. The components were visually inspected and photographs were taken to document the condition.



Figure 141: Painted Cd, Painted LHE Zn-Ni, Cd, and LHE Zn-Ni Plated Drag Braces (1/18/2017)



Figure 142: Painted Cd, Painted LHE Zn-Ni, Cd, and LHE Zn-Ni Plated Drag Braces (1/18/2017)



Figure 143: LHE Zn-Ni Plated Drag Brace (1/18/2017)



Figure 144: Cd Plated Drag Brace (1/18/2017)



Figure 145: Painted LHE Zn-Ni Plated Drag Brace (1/18/2017)



Figure 146: Painted Cd Plated Drag Brace (1/18/2017)



Figure 147: Cd Plated Drag Brace (1/18/2017)



Figure 148: LHE Zn-Ni Plated Drag Brace (1/18/2017)



Figure 149: LHE Zn-Ni (Left) and Cd (Right) Plated Rotational Collars (1/18/2017)

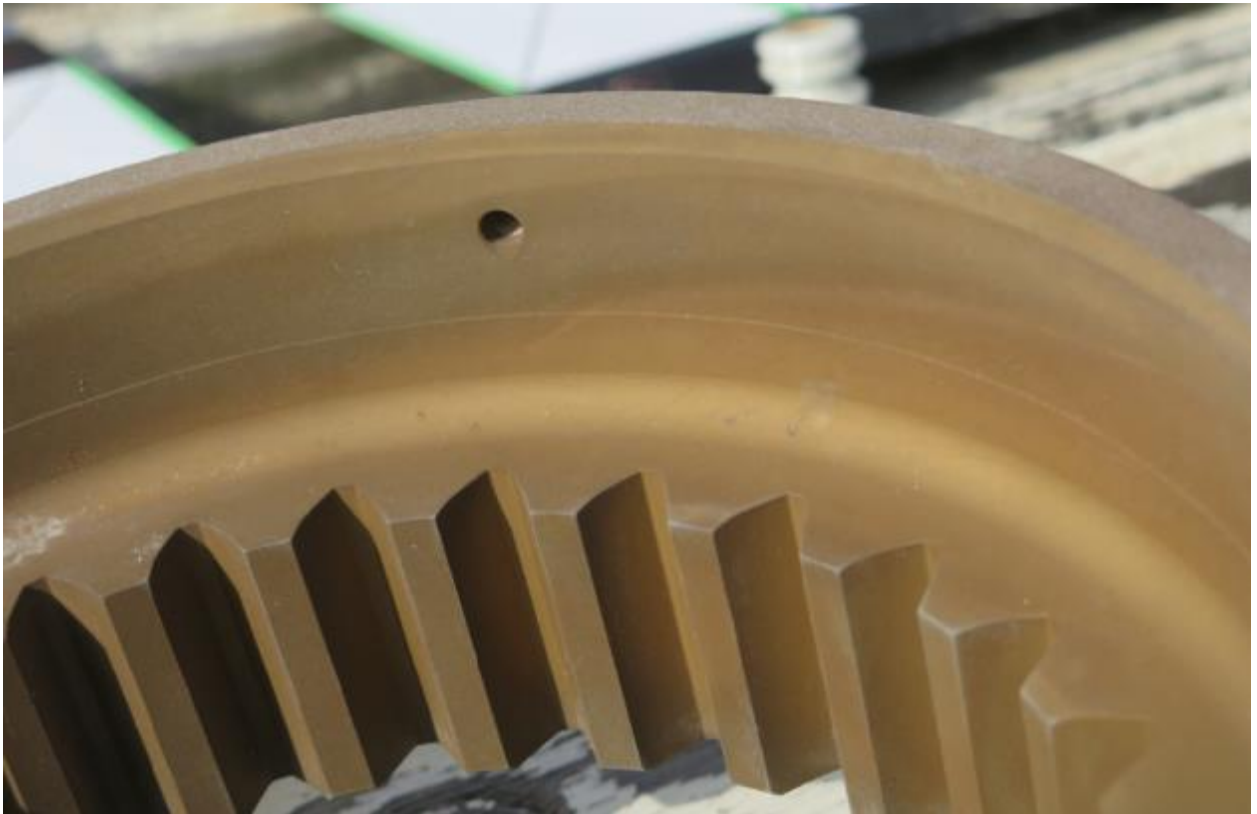


Figure 150: Cd Plated Rotational Collar (1/18/2017)



Figure 151: LHE Zn-Ni Plated Rotational Collar (1/18/2017)



Figure 152: LHE Zn-Ni Plated Rotational Collar (1/18/2017)



Figure 153: Cd Plated Rotational Collar (1/18/2017)

6.1.6.7 WHIDBEY ISLAND PHOTOS

The first interim site visit and inspection occurred on 13 May 2015 after 363 days. The components were visually inspected and photographs were taken to document the condition.



Figure 154: LHE Zn-Ni Plated Rotational Collar (5/13/2015)



Figure 155: LHE Zn-Ni Plated Rotational Collar (5/13/2015)



Figure 156: LHE Zn-Ni Plated Rotational Collar (5/13/2015)



Figure 157: Cd Plated Rotational Collar (5/13/2015)



Figure 158: Cd Plated Rotational Collar (5/13/2015)



Figure 159: Cd (left) and LHE Zn-Ni (right) Plated Drag Braces (5/13/2015)



Figure 160: Cd (left) and LHE Zn-Ni (right) Plated Drag Braces (5/13/2015)

An Interim site visit and inspection occurred on 2 March 2016 after 667 days. The components were visually inspected and photographs were taken to document the condition.



Figure 161: Drag Brace Test Subjects 3/2/2016



Figure 162: LHE Zn-Ni Plated Drag Brace (3/2/2016)



Figure 163: Painted LHE Zn-Ni Plated Drag Brace (3/2/2016)



Figure 164: Cd Plated Drag Brace (3/2/2016)



Figure 165: Painted Cd Plated Drag Brace (3/2/2016)



Figure 166: LHE Zn-Ni Plated Rotational Collar (3/2/2016)

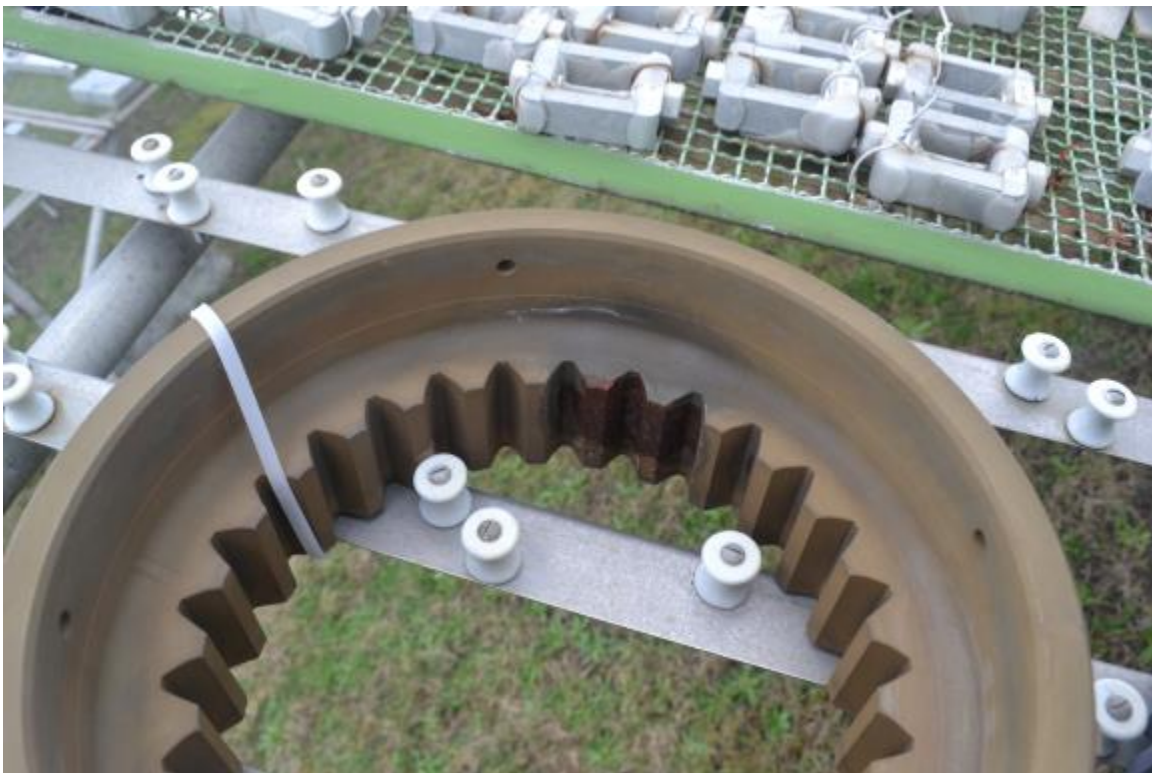


Figure 167: Cd Plated Rotational Collar (3/2/2016)

6.2 FINAL CONCLUSION

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. Additional studies involving de-zincification, hydrogen re-embrittlement and LHE Zn-Ni stripping were conducted.
- De-zincification was studied with Boeing Research & Technology. They found that accelerated or forced corrosion may start to cause de-zincification, however corrosion rates closer to actual corrosion in nature does not appear to have any impact on de-zincification. 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 salt water immersion test while Cd failed in less than 1 hour. Inspection of the Cd plated coupon under a microscope suggests that the notch may have not plated thick enough to protect the base material. Additional testing where the thickness of the notch plating is verified before testing is suggested.
- Stripping chemicals and procedures were experimented with for removing LHE Zn-Ni plating. Increasing the concentration of ammonium nitrate to 32 oz/gallon ammonium nitrate solution, which is currently used for stripping Cd, proved to be an acceptable method to remove the LHE Zn-Ni. Further testing is recommended to verify no unforeseen impacts from the higher concentrated solution. Success using the current Cd strip in conjunction with IVD strip has been achieved recently. Additional testing with this method and complex landing gear components is suggested.
- LHE Zn-Ni plated MLG components protected against corrosion as well 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 the F-16 brake fire, the test components were removed and condemned.
- The painted LHE 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 shown 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 LHE 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. The Non-Chrome paint system was qualified using aluminum samples, 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 Performance Tracking Program.

- The C-5 rotational collars located in Washington showed the most corrosion of un-painted test subjects. The Cd and LHE Zn-Ni collars were the only subjects to develop rust or red corrosion products. Un-painted drag braces and collars at all locations started to develop moderate white corrosion products after time.
- Subjects will continue to be monitored and inspected annually to help determine more conclusive results.

7.0 COST ASSESSMENT

7.1 COST MODEL

A standard cost basis analysis was developed on this project by OO-ALC/FMC team member, Dave Brinkerhoff. 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 cadmium plating to LHE Zn-Ni both operations run simultaneously to meet the need 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 has set a schedule to be transitioned from cadmium to LHE Zn-Ni by December 2017. During the interim the cost savings cannot be realized and quantified until after cadmium has been completely phased out of the overhaul facility.

Table 13 shows the cost associated with installation and start up of the LHE Zn-Ni plating line in the Start-Up column as well as a year cost for operation shown in the Operation & Maintenance column.

Table 20: Types of Costs by Category

Direct Environmental Activity			
Process Costs			
Start-Up		Operation & Maintenance	
Activity	\$	Activity	\$
Equipment purchase/Installation	1.3M	Labor to operate equipment	40k/yr
Equipment design	500k	Manage hazardous waste	10k/yr
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/yr
		Equipment maintenance	5k
Total Installation and Startup	2.037M	Total Yearly Operation Cost	151.7k/yr

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 each year required \$375,000. All of these maintenance costs could be eliminated due to the elimination of this process by implementation of LHE Zn-Ni.

8.0 IMPLEMENTATION ISSUES

Implementation of LHE Zn-Ni as a replacement for Cd is close to 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 to 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 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 in lieu of after as required by 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. Table 14 contains a list of commercial vendors that have installed or are currently installing LHE Zn-Ni plating lines following the successful demonstration of LHE Zn-Ni electroplating performance on HSS.

Table 21: Commercial Facilities

Company	Location	Company	Location
Hi-Tech Mtl Finishing	Denton, TX	ES3	Warner Robins, AL
DCI-Aerotech	Detroit, MI	Curtiss-Wright	Shelby, NC
Courter Hall	Garland, TX	UTAS	Oakville, ON, CA
Southwest United	Tulsa, OK	Hartwell Mfg	Cucamonga, CA
Omni Metal Finishing	Fountain Valley, CA	Installing Plating Lines	
Anoplate	Syracuse, NY	Ripak Aerospace	W. Babylon, NY
Tech Metals	Dayton, OH	Alcoa Fastening Systems	Torrance, CA

Art Brass Aerospace	Seattle, WA		Bristol Industries	Brea, CA
QC Plating	Ontario, CA		Embee	Santa Ana, CA
Metal Surfaces, Inc	Bell Gardens, CA		Electrolurgy	Irvine, CA
California Technical Plating	San Fernando, CA		Reid Metal Finishing	Santa Ana, CA
Moog Aircraft	Torrance, CA		Central Metal Finishing	N. Andover, MA
Heroux Devtek	Longueuil, QE, CA		QC Plating	Ontario, CA
Fitz Aerospace	N. Richland Hills, TX		SW United-Canada	Brampton, ON, CA

9.0 REFERENCES

Economic Analysis – Replace Cd Line G1110C – Hill AFB, UT, dated 1 December 2005

SBIR Phase I Engineering Report ER-9033-08-01; “Development of Alkaline Zinc Nickel Plating for USAF Landing Gear Application” Contract # FA8201-08-C-0054

SBIR Phase II Engineering Report 2008007-01; “Low Hydrogen Embrittlement LHE Zn-Ni SBIR Phase II” Contract # FA8201-07-C-0049