Low Hydrogen Embrittlement (LHE) Zn-Ni Plating Qualification and Implementation on Landing Gear Components

Dave Frederick
Craig Pessetto
Stephen Gaydos

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Report Documentation Page

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LHE Zn-Ni Partners

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STRENGTH AND HONOR
Primary Team Members

Ron Montgomery, GS-14, DAF
Chief Engineer, 417 SCMS/GUEA
Landing gear Systems
Comm: 801-777-7278

Chad Hogan, GS-14, DAF
Engineering Lead, 417 SCMS/GUEA
Landing gear Systems
Comm: 801-777-7278

David Frederick, GS-13, DAF
Lead Engineer, M&P, 417 SCMS/GUEA
Landing gear Systems
Comm: 801-777-7278

John Jusko, GS-13, DAF
SBIR Program Manager
Hill AFB
Comm: 801-586-2090

Ruth Schaefer, GS-12, DAF
Process Engineer
Hill AFB
Comm: 801-586-2128

Stephen Gaydos
Senior Technical Fellow
Boeing Research & Technology
314-233-3451

Tom Naguy, DR IV (GS-15)
Principle Program Manager AFRL/RXSC
Advance Power Technology Office (APTO) &
Environment and Energy RDT&E Program
Comm: 937-656-579

Bruce Sartwell
Weapons Systems and Platforms Program Manager
SERDP/ESTCP

Craig Pessetto
Chief Engineer Material Processes
ES3
801-928-2709

Kelly Smith
Project Engineer
ES3
801-926-1150

Joseph A. Martone, Ph.D., CIH, QEP, GS-13, DAF
Chief, Program Support Branch
75 CEG/CEVP
Comm: 801-775-3646

Chet Cragun, GS-12, DAF
Facilities Engineer
Hill AFB
Comm: 801-586-1535
Agenda

- Required Qualification Testing
- Questions/Answers of Original Phase II Fatigue Testing
- Additional Testing
- Specifications and Source Control Drawings
- Prototype Plating Line
- Component Corrosion Evaluation
- Performance Tracking Program
- Implementation of Large Scale Prototype LHE Zn-Ni Plating Line
Required Qualification Testing (Passed)

- Adhesion (ASTM B571) (Passed)
- Hydrogen Embrittlement (ASTM F519) (Passed)
- Re-embrittlement (ASTM F519 & USAF DWG 9825019) (All Failed)
- Liquid and Solid Metal Embrittlement (ASTM F519) (Passed)
- Fatigue (ASTM E466) (Passed)
- Corrosion (ASTM B117) (Passed)
- SO₂ Corrosion (ASTM G 85) (Did as well as Cadmium)
- Brush Plating for Repair of Damage LHE Zn-Ni Platings (Touch Up) (ASTM B117, ASTM B571 and ASTM F519) (Passed)
- Installation of small tank LHE Zn-Ni Prototype Line
Phase II Fatigue Testing

- Fatigue test were performed to evaluate the service life impacts associated with platings.
- Questions regarding the fatigue test program and interpretation of existing results to sufficiently characterize the service life impacts associated with LHE Zn-Ni plating in lieu of Cadmium plating were raised.
- 417 SCMS/GUEA Landing Gear Engineering Branch engaged the Landing Gear Design Industry to determine if the fatigue testing and test results per the following fatigue testing matrixes is adequate to approve the use of LHE Zn-Ni on HSS landing gear components.
Phase II Fatigue Testing

- All fatigue test data was included in the statistical analysis.
- A conservative approach was taken plating the Zn-Ni fatigue coupons:
  - All Zn-Ni fatigue coupons were plated thicker than cadmium fatigue coupons (typical thickness 0.0002 - 0.0006 inches).
  - The nickel content for Dipsol Zn-Ni IZ-C17+ was at the upper limit (18%) of the USAF 201027456 plating specification drawing.

<table>
<thead>
<tr>
<th>Average Plating Thickness</th>
<th>(Inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cadmium</td>
<td>0.00044</td>
</tr>
<tr>
<td>Dipsol Zn-Ni Tri CC</td>
<td>0.00091</td>
</tr>
<tr>
<td>Dipsol Zn-Ni Hex CC</td>
<td>0.00104</td>
</tr>
<tr>
<td>Atotech Zn-Ni Tri CC</td>
<td>0.00089</td>
</tr>
<tr>
<td>Atotect Zn-Ni Hex CC</td>
<td>0.00081</td>
</tr>
</tbody>
</table>
Phase II Fatigue Testing

- Boeing Commercial (SDT) group evaluated the LHE Zn-Ni fatigue data and saw nothing that would alter their conclusion of the acceptability of the use of LHE Zn-Ni on high strength steel landing gear components
  - Boeing Commercial has approved Atotech® LHE Zn-Ni for high strength steel and is currently installing a LHE plating line
  - Structural Design Team stated that only one stress ratio is necessary and testing at different R ratios will yield the same result.
- Dr. Andrew Halfpenny a fatigue expert, from HBN, reviewed the fatigue data and determined that the LHE Zn-Ni is a suitable drop in replacement for cadmium
Heroux-Devtek stress group evaluated the LHE Zn-Ni fatigue data and concluded it is acceptable for use on high strength steel landing gear components.

- Heroux-Devtek has approved LHE Zn-Ni for high strength steel and is currently installing a LHE plating line.
- Stress group stated that only one stress ratio is necessary and testing at different R ratios will yield the same result.

Boeing-Long Beach, structures group, would like to see additional testing (with more R ratios).

- Currently working with Boeing-Long Beach conduct more fatigue testing per their direction.
Additional Testing

- Corrosion Tests (Scribed Tests)
- Impact Tests (No further test information was required)
- Hydrogen Re-Embrittlement Tests
Questions about the original LHE Zn-Ni and Cd corrosion panels scribe processing

- It was determined that both types of panels were machined scribed.
- Many of the LHE Zn-Ni panels went over 5000 hours.
- Boeing machined scribed additional Zn-Ni and Cd panels and tested them per ASTM B117 for 1000 hours for a direct comparison.
- All the Zn-Ni plated panels passed the corrosion requirements called out in QQ-P-416 (no white corrosion products for 96 hours).
  - Results are shown in following slides below.
## Additional Corrosion Testing

### Table 1 - Machine vs. Carbide Scribed Corrosion Test

<table>
<thead>
<tr>
<th>Group No.</th>
<th>Test Specimen Identification</th>
<th>Plating Material</th>
<th>Conversion Coat Type</th>
<th>Plating Thickness (mils)</th>
<th>Primer + Topcoat</th>
<th>Type of Scribe</th>
<th>Test Duration**</th>
<th>Test Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>BC1</td>
<td>Zn-Ni</td>
<td>TriCr</td>
<td>0.6 +/- 0.15</td>
<td>Yes</td>
<td>Machined Scribe</td>
<td>1000 hrs</td>
<td>PASS</td>
</tr>
<tr>
<td></td>
<td>BC2</td>
<td>Zn-Ni</td>
<td>TriCr</td>
<td>0.7 +/- 0.1</td>
<td>Yes</td>
<td>Machined Scribe</td>
<td>1000 hrs</td>
<td>PASS</td>
</tr>
<tr>
<td></td>
<td>BC3</td>
<td>Zn-Ni</td>
<td>TriCr</td>
<td>0.7 +/- 0.1</td>
<td>Yes</td>
<td>Machined Scribe</td>
<td>1000 hrs</td>
<td>PASS</td>
</tr>
<tr>
<td>2</td>
<td>HC1</td>
<td>Zn-Ni</td>
<td>TriCr</td>
<td>0.8 +/- 0.2</td>
<td>Yes</td>
<td>Machined Scribe</td>
<td>1000 hrs</td>
<td>PASS</td>
</tr>
<tr>
<td></td>
<td>HC2</td>
<td>Zn-Ni</td>
<td>TriCr</td>
<td>0.8 +/- 0.1</td>
<td>Yes</td>
<td>Machined Scribe</td>
<td>1000 hrs</td>
<td>PASS</td>
</tr>
<tr>
<td></td>
<td>HC3</td>
<td>Zn-Ni</td>
<td>TriCr</td>
<td>0.8 +/- 0.2</td>
<td>Yes</td>
<td>Machined Scribe</td>
<td>1000 hrs</td>
<td>PASS</td>
</tr>
<tr>
<td>3</td>
<td>HC4</td>
<td>Cd</td>
<td>HexCr</td>
<td>0.8 +/- 0.05</td>
<td>Yes</td>
<td>Machined Scribe</td>
<td>1000 hrs</td>
<td>PASS</td>
</tr>
<tr>
<td></td>
<td>HC5</td>
<td>Cd</td>
<td>HexCr</td>
<td>0.7 +/- 0.1</td>
<td>Yes</td>
<td>Machined Scribe</td>
<td>1000 hrs</td>
<td>PASS</td>
</tr>
<tr>
<td></td>
<td>HC6</td>
<td>Cd</td>
<td>HexCr</td>
<td>0.5 +/- 0.1</td>
<td>Yes</td>
<td>Machined Scribe</td>
<td>1000 hrs</td>
<td>PASS</td>
</tr>
<tr>
<td>4</td>
<td>BS1</td>
<td>Zn-Ni</td>
<td>TriCr</td>
<td>0.8 +/- 0.05</td>
<td>No</td>
<td>Machined Scribe</td>
<td>1000 hrs</td>
<td>PASS</td>
</tr>
<tr>
<td></td>
<td>BS2</td>
<td>Zn-Ni</td>
<td>TriCr</td>
<td>0.7 +/- 0.05</td>
<td>No</td>
<td>Machined Scribe</td>
<td>1000 hrs</td>
<td>PASS</td>
</tr>
<tr>
<td></td>
<td>BS3</td>
<td>Zn-Ni</td>
<td>TriCr</td>
<td>0.8 +/- 0.05</td>
<td>No</td>
<td>Machined Scribe</td>
<td>1000 hrs</td>
<td>PASS</td>
</tr>
<tr>
<td>5</td>
<td>HS1</td>
<td>Zn-Ni</td>
<td>TriCr</td>
<td>0.8 +/- 0.1</td>
<td>No</td>
<td>Machined Scribe</td>
<td>1000 hrs</td>
<td>PASS</td>
</tr>
<tr>
<td></td>
<td>HS2</td>
<td>Zn-Ni</td>
<td>TriCr</td>
<td>0.8 +/- 0.05</td>
<td>No</td>
<td>Machined Scribe</td>
<td>1000 hrs</td>
<td>PASS</td>
</tr>
<tr>
<td></td>
<td>HS3</td>
<td>Zn-Ni</td>
<td>TriCr</td>
<td>0.8 +/- 0.1</td>
<td>No</td>
<td>Machined Scribe</td>
<td>1000 hrs</td>
<td>PASS</td>
</tr>
<tr>
<td>6</td>
<td>HS4</td>
<td>Cd</td>
<td>HexCr</td>
<td>0.8 +/- 0.1</td>
<td>No</td>
<td>Machined Scribe</td>
<td>1000 hrs</td>
<td>FAIL</td>
</tr>
<tr>
<td></td>
<td>HS5</td>
<td>Cd</td>
<td>HexCr</td>
<td>0.7 +/- 0.1</td>
<td>No</td>
<td>Machined Scribe</td>
<td>1000 hrs</td>
<td>FAIL</td>
</tr>
<tr>
<td></td>
<td>HS6</td>
<td>Cd</td>
<td>HexCr</td>
<td>0.8 +/- 0.1</td>
<td>No</td>
<td>Machined Scribe</td>
<td>1000 hrs</td>
<td>FAIL</td>
</tr>
<tr>
<td>7</td>
<td>BS4</td>
<td>Zn-Ni</td>
<td>None</td>
<td>0.8 +/- 0.1</td>
<td>No</td>
<td>No Scribe</td>
<td>1000 hrs</td>
<td>FAIL ****</td>
</tr>
<tr>
<td></td>
<td>BN1</td>
<td>Zn-Ni</td>
<td>None</td>
<td>0.7 +/- 0.1</td>
<td>No</td>
<td>No Scribe</td>
<td>1000 hrs</td>
<td>PASS ****</td>
</tr>
</tbody>
</table>

**** Group 7 test coupons were run without conversion coating and were not required to pass (i.e. information only)

BR&T ASTM B 117 Corrosion Test Results
BR&T IZ-C17+ Zn-Ni w/Tri CC
Scribed & Painted

336 hours
672 hours
1000 hours
Hill AFB IZ-C17+ Zn-Ni w/Tri CC Scribed & Painted

336 hours

672 hours

1000 hours
Hill AFB LHE Cd w/Hex CC
Scribed & Painted

336 hours

672 hours

1000 hours
BR&T IZ-C17+ Zn-Ni w/Tri CC Scribed

336 hours

672 hours

1000 hours
Hill AFB IZ-C17+ Zn-Ni w/Tri CC Scribed

336 hours

672 hours

1000 hours
Group 7 test coupons were run without conversion coating and were not required to pass (i.e. information only)
Additional Adhesion Testing
Gardner Impact Adhesion Tester
Additional Adhesion Testing
LHE Zn-Ni Adhesion Impact Test Result

Impact at 70 in-lbs
Additional Adhesion Testing
Garner Impact Testing: Zn-Ni

Specimen Zi Ni 4-7F
convex surface
Additional Adhesion Testing
Garner Impact Testing: Zn-Ni

Specimen Zn Ni 4-7F
concave surface
Additional Adhesion Testing
Cadmium Adhesion Impact Test Result

Impact at 70 in-lbs
Additional Adhesion Testing
Garner Impact Testing: Cadmium

Specimen CD – 1
convex surface
Additional Adhesion Testing
Garner Impact Testing: Cadmium

Specimen CD – 1
concave surface
Conclusion: Zn-Ni has good adhesion when tested by bend-to-break and impact test methods
Additional LHE Zn-Ni Hydrogen Re-Embrittlement Testing

- The original LHE Zn-Ni test coupons failed due to poor plating in notch
- The reason for the poor plating on the original LHE Zn-Ni 1a.1 re-embrittlement coupons are as follows:
  - LHE Zn-Ni tank contamination
    - Spring ‘09 Lab analysis showed organic contamination
    - The PVC tank liner had begun to break down and had to be replaced in the Summer ‘09 with a more robust grade of PVC liner
    - Two years operating with new liner with no problems
  - Inconsistent plating in notch area
    - Specimens were chained in series when they were plated for the first series of tests
    - Now a fixture and conformal anode is used to ensure that there is uniform plating throughout the notch area per production process specification
    - Also circulation has been added around the notch area during plating
Additional LHE Zn-Ni Hydrogen Re-Embrittlement Testing

Original Coupons Chained in Series

New fixture and Conformal Anode
Additional LHE Zn-Ni Hydrogen Re-Embrittlement Testing

Current plating with fixture and conformal anode

Contaminated plating chained in series
Additional LHE Zn-Ni Hydrogen Re-Embrittlement Testing

- Additional, 3.5% salt water, re-embrittlemnt testing was conducted on LHE Zn-Ni plated coupons and they all passed the ASTM 519-06 150 hour requirement.
- Cadmium and IVD Aluminum coupons were not re-tested because they are already approve for use on high strength steel.

<table>
<thead>
<tr>
<th>Plating</th>
<th>Distilled Water @ Room Temp Tested 45% NFS for 150Hrs</th>
<th>3.5% Salt Water @ Room Temp Tested 45% NFS for 150Hrs</th>
<th>Dwg 9825019° Diluted Calla 296 @ Max Temp 180°F Tested 75% NFS for 200Hrs</th>
<th>Dwg 9825019° Diluted Calla 602 LF Max Temp 160°F Tested 75% NFS for 200Hrs</th>
<th>Concentrated Calla 296 @ Room Temp tested 45% NFS for 150Hrs</th>
<th>Concentrated Calla 602LF @ Room Temp tested 45% NFS for 150Hrs</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHE Zn-Ni</td>
<td>Passed</td>
<td>Passed</td>
<td>Passed</td>
<td>Passed</td>
<td>Passed</td>
<td>Passed</td>
</tr>
<tr>
<td>Cadmium</td>
<td>Passed</td>
<td>Failed</td>
<td>Passed</td>
<td>Passed</td>
<td>Passed</td>
<td>Passed</td>
</tr>
<tr>
<td>IVD</td>
<td>Failed</td>
<td>Failed</td>
<td>Not Tested</td>
<td>Not Tested</td>
<td>Not Tested</td>
<td>Not Tested</td>
</tr>
</tbody>
</table>

*The specimens were immersed in the cleaning compound at the manufacturer’s maximum recommended temperature, and appropriate cleaning concentration, for 30 minutes. Removed. Air dried and loaded to 75% NFS for 200Hrs.*
Due to the inconsistent test results of ASTM 519 re-embrittlenent tests, the ASTM 519 committee no longer approves the use of this test for new coatings or platings.

It was originally designed to test new maintenance fluids on cadmium plated components:
- Basically, the maintenance fluids had to have corrosion inhibitors in them so that they would perform better than water during the 45% UTS notch fracture strength testing.

Army Research Labs, BR&T and 417 SCMS/GUEA are currently developing a new re-embrittlenent test for coatings and plating.
De-Zincification Testing

- Questions have been raised about the potential impact of dezincification of the Zn-Ni plating.
- 417 SCMS/GUEA, BR&T and ES3 are currently reviewing past industry de-zincification studies.
  - Initial findings show that the corrosion electro-potential is consistent throughout the corrosion process.
- 417 SCMS/GUEA, BR&T and ES3 will identify any addition testing that might be required to address dezincification.
Low Hydrogen Embrittlement Plating Process Specification Zinc - Nickel
Phase III Effort
Prototype Process Line

<table>
<thead>
<tr>
<th>Component</th>
<th>Part #</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-5 MLG Stop Plate</td>
<td>4G11453-101B</td>
</tr>
<tr>
<td>F-15 MLG Outer Cylinder</td>
<td>68A412702-1001/1002</td>
</tr>
<tr>
<td>B-1 MLG Axle</td>
<td>1881B85</td>
</tr>
<tr>
<td>F-15 MLG Lower Drag Brace</td>
<td>68A410792-2001</td>
</tr>
<tr>
<td>A-10 MLG Torque Arm</td>
<td>19046-1</td>
</tr>
<tr>
<td>F-16 NLG Inner Cylinder</td>
<td>2007644-103</td>
</tr>
<tr>
<td>C-5 MLG Rotation Collar</td>
<td>4G13565-101A/-101B</td>
</tr>
<tr>
<td>A-10 NLG Axle</td>
<td>18800-3</td>
</tr>
</tbody>
</table>

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Phase III Effort
Solid Model Prototype Parts

A-10 NLG Axle
A-10 MLG Torque Arm
Phase III Effort
Solid Model Prototype Parts

B-1 MLG Axle
C-5 MLG Rotation Collar
Phase III Effort
Solid Model Prototype Parts

F-15 MLG Cylinder
F-16 NLG Inner Cylinder
F-15 MLG Lower Drag Brace

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LHE Zn-Ni Plating Process

Prototype LHE Zn-Ni Plating Tank

Prototype Tri-Chromium Conversion Coating Tank
Prototype Conformal Anode & Fixture Design

LHE Zn-Ni Plated MLG Axle
MLG Axle Plating

MLG Axle before Fixture
MLG Axle with Fixture

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MLG Axle after LHE Zn-Ni Plating

MLG Axle Finished Plated Outer Diameter

MLG Axle Finished Plated Inner Diameter

BE AMERICA'S BEST
STRENGTH AND HONOR
LHE Zn-Ni Plating – Ph III (FY 12)
Component Corrosion Eval. (Whidbey Island)

F-15 MLG Lower Drag Brace
C-5 MLG Rotation Collar

Parts Placed 10/13/2010, Pictures taken 7/24/2012
LHE Zn-Ni Plating – Ph III (FY 12)
Component Corrosion Eval. (Whidbey Island)

F-15 MLG Lower Drag
Brace CAD

F-15 MLG Lower Drag
Brace Zn-Ni
LHE Zn-Ni Plating – Ph III (FY 12)
Component Corrosion Eval. (Whidbey Island)

C-5 MLG Rotation Collar
C-5 MLG Rotation Collar
CAD
Zn-Ni

BE AMERICA'S BEST
STRENGTH AND HONOR
LHE Zn-Ni Plating – Ph III (FY 12)
Component Corrosion Eval. (Cape Kennedy)

F-15 MLG Lower Drag Brace
C-5 MLG Rotation Collar

Parts Placed 9/30/2010, Pictures taken 8/07/2012
LHE Zn-Ni Plating – Ph III (FY 12)
Component Corrosion Eval. (Cape Kennedy)

F-15 MLG Lower Drag
Brace CAD

BE AMERICA'S BEST
STRENGTH AND HONOR
LHE Zn-Ni Plating – Ph III (FY 12)
Component Corrosion Eval. (Cape Kennedy)

C-5 MLG Rotation Collar
CAD

C-5 MLG Rotation Collar
Zn-Ni
LHE Zn-Ni Performance Tracking Program (PTP)

- Criteria for part selection
  - Fixture Completed
  - 2 to 3 Parts from each Weapon System (NLG & MLG)
  - Ease of access to component on aircraft
  - Air Force Base
    - Location
    - Corrosive Environment
  - Overhauled at Hill AFB
## LHE Zn-Ni Performance Tracking Program (PTP) Components

<table>
<thead>
<tr>
<th>Weapon System</th>
<th>Component</th>
<th>BASE 1</th>
<th>BASE 2</th>
<th>BASE 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-130</td>
<td>MLG TORQUE STRUT AFT P/N 388066-3</td>
<td>Kadena AB AFSOC</td>
<td>Hurlburt, FL ACTIVE</td>
<td></td>
</tr>
<tr>
<td>C-130</td>
<td>MLG TORQUE STRUT FWD P/N 388065-3</td>
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<tr>
<td>F-15</td>
<td>MLG LOWER DRAG BRACE 68A410792-2001</td>
<td>Kadena AB PACAF</td>
<td>Jacksonville, FL ANG</td>
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<td>KC-135</td>
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<td>Hickam AFB, HI ANG</td>
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<tr>
<td>KC-135</td>
<td>MLG BRAKE COLLAR P/N 8853035-05</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**NOTE:** Bases with multiple aircraft systems are highlighted in color.
C-130 Main Landing Gear
PTP Components
F-15 Landing Gear  PTP
Components

MLG PISTON

MLG LOWER DRAG BRACE
F-16 Landing Gear PTP Components

MLG TENSION STRUT

MLG DRAG BRACE

MLG COLLAR
KC-135 Landing Gear
PTP Components
PROPOSED Zn-Ni PLATING LINE
TANK REQUIREMENTS

NORTH

WEST END
Zn-Ni PLATING
1ST RINSE
2ND RINSE
ACID ACTIVATOR
RINSE
CONVERSION COAT
RINSE
EAST END
LHE Zn-Ni Prototype Plating Line Tank Drawing
LHE Zn-Ni Prototype Plating Line
Rectifier Controller

NOTES:
1. REMOTE PANEL TO CONTAIN TOUCHPADS FOR ALL 3 RECTIFIER UNITS
2. ALL 3 TOUCHPADS TO USE FAB-7-731100001
3. REMOTE ENCLOSURE TO BE WALL-MOUNTABLE
4. REMOTE CONTAINS 1 FRONT HINGED DOORS
Removal of Oven 3 for LHE Zn-Ni Prototype Plating

Before, view from plating line

After, view from basement
LHE Zn-Ni Prototype Line Installation/Demolition
Questions
Back Up Slides: Phase II Qualification Testing
ES3 has implemented a tank of approximately 325 gallons for the purpose of demonstrating the LHE Zn-Ni plating process on some full sized gear components.

The demonstration tank was used to develop uniform plating thicknesses and process parameters on test coupons and full scale landing gear components.

During the plating operations, Quality Assurance testing has been conducted to ensure the alkaline LHE Zn-Ni solution is within proper process limits.
Prototype Tank Implementation

Tri-Chromium Conversion Coat Tank
Bend to Break Adhesion Test Coupons

- Adhesion of the LHE Zn-Ni coating to the substrate was tested per ASTM B571
- All adhesion test coupons were manufactured from 1”x 4”x 0.040” 4130 steel sheet
- Results: All Test coupons passed
LHE Zn-Ni Test Panels After Dry and Wet Tape Adhesion Test of Primer (Passed)

Deft 44-GN-072

Deft 44-GN-098
# Dry and Wet Paint Adhesion Test Results per ASTM D3359 (Passed)

## Scribed Dry and Wet Tape Adhesion Test Results

<table>
<thead>
<tr>
<th>PANEL</th>
<th>ID</th>
<th>PRETREATMENT</th>
<th>COATING</th>
<th>DRY TAPE ADHESION</th>
<th>WET TAPE ADHESION</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>LHE Zn-Ni Plating</td>
<td>Deft 44-GN-72</td>
<td>0</td>
<td>5A</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>Cd Plated w/ Hex Cr Conversion Coating</td>
<td>Deft 44-GN-72</td>
<td>0</td>
<td>5A</td>
</tr>
<tr>
<td>1</td>
<td>3</td>
<td>LHE Zn-Ni Plating</td>
<td>Deft 44-GN-008</td>
<td>0</td>
<td>5A</td>
</tr>
<tr>
<td>1</td>
<td>4</td>
<td>Cd Plated w/ Hex Cr Conversion Coating</td>
<td>Deft 44-GN-008</td>
<td>0</td>
<td>5A</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>LHE Zn-Ni Plating</td>
<td>Deft 44-GN-72</td>
<td>0</td>
<td>5A</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>Cd Plated w/ Hex Cr Conversion Coating</td>
<td>Deft 44-GN-72</td>
<td>0</td>
<td>5A</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>LHE Zn-Ni Plating</td>
<td>Deft 44-GN-008</td>
<td>0</td>
<td>5A</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>Cd Plated w/ Hex Cr Conversion Coating</td>
<td>Deft 44-GN-008</td>
<td>0</td>
<td>5A</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>LHE Zn-Ni Plating</td>
<td>Deft 44-GN-72</td>
<td>0</td>
<td>5A</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>Cd Plated w/ Hex Cr Conversion Coating</td>
<td>Deft 44-GN-72</td>
<td>0</td>
<td>5A</td>
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<td>Deft 44-GN-008</td>
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<td>4</td>
<td>Cd Plated w/ Hex Cr Conversion Coating</td>
<td>Deft 44-GN-008</td>
<td>0</td>
<td>5A</td>
</tr>
</tbody>
</table>

### Notes:
- Panels immersed in distilled water at room temperature for 24 hours.
- [1]: ASTM D3359 Criteria:
  - 5A - No peeling or removal
  - 4A - Trace peeling or removal along incisions
  - 3A - Jagged removal along incisions up to 1/16 inch on either side
  - 2A - Jagged removal along most of incisions up to 1/8 inch on either side
  - 1A - Removal from most of the area of the “X” under the tape
  - 0A - Removal beyond the area of the “X” under the tape
- [2]: The primer shall show no adhesion failure.
LHE Zn-Ni Hydrogen Embrittlement Testing

- Coupons manufactured per ASTM F519 specifications (4340)
- Coupons plated and tested 28th April, 2009 upon initial installment of LHE Zn-Ni demonstration tank
- Additional coupons plated and tested at additional dates
- All coupons tested per ASTM F519 and passed the 200 hour sustained load tests @ 75% of the tensile notch fracture strength

ASTM F519 Type 1A.1 Test Coupons
HE Plated Cross Section

Cad Plated in Bldg 505 for 5 mins - 200x

.274 mils

.772 mils
LHE Zn-Ni Plated @ 40 ASF for 20 mins - 200x
LHE Zn-Ni Hydrogen
Re-Embrittlement Testing

LHE Zn-Ni Re-Embrittlement Testing Machine
Original LHE Zn-Ni Hydrogen Re-Embrittlement Testing

Re-Embrittlement results:

- Coupons tested by an ISO 9001 certified facility. Coupons tested IAW ASTM F519.
  - The coupons tested immersed in solutions of Water, 3.5% Salt Water, Dilute* Calla 296, Dilute* Calla 602LF, Concentrated Calla 296, and Concentrated Calla 602LF.
  - *NOTE – *Dilute means mix cleaning solution to manufacturer’s recommended use concentration and heat to manufacturer’s maximum recommended use temperature.

- Cleaning solutions used in testing were:
  - Calla 296
  - Calla 602LF
- LHE Zn-Ni performs better than IVD and as well as Cad

*The specimens were immersed in the cleaning compound at the manufacturer's maximum recommended temperature, and appropriate cleaning concentration, for 30 minutes. Removed. Air dried and loaded to 75% NFS for 200Hrs.

Re-Embrittlement Test Matrix

<table>
<thead>
<tr>
<th>Plating</th>
<th>Test Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Distilled Water @ Room Temp Tested 45% NFS for 150Hrs</td>
</tr>
<tr>
<td>LHE Zn-Ni</td>
<td>Pass</td>
</tr>
<tr>
<td>Cadmium</td>
<td>Pass</td>
</tr>
<tr>
<td>IVD</td>
<td>Failed</td>
</tr>
</tbody>
</table>
Liquid/Solid Metal Embrittlement Testing

LHE Zn-Ni Plated and Cad Plated 300M Type 1a.1 Test Specimens in Self-Loading Bend Frames
Liquid/Solid Embrittlement Testing

Liquid and Solid Metal Embrittlement (LME and SME) occur when one metal, either as a liquid or solid, intrudes into the structure of another, potentially causing embrittlement in the base metal.

Melting points for the coating metals are as follows:
- Cadmium ~610°F
- Zinc ~787°F
- Nickel ~2650°F

<table>
<thead>
<tr>
<th>Temp/NFS</th>
<th>Material</th>
<th>Zn-Ni 200Hr</th>
<th>Cad 200Hr</th>
<th>Zn-Ni Step Load</th>
<th>Cad Step Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>600F/85%</td>
<td>300M</td>
<td>Pass</td>
<td>Fail</td>
<td>100% NFS</td>
<td>-N/A-</td>
</tr>
<tr>
<td>500F/85%</td>
<td>300M</td>
<td>Pass</td>
<td>Fail</td>
<td>100% NFS</td>
<td>87% NFS</td>
</tr>
<tr>
<td>400F/85%</td>
<td>300M</td>
<td>Pass</td>
<td>Fail</td>
<td>100% NFS</td>
<td>91% NFS</td>
</tr>
<tr>
<td>400F/75%</td>
<td>300M</td>
<td>Pass</td>
<td>Fail</td>
<td>100% NFS</td>
<td>81% NFS</td>
</tr>
</tbody>
</table>
Liquid/Solid Metal Embrittlement Testing

LHE Zn-Ni and Cad Type 1a.1 Specimens After ISL Test to Determine the NFS After Exposure to 400°F for 200 Hours
Fatigue Testing

- Phase II LHE Zn-Ni fatigue testing is an extension of Phase I work
- Phase II LHE Zn-Ni fatigue testing continues to broaden the data base and increase the statistical validity of the data
- Manufacturing of coupons and Fatigue Testing IAW ASTM E466
  - All coupons were plated per manufacture’s plating solution limits
Phase I Fatigue Testing
(Shotpeened Coupons)

C-17 P2 Program Fatigue Data
(IZ-C17 with Hex conversion coating)

![Graph showing fatigue test data for Zinc-Nickel Plated and Cad Plated samples with cycles to failure and maximum stress](image-url)
## Phase II Fatigue Testing

### UnPeened Coupons

<table>
<thead>
<tr>
<th>Stress Loads (KSI) R= -0.3</th>
<th>Total Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>120</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Material Type</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bare</td>
<td>15</td>
</tr>
<tr>
<td>Cad Plated</td>
<td>15</td>
</tr>
<tr>
<td>LHE Zn-Ni Plated Tri CC</td>
<td>15</td>
</tr>
<tr>
<td>LHE Zn-Ni Plated Hex CC</td>
<td>15</td>
</tr>
<tr>
<td>*Zn-Ni Plated Atotech Tri CC</td>
<td>15</td>
</tr>
<tr>
<td>Zn-Ni Plated Atotech Hex CC</td>
<td>15</td>
</tr>
<tr>
<td>Spares</td>
<td>15</td>
</tr>
<tr>
<td>Total</td>
<td>120</td>
</tr>
</tbody>
</table>

* Bake before Tri CC

### Peened Coupons

<table>
<thead>
<tr>
<th>Stress Loads (KSI) R= -0.3</th>
<th>Total Quantity</th>
</tr>
</thead>
<tbody>
<tr>
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<td>120</td>
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</tbody>
</table>

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<td>Bare</td>
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</tr>
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<td>*Zn-Ni Plated Atotech Tri CC</td>
<td>15</td>
</tr>
<tr>
<td>Zn-Ni Plated Atotech Hex CC</td>
<td>15</td>
</tr>
<tr>
<td>Spares</td>
<td>15</td>
</tr>
<tr>
<td>Total</td>
<td>120</td>
</tr>
</tbody>
</table>

* Bake before Tri CC
Phase II Fatigue Testing

Means Compared @ 95% limits: 200 ksi Unpeened

2 groups have means significantly different from Cad
Phase II Fatigue Testing

Means Compared @ 95% limits: 180 ksi Unpeened

No groups have means significantly different from Cad.
Phase II Fatigue Testing

Means Compared @ 95% limits: 160 ksi Unpeened

No groups have means significantly different from Cad x 10^5.
Phase II Fatigue Testing

Peened Fatigue Coupon Test Results

Test Load (KSI)
R = -0.3

Number of Cycles

- Bare
- Cad
- Zn-Ni Tri CC (Dipsol)
- Zn-Ni Hex CC (Dipsol)
- Zn-Ni Tri CC (Atotech)
- Zn-Ni Hex CC (Atotech)
Phase II Fatigue Testing

Means Compared @ 95% limits: 200 ksi Peened

- The means of groups Cad and bare are significantly different

- Bare: 70542
- Cad: 33104
- ZnNi3: 26275
- ZnNi6: 30496
- Atot3: 33482
- Atot6: 31037
Phase II Fatigue Testing

Means Compared @ 95% limits: 180 ksi Peened

No groups have means significantly different from Cad.
Phase II Fatigue Testing

Means Compared @ 95% limits: 160 ksi Peened

No groups have means significantly different from Cad.
Corrosion Performance

- Corrosion tests were conducted on LHE Zn-Ni coupons with cadmium as the baseline.
- Testing was also performed on both cadmium and LHE Zn-Ni coated coupons with a prime/paint topcoat after being scribed (See Table below). All test coupons were 4”x 6”x 0.040” 4130 steel sheet.
- All testing was performed per ASTM B117.
- Test specimens were both scribed and un-scribed.

Corrosion Test Matrix

<table>
<thead>
<tr>
<th># of steel Panels</th>
<th>Plating</th>
<th>Scribed</th>
<th>Prime/Paint</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>LHE Zn-Ni</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>3</td>
<td>LHE Zn-Ni</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>3</td>
<td>Cd</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>3</td>
<td>Cd</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>3</td>
<td>LHE Zn-Ni</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>3</td>
<td>Cd</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Corrosion Performance

Test Panel Removed From Salt Spray Cabinet – Excess Amount of Red Rust Detected

Test Panel Removed From Salt Spray Cabinet – Excess Amount of Red Rust Detected

Test Panel Removed From Salt Spray Cabinet – Excess Amount of Red Rust Detected

Test Panel Removed From Salt Spray Cabinet – Excess Amount of Red Rust Detected

Test Panel Removed From Salt Spray Cabinet – Excess Amount of Red Rust Detected

Test Panel Removed From Salt Spray Cabinet – Excess Amount of Red Rust Detected

Cadmium Coatings – Phase II ASTM B 117 Panels @ Boeing Unscribed

BE AMERICA'S BEST             STRENGTH AND HONOR
Corrosion Performance

IZ-C17+ Zn-Ni with Trivalent Chrome Conversion Coating
Unscribed – ASTM B 117

Figure 4

LHE Zinc Nickel Coatings – Phase II ASTM B 117 Panels @ Boeing (Unscribed)
Corrosion Performance

Cadmium Coatings – Phase II ASTM B 117 Panels @ Boeing (Scribed)

Test Panel Removed From Salt Spray Cabinet – Excess Amount of Red Rust Detected

Test Panel Removed From Salt Spray Cabinet – Excess Amount of Red Rust Detected

Test Panel Removed From Salt Spray Cabinet – Excess Amount of Red Rust Detected

1000 hours

3000 hours

5000 hours

Cadmium with Hexavalent Chrome Conversion Coating Scribed – ASTM B 117

Figure 5

BE AMERICA'S BEST

STRENGTH AND HONOR
Corrosion Performance

LHE Zinc Nickel Coatings – Phase II ASTM B 117 Panels @ Boeing (Scribed)

IZ-C17+ Zn-Ni with Trivalent chrome conversion coating
Scribed – ASTM B 117

Figure 6

1000 hours
3000 hours
5000 hours
Corrosion Performance

Cadmium Coatings – Phase II ASTM B 117 Panels @ Boeing (Painted/Scribed)

Cadmium with Hexavalent Chrome Conversion Coating

Test Panel Removed From Salt Spray Cabinet – Excess Amount of Red Rust Detected

Test Panel Removed From Salt Spray Cabinet – Excess Amount of Red Rust Detected

Test Panel Removed From Salt Spray Cabinet – Excess Amount of Red Rust Detected

Test Panel Removed From Salt Spray Cabinet – Excess Amount of Red Rust Detected

1000 hours

3000 hours

5000 hours

Figure 9
Corrosion Performance

IZ-C17+ Zn-Ni with Trivalent Chrome Conversion Coating
Scribed Painted – ASTM B 117

LHE Zinc Nickel Coatings – Phase II ASTM B 117 Panels @ Boeing (Painted/Scribed)

Figure 10

Test Panel Removed From Salt Spray Cabinet – Excess Amount of Red Rust Detected

1000 hours
3000 hours
5000 hours

BE AMERICA’S BEST               STRENGTH AND HONOR
Brush Plating Repair

- In order for a brush LHE Zn-Ni plating to qualify, it must pass the following tests:
  - Hydrogen Embrittlement (HE) testing per ASTM F519
  - Bend to break adhesion test per ASTM B571
  - Corrosion testing per ASTM B117
- SIFCO recommended procedures were used to plate several sets of HE type 1a.1 coupons, adhesion coupons, and corrosion coupons, using SIFCO 4018 No Bake LHE Zn-Ni brush plating solution
- Test Results Summary:
  - Passed HE testing
  - Passed adhesion testing on steel and LHE Zn-Ni plated steel
  - Corrosion test performance is excellent
Torque Tension

- Robins AFB Cad plating replacement on threaded fastener and components
- Typical chart for run on – break away test showing Cad vs. LHE Alkaline Zn-Ni

![Typical Run-On & Breakaway Torque - Cad Bare](chart1)

![Typical Run-On & Breakaway Torque - Zn-Ni Bare](chart2)
Torque Tension

- Robins AFB Cad plating replacement on threaded fastener and components
  - Typical chart for Torque Tension Test showing Cad vs. LHE Alkaline Zn-Ni with MIL-PRF-83483 Anti-seize grease lubricant
Back Up Slides:
Zn-Ni Conformal Anode Fixtures
Phase III Effort
Prototype Anode Design

MLG Rotation Collar
Phase III Effort
Prototype Anode Design

NLG Axle
LHE Zn-Ni Plating Conformal Anode and Fixture Models

NLG Outer Cylinder

MLG Lower Side Brace
LHE Zn-Ni Conformal Anode and Fixture Models

MLG Outer Cylinder
LHE Zn-Ni Plating Conformal Anode and Fixtures Models

MLG Torque Arm

MLG Pin
LHE Zn-Ni Completed Fixtures

MLG Lower Drag Brace

NLG Gimbble Ring
LHE Zn-Ni Completed Fixture

NLG Inner Piston
Phase III Effort
Prototype B-1 Bushing

Plating B-1 Bushings LHE Zn-Ni

Plated LHE Zn-Ni B-1 Bushings