Ogden Air Logistics Center

U.S. AIR FORCE

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

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Report Documentation Page

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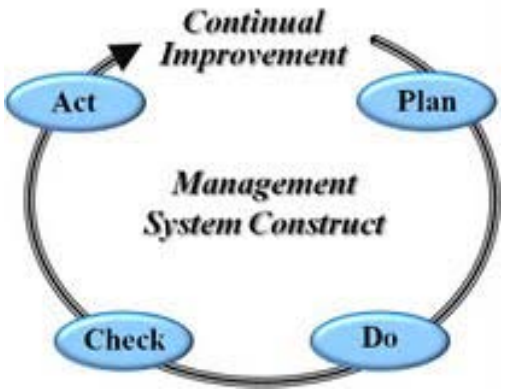
LHE Zn-Ni Partners

ESTCP

SBIR/STTR
SMALL BUSINESS INNOVATION RESEARCH
SMALL BUSINESS TECHNOLOGY TRANSFER



BOEING®

ESB

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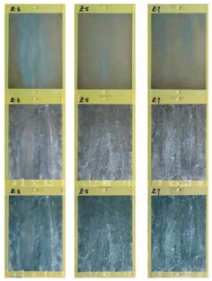
Agenda

- 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)
- SO_2 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

Average Plating Thickness	(Inches)
Cadmium	0.00044
Dipsol Zn-Ni Tri CC	0.00091
Dipsol Zn-Ni Hex CC	0.00104
Atotech Zn-Ni Tri CC	0.00089
Atotect Zn-Ni Hex CC	0.00081

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

Phase II Fatigue Testing

- **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

Additional Corrosion Testing

- 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

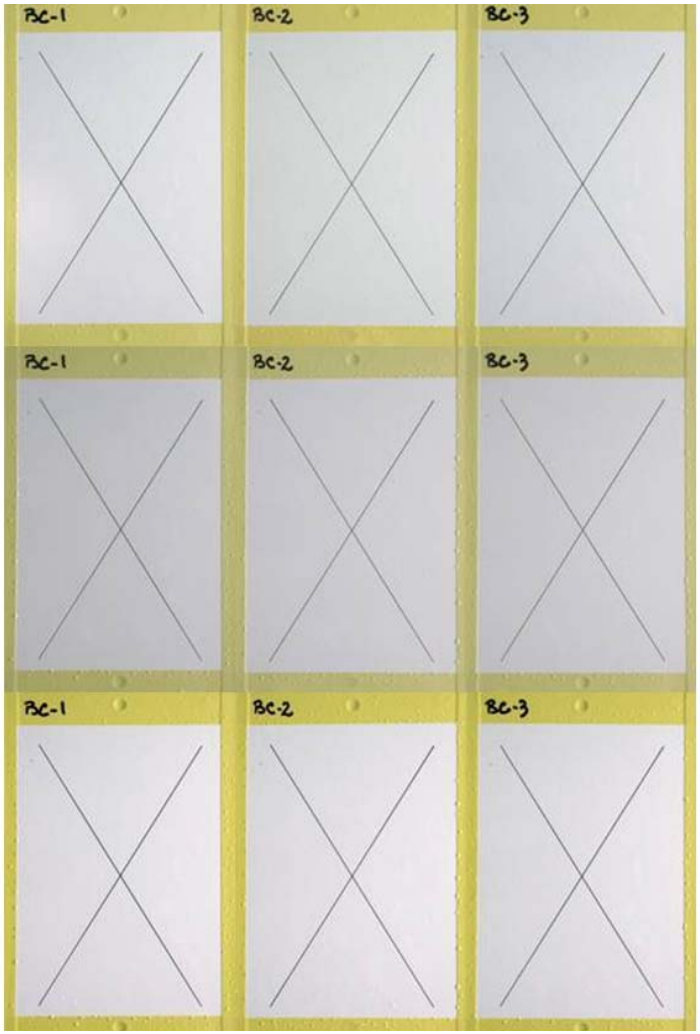
Additional Corrosion Testing

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

**** 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

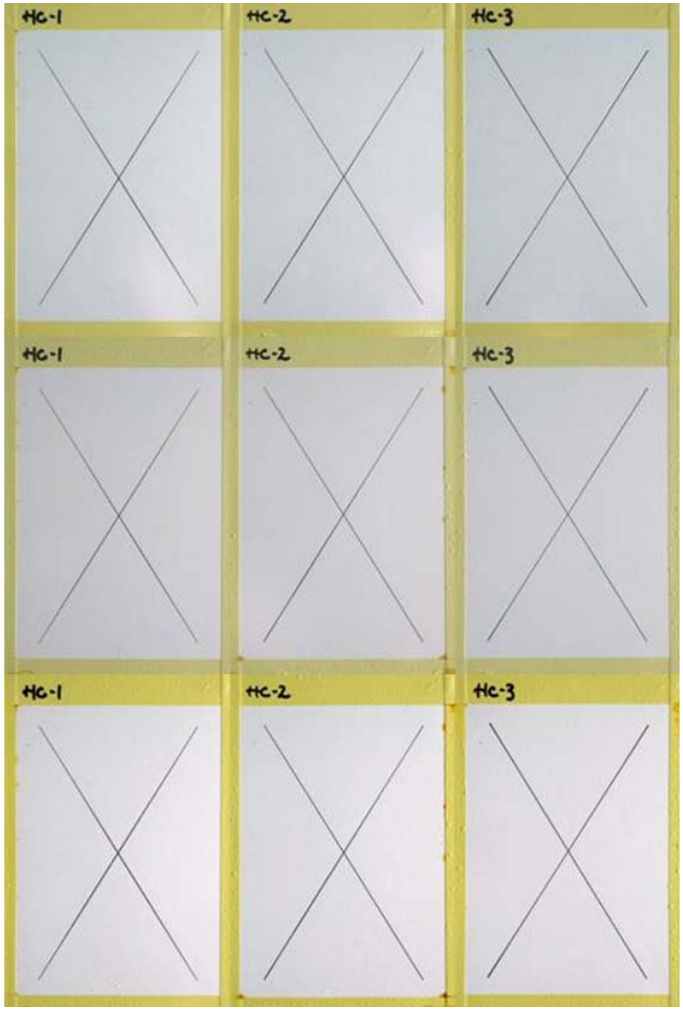


336 hours

672 hours

1000 hours

Hill AFB IZ-C17+ Zn-Ni w/Tri CC Scribed & Painted

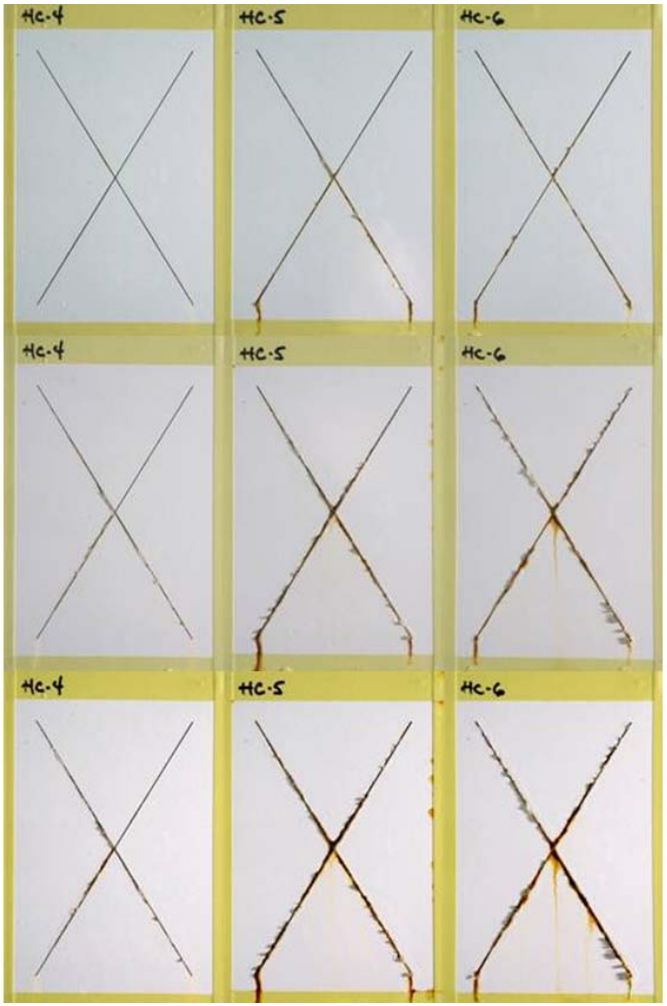


336 hours

672 hours

1000 hours

Hill AFB LHE Cd w/Hex CC Scribed & Painted

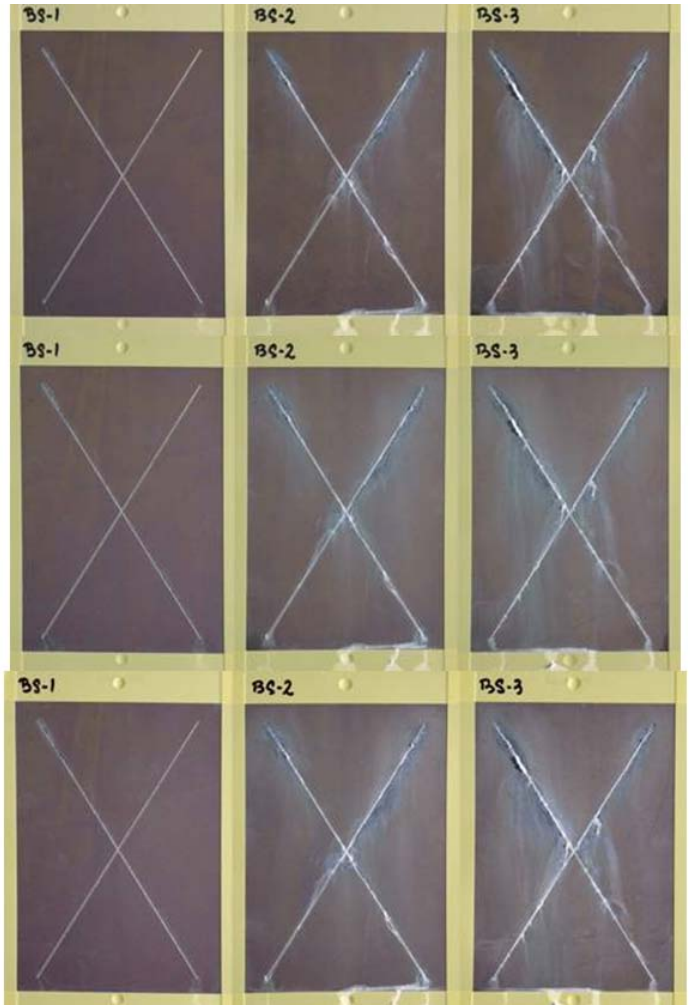


336 hours

672 hours

1000 hours

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

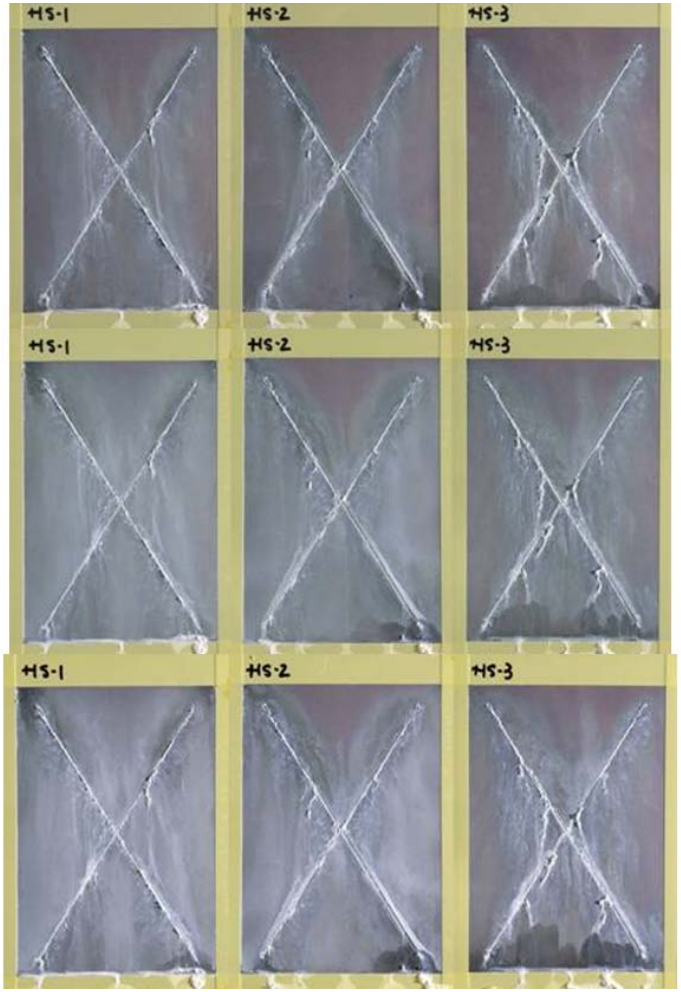


336 hours

672 hours

1000 hours

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



336 hours

672 hours

1000 hours

Hill AFB LHE Cd w/Hex CC Scribed

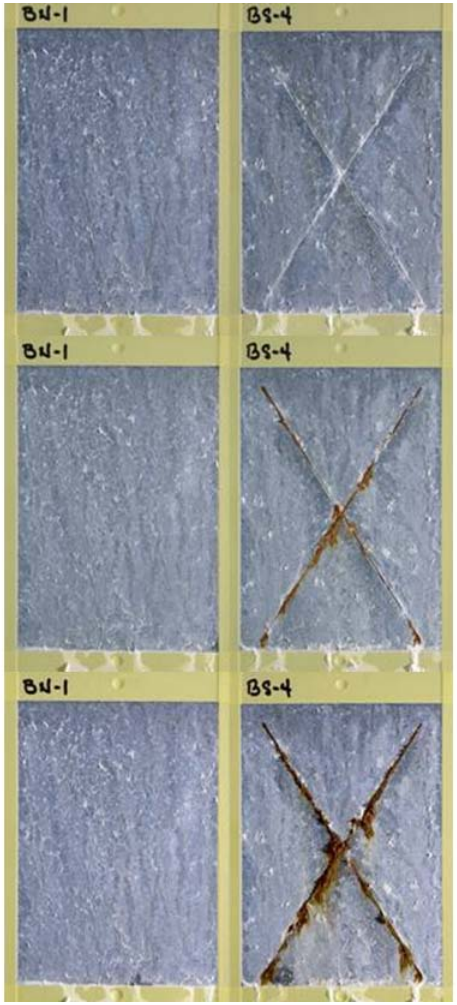
336 hours

672 hours

1000 hours

BR&T IZ-C17+ Zn-Ni w/ No CC Unscribed & Scribed

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



336 hours

672 hours

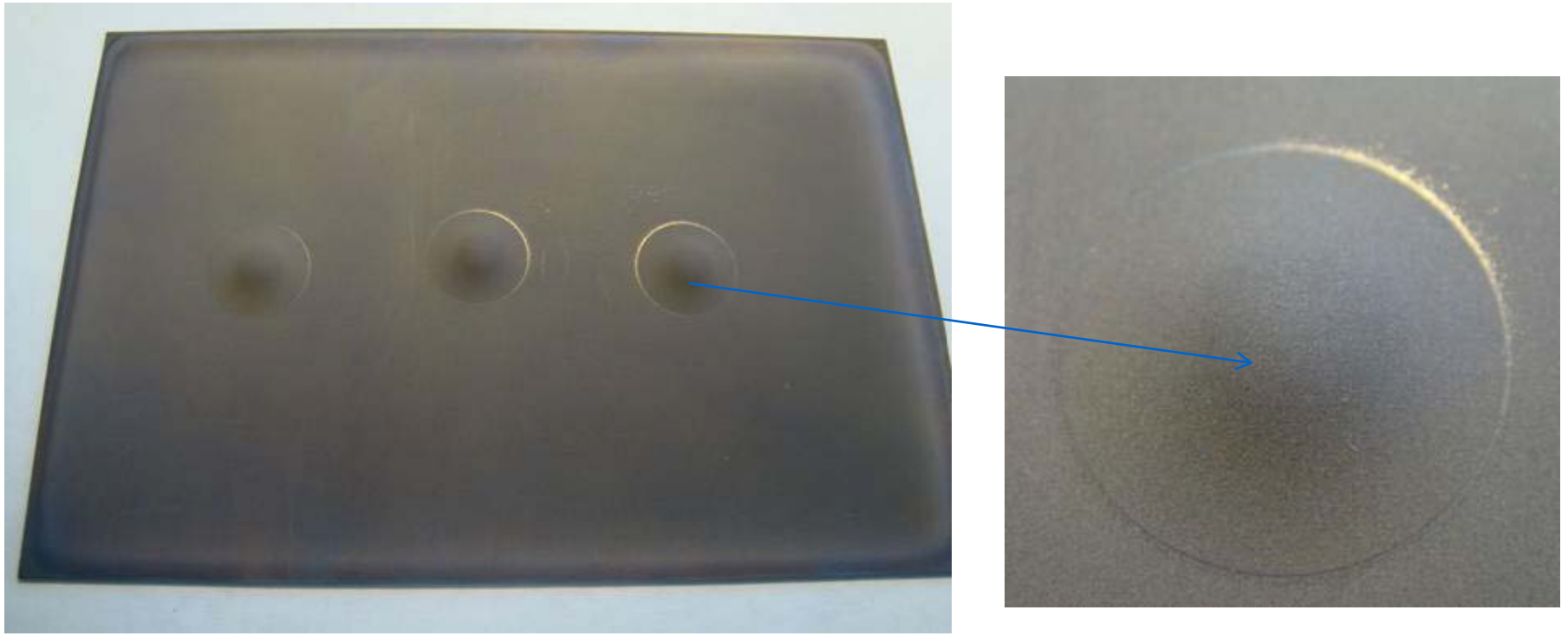
1000 hours

Additional Adhesion Testing

Gardner Impact Adhesion Tester

Additional Adhesion Testing

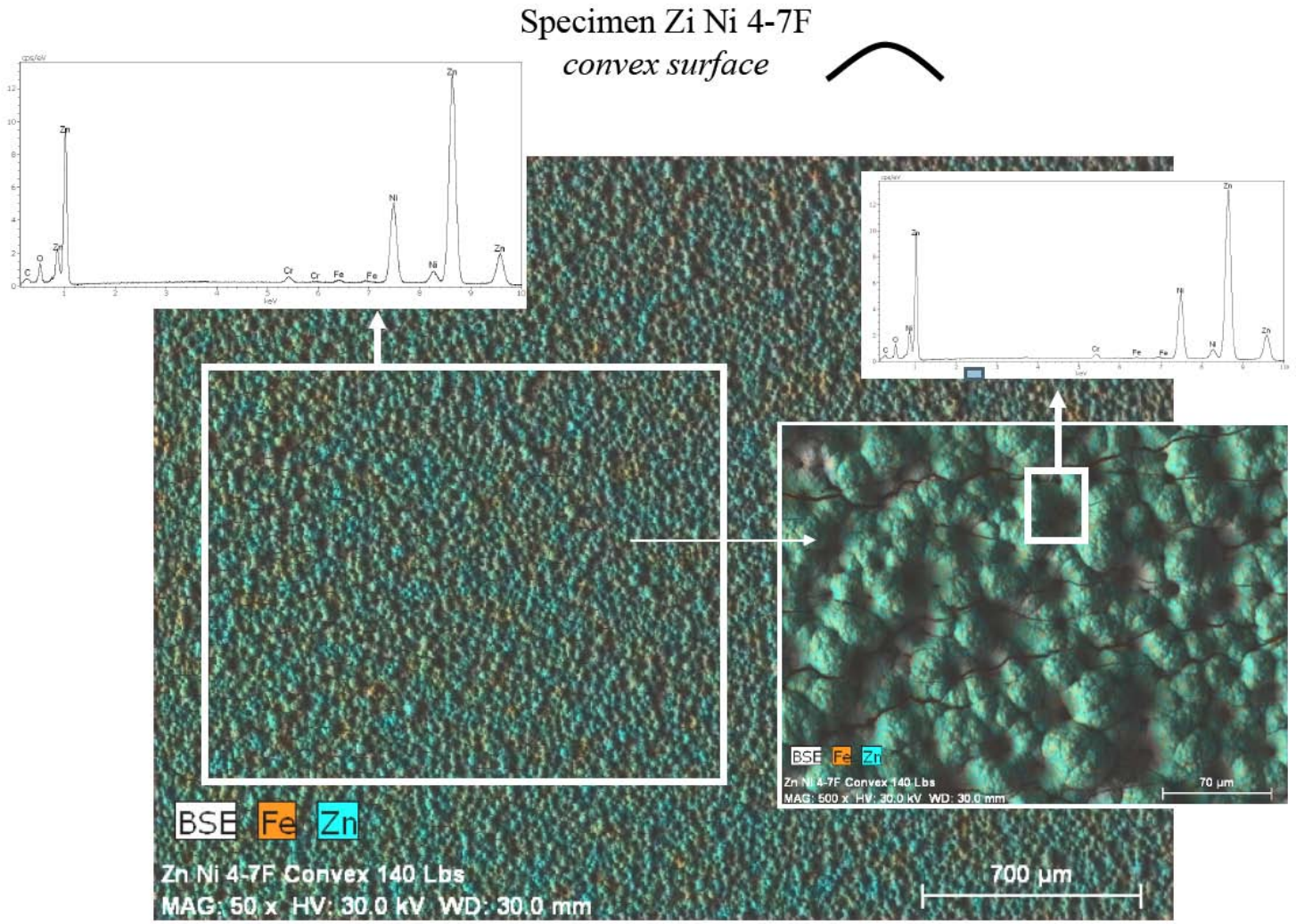
LHE Zn-Ni Adhesion Impact Test Result



Impact at 70 in-lbs

Additional Adhesion Testing

Garner Impact Testing: Zn-Ni

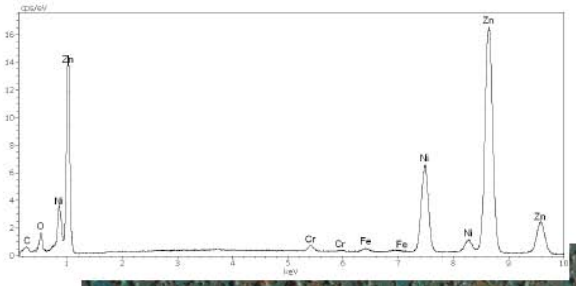


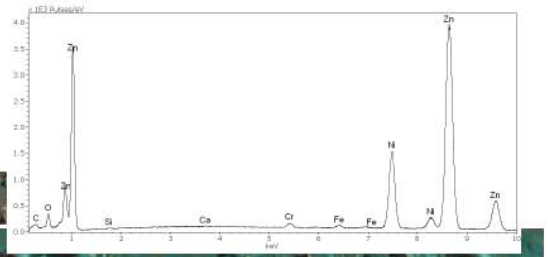
Additional Adhesion Testing

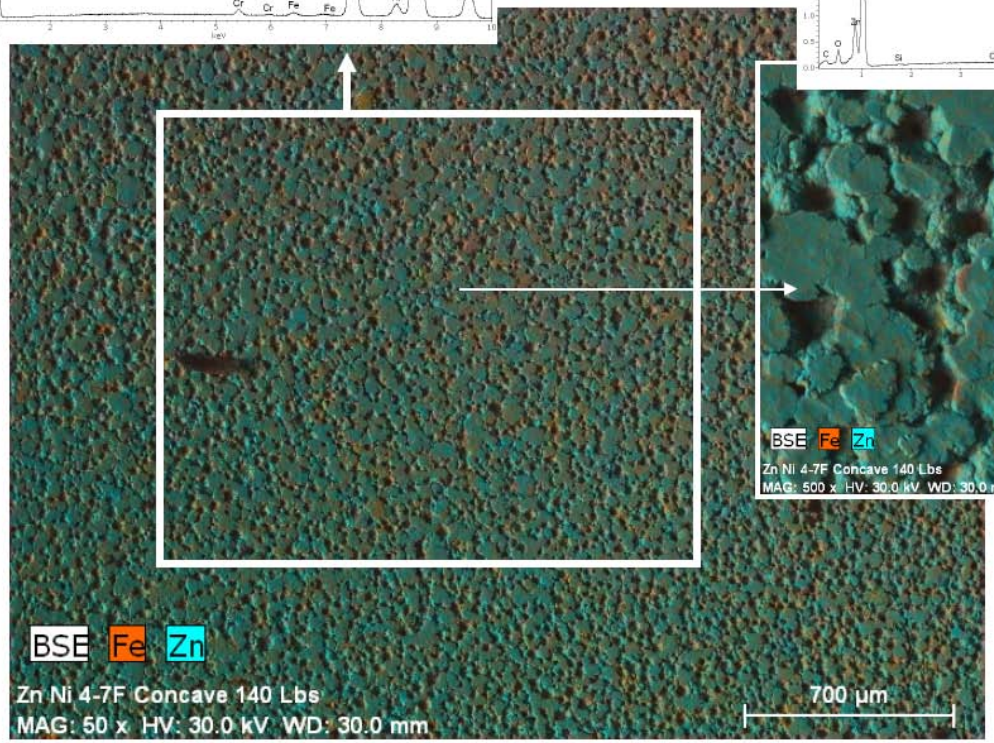
Garner Impact Testing: Zn-Ni

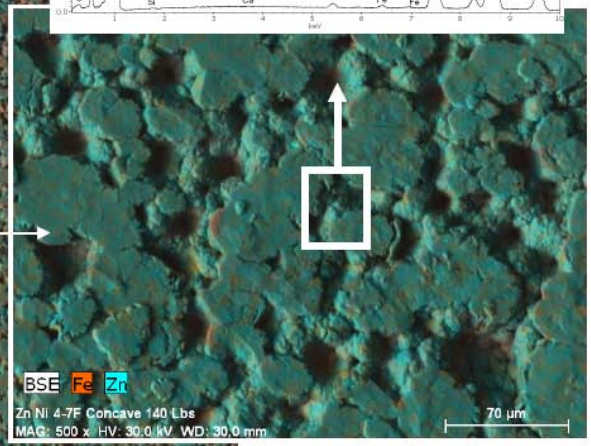
Specimen Zi Ni 4-7F

concave surface

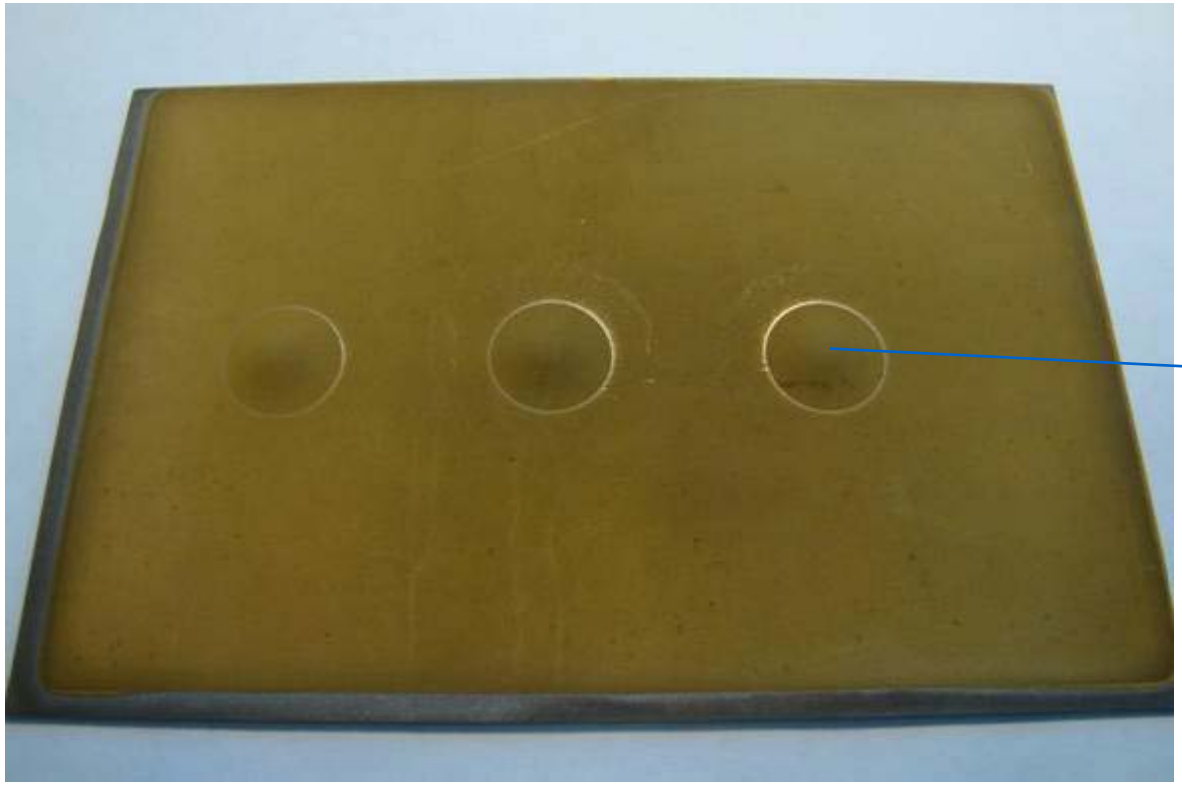


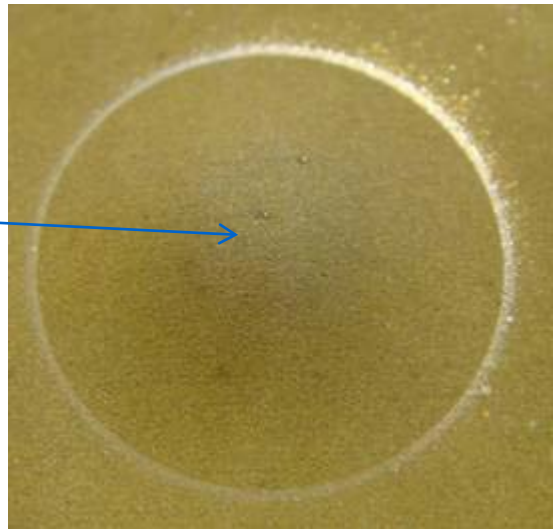






Additional Adhesion Testing
Cadmium Adhesion Impact Test Result





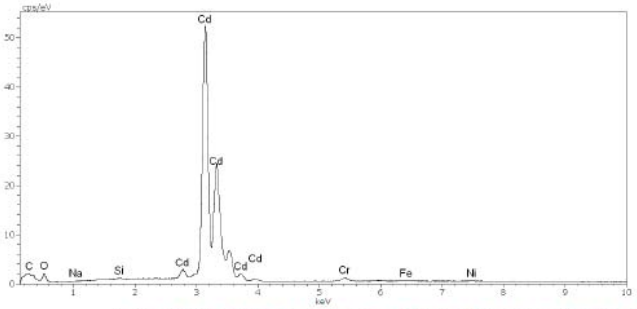
Impact at 70 in-lbs

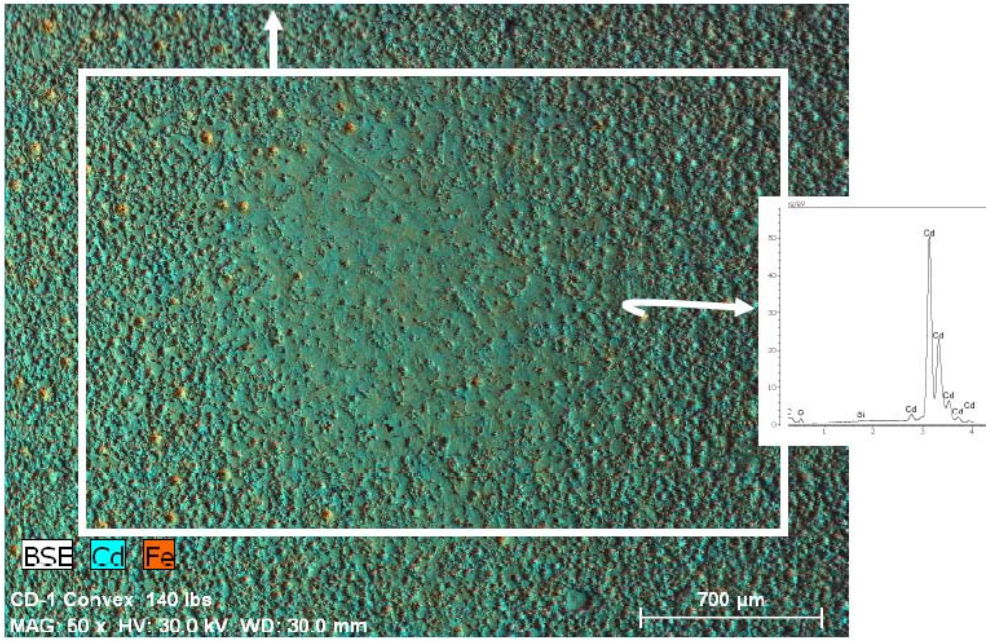
Additional Adhesion Testing

Garner Impact Testing: Cadmium

Specimen CD – 1

convex surface

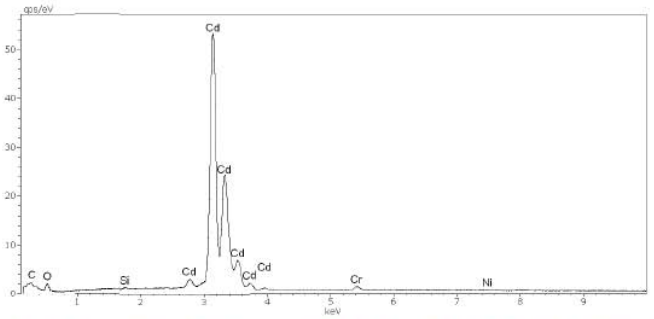


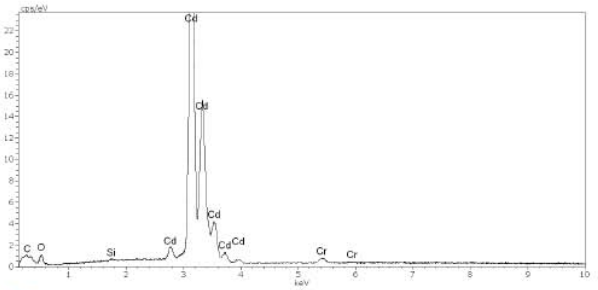


Additional Adhesion Testing

Garner Impact Testing: Cadmium

Specimen CD – 1
concave surface





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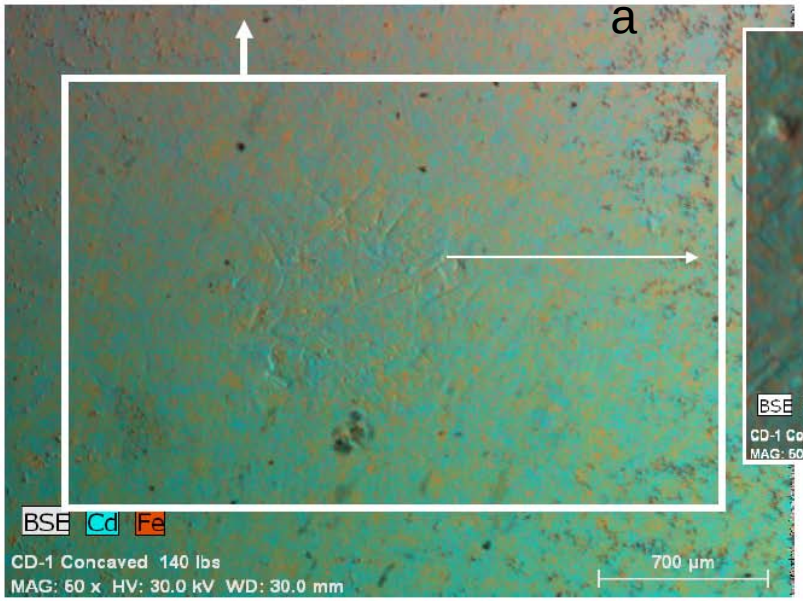
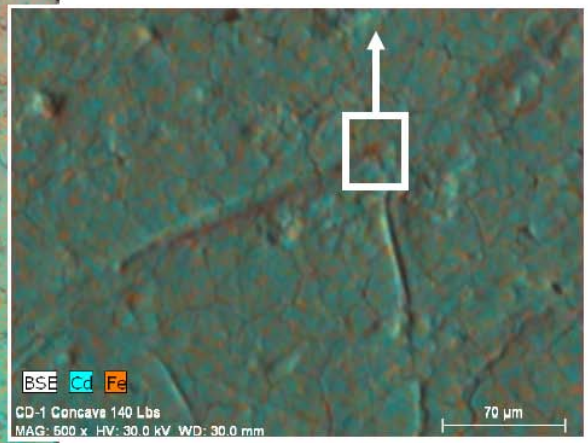




Additional Adhesion Testing

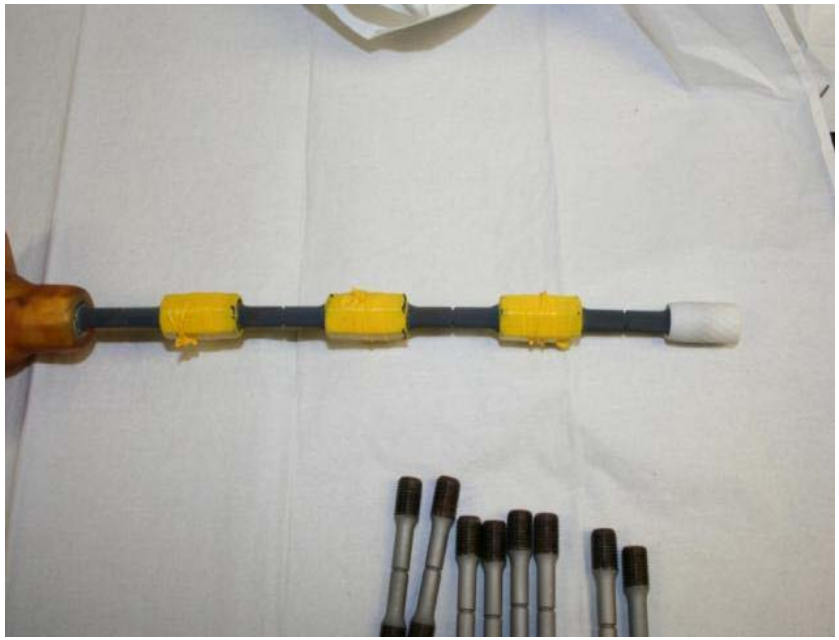
- **Conclusion: Zn-Ni has good adhesion when tested by bend-to-break and impact test methods**

Additional LHE Zn-Ni Hydrogen Re-Embrittlement Testing

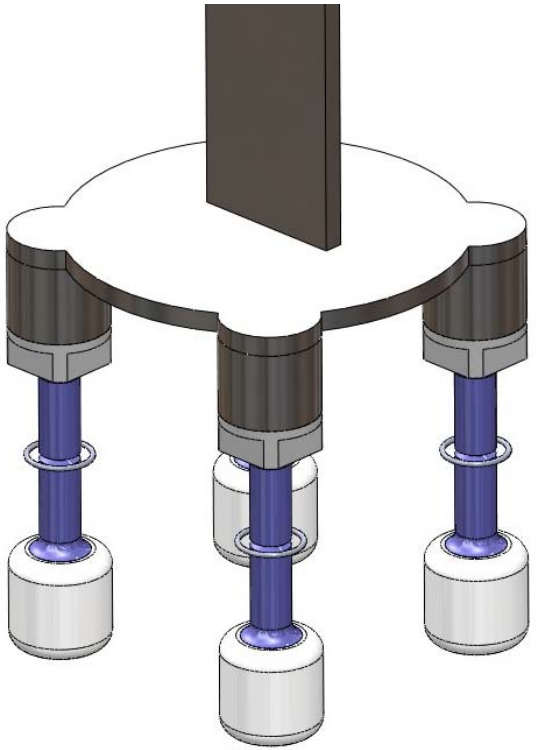
- The original LHE Zn-Ni test coupons failed due to poor plating in notch
- The reason for the poor plating on the original LHE Zn-Ni 1a.1 re-embrittlement coupons are as follows:
  - LHE Zn-Ni tank contamination
    - Spring ‘09 Lab analysis showed organic contamination
    - The PVC tank liner had 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

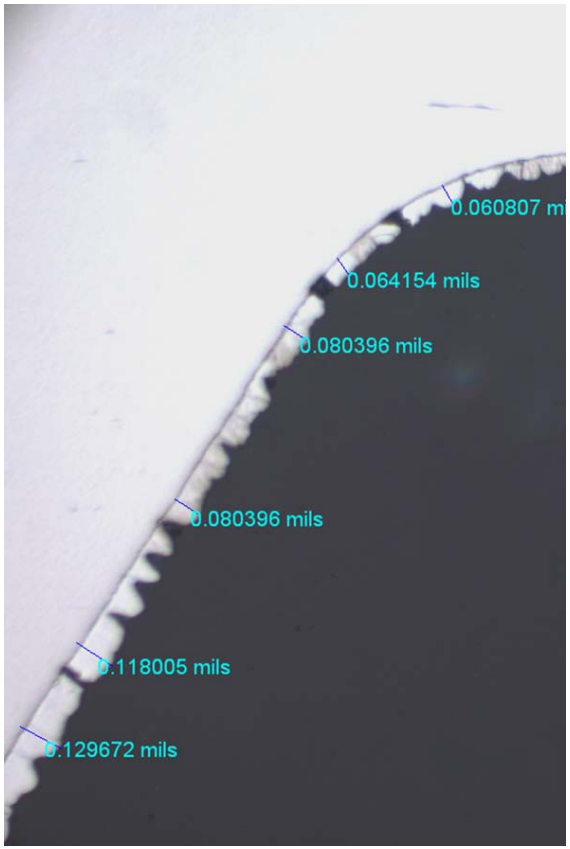
Original Coupons Chained in Series



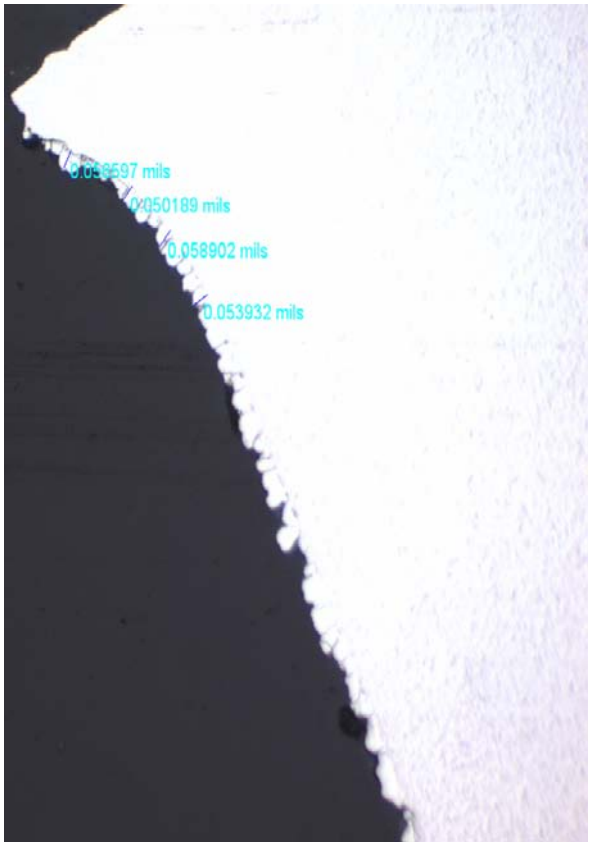
New fixture and Conformal Anode



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-embrittlement 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**

Re Embrittlement Test Matrix						
Plating	Test Solution					
	Distilled Water @ Room Temp Tested 45% NFS for 150Hrs	3.5% Salt Water @ Room Temp Tested 45% NFS for 150Hrs	Dwg 9825019* Diluted Calla 296 @ Max Temp 180 °F Tested 75% NFS for 200Hrs	Dwg 9825019* Diluted Calla 602 LF Max Temp 160 °F Tested 75% NFS for 200Hrs	Concentrated Calla 296 @ Room Temp tested 45% NFS for 150Hrs	Concentrated Calla 602LF @ Room Temp tested 45% NFS for 150Hrs
LHE Zn-Ni	Passed	Passed	Passed	Passed	Passed	Passed
Cadmium	Passed	Failed	Passed	Passed	Passed	Passed
IVD	Failed	Failed	Not Tested	Not Tested	Not Tested	Not Tested

*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.

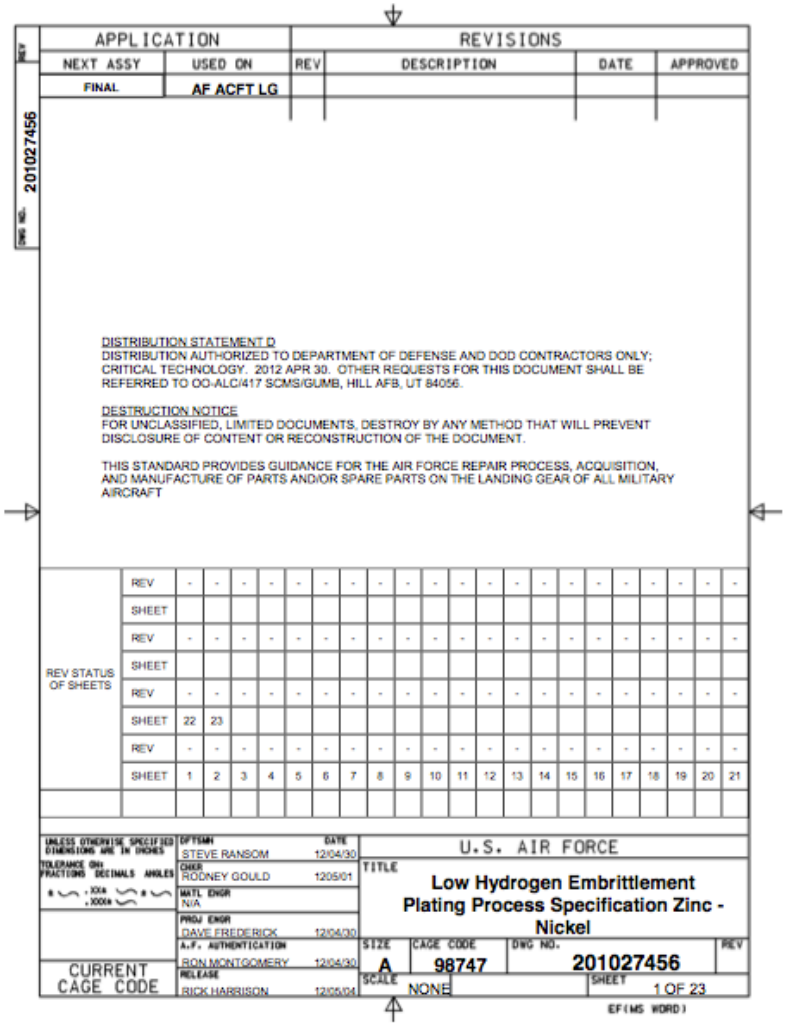
Additional LHE Zn-Ni Hydrogen Re-Embrittlement Testing

- Due to the inconsistent test results of ASTM 519 re-embrittlement 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-embrittlement 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

Specification Drawing



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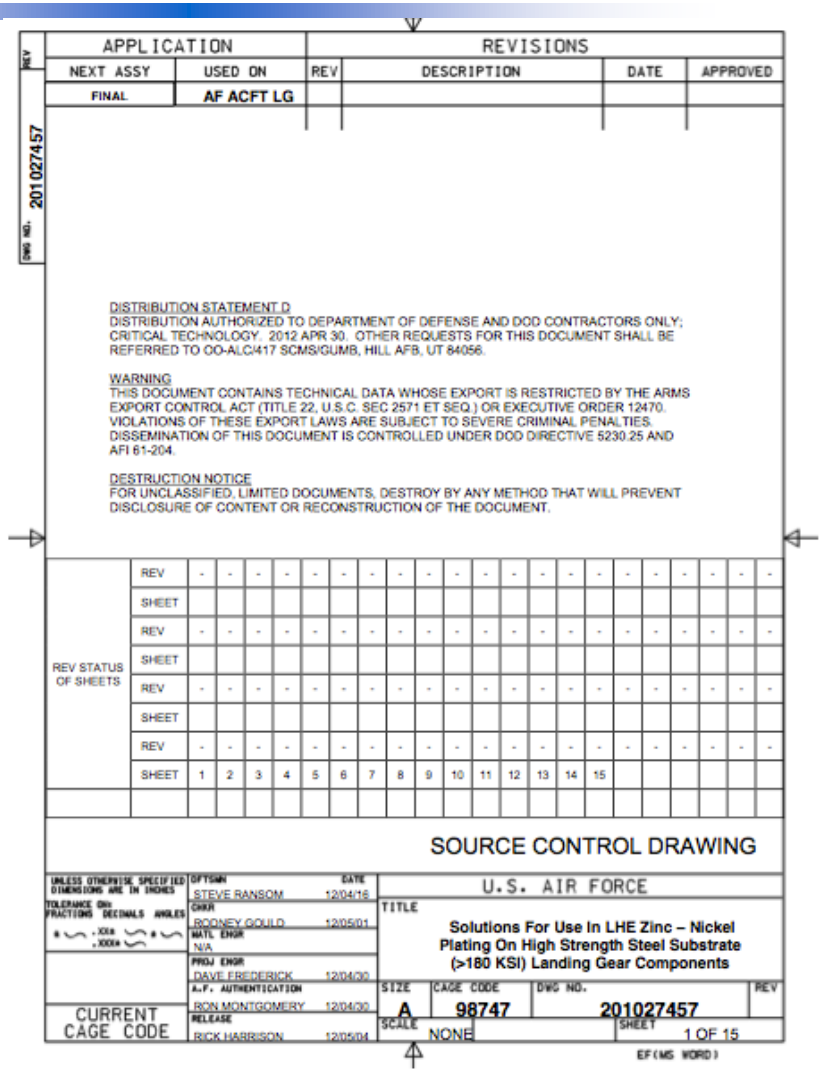
	SHEET	22	23																	
	REV	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	SHEET	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCE ON: FRACTIONS DECIMALS ANGLES ± .XXX ± .XXXX ± ° ' "	OPTIMIN STEVE RANSOM 12/04/30 CHKR RODNEY GOULD 12/05/01 MATL ENGR N/A PROJ ENGR DAVE FREDERICK 12/04/30 A.F. AUTHENTICATION RON MONTGOMERY 12/04/30 RELEASE RICK HARRISON 12/05/04	U.S. AIR FORCE TITLE: Low Hydrogen Embrittlement Plating Process Specification Zinc - Nickel	
CURRENT CAGE CODE		SIZE: A CAGE CODE: 98747 DWG NO.: 201027456 REV: SCALE: NONE SHEET: 1 OF 23	

EF(MS WORD)

Source Control Drawing



APPLICATION		REVISIONS			
NEXT ASSY	USED ON	REV	DESCRIPTION	DATE	APPROVED
FINAL	AF ACFT LG				

DWG NO. 201027457

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REV STATUS OF SHEETS																					
	REV	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	SHEET																				
	REV	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	SHEET																				
	REV	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	SHEET																				
	REV	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	SHEET	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15					

SOURCE CONTROL DRAWING

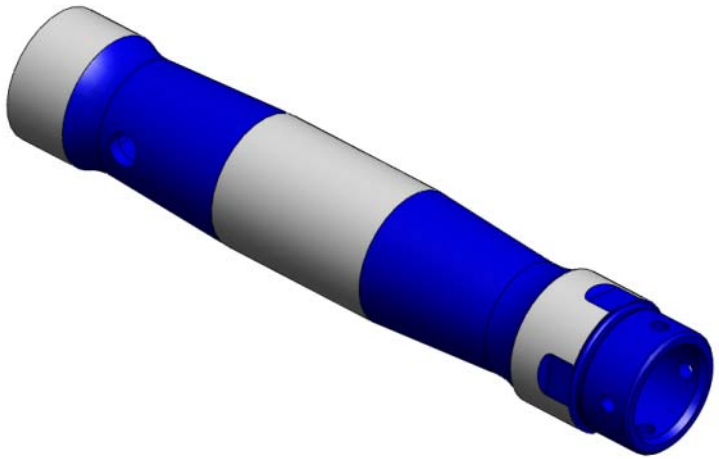
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCE ON FRACTIONS DECIMALS ANGLES # ±.XX ±.XXX # ±	OPTSMN: STEVE RANSOM — DATE: 12/04/16 CHKR: RODNEY GOULD — 12/05/01 MATL ENGR: N/A PROJ ENGR: DAVE FREDERICK — 12/04/30 A-F- AUTHENTICATION: RON MONTGOMERY — 12/04/30 RELEASE: RICK HARRISON — 12/05/04	U.S. AIR FORCE TITLE: Solutions For Use In LHE Zinc – Nickel Plating On High Strength Steel Substrate (>180 KSI) Landing Gear Components	
CURRENT CAGE CODE		SIZE: A — CAGE CODE: 98747 — DWG NO.: 201027457 — REV	
		SCALE: NONE — SHEET: 1 OF 15	

EF(MS WORD)

Phase III Effort
Prototype Process Line

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

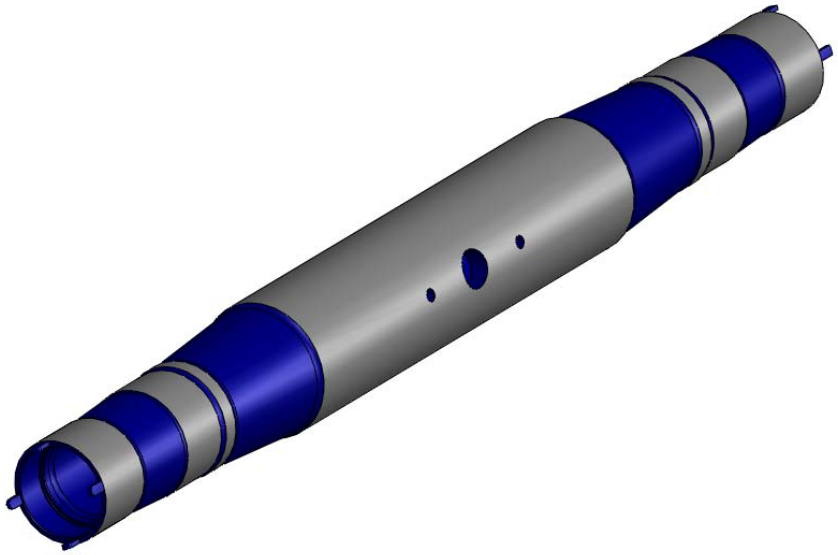
Phase III Effort
Solid Model Prototype Parts



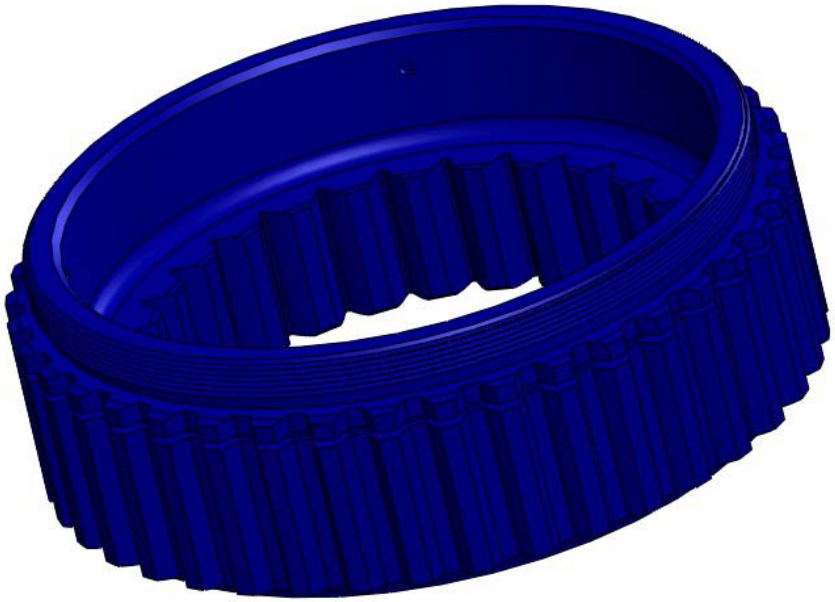
A-10 NLG Axle

A-10 MLG Torque Arm

Phase III Effort
Solid Model Prototype Parts

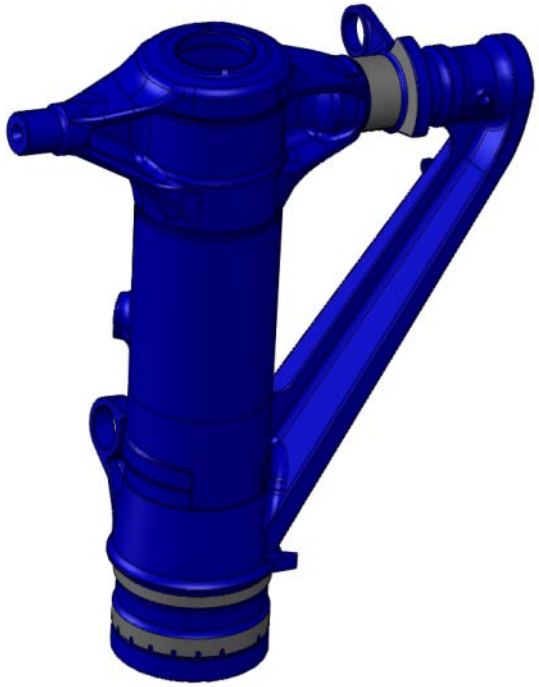


B-1 MLG Axle

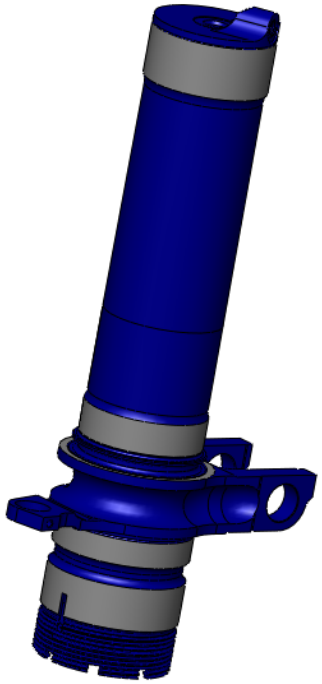


C-5 MLG Rotation Collar

Phase III Effort
Solid Model Prototype Parts



F-15 MLG Cylinder



F-16 NLG Inner Cylinder

F-15 MLG Lower Drag Brace

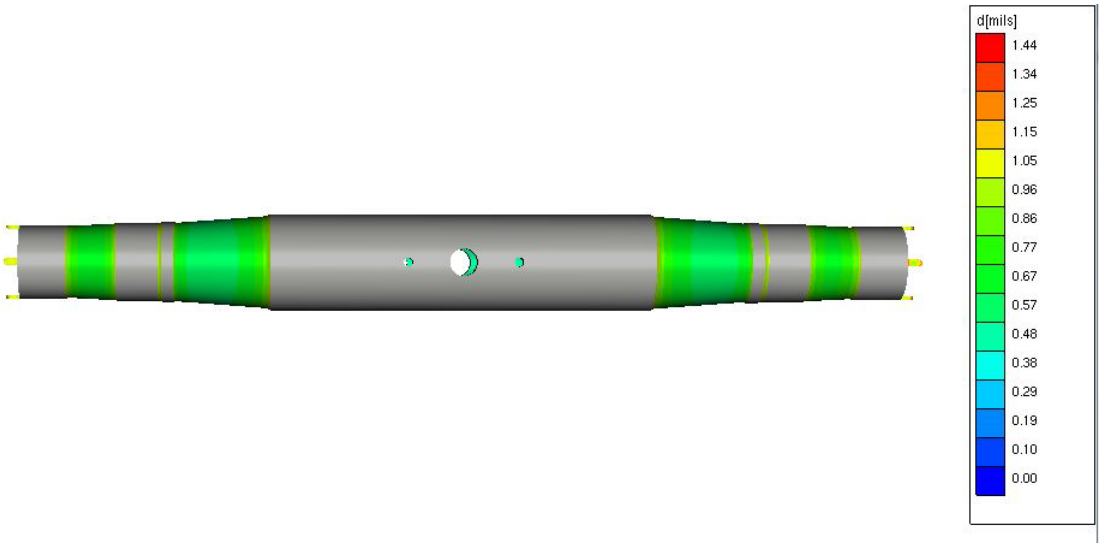
LHE Zn-Ni Plating Process

Zn-Ni PLATING	1ST RINSE	2ND RINSE	ACID ACTIVATOR	RINSE	CONVERSION COAT	RINSE

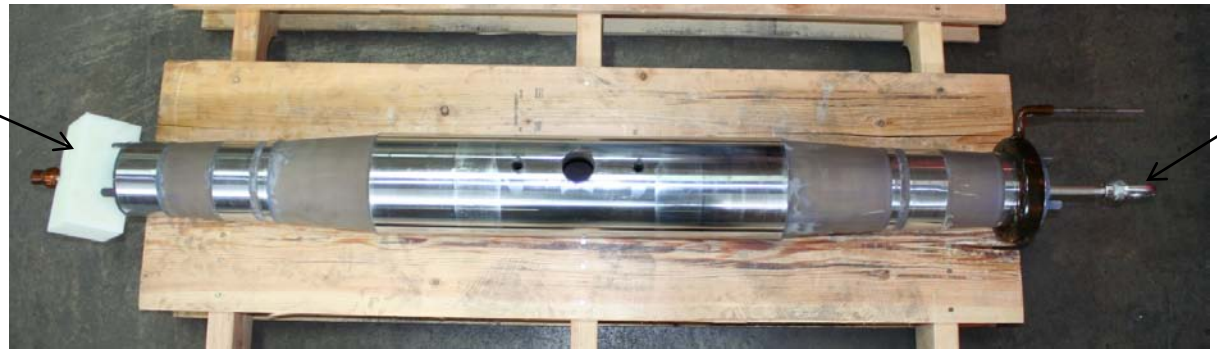
Prototype LHE Zn-Ni Plating Tank

Prototype Tri-Chromium Conversion Coating Tank

Prototype Conformal Anode & Fixture Design



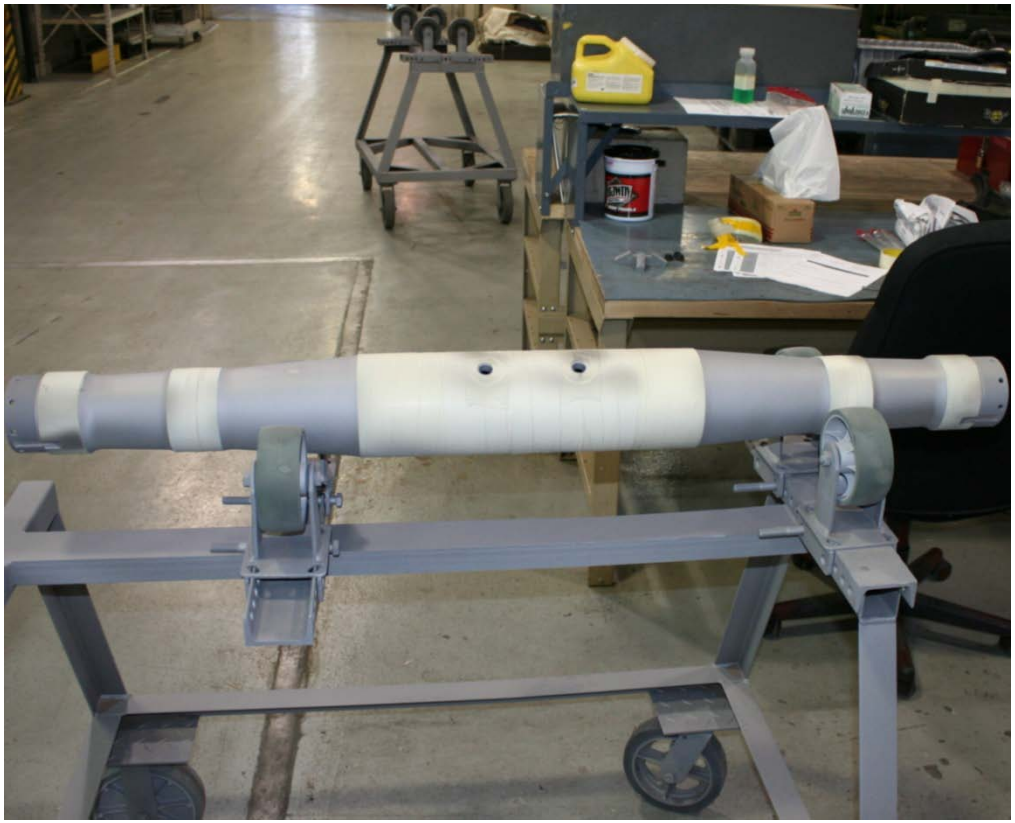
Conformal Anode & Fixture



Conformal Anode & Fixture

LHE Zn-Ni Plated MLG Axle

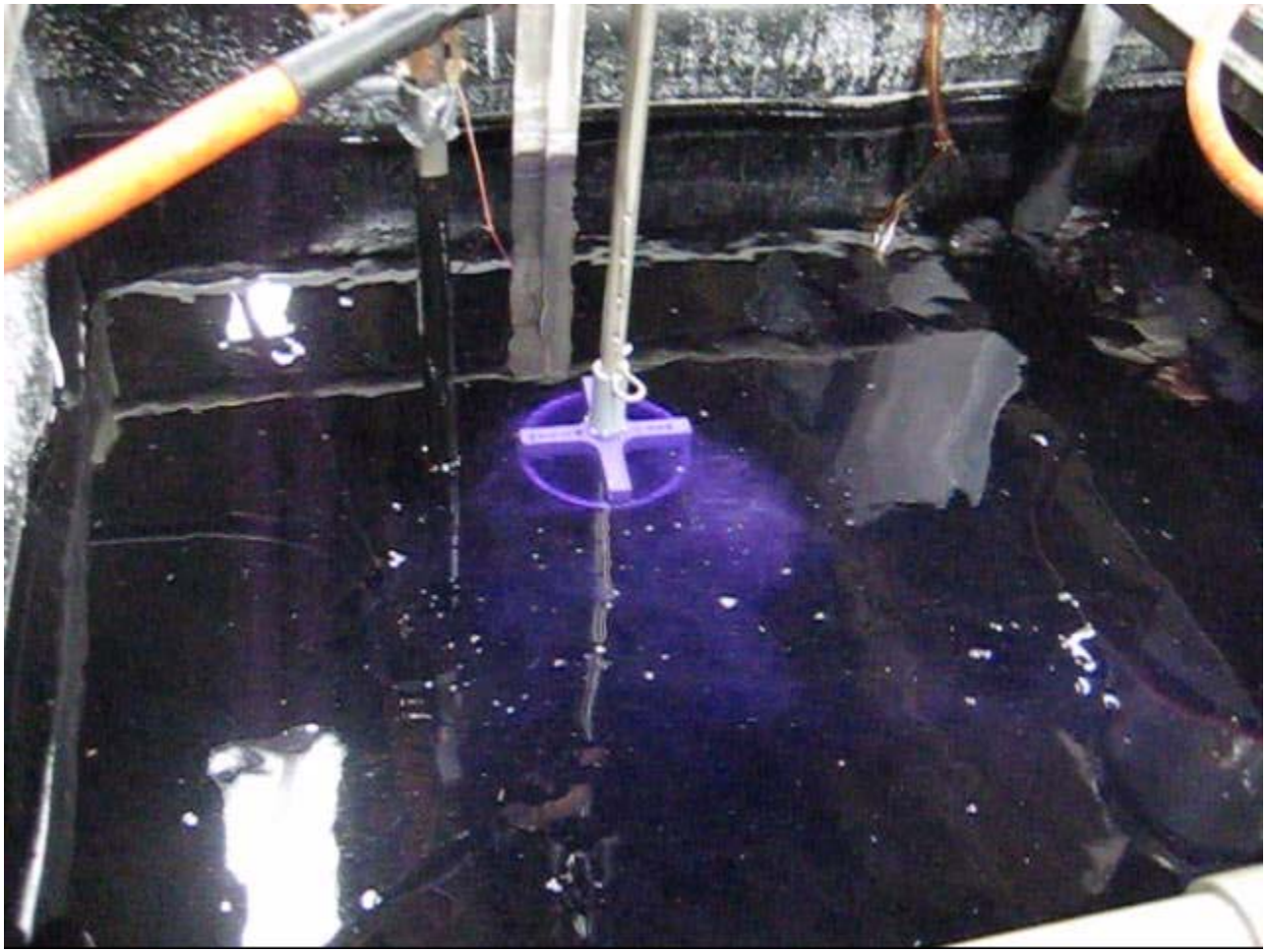
MLG Axle Plating



MLG Axle before Fixture

MLG Axle with Fixture

MLG Axle During LHE Zn-Ni Plating



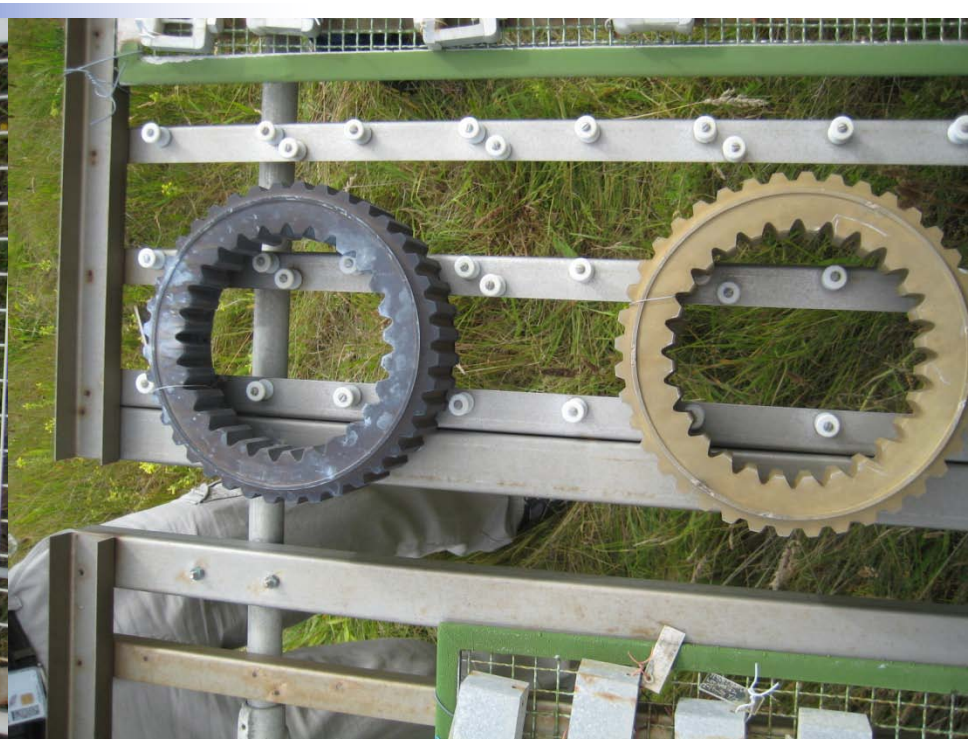
MLG Axle after LHE Zn-Ni Plating

MLG Axle Finished Plated Outer Diameter

MLG Axle Finished Plated Inner Diameter

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
CAD

C-5 MLG Rotation Collar
Zn-Ni

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

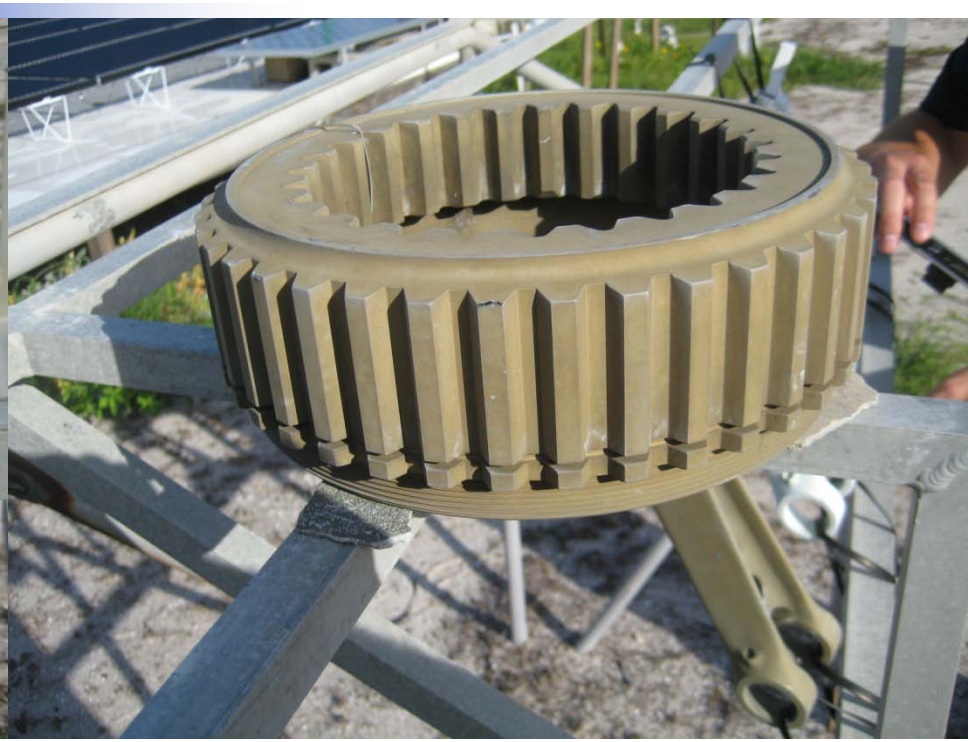
LHE Zn-Ni Plating – Ph III (FY 12)
Component Corrosion Eval. (Cape Kennedy)

F-15 MLG Lower Drag Brace CAD

F-15 MLG Lower Drag Brace Zn-Ni

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

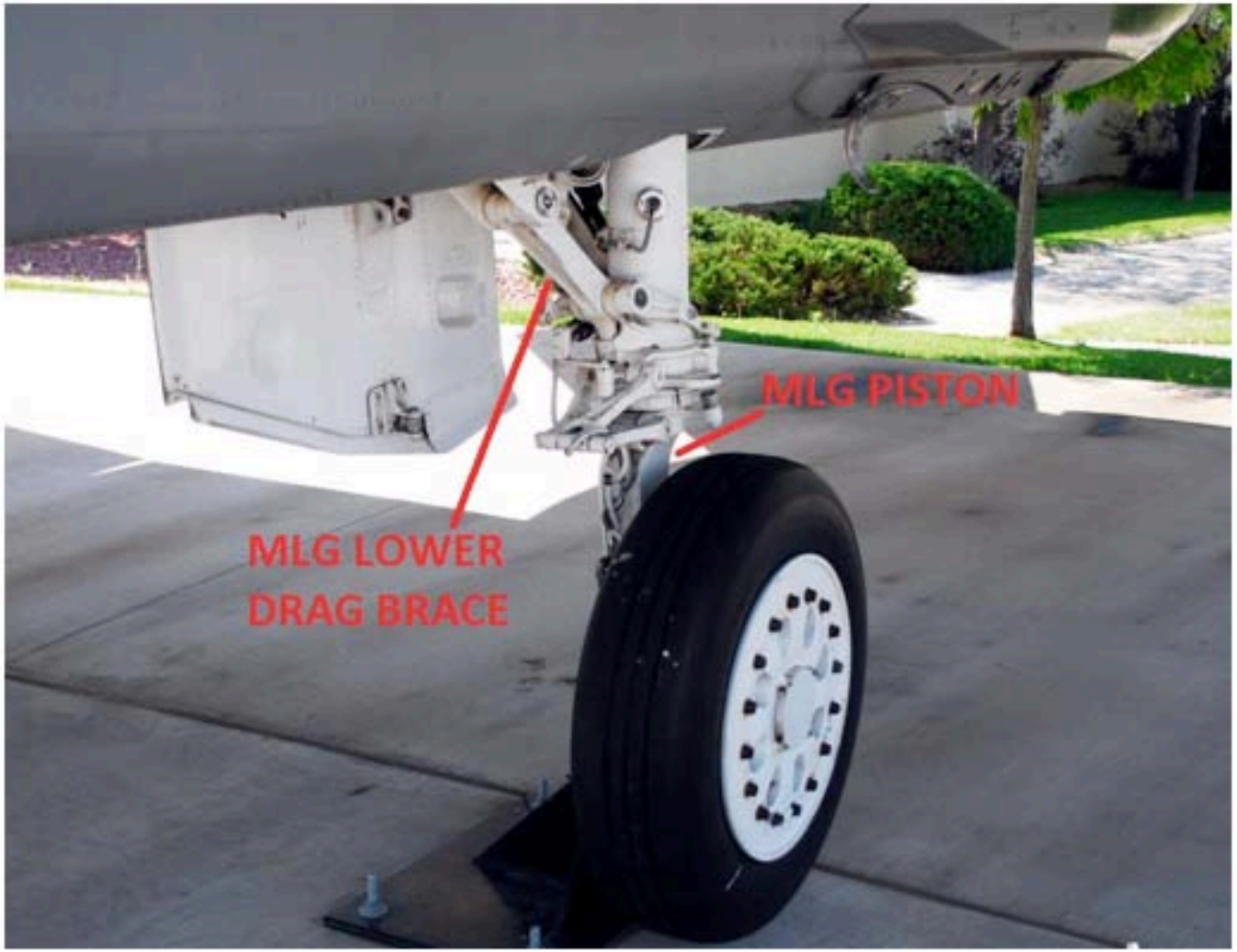
LHE Zn-Ni Performance Tracking Program (PTP) Components

Weapon System	Component	BASE 1	BASE 2	BASE 3
C-130	MLG TORQUE STRUT AFT P/N 388066-3	Kadena AB AFSOC	Hurlburt, FL ACTIVE	
C-130	MLG TORQUE STRUT FWD P/N 388065-3			
F-15	MLG LOWER DRAG BRACE 68A410792-2001	Kadena AB PACAF	Jacksonville, FL ANG	
F-15	MLG PISTON P/N 68A410704-1011 (LH) P/N 68A410704-1012 (RH)			
F-16	MLG TENSION STRUT P/N 2007003-3	Shaw AFB, NC	Kunsan AB, PACAF	
F-16	MLG COLLAR P/N 2007307-105 (LH) P/N 2007307-106 (RH)			
F-16	MLG DRAG BRACE P/N 2007304-101			
KC-135	MLG BRAKE EQUALIZER ROD P/N 65-1266-2	Kadena AB PACAF	Hickam AFB, HI ANG	MacDill AFB, FL AMW
KC-135	MLG BRAKE COLLAR P/N 8853035-05			

NOTE: Bases with multiple aircraft systems are highlighted in color

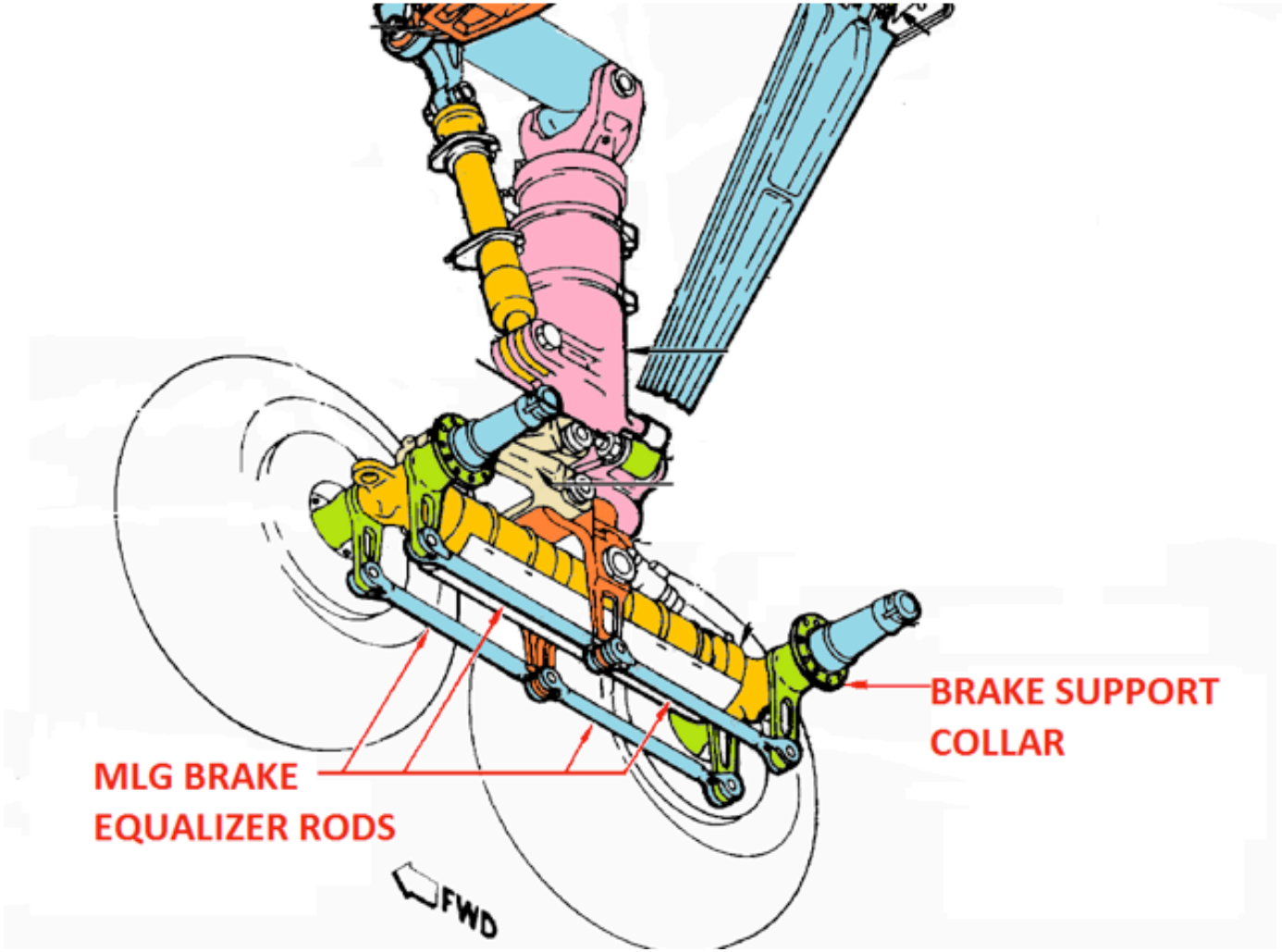
C-130 Main Landing Gear PTP Components

F-15 Landing Gear PTP Components



F-16 Landing Gear PTP Components

KC-135 Landing Gear PTP Components

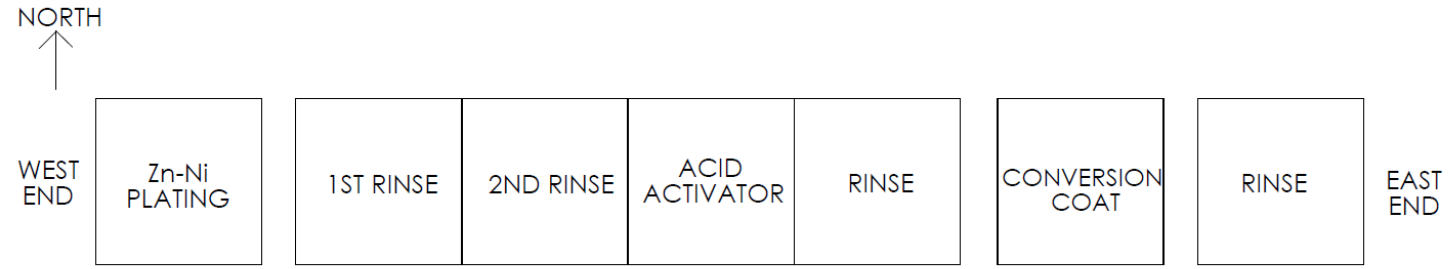


ESTCP/P2/STTP Effort Full Size Prototype Plating Line

REVISIONS				
REV.	ZONE	DESCRIPTION	DATE	APPROVED
-		INITIAL RELEASE		G. KESSLER)

PROPOSED Zn-Ni PLATING LINE

TANK REQUIREMENTS



UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES
TOLERANCES ON: FRACTIONS ±1/16 DECIMALS .X ±.030 .XX ±.010 .XXX ±.005 ANGLES ±2°

PROJECT LEAD | PROGRAM MGR | PROJECT ENGR | DESIGNED BY | CHECK BY | APPROVALS | DATE

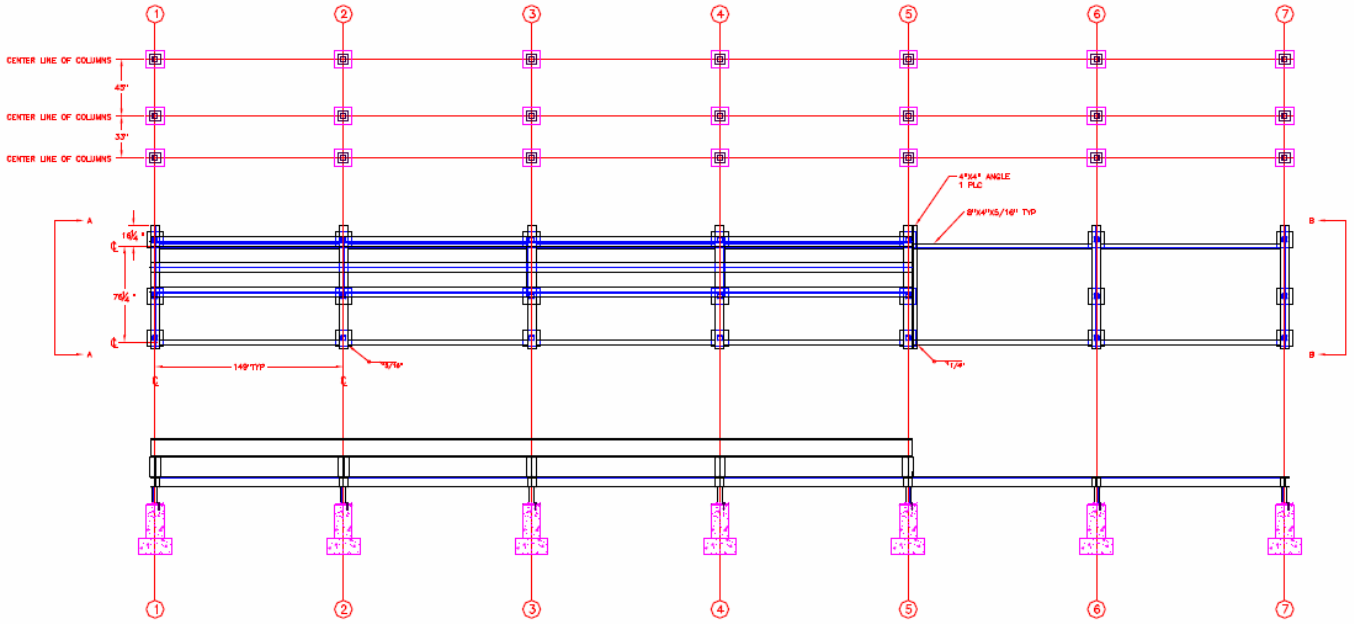
CONTRACT NO. | PROJECT NO.

Engineering & Software System Solutions Inc

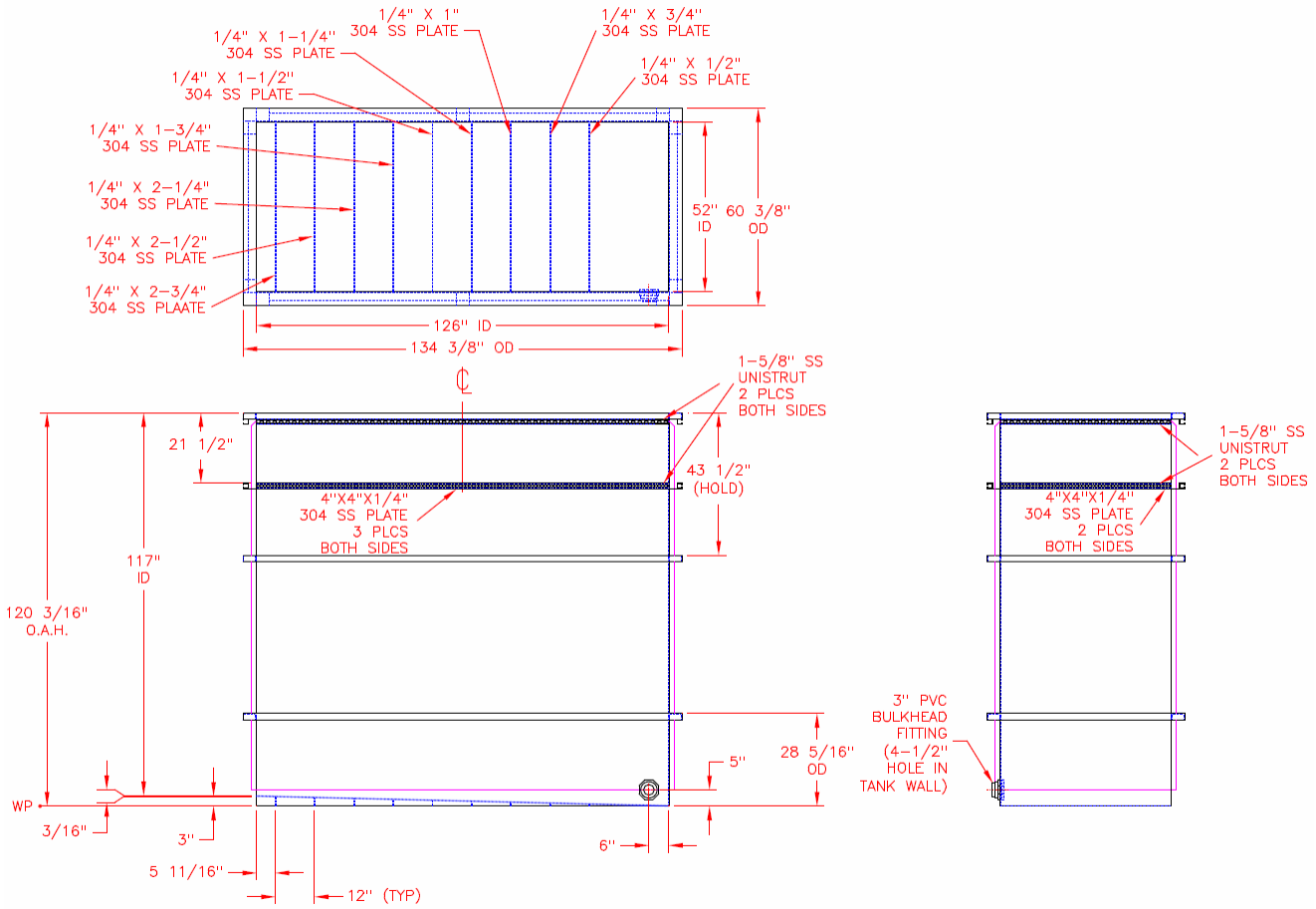
SIZE	ES3 PART NO.	REV.
B	2009-9074-0002	-

CAGE 1PHL4 | PART ORIG. | SHEET 1 OF 3

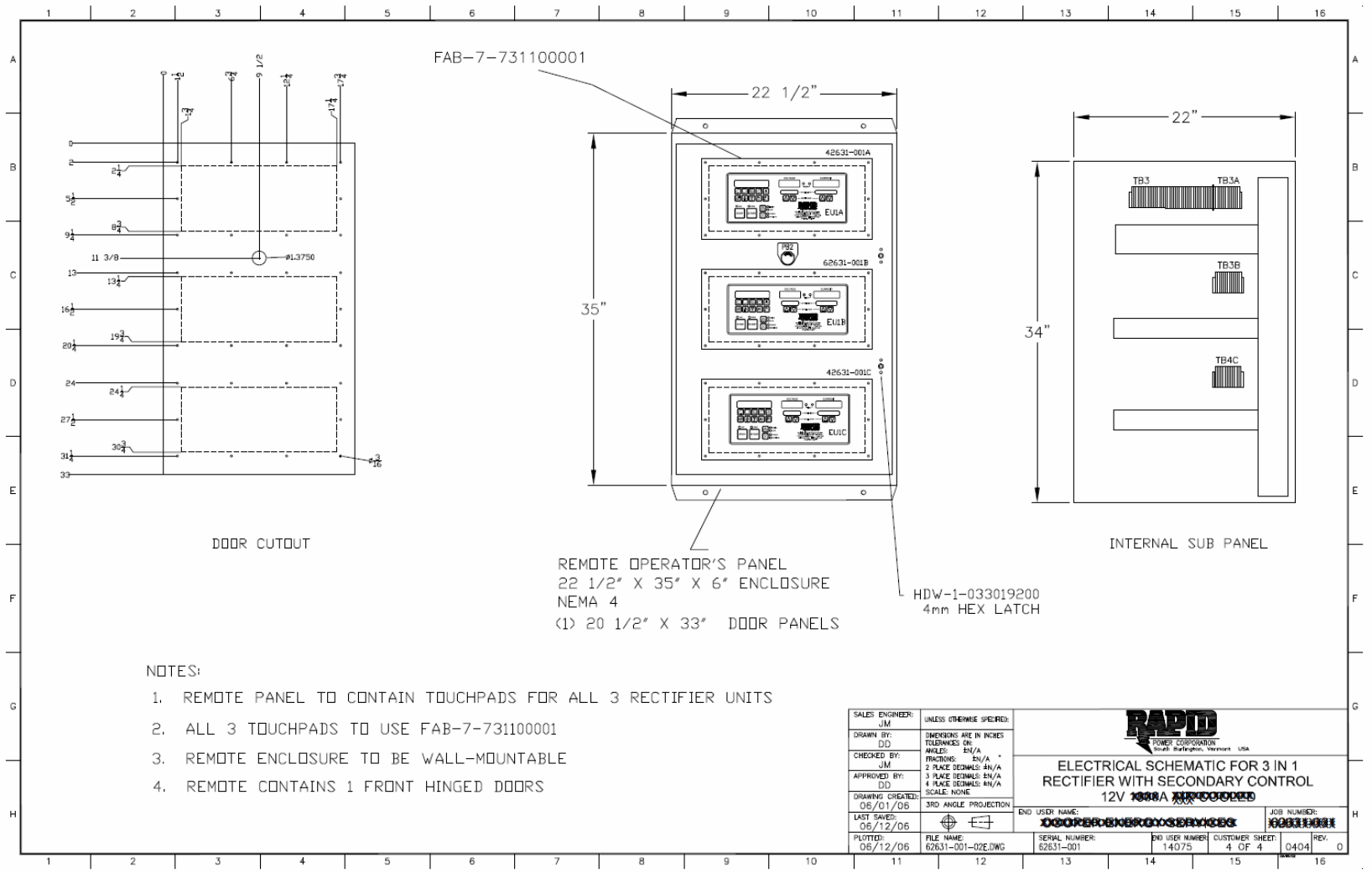
LHE Zn-Ni Preliminary Tank Structure Drawing



LHE Zn-Ni Prototype Plating Line Tank Drawing



LHE Zn-Ni Prototype Plating Line Rectifier Controller

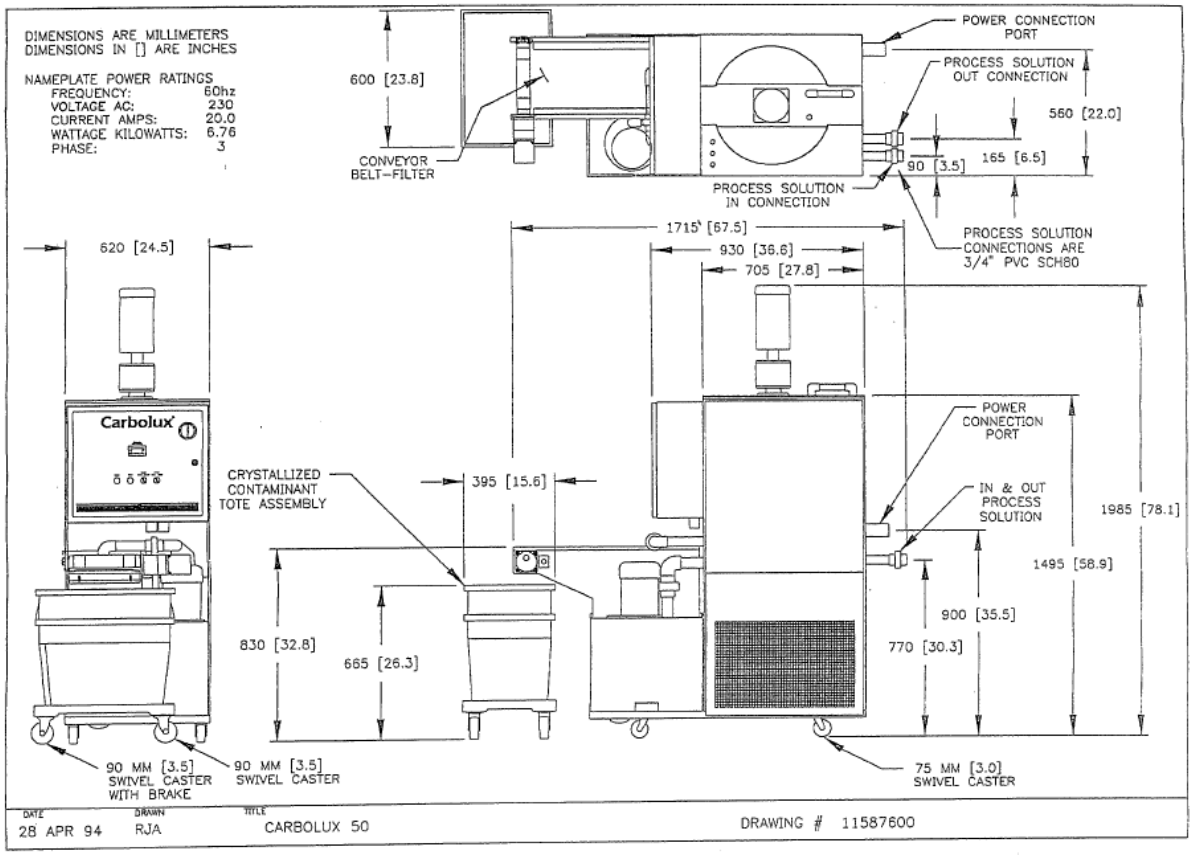


NOTES:

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

SALES ENGINEER: JM	UNLESS OTHERWISE SPECIFIED:	RAPID POWER CORPORATION South Burlington, Vermont USA
DRAWN BY: DD	DIMENSIONS ARE IN INCHES	ELECTRICAL SCHEMATIC FOR 3 IN 1 RECTIFIER WITH SECONDARY CONTROL
CHECKED BY: JM	TOLERANCES ON: ANGLES: ±N/A FRACTIONS: ±N/A	12V [redacted]A [redacted]
APPROVED BY: DD	2 PLACE DECIMALS: ±N/A 3 PLACE DECIMALS: ±N/A 4 PLACE DECIMALS: ±N/A	END USER NAME: [redacted] JOB NUMBER: [redacted]
DRAWING CREATED: 06/01/06	SCALE: NONE	
LAST SAVED: 06/12/06	3RD ANGLE PROJECTION	
PLOTTED: 06/12/06	FILE NAME: 62631-001-02E.DWG	SERIAL NUMBER: 62631-001 / END USER NUMBER: 14075 / CUSTOMER SHEET: 4 OF 4 / 0404 / REV. 0

LHE Zn-Ni Prototype Plating Line Carbolux™ System



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

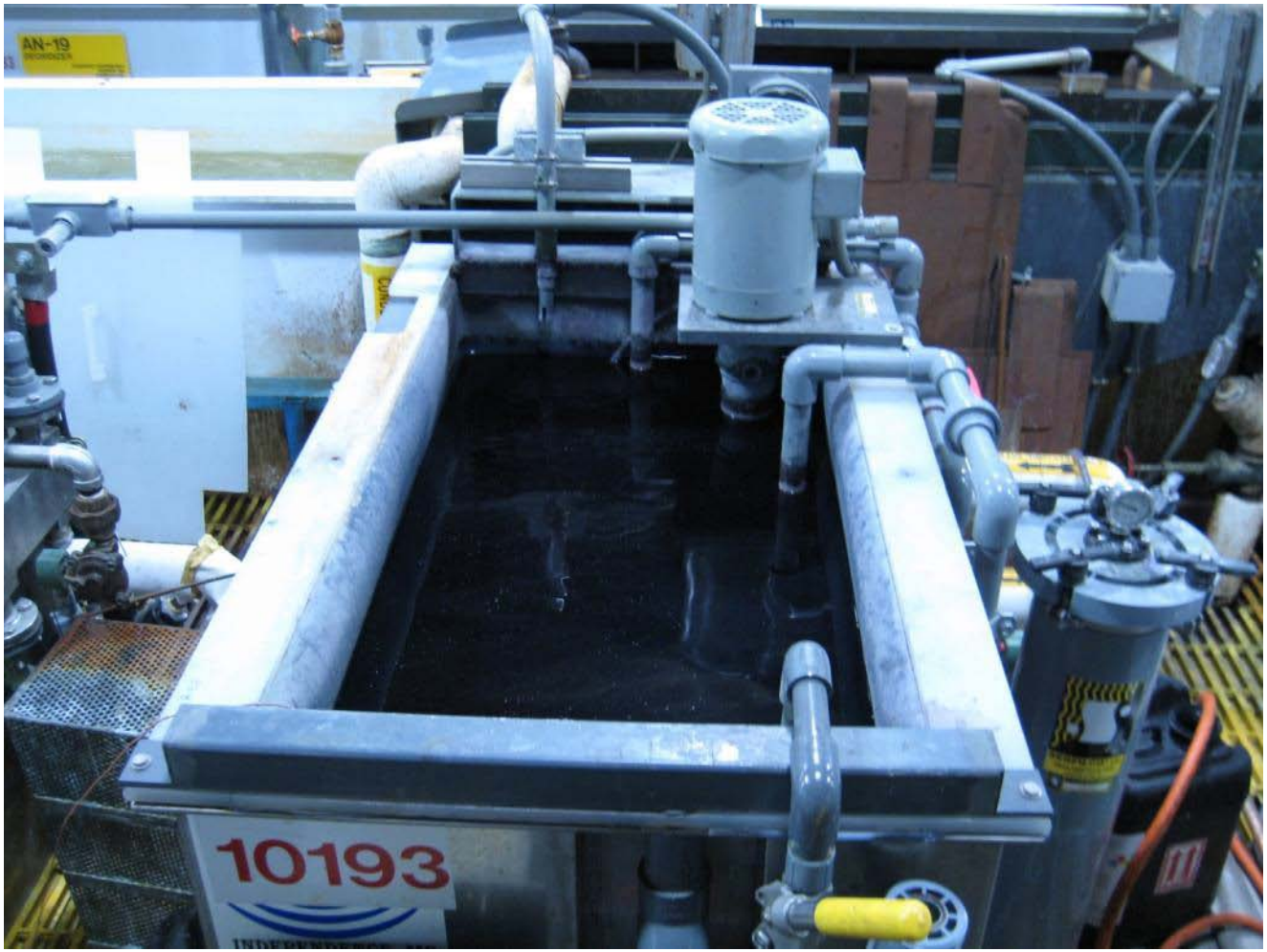
Back Up Slides: Phase II Qualification Testing

Small Prototype Tank Implementation

- 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

LHE Zn-Ni Plating Tank

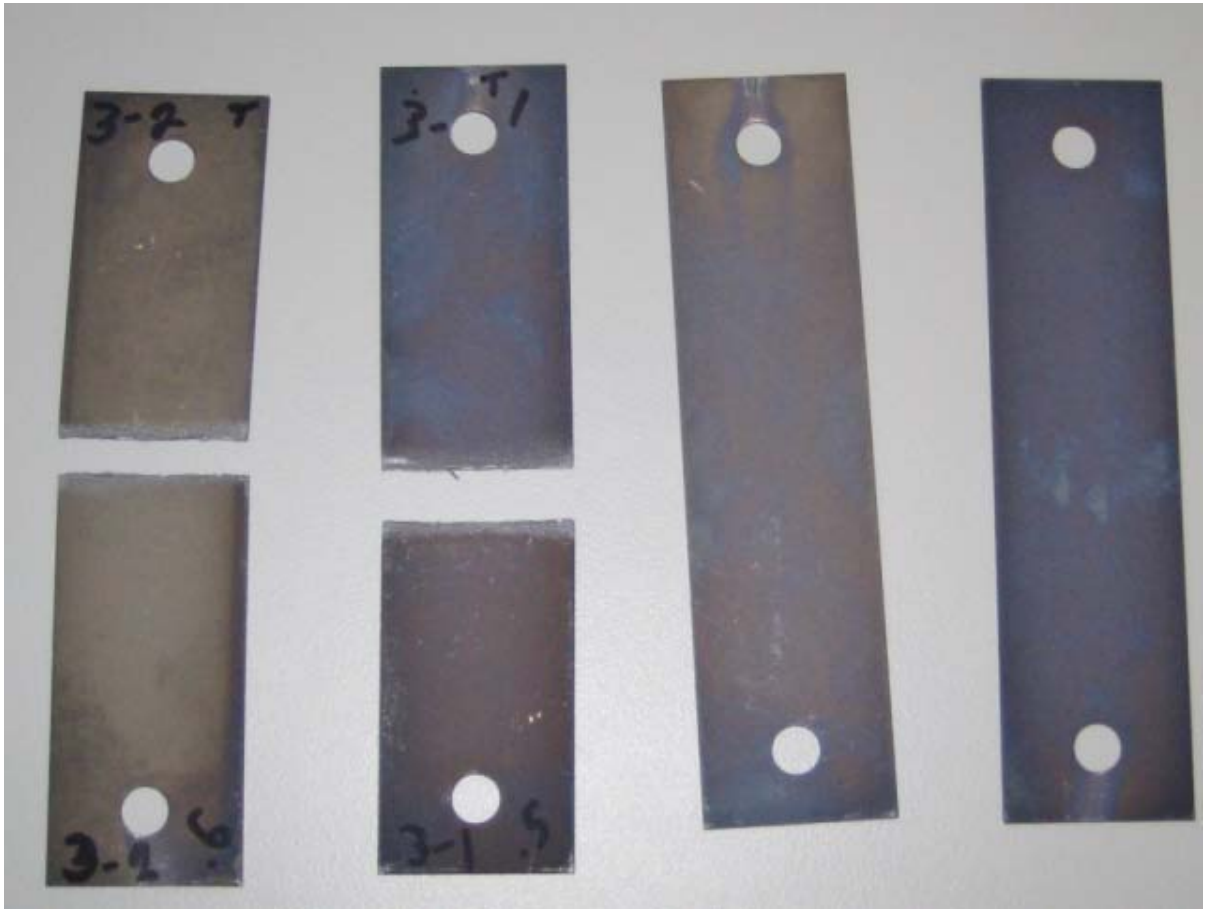
Prototype Tank Implementation



Tri-Chromium Conversion Coat Tank

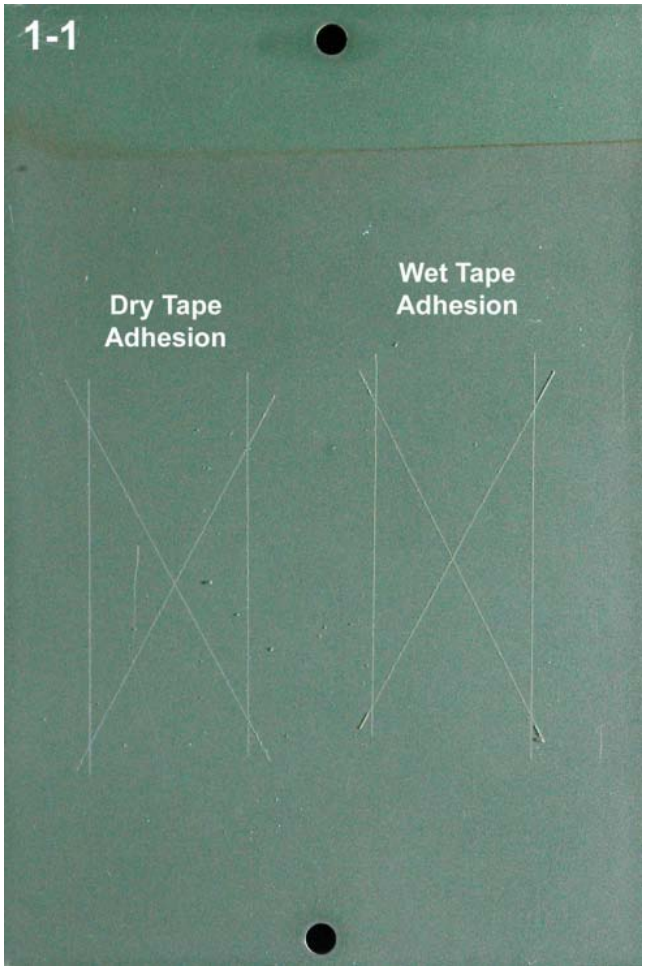
Bend to Break Adhesion Test Coupons

- 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

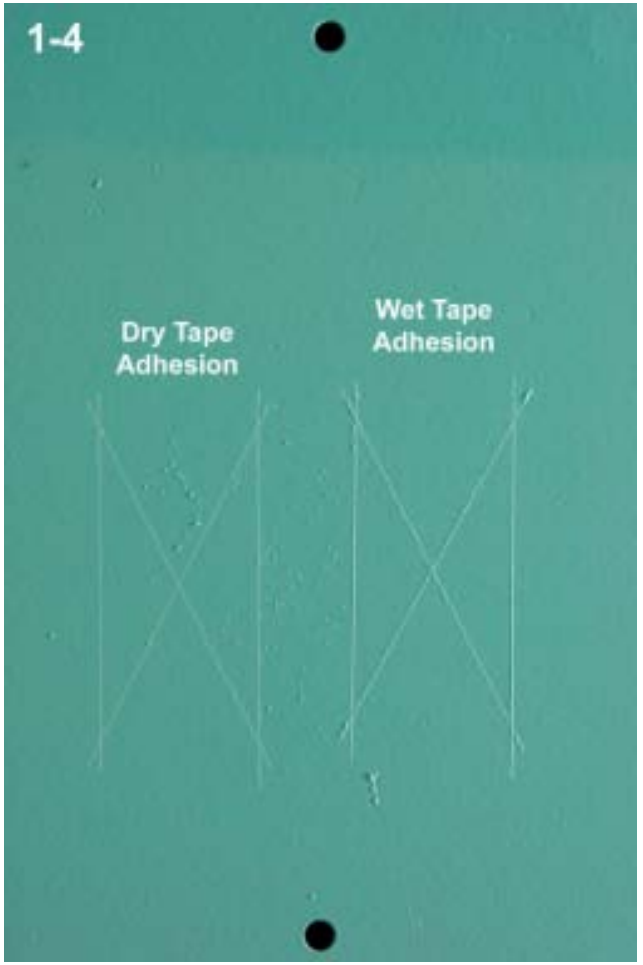


Adhesion Test Coupons

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

4" x 6" x 0.040" 4130 Steel Substrate

			DRY TAPE ADHESION			WET TAPE ADHESION		
PANEL ID	PRETREATMENT	COATING	PERCENTAGE COATING REMOVED	ASTM D 3359 [1]	Pass / Fail [2]	PERCENTAGE COATING REMOVED	ASTM D 3359 [1]	Pass / Fail [2]
1	LHE Zn-Ni Plating	Deft 44-GN-72	0	5A	Pass	0	4A	Pass
2			0	5A	Pass	2	4A	**Fail**
3			0	5A	Pass	0	5A	Pass
1	Cd Plated w/ Hex Cr Conversion Coating		0	5A	Pass	0	5A	Pass
2			0	5A	Pass	0	5A	Pass
3			0	5A	Pass	0	5A	Pass
4	LHE Zn-Ni Plating	Deft 44-GN-098	0	5A	Pass	0	5A	Pass
5			0	5A	Pass	0	5A	Pass
6			0	5A	Pass	10	4A	**Fail**
4	Cd Plated w/ Hex Cr Conversion Coating		0	5A	Pass	0	5A	Pass
5			0	5A	Pass	0	5A	Pass
6			0	5A	Pass	0	5A	Pass

Notes:

Panels immersed in distlled water at room temperature for 24 hours.

[1]- ASTM D 3359 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"

[2]- The primer shall show no adhesion failure.

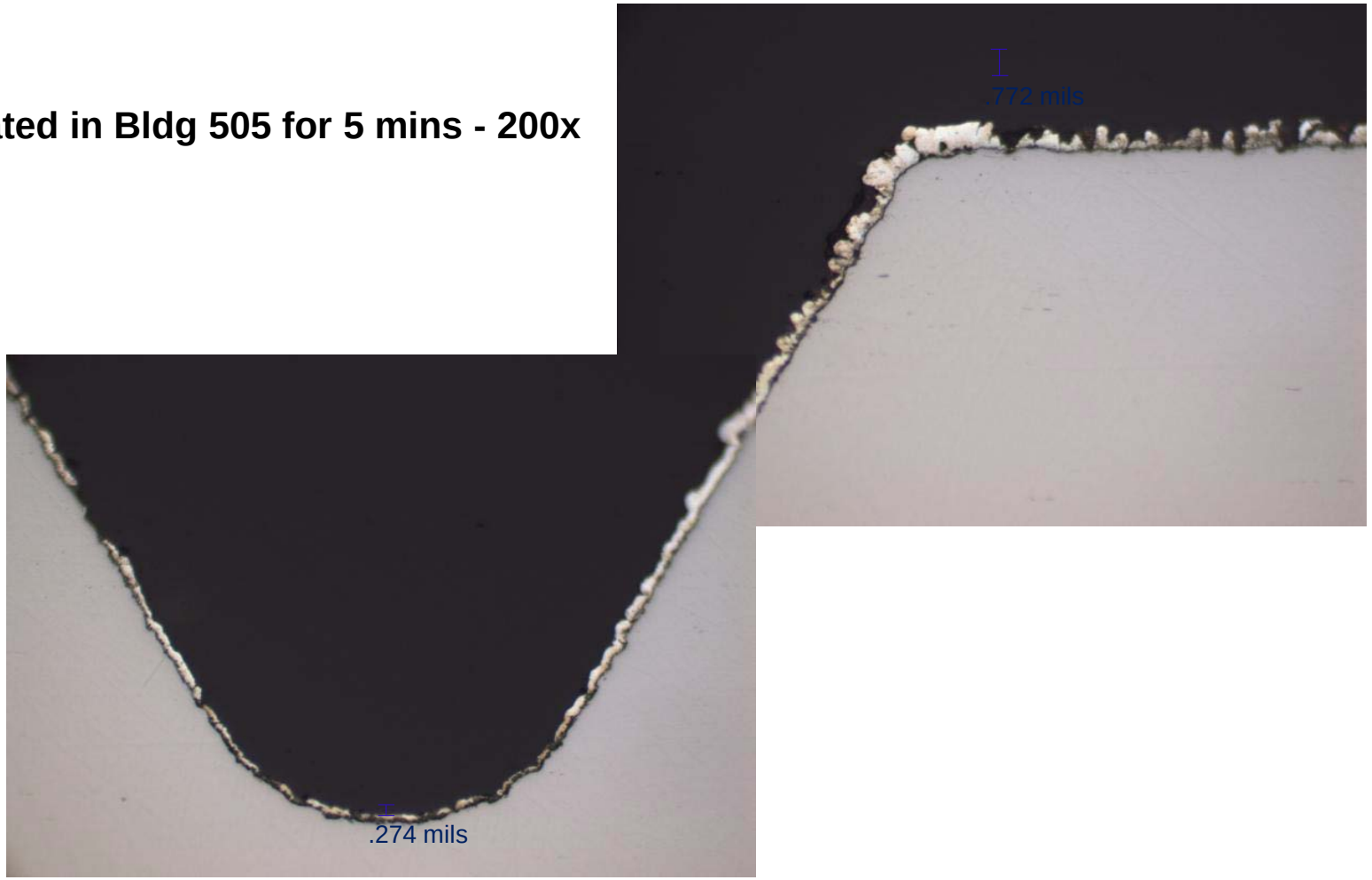
LHE Zn-Ni Hydrogen Embrittlement Testing

- 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

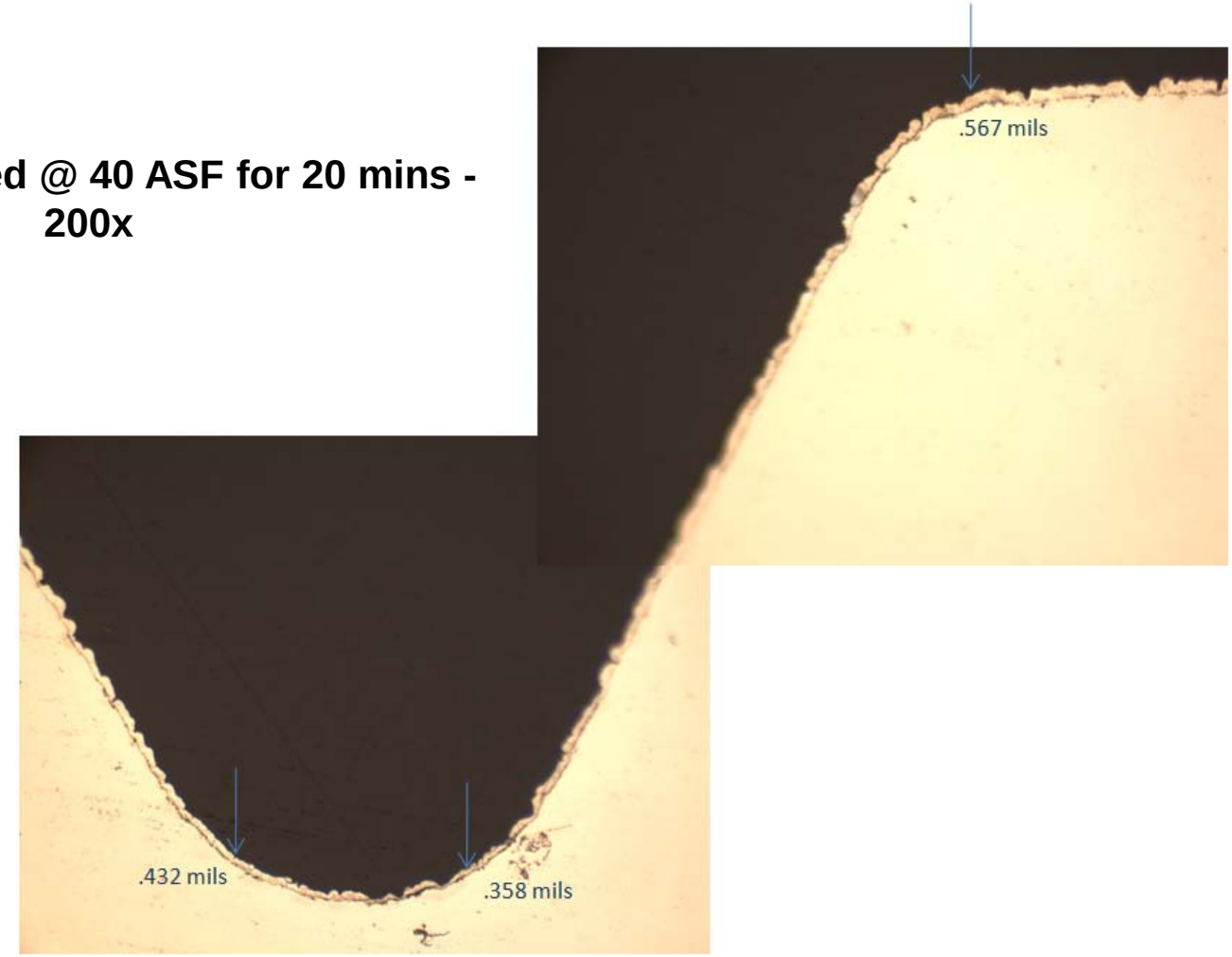
HE Plated Cross Section

Cad Plated in Bldg 505 for 5 mins - 200x

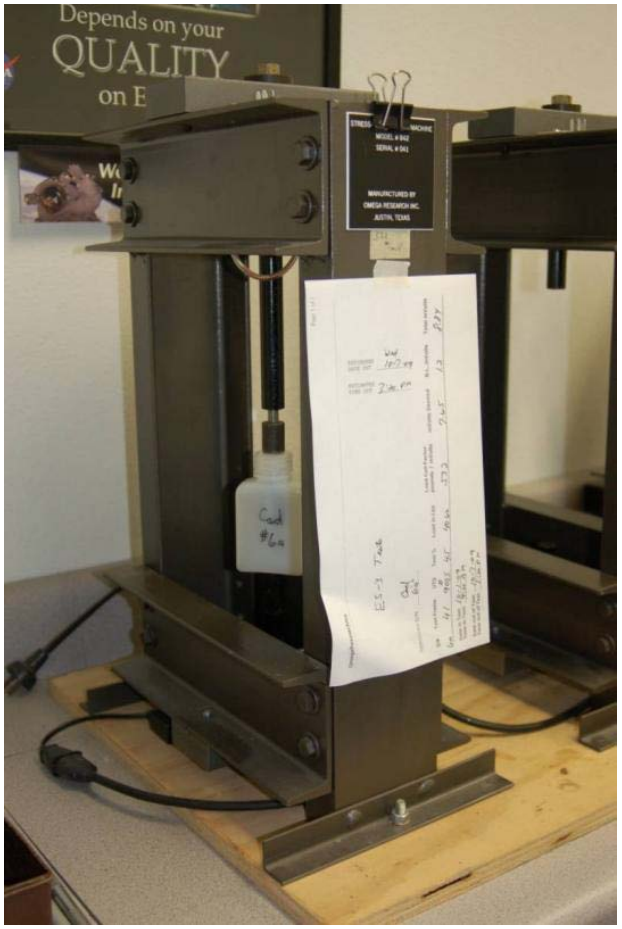


HE Plated Cross Section

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

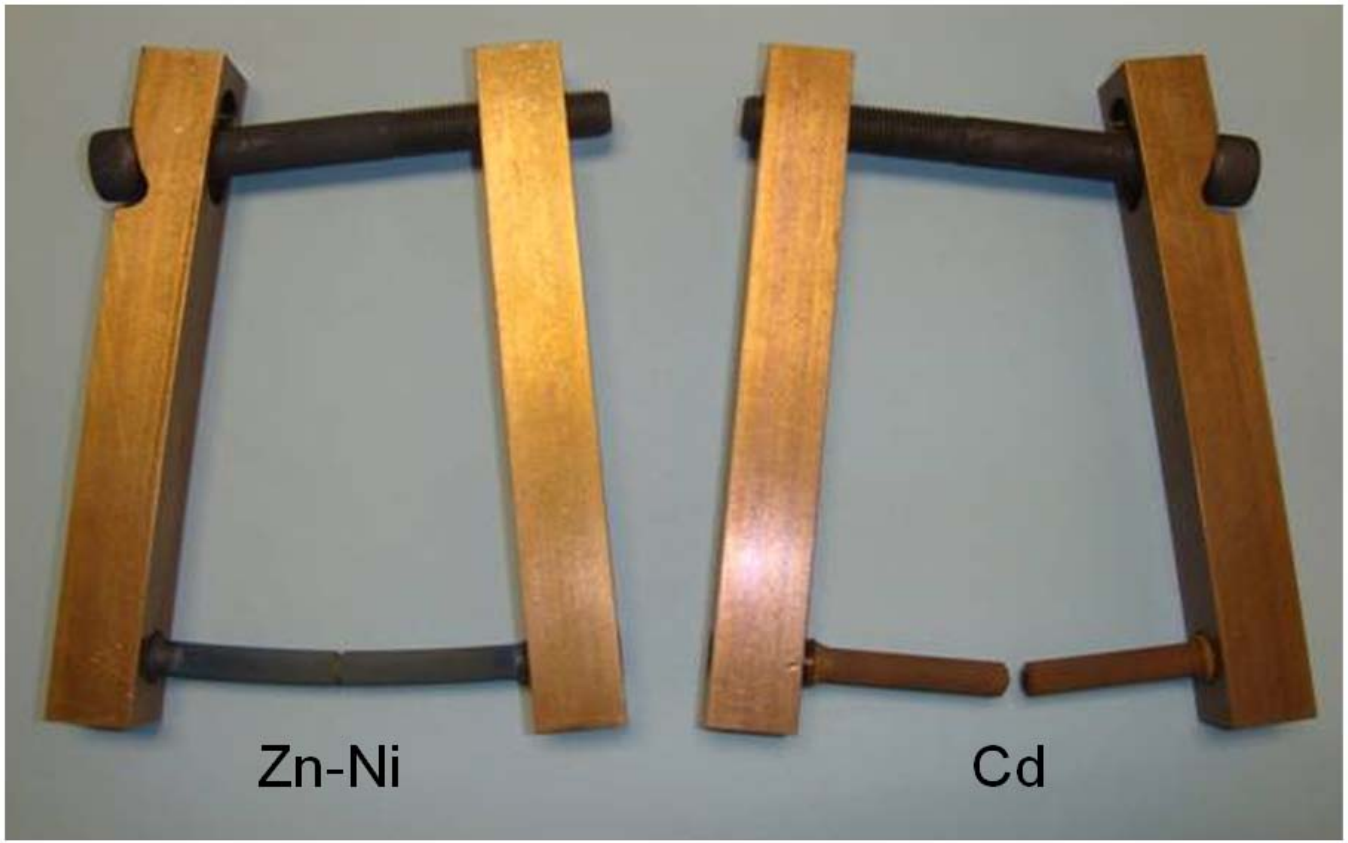
Re Embrittlement Test Matrix						
Plating	Test Solution					
	Distilled Water @ Room Temp Tested 45% NFS for 150Hrs	3.5% Salt Water @ Room Temp Tested 45% NFS for 150Hrs	Dwg 9825019* Diluted Calla 296 @ Max Temp 180 °F Tested 75% NFS for 200Hrs	Dwg 9825019* Diluted Calla 602 LF Max Temp 160 °F Tested 75% NFS for 200Hrs	Concentrated Calla 296 @ Room Temp tested 45% NFS for 150Hrs	Concentrated Calla 602LF @ Room Temp tested 45% NFS for 150Hrs
LHE Zn-Ni	Pass	Failed	Pass	Pass	Pass	Pass
Cadmium	Pass	Failed	Pass	Pass	Pass	Pass
IVD	Failed	Failed	Not Tested	Not Tested	Not Tested	Not Tested

*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 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

Liquid/Solid Metal Embrittlement Testing



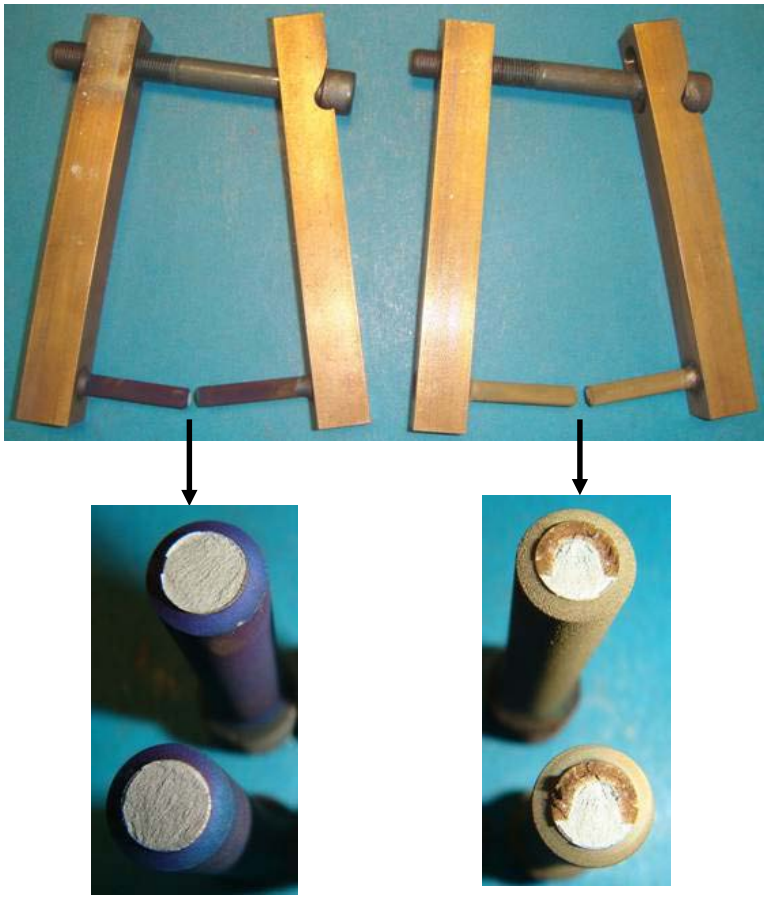
LHE Zn-Ni Plated and Cad Plated 300M Type 1a.1 Test Specimens in Self-Loading Bend Frames

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**

Temp/NFS	Material	Zn-Ni 200Hr	Cad 200Hr	Zn-Ni Step Load	Cad Step Load
600F/85%	300M	Pass	Fail	100% NFS	-N/A-
500F/85%	300M	Pass	Fail	100% NFS	87% NFS
400F/85%	300M	Pass	Fail	100% NFS	91% NFS
400F/75%	300M	Pass	Fail	100% NFS	81% NFS

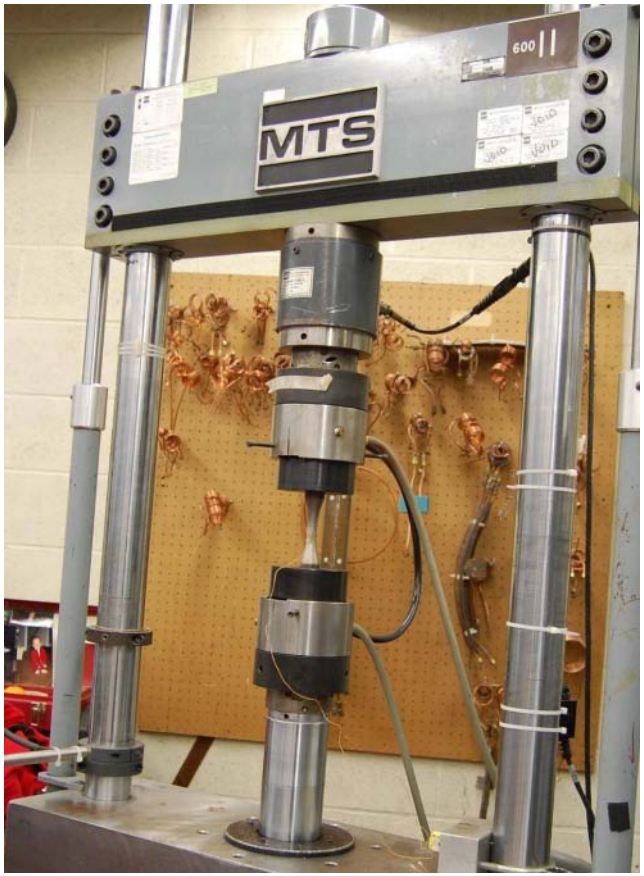
Liquid/Solid Metal Embrittlement Testing



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

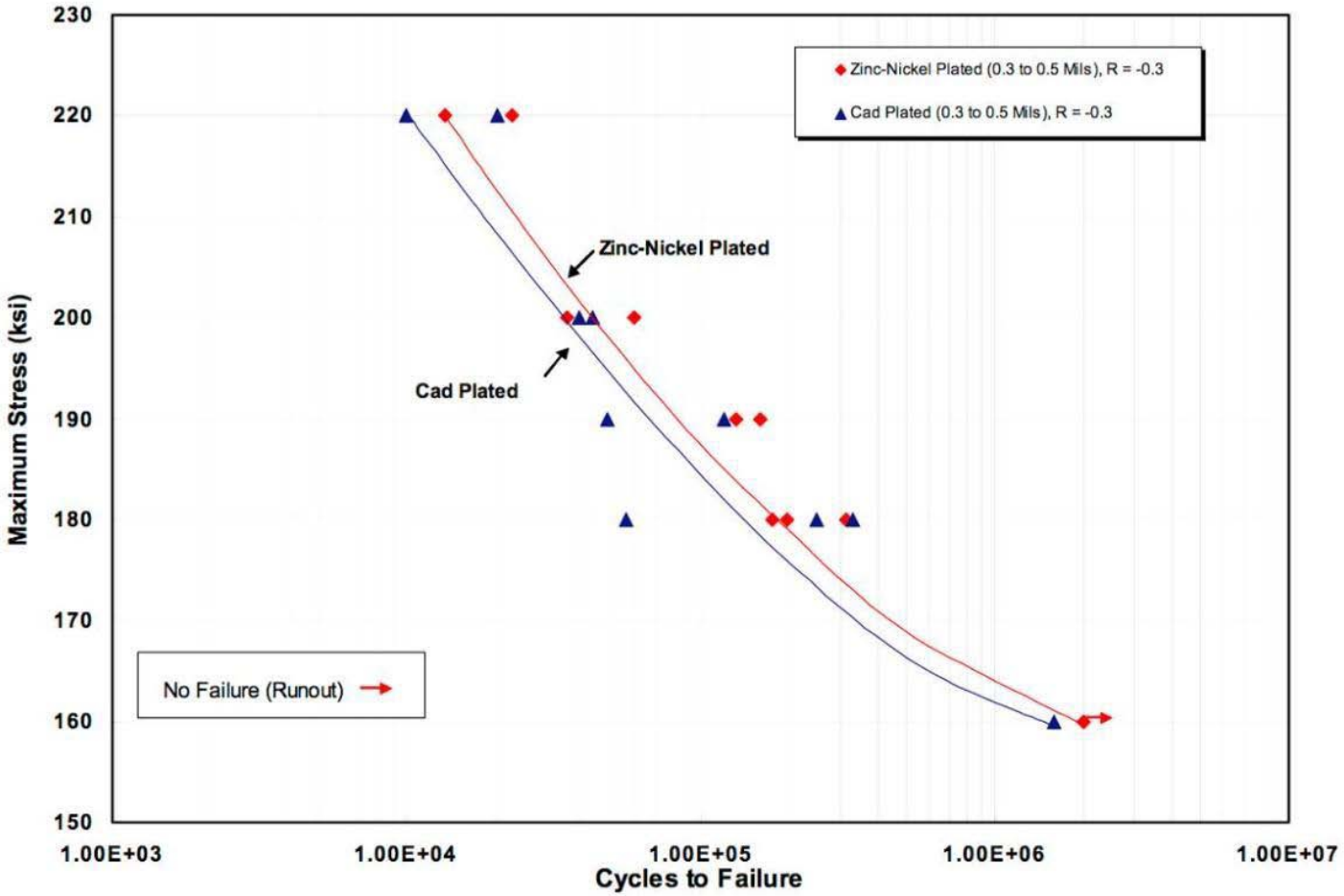
Fatigue Testing

- 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)

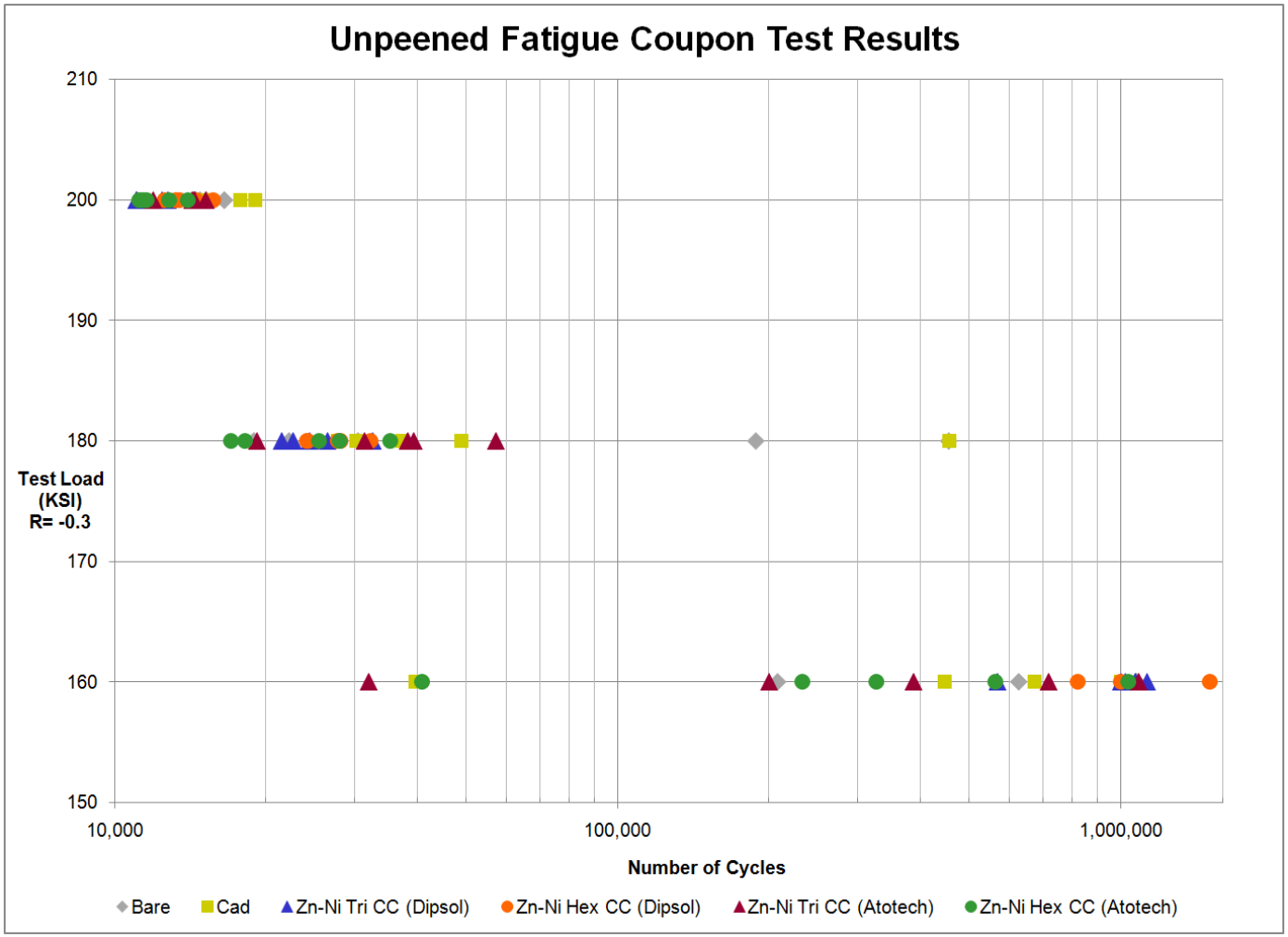


Phase II Fatigue Testing

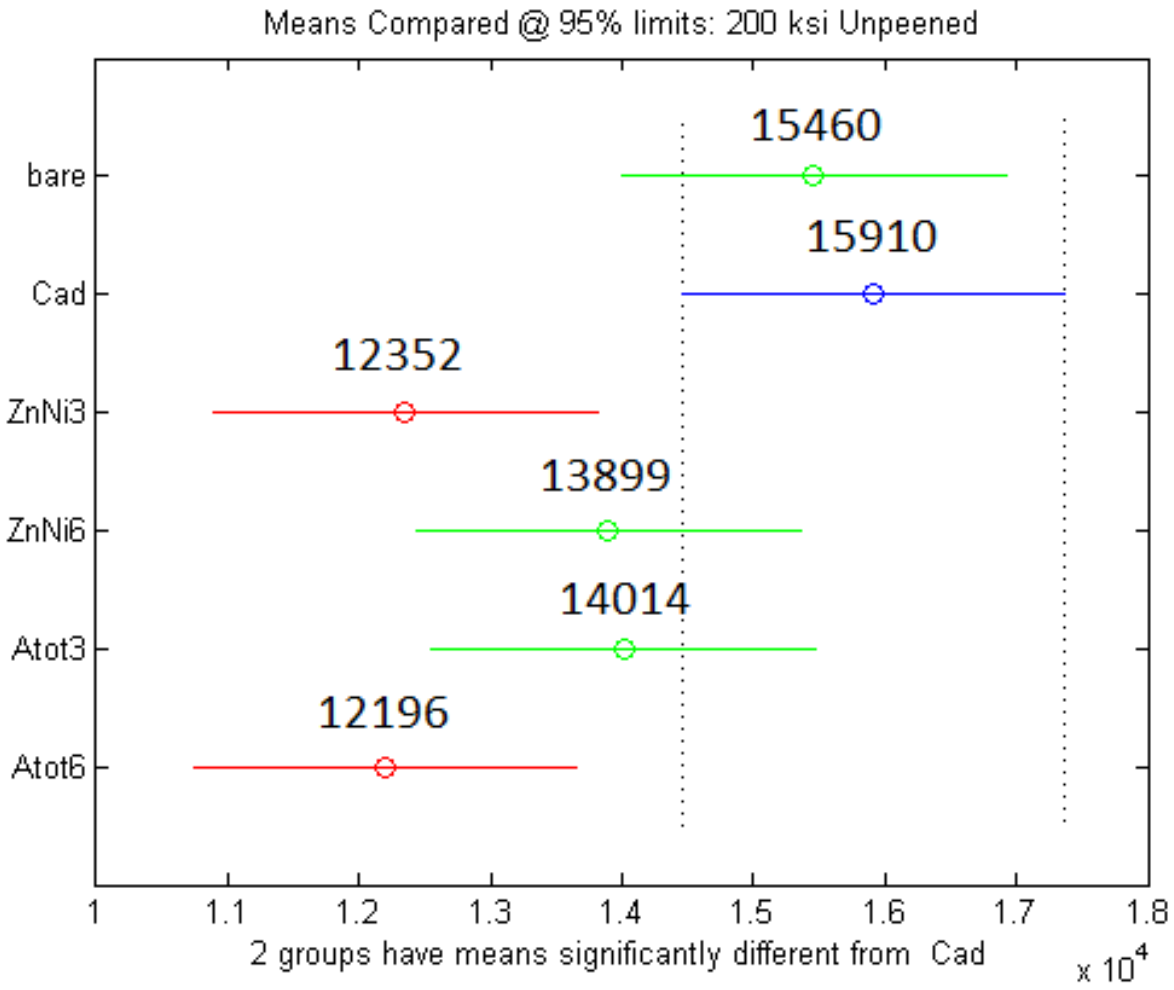
UnPeened Coupons	Stress Loads (KSI) R= -0.3			Total Quantity
	160	180	200	
Bare	5	5	5	15
Cad Plated	5	5	5	15
LHE Zn-Ni Plated Tri CC	5	5	5	15
LHE Zn-Ni Plated Hex CC	5	5	5	15
*Zn-Ni Plated Atotech Tri CC	5	5	5	15
Zn-Ni Plated Atotech Hex CC	5	5	5	15
Spares	5	5	5	15
Spares	5	5	5	15
Total Fatigue Coupons				120
* Bake before Tri CC				

Peened Coupons	Stress Loads (KSI) R= -0.3			Total Quantity
	160	180	200	
Bare	5	5	5	15
Cad Plated	5	5	5	15
LHE Zn-Ni Plated Tri CC	5	5	5	15
LHE Zn-Ni Plated Hex CC	5	5	5	15
*Zn-Ni Plated Atotech Tri CC	5	5	5	15
Zn-Ni Plated Atotech Hex CC	5	5	5	15
Spares	5	5	5	15
Spares	5	5	5	15
Total Fatigue Coupons				120
* Bake before Tri CC				

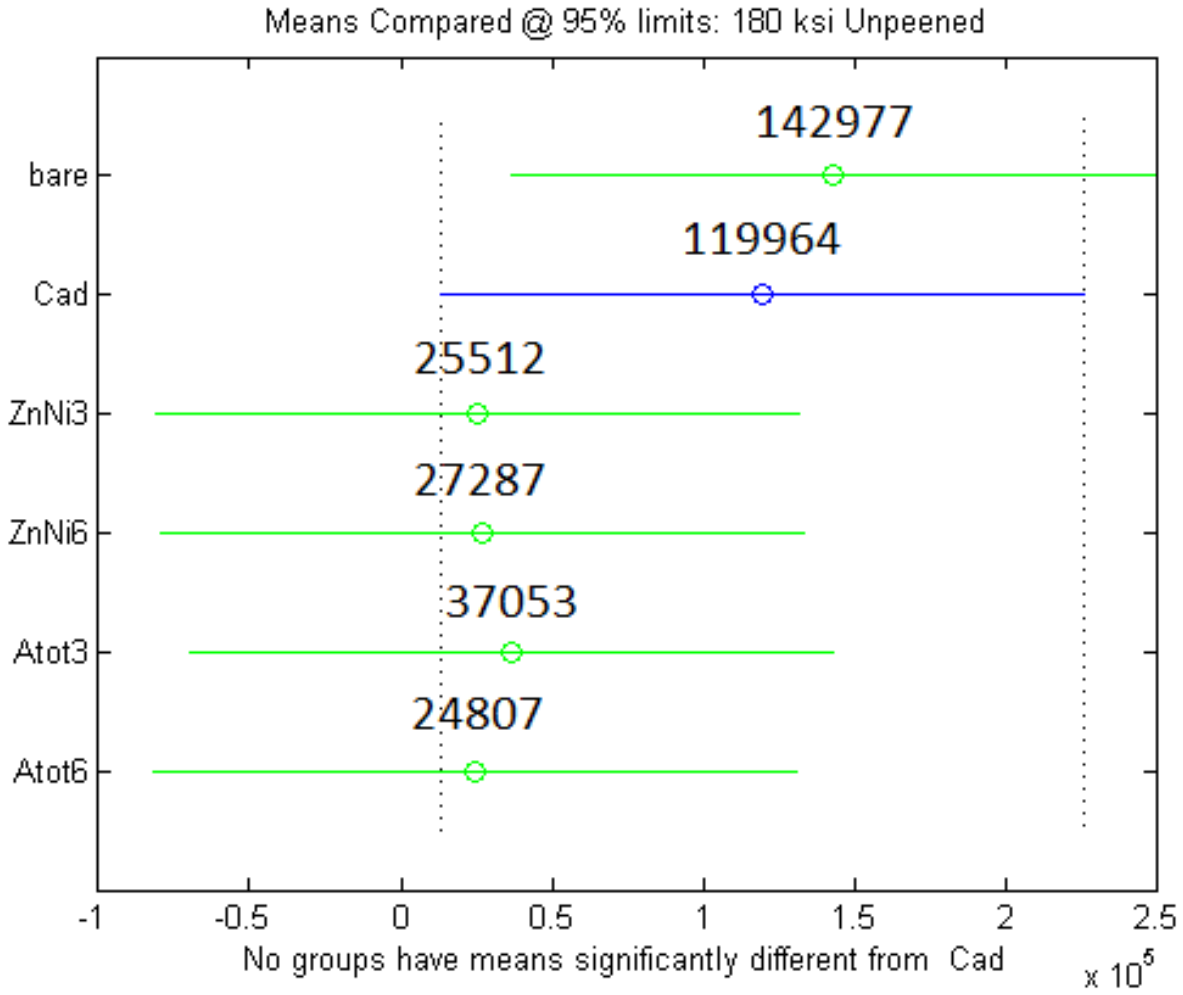
Phase II Fatigue Testing



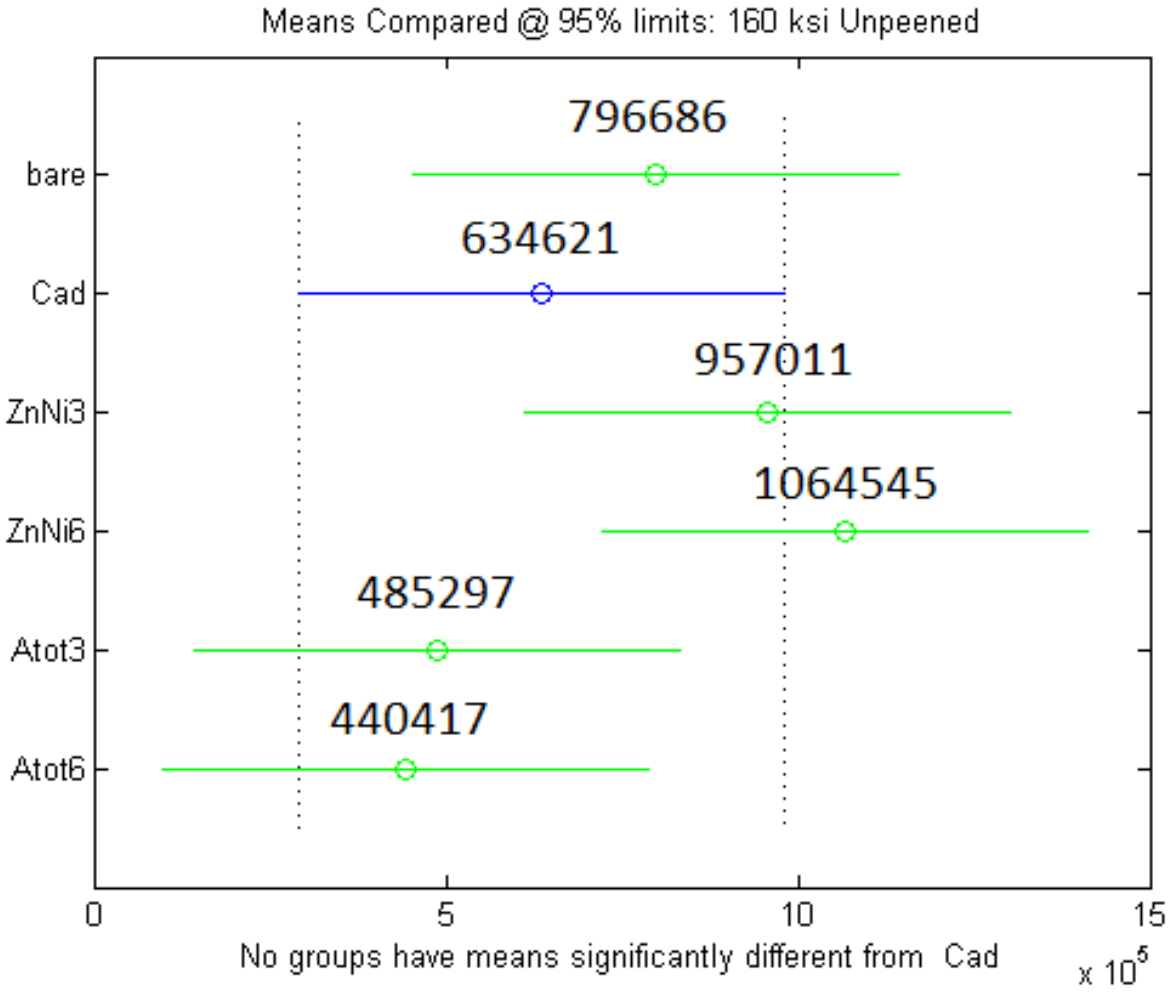
Phase II Fatigue Testing



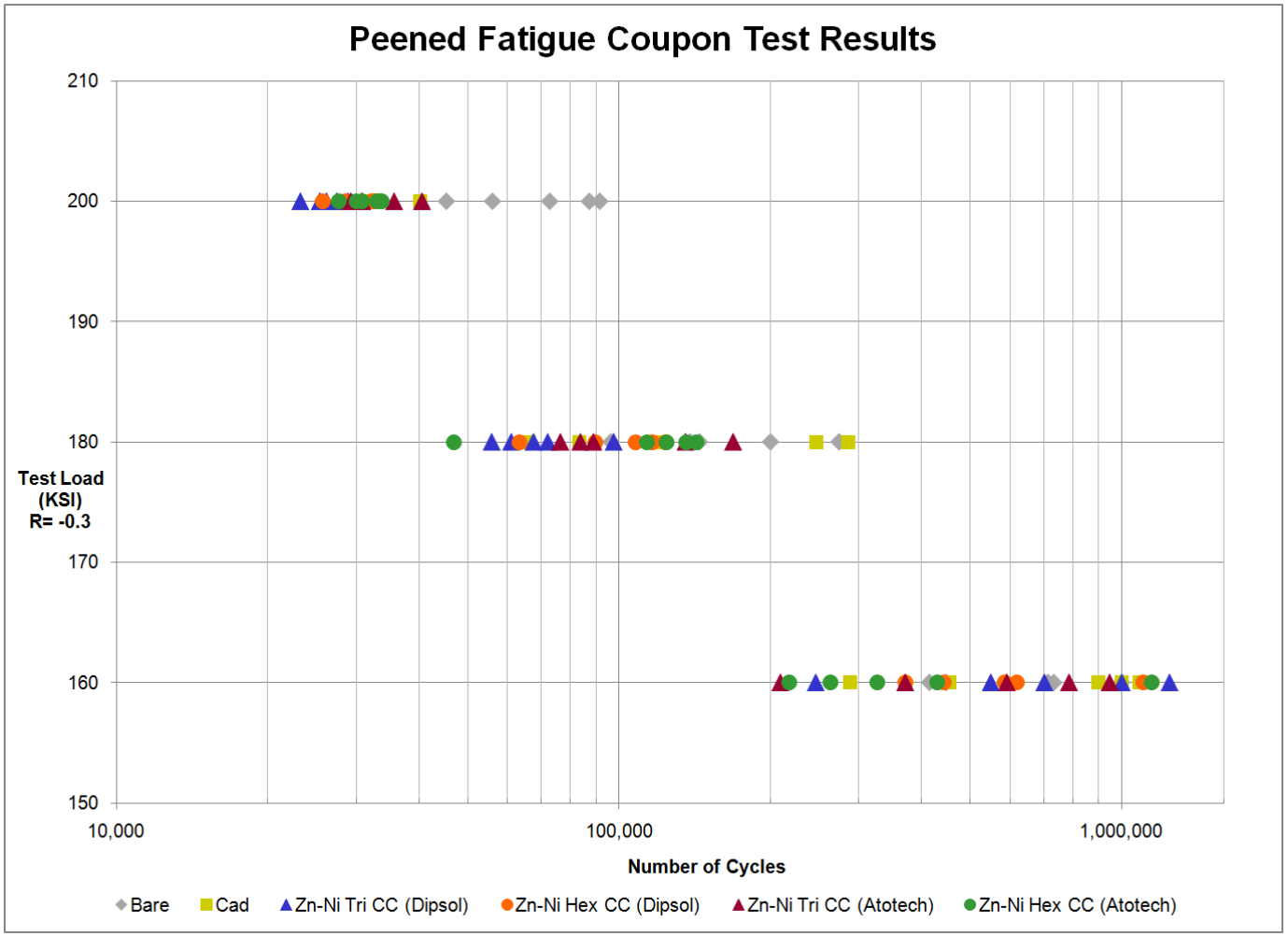
Phase II Fatigue Testing



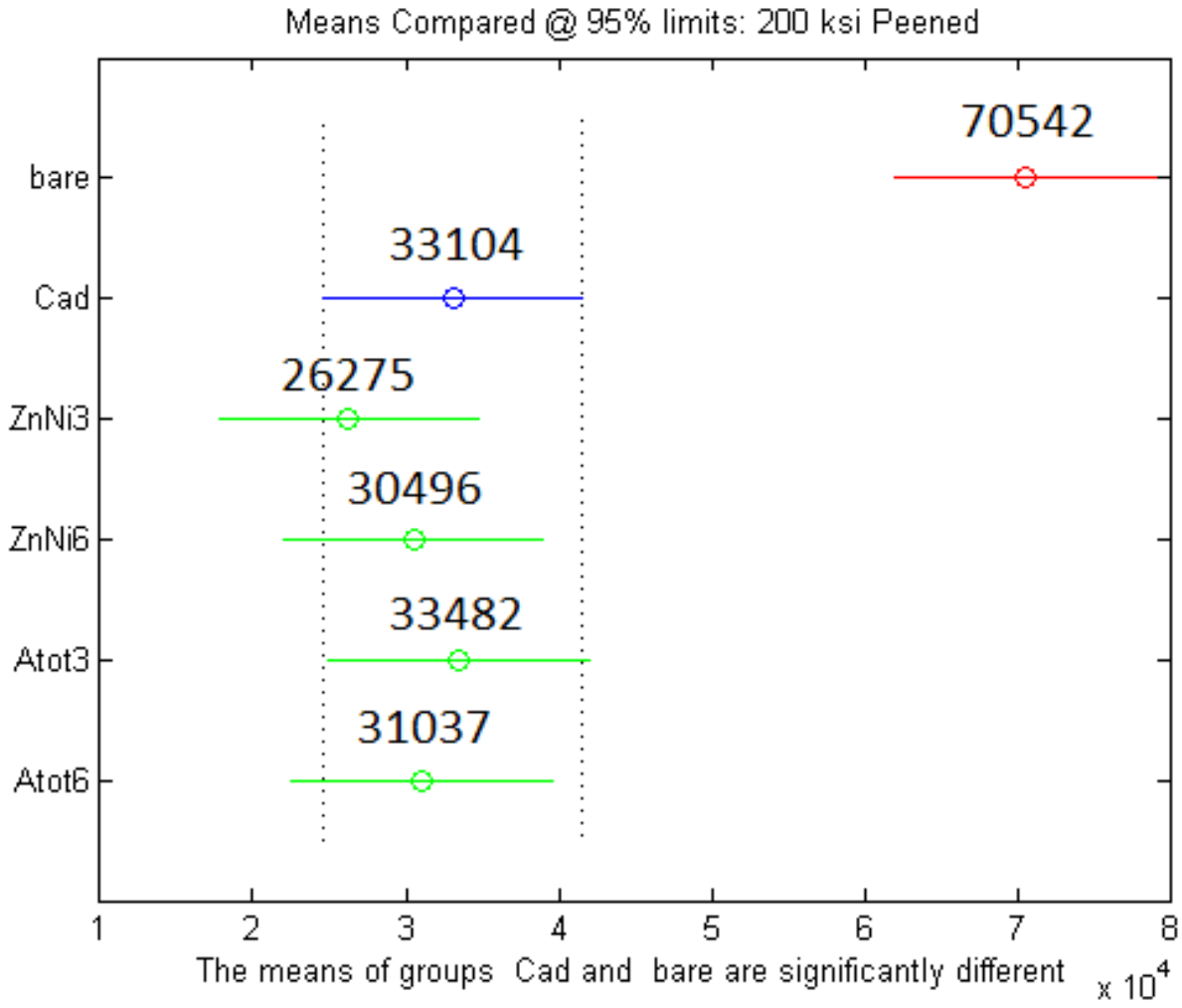
Phase II Fatigue Testing



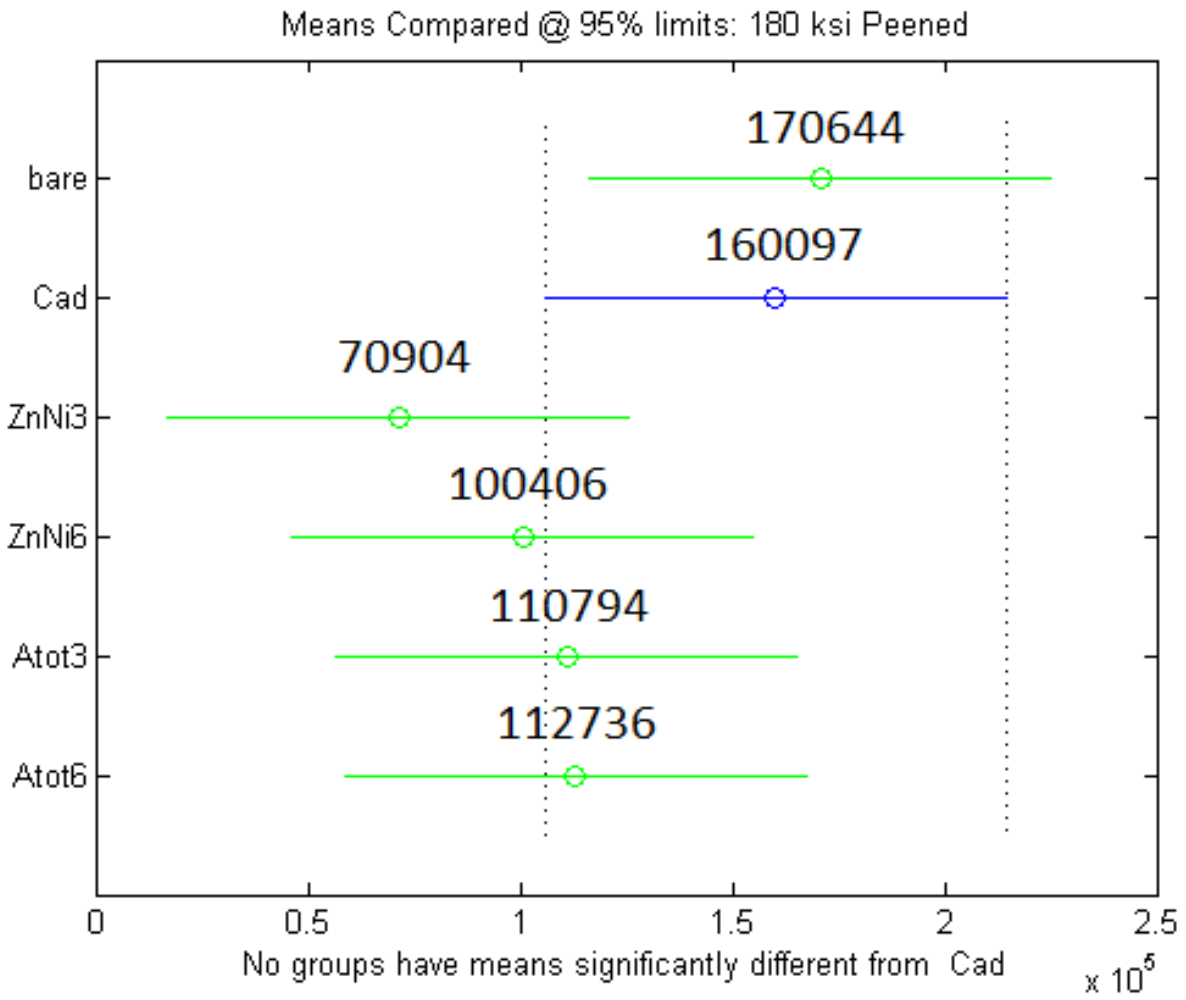
Phase II Fatigue Testing



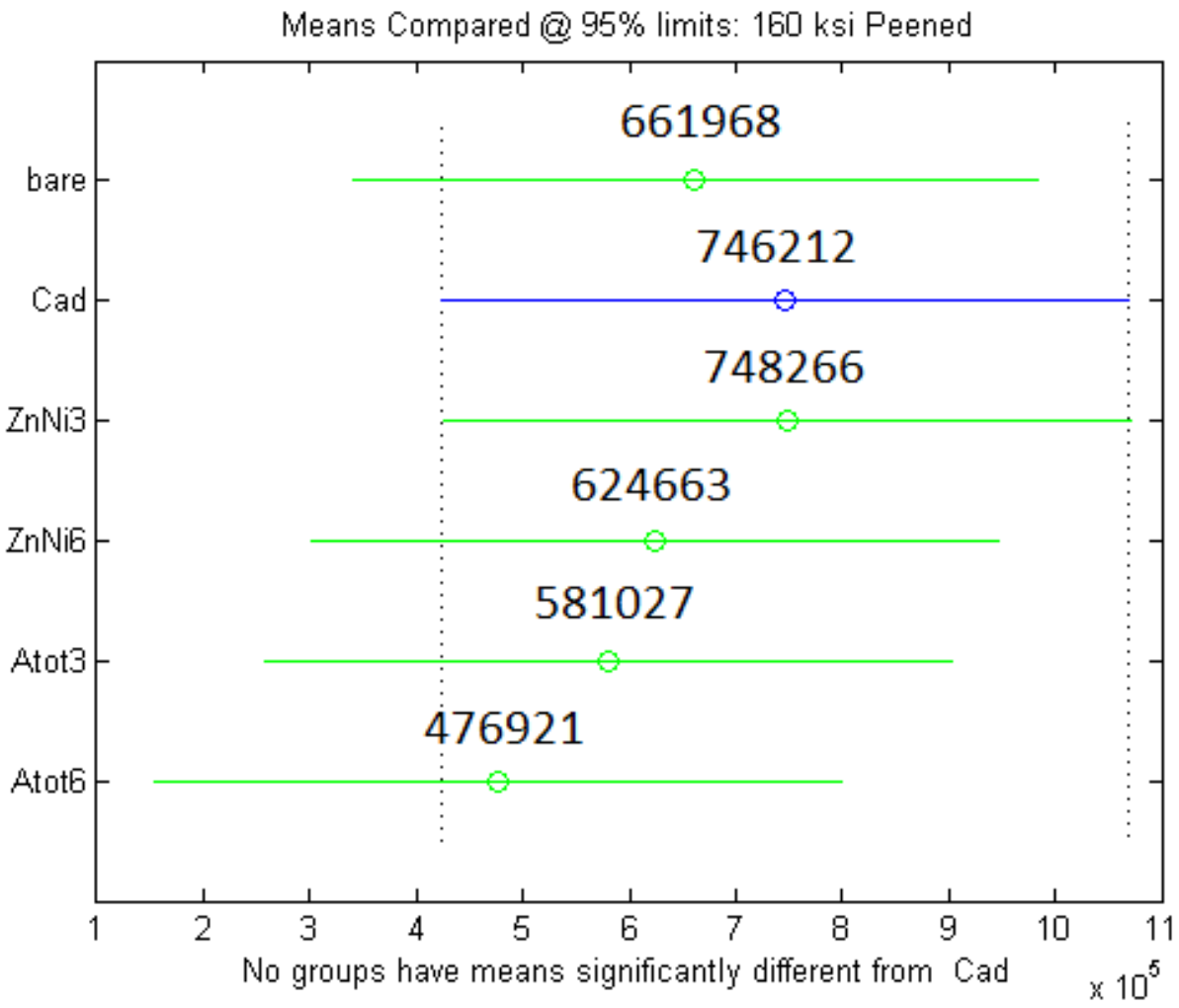
Phase II Fatigue Testing



Phase II Fatigue Testing



Phase II Fatigue Testing



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

# of steel Panels	Plating	Scribed	Prime/Paint
3	LHE Zn-Ni	Yes	No
3	LHE Zn-Ni	No	No
3	Cd	Yes	No
3	Cd	No	No
3	LHE Zn-Ni	Yes	Yes
3	Cd	Yes	Yes

Corrosion Performance

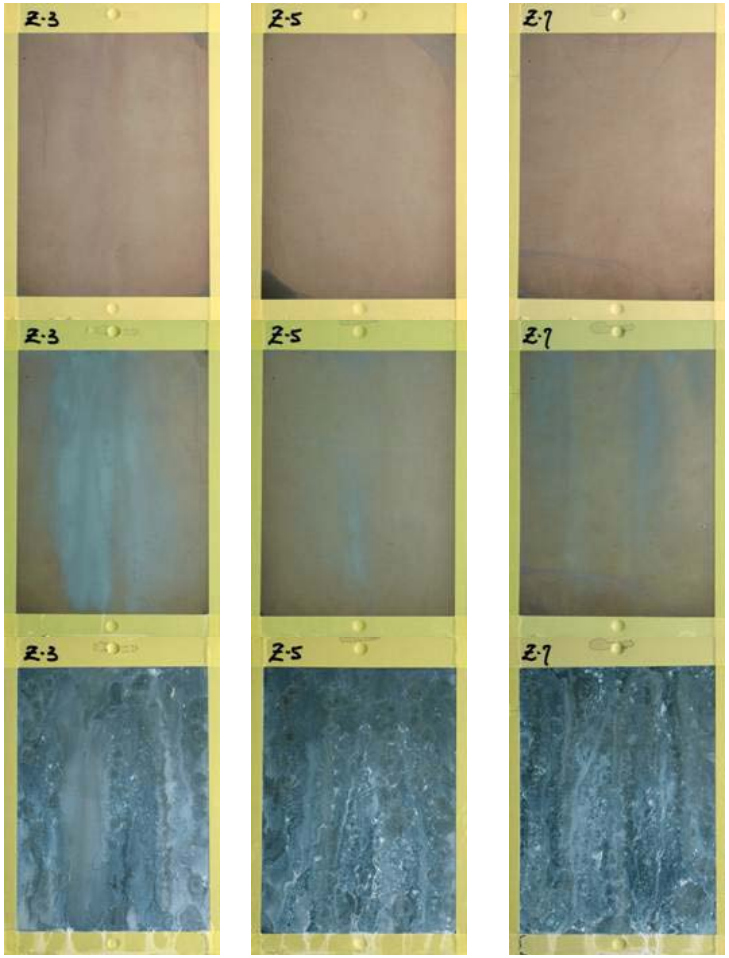
Cadmium with Hexavalent Chrome Conversion Coating
Unscribed – ASTM B 117
Figure 3

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
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	3000 hours
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	5000 hours

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

Corrosion Performance

IZ-C17+ Zn-Ni with Trivalent Chrome Conversion Coating
Unscribed – ASTM B 117
Figure 4



1000 hours

3000 hours

5000 hours

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

Corrosion Performance

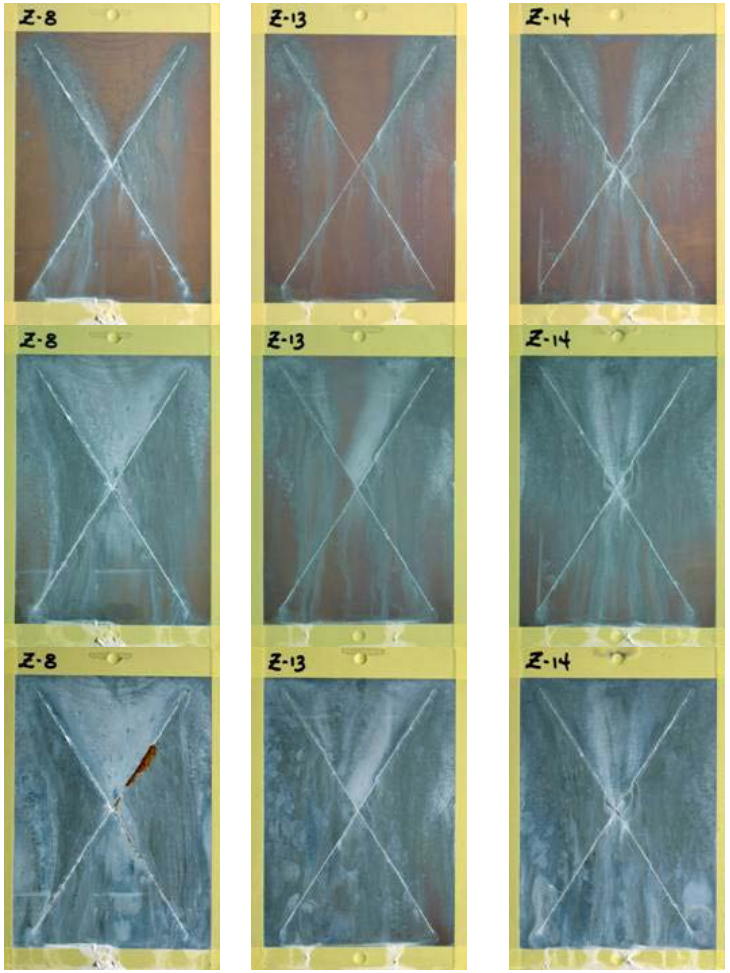
Cadmium with Hexavalent Chrome Conversion Coating
Scribed – ASTM B 117
Figure 5

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
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	3000 hours
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	5000 hours

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

Corrosion Performance

IZ-C17+ Zn-Ni with Trivalent Chrome Conversion Coating
Scribed – ASTM B 117
Figure 6



1000 hours

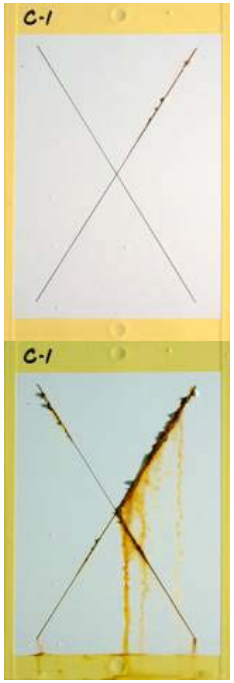
3000 hours

5000 hours

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

Corrosion Performance

Cadmium with Hexavalent Chrome Conversion Coating
Scribed Painted – ASTM B 117
Figure 9

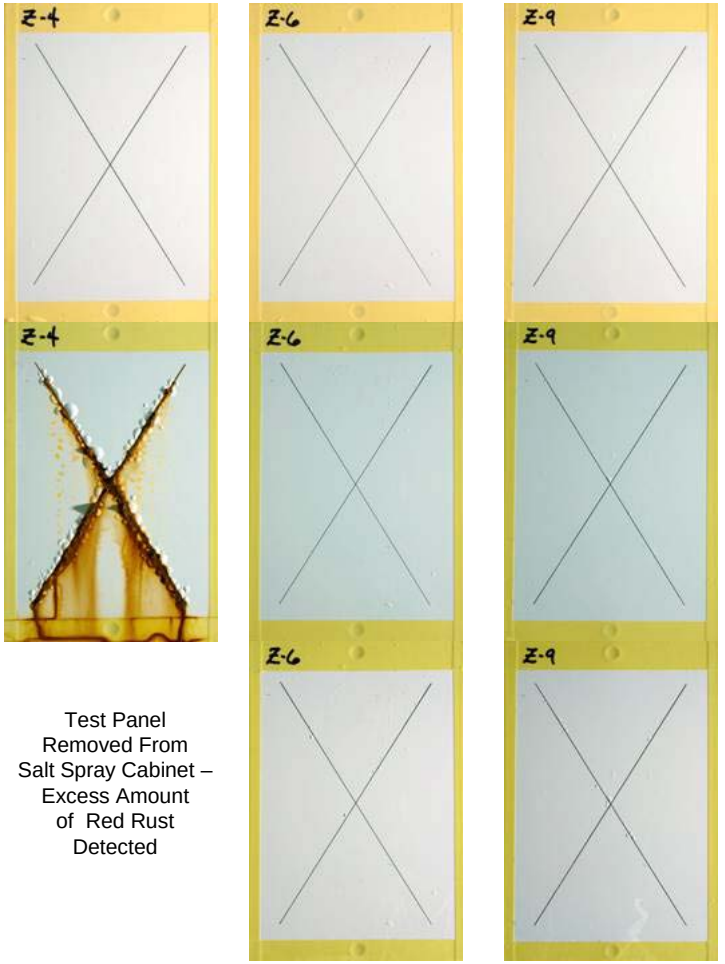


Test Panel Removed From Salt Spray Cabinet – Excess Amount of Red Rust Detected	Test Panel Removed From Salt Spray Cabinet – Excess Amount of Red Rust Detected	1000 hours
Test Panel Removed From Salt Spray Cabinet – Excess Amount of Red Rust Detected	Test Panel Removed From Salt Spray Cabinet – Excess Amount of Red Rust Detected	3000 hours
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	5000 hours

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

Corrosion Performance

IZ-C17+ Zn-Ni with Trivalent Chrome Conversion Coating
Scribed Painted – ASTM B 117
Figure 10



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

1000 hours

3000 hours

5000 hours

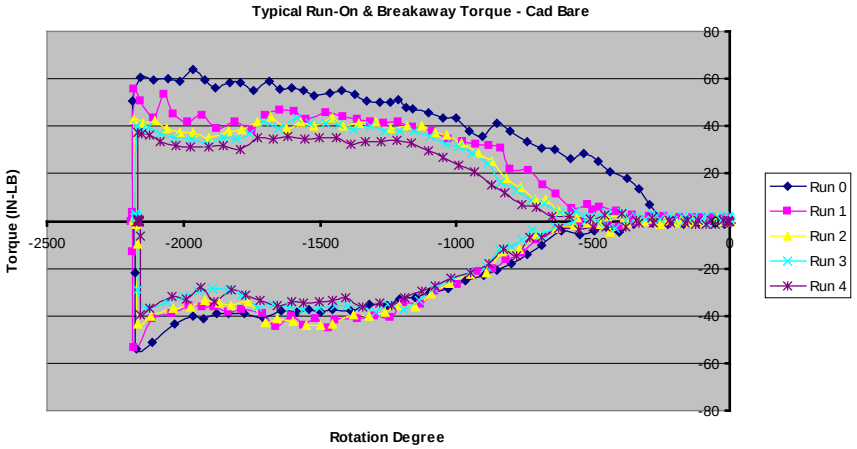
LHE Zinc Nickel Coatings – Phase II ASTM B 117 Panels @ Boeing (Painted/Scribed)

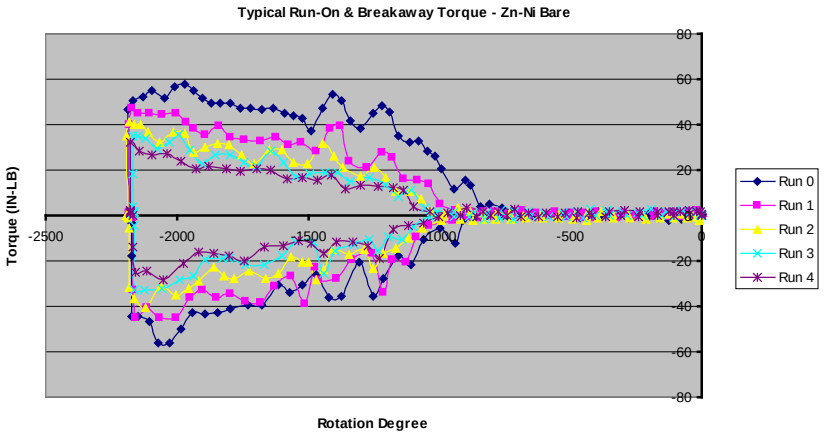
Brush Plating Repair

- 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

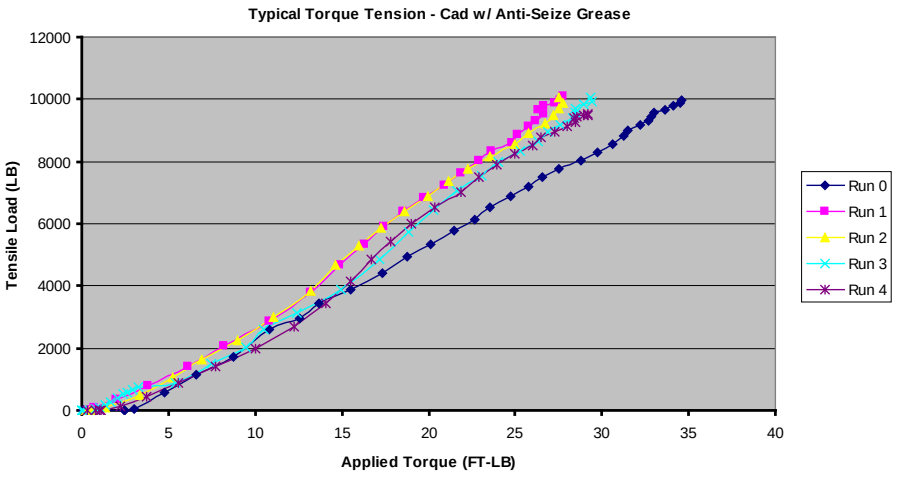
- **Robins AFB Cad plating replacement on threaded fastener and components**
  - **Typical chart for run on – break away test showing Cad vs. LHE Alkaline Zn-Ni**

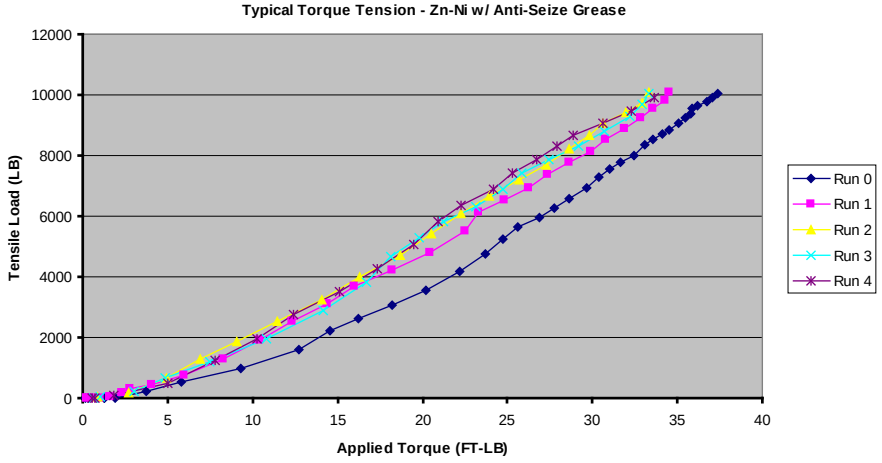




Torque Tension

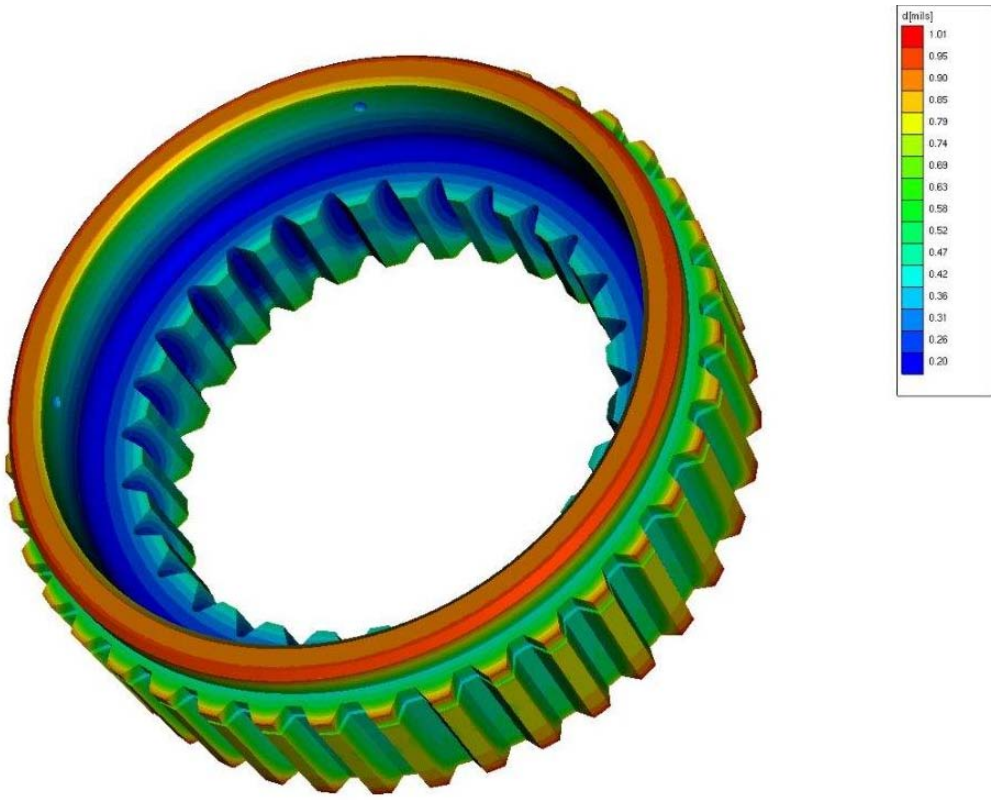
- **Robins AFB Cad plating replacement on threaded fastener and components**
  - **Typical chart for Torque Tension Test showing Cad vs. LHE Alkaline Zn-Ni with MIL-PRF-83483 Anti-seize grease lubricant**





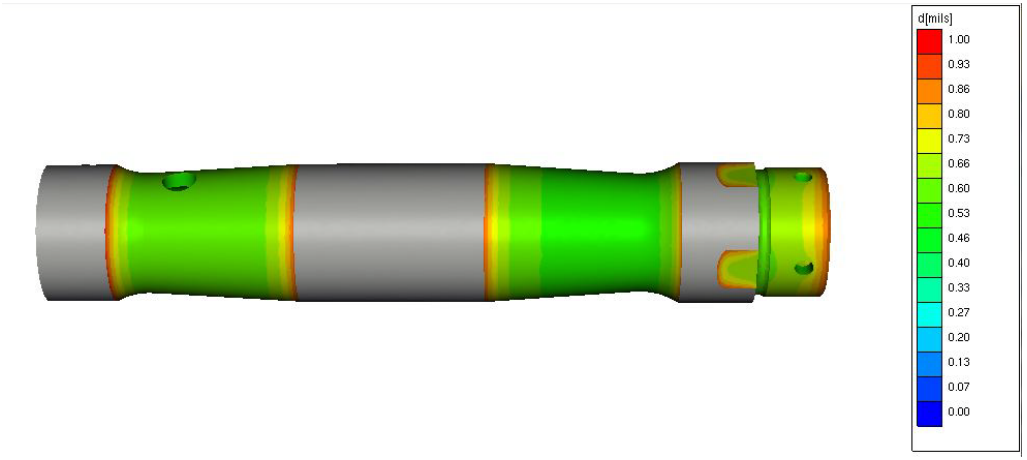
Back Up Slides:
Zn-Ni Conformal Anode Fixtures

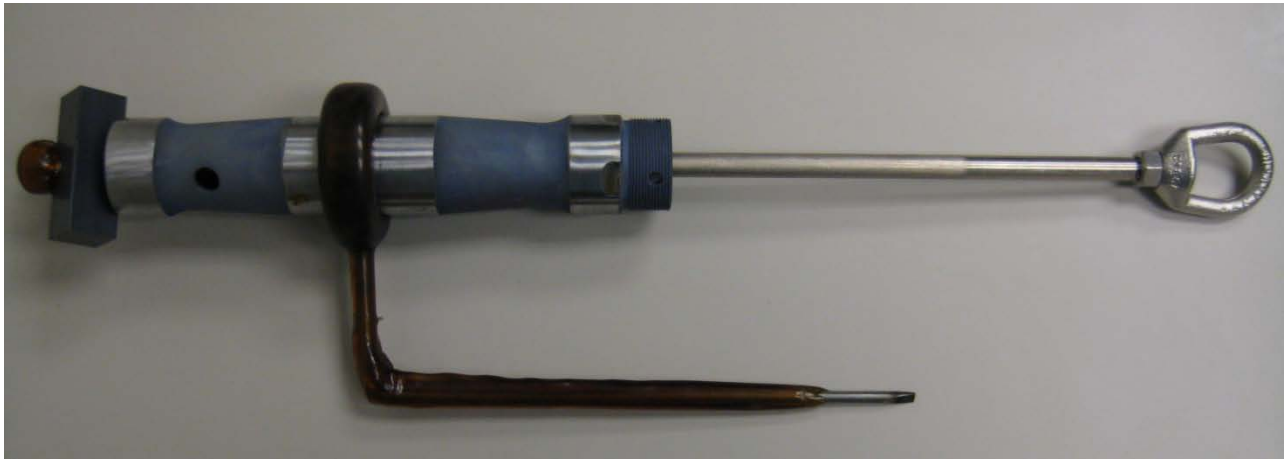
Phase III Effort
Prototype Anode Design



MLG Rotation Collar

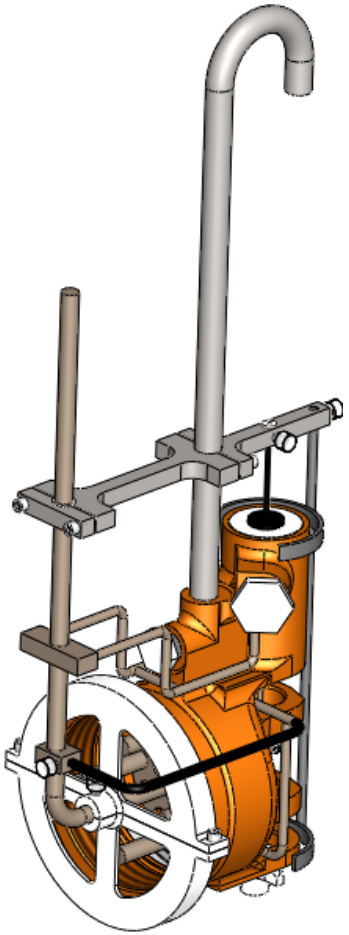
Phase III Effort
Prototype Anode Design



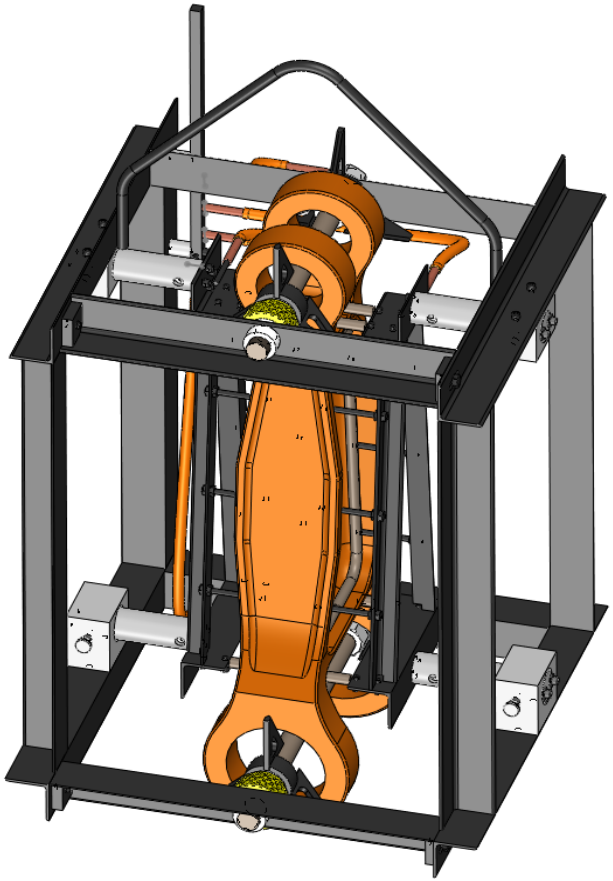


NLG Axle

LHE Zn-Ni Plating Conformal Anode and Fixture Models

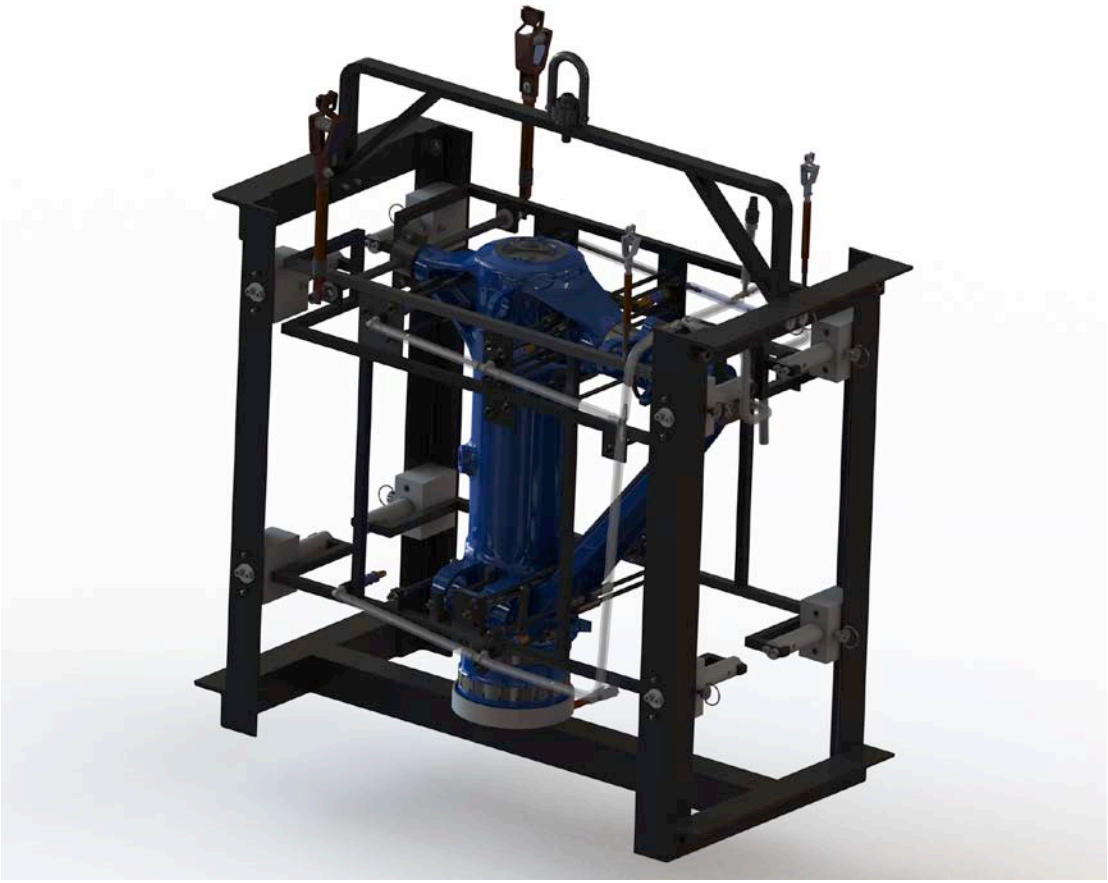


NLG Outer Cylinder



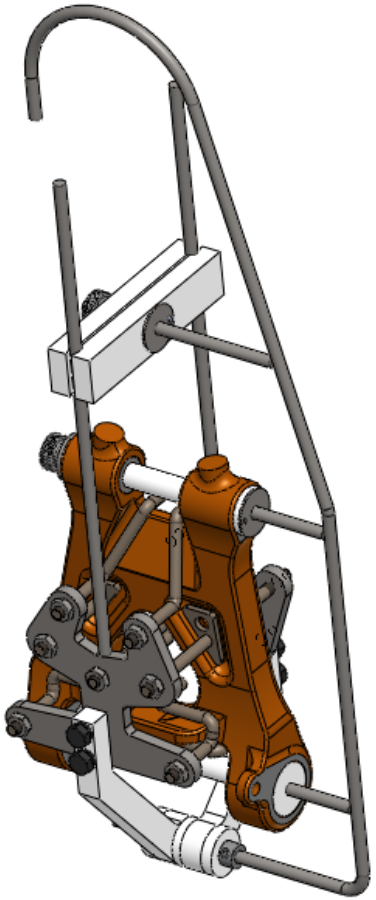
MLG Lower Side Brace

LHE Zn-Ni Conformal Anode and Fixture Models

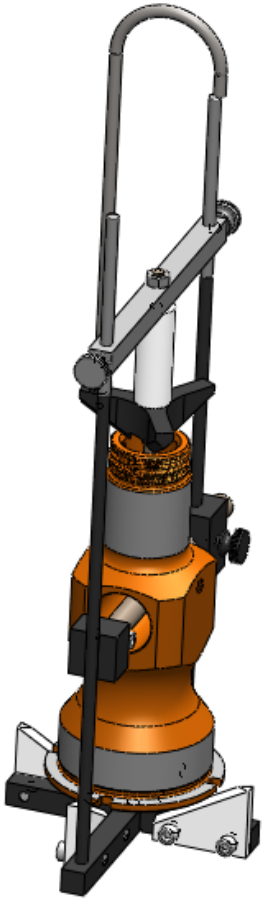


MLG Outer Cylinder

LHE Zn-Ni Plating Conformal Anode and Fixtures Models



MLG Torque Arm



MLG Pin

LHE Zn-Ni Completed Fixtures

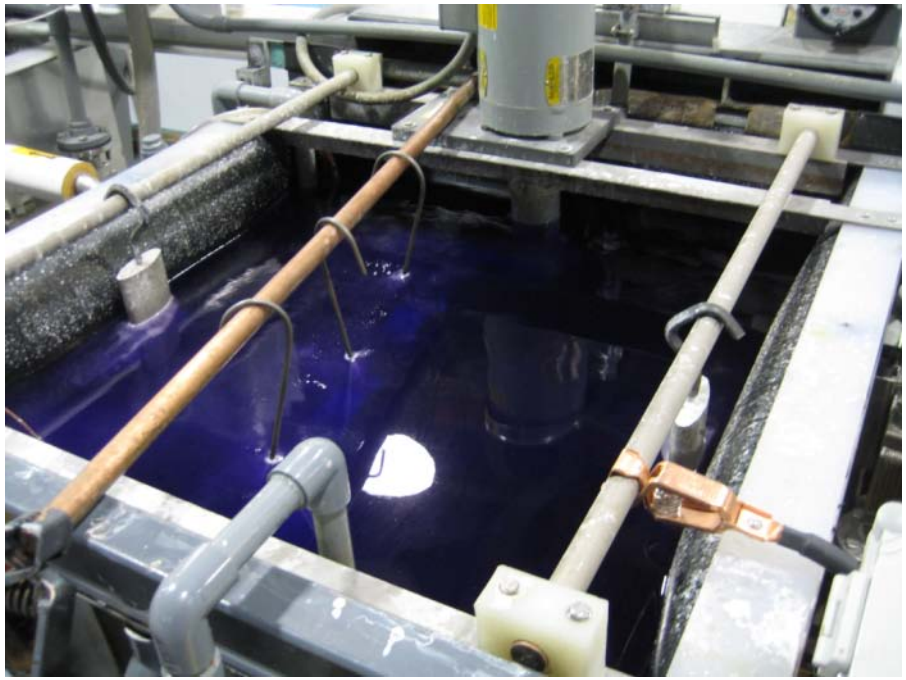
MLG Lower Drag Brace

NLG Gimble 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