# Low Hydrogen Embrittlement (LHE) Zinc-Nickel (Zn-Ni) Qualification Test Result and Process Parameters Development

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# Report Documentation Page

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# LHE Zn-Ni Background

- Boeing C-17 Program cadmium replacement research (2002-2006)
- Small Business Innovative Research (SBIR) Phase I Feasibility Study (2007-2008)
- SBIR Phase II Qualification Testing (2008-2010):

# AFRL TIM 26 May 2011

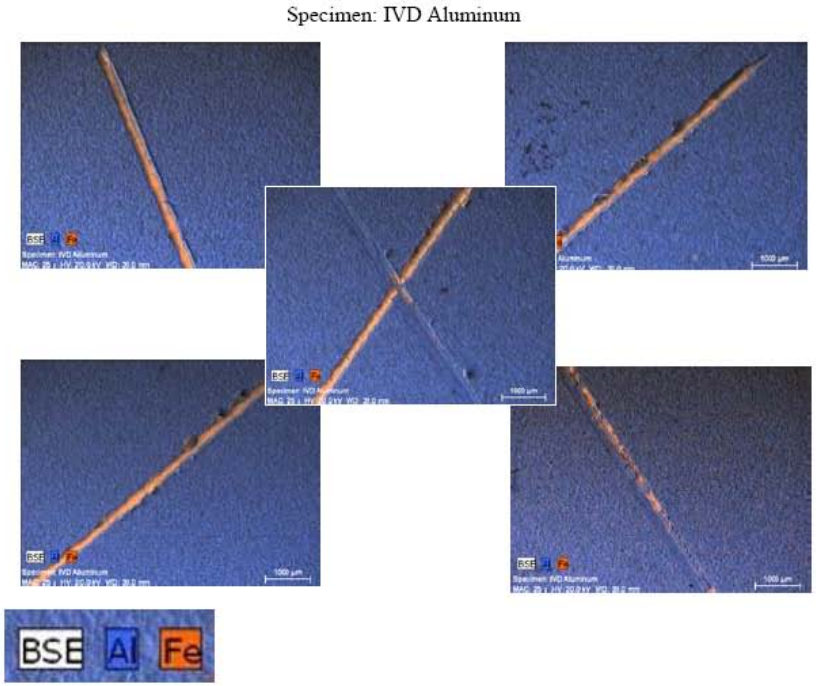
- A Technical Interchange Meeting (TIM) was conducted at ASC/EN on 26 May 2011 with participants from: OO-ALC/GH, ES3, AFRL/RX, Boeing, and ASC/EN Following AFRL concerns were discussed about the Zn-Ni Phase II test report:
  - Scribe Tests (Corrosion Tests)
  - Hydrogen 'Re-'Embrittlement Tests
  - Fatigue Tests
- These were the only items in which action items were opened

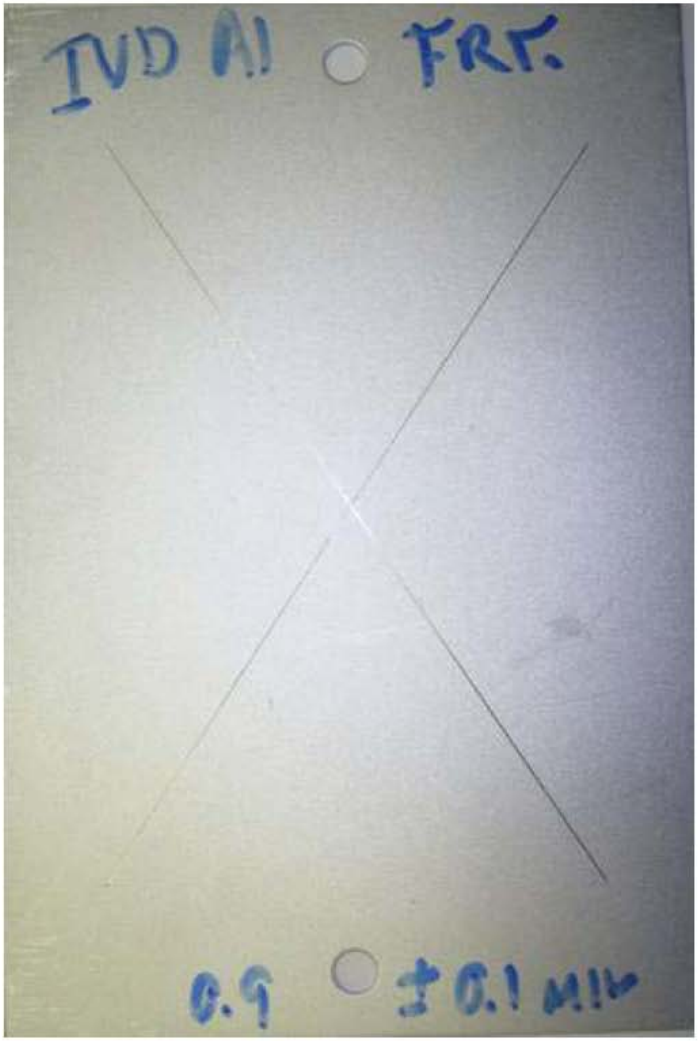
# Corrosion (Scribe) Testing

- Scribe Test Action Item #1:
  - Provide 1000 hrs panel scribe data to AFRL for evaluation.
- Response:
  - Original 1000 hrs panels are not available - they were tested to 5000 hrs
  - Consequently, Boeing Research & Technology (BR&T) evaluated standard carbide scribe technique and the team determined that the process is repeatable and exposes a sufficient amount of base metal to provide valid test results
  - Also, BR&T determine that the original corrosion panels were machined scribed and not carbide scribed by hand (i.e. machined scribed the preferred AFRL scribing method)
  - BR&T hand scribed panels and ran SEM EDX scans to determine IF they could reach the bare metal substrate; see following slides

# Corrosion (Scribe) Testing

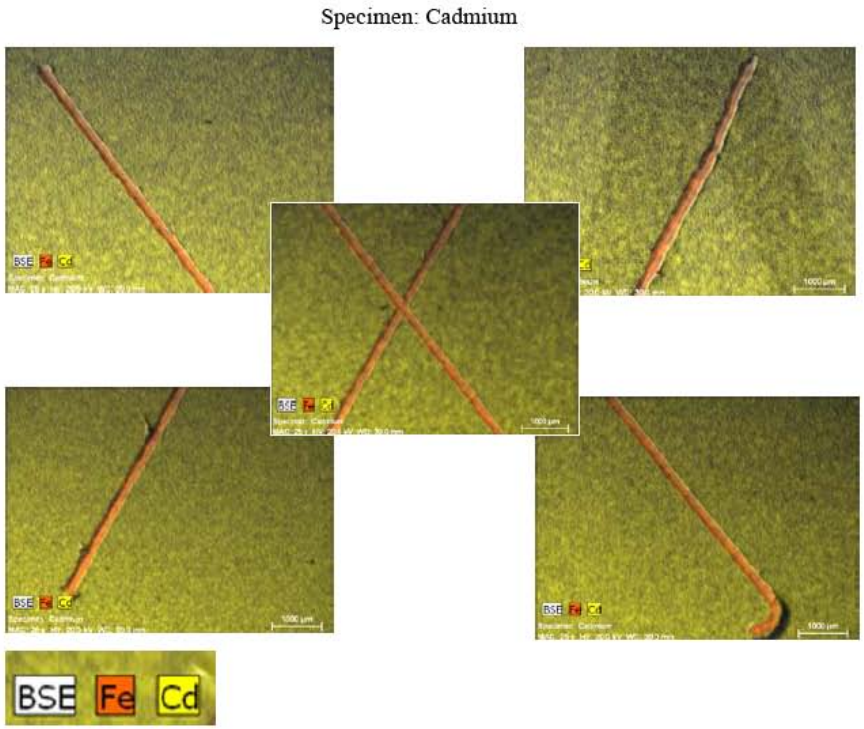
## IVD Aluminum

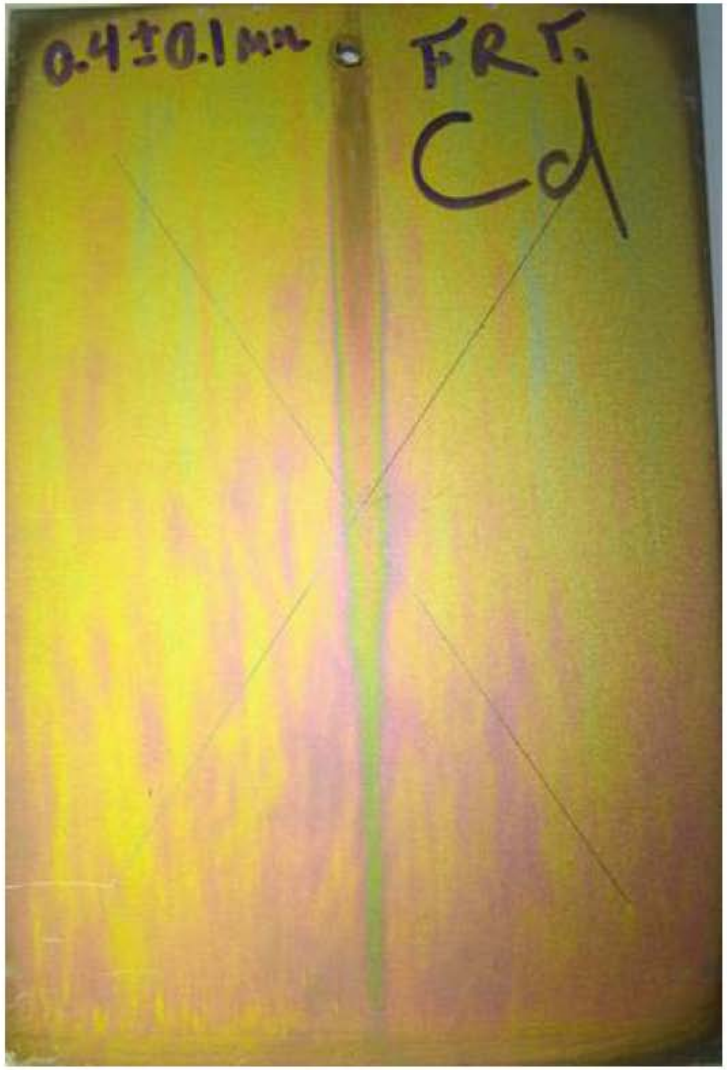


# Corrosion (Scribe) Testing

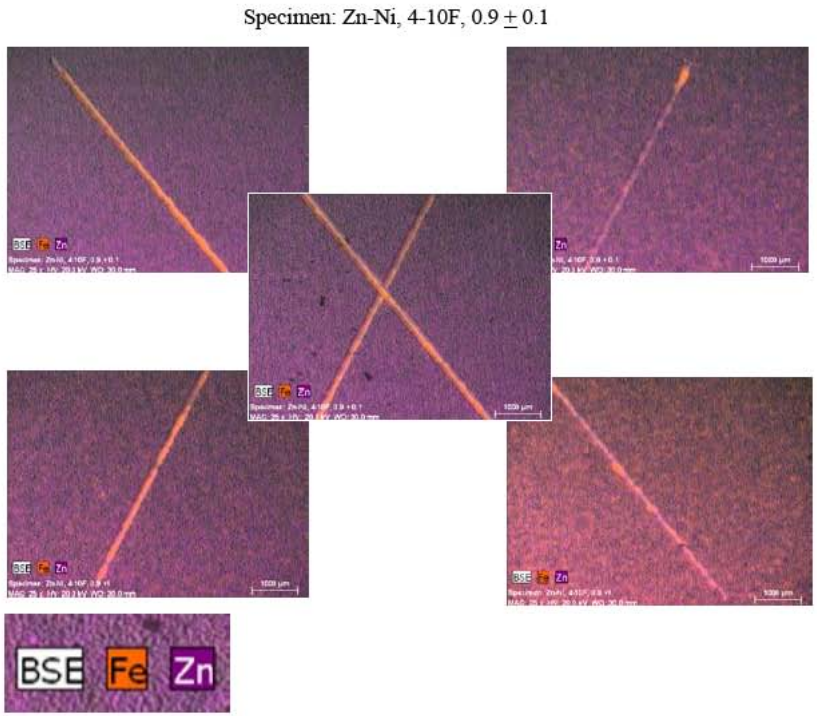
## Cadmium



# Corrosion (Scribe) Testing

## Zn-Ni




# Corrosion (Scribe) Testing

- Scribe Test Action Item #2:
  - Boeing to machine scribe Zn-Ni and Cd panels and test them for 1000 hours for a direct comparison
- Response:
  - Additional machined scribed Zn-Ni and Cd panels have been corrosion tested by BR&T per ASTM B 117
  - 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

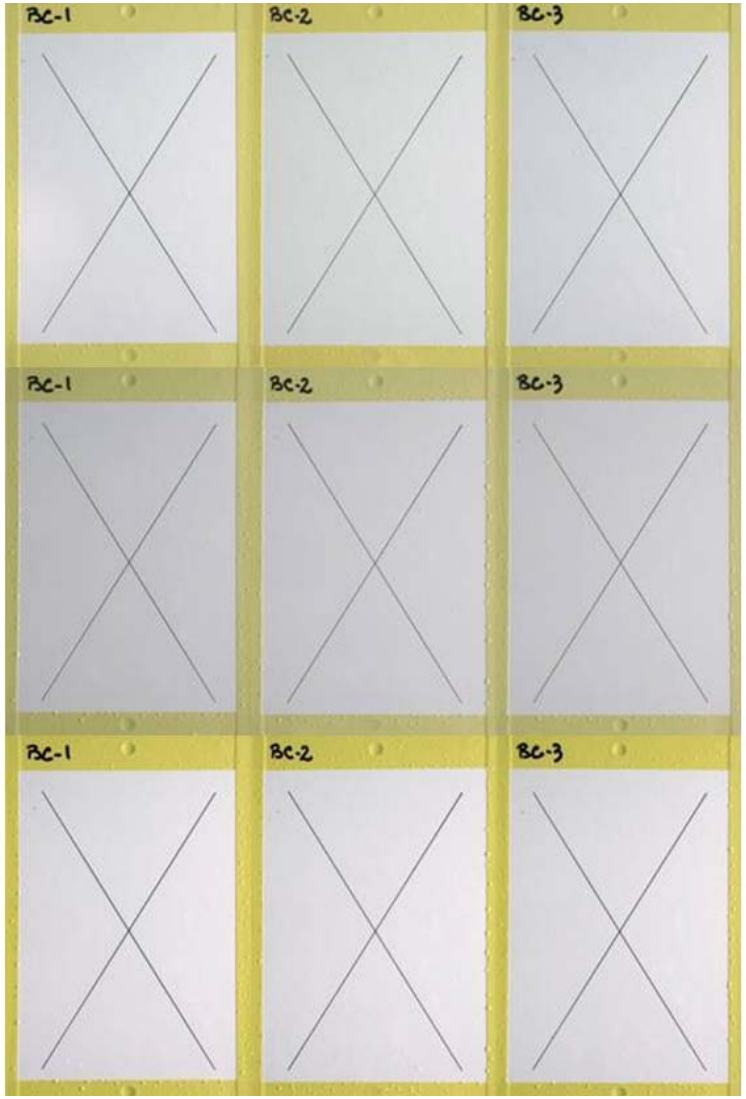
# Corrosion Re-Testing

| 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

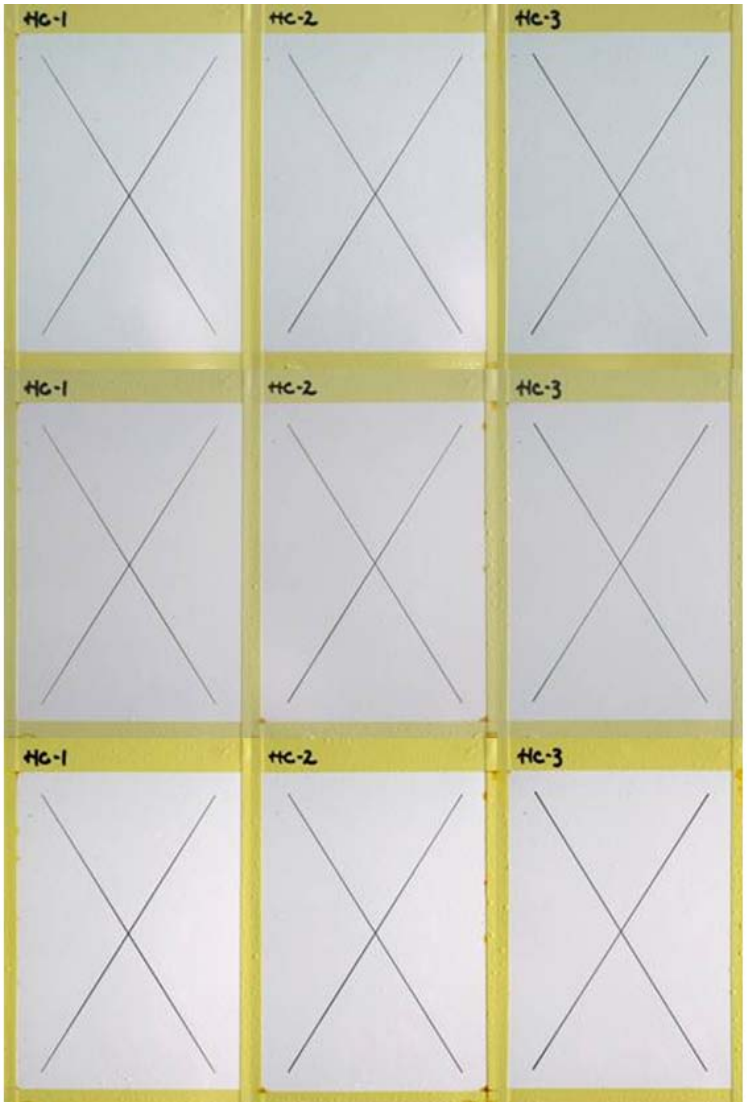



336 hours

672 hours

1000 hours

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

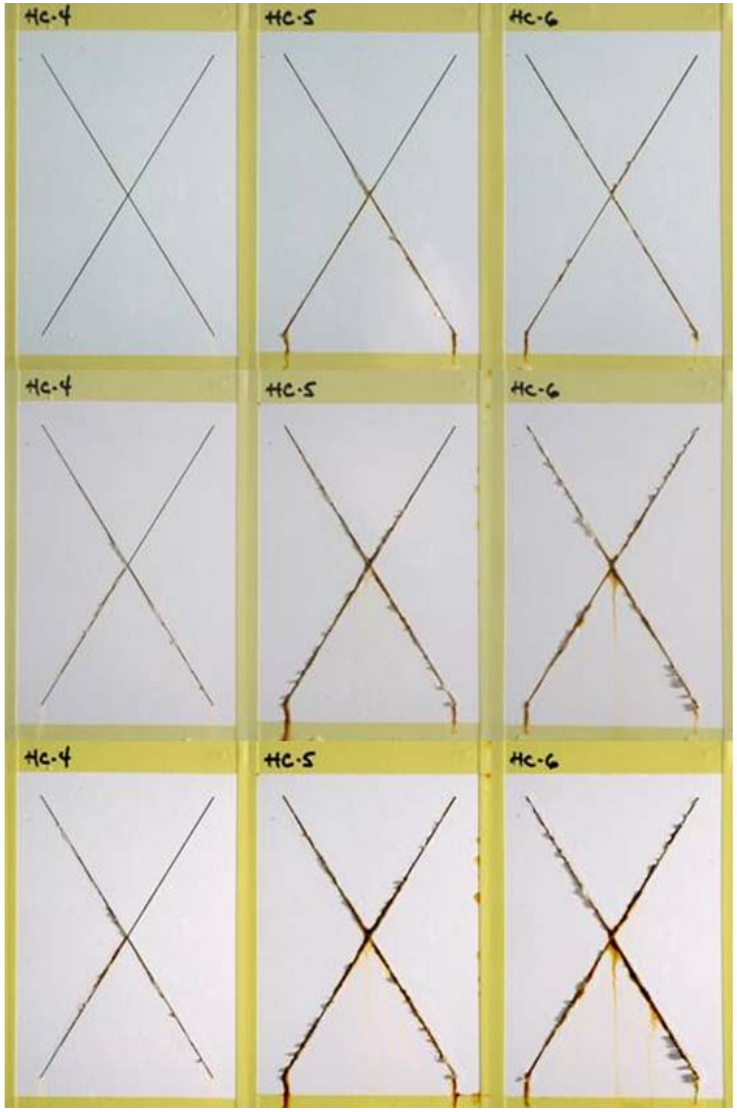



336 hours

672 hours

1000 hours

# Hill AFB LHE Cd w/Hex CC Scribed & Painted

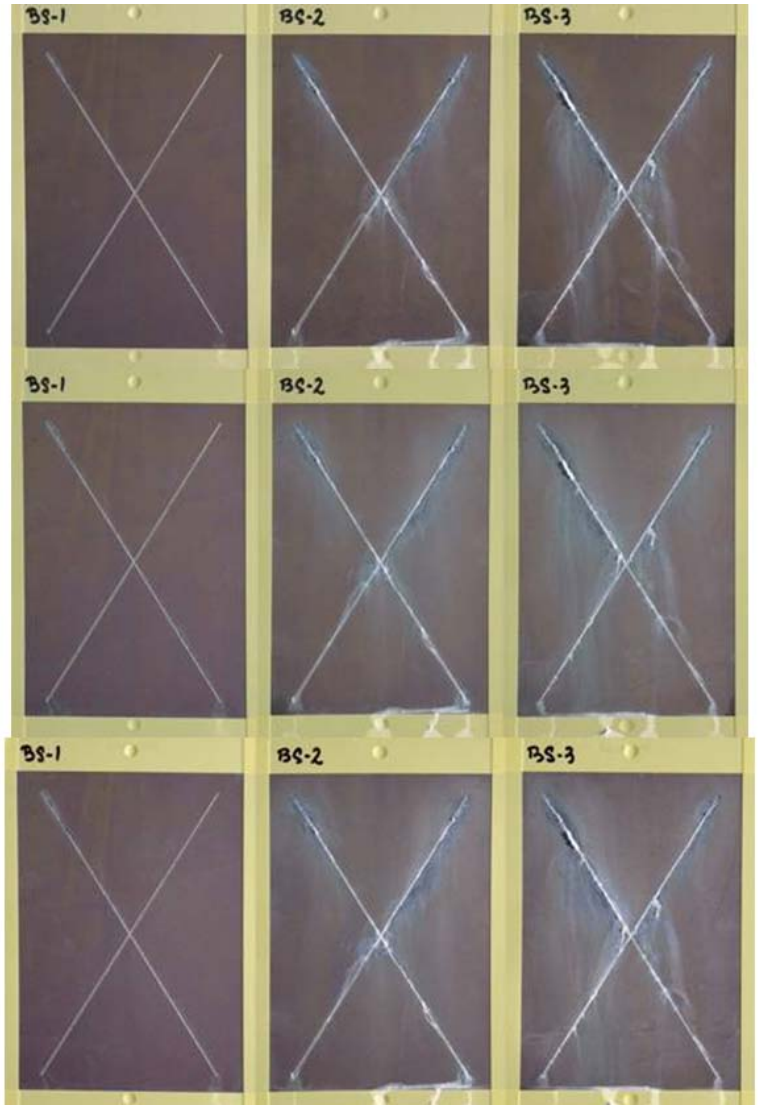



336 hours

672 hours

1000 hours

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

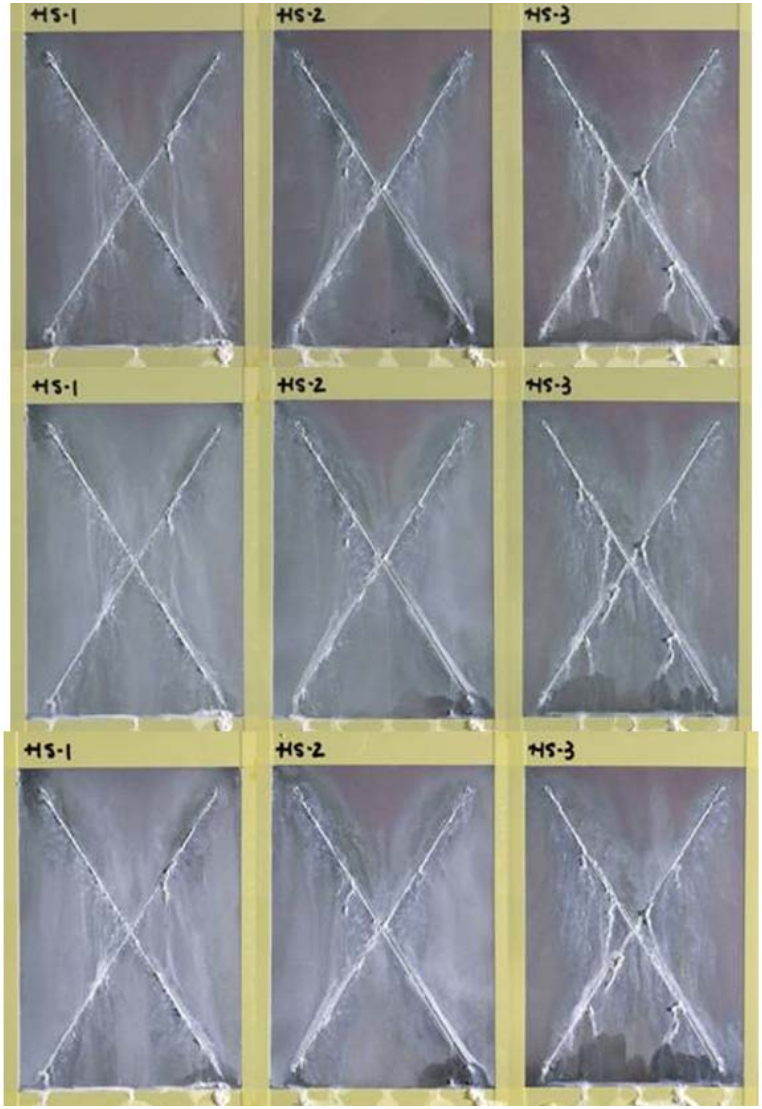



336 hours

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

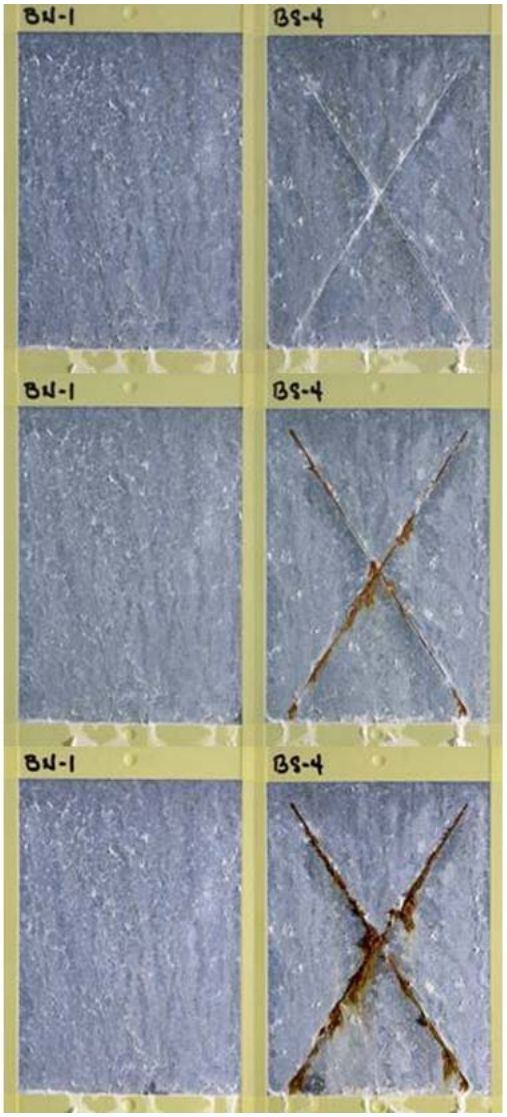
672 hours

1000 hours

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

Requirements for Chrome Reduction / Elimination; determine how the plating works without ‘any’ conv. coat.

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

# Hydrogen 'Re-'Embrittlement For Service Environments Testing

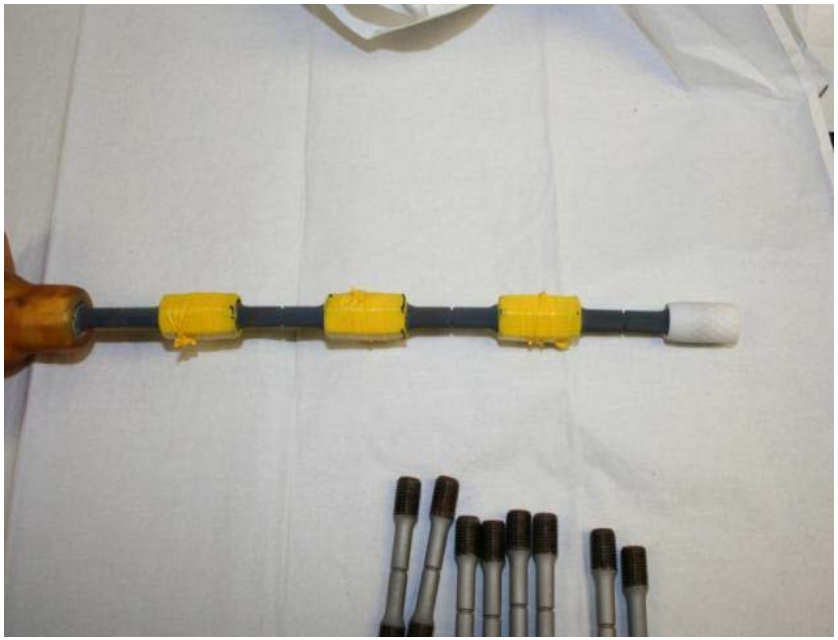
- 'Re-' Embrittlement Test Action Item #1:
  - Determine the reason for the poor plating on the original LHE Zn-Ni 1a.1 re-embrittlement coupons
- Response: See following slides

# Hydrogen 'Re-'Embrittlement For Service Environments Testing

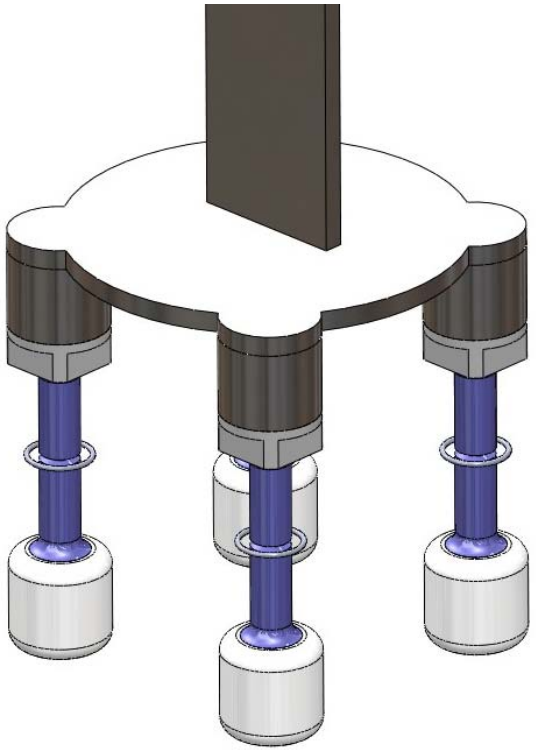
- The reason for the poor plating on the original LHE Zn-Ni 1a.1 re-embrittlement coupons are as follows:
  - Zn-Ni tank contamination
    - Spring '09 Lab analysis showed organic contamination
    - The PVC tank liner had begun to break down and had to be replaced in the Summer '09 with a more robust 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
    - Also circulation has been added around the notch area during plating

# Hydrogen 'Re-'Embrittlement For Service Environments Testing

## Original Coupons Chained in Series



## New fixture and Conformal Anode



# Hydrogen 'Re-'Embrittlement For Service Environments Testing

- Additional, 3.5% salt water, re-embrittlement testing has been conducted on LHE Zn-Ni plated coupons and they all passed the ASTM 519-06 150 hour requirement

| 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.

# Hydrogen 'Re-'Embrittlement For Service Environments Testing

- 'Re-'Embrittlement Test Action Item #2:
  - If possible, repeat the Boeing voltage potential test on plating of the original LHE Zn-Ni 1a.1 re-embrittlement coupons and compare the voltage readings to current LHE Cd and LHE Zn-Ni plated coupons. Boeing indicated that it might not be possible due to the shape and amount of surface area on the 1a.1 re-embrittlement coupons. (if possible)
- Response:
  - An accurate corrosion potential test in salt water per ASTM G5 could not be conducted because of the following:
    - Geometry differences of the 1a.1 coupon vs. standard ASTM G5 corrosion potential test coupon
    - The 1a.1 coupons were contaminated by salt water exposure during initial re-embrittlement testing.

# Hydrogen 'Re-'Embrittlement For Service Environments Testing

- 'Re-'Embrittlement Test Action Item #3:
  - Determine the quality thickness of the Cd, Zn-Ni and IVD evaluated in the salt water test.
- Response:
  - Quality and thickness of plating were unacceptable
  - See Action Item #1 addressed poor plating quality
  - Salt water testing was repeated

# Hydrogen ‘Re-’Embrittlement For Service Environments Testing

- Conclusion: Poor plating cause identified and corrected
- Zn-Ni testing was repeated with production plating process and passed ASTM 519 hydrogen ‘re-’ embrittlement service environment test in 3.5% salt water

# Fatigue Testing

- Fatigue Test Action Item #1:
  - Clearly document any test data that was discarded in the fatigue test plots and the supporting rational and provide it to OO-ALC/GH, AFRL/RX and ASC/EN
- Response:
  - All fatigue test data was included in the statistical analysis

# Fatigue Testing

- Fatigue Test Action Item #2:
  - Provide information on the measured plating thickness on each specimen to OO-ALC/GH, AFRL/RX, and ASC/EN
- Response:
  - A conservative approach was taken when the Zn-Ni fatigue coupons were plated:
    - 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 closer to 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 |

# Fatigue Testing

- Fatigue Test Action Item #3:
  - OO-ALC/GH to engage the Landing Gear Design Industry and determine if the fatigue testing and test results per the following fatigue testing matrixes is adequate to approve the use of LHE Response:

- Goodrich Landing Gear, John Goering; when asked, "…considering the test method for comparative fatigue debit that we have conducted; would you say that you have complete, very high, high, medium or low confidence that this LHE Zn-Ni coating would not induce a greater fatigue debit than cadmium?" Response was high to very high.

# 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 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 Inc., 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)
  - ES3 conducted two different R rations during testing
  - Boeing-Long Beach did not indicate how many test, at what R ratio would be satisfactory to them

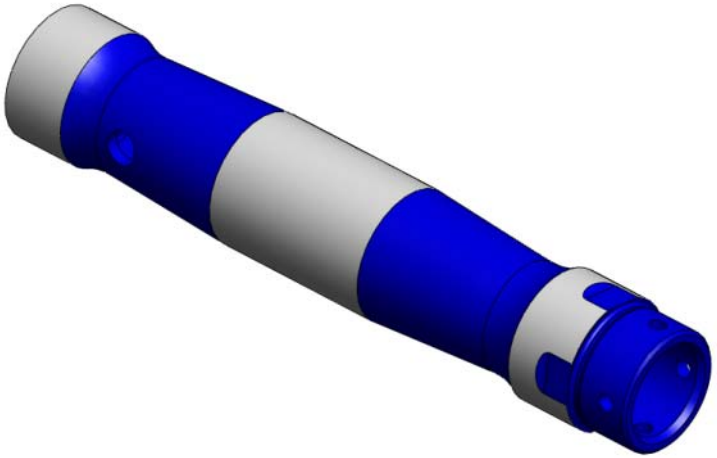
# Planned Evaluation

- Prototype line in Bldg 505
- Field Performance Evaluations

# Phase III Effort
# Prototype Process Line

| 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
# Prototype Parts



A-10 NLG Axle

A-10 MLG Torque Arm

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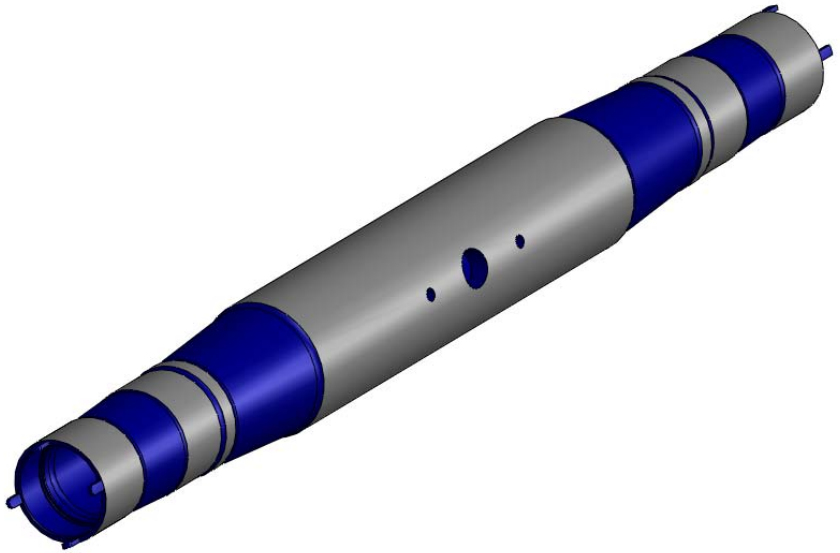
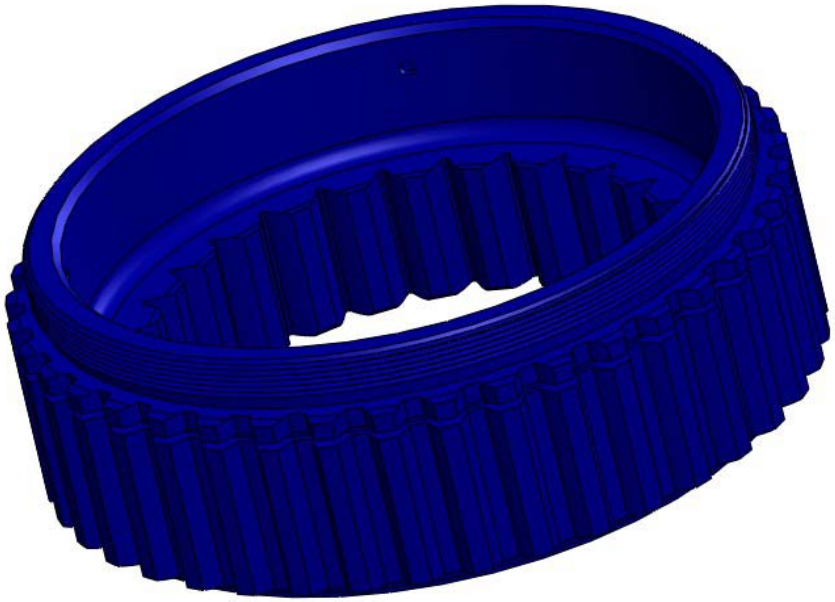
# Phase III Effort
# Prototype Parts



B-1B MLG Axle



C-5 MLG Rotation Collar

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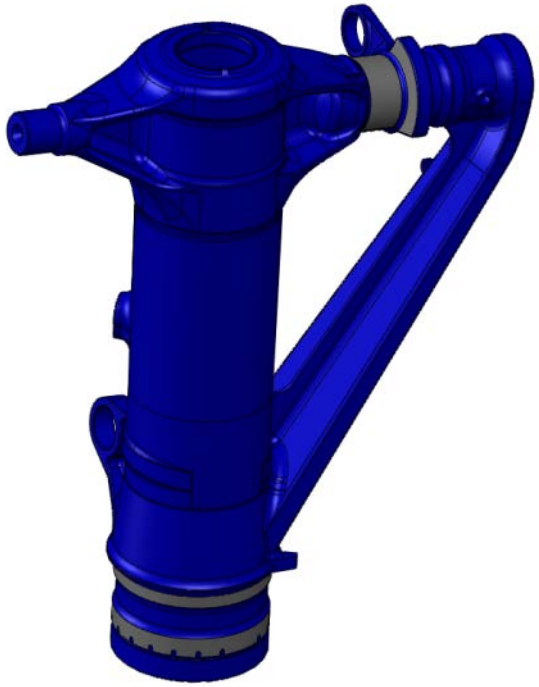
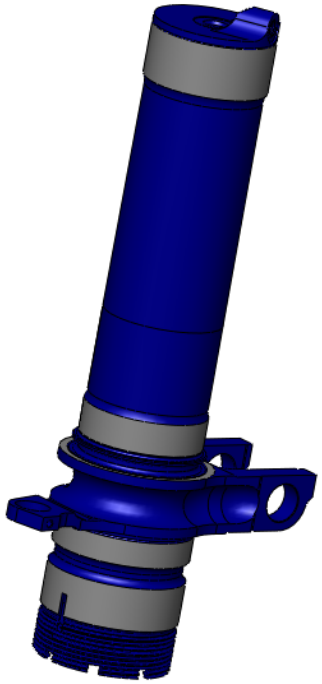
# Phase III Effort
# Prototype Parts



**F-15 MLG Cylinder**



**F-16 NLG Inner Cylinder**

**F-15 MLG Lower Drag Brace**

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# Discussion/Questions

# QUESTIONS