Nanocrystalline Cobalt-Phosphorus Electroplating as an Alternative to Hard Chromium Electroplating

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ASETS Defense Workshop  
Sustainable Surface Engineering for Aerospace & Defense  
(August 2012)
# Nanocrystalline Cobalt-Phosphorous Electroplating as an Alternative to Hard Chromium Electroplating

**Title:** Nanocrystalline Cobalt-Phosphorous Electroplating as an Alternative to Hard Chromium Electroplating

**Authors:**

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**Performing Organization:**

Naval Air Systems Command, 47123 Buse Road, Patuxent River, MD, 20670

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Naval Air Systems Command, 47123 Buse Road, Patuxent River, MD, 20670

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**Abstract:**


**Security Classification:**

Unclassified
Project Team

NAVAIR:

- PI: Ruben Prado, NAVAIR JAX
- Co-PI: Jack Benfer, NAVAIR JAX

Integran Technologies:

- Diana Facchini, Neil Mahalanobis
  Integran – Technology Development & Optimization, Dem/Plan
- Keith Legg, Rowan Technology Group, Libertyville, IL, -- CBA, reports, Implementation Assessment, ASETSDefense website

<table>
<thead>
<tr>
<th>Name</th>
<th>NAVAIR CP - Requirements and Demonstrations across NAVAIR programs and OEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Robert Kestler</td>
<td>NAVAIR CP - Requirements and Demonstrations across NAVAIR programs and OEM</td>
</tr>
<tr>
<td>Mike Firth</td>
<td>NAVAIR LK - Ground Support Equipment requirements and components</td>
</tr>
<tr>
<td>Steve Brown</td>
<td>NAVAIR PAX - Test requirements and Qualification, JTP</td>
</tr>
<tr>
<td>Denise Aylor</td>
<td>NAVSEA - Leveraged Effort, NAVSEA Systems Requirements, Mil-Spec development</td>
</tr>
</tbody>
</table>
Demonstrate/Validate pulsed electrodeposition of Nanocrystalline Cobalt-Phosphorous (nCoP) alloy coatings as a Hard Chrome electroplating alternative for DoD manufacturing and repair.

- Fully define deposition parameters and properties
- Establish production plating processes (i.e., cleaning, racking, masking, activation, pre-plates, stripping, etc.)
- Demonstrate/Validate performance
- Develop Eng Tech Data Packages
  - Manuals
  - Specifications
  - Eng. Circular
- Initiate DoD and OEM approval process

Demo Site: FRC JAX
NAVAIR Fleet Readiness Center Jacksonville

- Dem/Val line in operation since 2006
- 250 gallon Plating Tank
- Pulse Power supply (1500A Peak Current)
- Activation tank used for most all alloys
- CIP # 0466 Established

Process Line

Dem/Val Tank Pulse Power Supply

Activation Tank Power Supply
Coating applied by electrodeposition

- Pulsed Current Waveform Engineering
  - Frequency (Hz) = 1/(ton+toff)
  - Duty Cycle (%) = ton/(ton+toff) x 100

Electrodeposited nanocrystalline materials

- *Favors nucleation of new grains over growth*
- Results in an ultra-fine grain structure
- Uniform throughout thickness

Leads to unique properties

- ↑ Yield Strength, wear, ultimate tensile strength
- ↑ Density
- ↓ Coefficient of friction

*Smaller grain size impedes dislocation movement and increases yield strength*
## Technical Approach (Nanocrystalline Co-P Deposits)

### Process Comparison

<table>
<thead>
<tr>
<th></th>
<th>Nanovate™ CoP</th>
<th>EHC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Deposition Method</strong></td>
<td>Electrodeposition (Pulse)</td>
<td>Electrodeposition (DC)</td>
</tr>
<tr>
<td><strong>Part Geometries</strong></td>
<td>LOS and NLOS</td>
<td>LOS and NLOS</td>
</tr>
<tr>
<td><strong>Efficiency</strong></td>
<td>85-95%</td>
<td>15-35%</td>
</tr>
<tr>
<td><strong>Deposition Rate</strong></td>
<td>0.002&quot;-0.008&quot; /hr</td>
<td>0.0005&quot;-0.001&quot; /hr</td>
</tr>
<tr>
<td><strong>Emission Analysis</strong></td>
<td>*Below OSHA limits</td>
<td>Cr+6</td>
</tr>
</tbody>
</table>

*Co PEL is 20 µg/m³

### Cathode Efficiency

*Approaches 100% Efficiency*

- ≈5X faster than Chrome plating
- Increased throughput
- One nCo-P tank can replace several hard chrome tanks
- Bath is Stable
Overview of Prior Work

Electrochemical Modeling

Phase I Characterization (JTP) Tests

<table>
<thead>
<tr>
<th>Requirement</th>
<th>nCoP</th>
<th>EHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Appearance</td>
<td>Smooth, uniform, free of pits/defects</td>
<td>Pass</td>
</tr>
<tr>
<td>Adhesion</td>
<td>No separation between deposit/substrate</td>
<td>Pass</td>
</tr>
<tr>
<td>Ductility</td>
<td>&gt; 2%</td>
<td>Pass 2.9%</td>
</tr>
<tr>
<td>Grain Size</td>
<td>&lt;20 nm (HCP)</td>
<td>Pass 6 nm(HCP)</td>
</tr>
<tr>
<td>Porosity</td>
<td>&lt;1/32&quot;, &lt;15 pits/150 in², &lt;5 pits/30 in²</td>
<td>Pass</td>
</tr>
</tbody>
</table>

Chemical Strip Demonstrated

Demonstrated on T-45 Pivot at JAX

Plated Pivot

Stripped Pivot

Masking Evaluation/Downselect

- MICCRO XP-2000 by Tolber Chemical Division Inc
- ENPLATE Stop Off No.1 by Enthone OMI Inc.
- MICCROSshield by Tolber Chemical Division Inc
- MT-1024 by Masktec Inc.
- MT-920 by Masktec Inc.
Overview of Prior Work

Rotating Beam Fatigue Test

- Bare
- nCoP
- EHC

4340 substrate (UTS: 260-280 ksi)

Cycles to Failure

Stress (ksi)

nCoP hardness comparable to EHC after heat treatment at standard conditions for hydrogen embrittlement relief (375°F)

nCoP Heat Treat Study

- EHC
- Nanovate CR

Microhardness (HV100)

Baking Time (hrs)

OSD Coupon Testing Completed

Taber Abrasion, Impact, Adhesion, Corrosion

Carburized 1018 Steel Coupons

EHC Plating of T-45 Pivot Assy

NAVAIR JAX Base line Plating - Dem/Val
nCoP Plating of T-45 Arresting Hook Pivot

Mask/Rack

nCoP Plate

As Plated

Ready for Field Demo
Dem/Val Component on Aircraft!

- T-45 Arresting Hook Pivot Assembly
- Installed Mar 2012 (BUNO# 165479) ≈ 30 Traps

Dem/Val Component installed on T-45 Goshawk Trainer Aircraft NAS Meridian, MS

nCoP Plated Dem/Val Component
Phase II OSD Rig Testing:

Cylinder Testing Cycle (1 mil coating):

1. Cylinder cycling 1000 cycles then
2. ASTM B117 10 days

To date, two nCoP cylinders have completed a cumulative total of 100 days ASTM B117 and 10,000 cylinder cycles with **no reported failure due to seal leakage.**

---

**nCoP**

- **10,000 cycles/ 100 Days**
  - No Failures

**EHC**

- **4000 cycles/ 40 Days**
  - EHC-1 Still in test
  - EHC-2 Failed
LHD1 Stern Gate

- Replace Cr plated shaft with nCoP
- Perform Field Demonstration
- Evaluate Performance as compared to baseline
Assess wear performance vs. chrome as an ID actuator
- Currently conducting dimensional inspections
- ECD is Q4/2012
- Test developed by Messier-Dowty
  - 20,000 Cycles
  - Observe effect of surface finish, seal types, and hardening condition

Plating/Grinding Completed for Messier Testing

<table>
<thead>
<tr>
<th>Coating</th>
<th>Surface Finish (Microinches)</th>
<th>Piston Seal</th>
<th>Rod Seal</th>
</tr>
</thead>
<tbody>
<tr>
<td>EHC</td>
<td>4-6, 12-16</td>
<td>Buna-N Tee Seal</td>
<td>Buna-N Tee Seal</td>
</tr>
<tr>
<td>nCoP</td>
<td>4-6, 12-16</td>
<td>Nitrile Butadiene Rubber</td>
<td>Nitrile Butadiene Rubber</td>
</tr>
<tr>
<td>nCoP HE Bake</td>
<td>4-6, 12-16</td>
<td></td>
<td></td>
</tr>
<tr>
<td>nCoP Max Heat Treat</td>
<td>4-6, 12-16</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EHC</td>
<td>12-16</td>
<td>Viton Tee Seal Synthetic Rubber Fluoropolymer Elastomer</td>
<td>Viton Tee Seal Synthetic Rubber Fluoropolymer Elastomer</td>
</tr>
<tr>
<td>nCoP</td>
<td>12-16</td>
<td>PTFE Cap</td>
<td>Spring Energized PTFE</td>
</tr>
<tr>
<td>EHC</td>
<td>12-16</td>
<td>Buna-N O-Ring/Back-up - Nitrile Butadiene Rubber O-Ring</td>
<td>Buna-N O-Ring/Back-up - Nitrile Butadiene Rubber O-Ring</td>
</tr>
</tbody>
</table>

*$121K In kind funding (Messier-Dowty)
Technical Progress
(P-3 Producingibility Item)

P-3 Uplock Roller Pin

- P-3 Producingibility Item at JAX
- Field evaluation Planned
- Interested Air Programs?

Existing chrome Plated Roller Pin Shown on P-3 MLG

nCoP Plated Uplock Roller Pins
Technical Progress
(Spotting Dolly Lifting Pin)

- Visit to Solomons to assess Spotting Dolly Lifting Arm Pin
- Obtain Lifting Pins for Plating
- Fit/Function Confirmed
- Scheduled for Plating
### Technical Progress

*(Joint Test Protocol - Demonstration/Validation)*

- **JTP Testing in Progress**
- **T-45 Dem/Val component on Aircraft**
- **50% of Core Tests Completed**
- ✔️ = Completed Tests, T = In Test, P = Plating

#### 24 Core Tests Defined in JTP

<table>
<thead>
<tr>
<th>Test Type</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Appearance</td>
<td>✔️</td>
</tr>
<tr>
<td>2. Thickness</td>
<td>✔️</td>
</tr>
<tr>
<td>3. Porosity</td>
<td>✔️</td>
</tr>
<tr>
<td>4. Hardness</td>
<td>✔️</td>
</tr>
<tr>
<td>5. Grain Size</td>
<td>✔️</td>
</tr>
<tr>
<td>6. Ductility</td>
<td>✔️</td>
</tr>
<tr>
<td>7. Stress</td>
<td>✔️</td>
</tr>
<tr>
<td>8. Fatigue</td>
<td>T, P</td>
</tr>
<tr>
<td>9. Coating Integrity</td>
<td>T, P</td>
</tr>
<tr>
<td>10. Corrosion (B117)</td>
<td>✔️</td>
</tr>
<tr>
<td>11. Corrosion (SO2)</td>
<td>✔️</td>
</tr>
<tr>
<td>12. Corrosion (Beach)</td>
<td>T</td>
</tr>
<tr>
<td>13. Corrosion (OCP)</td>
<td>✔️</td>
</tr>
<tr>
<td>14. Adhesion</td>
<td>P</td>
</tr>
<tr>
<td>15. HE</td>
<td>P</td>
</tr>
<tr>
<td>16. HE (No Bake)</td>
<td>P</td>
</tr>
<tr>
<td>17. Fluid Compatibility</td>
<td>✔️</td>
</tr>
<tr>
<td>18. HRE</td>
<td>P</td>
</tr>
<tr>
<td>19. Wear - Taber</td>
<td>✔️</td>
</tr>
<tr>
<td>20. Wear - Pin on Disk</td>
<td>✔️</td>
</tr>
<tr>
<td>21. Wear - Endurance Rig</td>
<td>T</td>
</tr>
<tr>
<td>22. Wear - Falex</td>
<td>T</td>
</tr>
<tr>
<td>23. Wear - Gravelometry</td>
<td>T</td>
</tr>
<tr>
<td>24. Wear - SATEC</td>
<td>T</td>
</tr>
</tbody>
</table>

Approved – Feb 2011

---

**Note:**

- The images show the Joint Test Protocol (JTP) documents, indicating that the testing protocols are in progress. The packages have been approved for February 2011.
## Technical Progress

(Fluid Compatibility)

Assess nCoP ability to withstand operational service conditions and overhaul fluids

<table>
<thead>
<tr>
<th>Fluid</th>
<th>Purpose</th>
<th>nCoP</th>
<th>EHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIL-PRF-83282</td>
<td>Hydraulic</td>
<td>PASS</td>
<td>-</td>
</tr>
<tr>
<td>MIL-PRF-680</td>
<td>degreaser</td>
<td>PASS</td>
<td>-</td>
</tr>
<tr>
<td>Fluorescent penetrant</td>
<td>NDI</td>
<td>PASS</td>
<td>-</td>
</tr>
<tr>
<td>Nital</td>
<td>Grind burn</td>
<td>FAIL</td>
<td>*PASS</td>
</tr>
<tr>
<td>Ammonium persulfate</td>
<td>Grind burn etch</td>
<td>FAIL</td>
<td>*PASS</td>
</tr>
<tr>
<td>Cimstar 40</td>
<td>Grinding fluid</td>
<td>PASS</td>
<td>-</td>
</tr>
<tr>
<td>Turco 4181L Alkaline Cleaner</td>
<td>Cleaner</td>
<td>PASS</td>
<td>-</td>
</tr>
<tr>
<td>MIL PRF 85570 type 2</td>
<td>Cleaner</td>
<td>PASS</td>
<td>-</td>
</tr>
<tr>
<td>Bioact 280</td>
<td>Cleaner</td>
<td>PASS</td>
<td>-</td>
</tr>
<tr>
<td>Chlorine Bleach</td>
<td>Disinfectant</td>
<td>FAIL</td>
<td>*PASS</td>
</tr>
</tbody>
</table>

*EHC samples showed some form of minor attack. However, it did pass according to JTP acceptance criteria.*
Technical Progress
Sliding Wear

- Pin-on-Disc testing conducted as per ASTM G99
  ("Standard Test Method for Wear Testing on a Pin on Disc Apparatus")

<table>
<thead>
<tr>
<th>Coating</th>
<th>EHC coated</th>
<th>4130</th>
<th>13-8 stainless</th>
<th>7075 Al</th>
<th>70-30 Cu-Ni</th>
</tr>
</thead>
<tbody>
<tr>
<td>nCoP</td>
<td>✓ PASS</td>
<td>✓ PASS</td>
<td>✓ PASS</td>
<td>✓ PASS</td>
<td>✓ PASS</td>
</tr>
<tr>
<td>nCoP (HE bake)</td>
<td>✓ PASS</td>
<td>✓ PASS</td>
<td>✓ PASS</td>
<td>✓ PASS</td>
<td>✓ PASS</td>
</tr>
<tr>
<td>nCoP (Max hardness)</td>
<td>✓ PASS</td>
<td>✓ PASS</td>
<td>✓ PASS</td>
<td>✓ PASS</td>
<td>✓ PASS</td>
</tr>
</tbody>
</table>

* Does not include nCoP ball on EHC results
Technical Progress
(Abrasive Wear)

- Taber wear testing to assess abrasive wear resistance of coatings
- Performed ASTM D4060
- Performed ASTM F1978

Wear Index of nCoP and EHC Coatings (ASTM D4060)

Total Mass Loss over 2000 cycles of nCoP and EHC Coatings (ASTM F1978)

- CS-17 wheels
- 1000g load
- H-22 wheels
- 250g load
Technical Progress

**FALEX Block on Ring**
- Test per ASTM G77
- Determines the resistance of materials to sliding wear
- Different Alloy/Coatings against Ring

**Gravelometry**
- Test per ASTM D3170
- Specimens mounted perpendicular to projected path
- Pea size gravel; air pressure 70 psi

**SATEC Oscillating Load**
- Boeing Specific Test
- Pin/Bushing Oscillating Wear Test
- Constant/ Sinusoidal load-motion profile

**Wear Samples plated and at Boeing for Testing**
AISI 4130 steel coupons

Environment:
- 0.5M NaCl, 7 day OCP 1-hr interval
- Reference electrode: SCE
- nCoP shows tendency to reach more noble potentials than EHC

<table>
<thead>
<tr>
<th>Coating</th>
<th>Mean OCP (mV-SCE)</th>
<th>Final OCP (mV-SCE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>nCoP</td>
<td>-470</td>
<td>-470</td>
</tr>
<tr>
<td>EHC</td>
<td>-600</td>
<td>-600</td>
</tr>
</tbody>
</table>
Technical Progress
(ASTM B-117 Corrosion Testing)

Salt Fog Testing (ASTM B-117)

- Test conducted as per ASTM B-117
- Rankings assigned as per ASTM B537
- Major improvement in performance between Ni+EHC and EHC
- No observable difference between Ni+nCoP and nCoP.

Nanovate™ CoP

Coating Oxidation

μ-EDXRF Spectra

Hard Chrome

Substrate Corrosion

μ-EDXRF Spectra

Nanovate™ CoP

Coating Oxidation

μ-EDXRF Spectra

Hard Chrome

Substrate Corrosion

μ-EDXRF Spectra

Nanovate™ CoP

Coating Oxidation

μ-EDXRF Spectra

Hard Chrome

Substrate Corrosion

μ-EDXRF Spectra

Nanovate™ CoP

Coating Oxidation

μ-EDXRF Spectra

Hard Chrome

Substrate Corrosion

μ-EDXRF Spectra
SO2, Salt Fog Testing (ASTM G85-A4)

- Test conducted as per ASTM G85-A4
- Rankings assigned as per ASTM B537
- Major improvement in performance between Ni+EHC and EHC
- No observable difference between Ni+nCoP and nCoP.
Technical Progress
(Corrosion – Beach Exposure)

- Beachside Atmospheric Test Facility, NASA Kennedy Space Center
- EHC exhibits red rust
- No red rust for all other coatings in test to date
OXIDE CHARACTERIZATION
(WHITE PAPER SUBMITTED)

Surface Characterization
- X-ray photoelectron spectroscopy (XPS) analysis to determine composition of the surface oxide.
- X-ray diffraction (XRD) analysis to determine presence of oxides or intermetallic compounds.
- Scanning electron microscope (SEM) to be conducted on mounted cross-section to determine the concentration profiles for Co, Fe and O.

Performance Testing
- Ball-on-flat with linear reciprocating motion (ASTM G133)
- Ambient conditions and simulated salt water solution (i.e., 3.56 wt% NaCl)
- Mass loss, contact surface profilometry, coefficient of friction and depth profiling (3D imaging)
Axial Fatigue Testing

- 4340 steel (260-280 ksi)
- Shot peened (S110 - 0.008-0.010)
- 16 Ra Minimum
- R ratio: $R = -1$
- Loads: 85% YS to $10^6$ Cycles
Technical Progress

SPECIFICATION DEVELOPMENT

NAVAIR LPS (Draft Version)

MIL Spec (MFFP-2011-002)

AMS Spec (Being Pursued)
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Backup Material
Technology Transfer

(Extended Stakeholder POCs)

Boeing - Steve Gaydos

Heroux Devtek - Nihad Ben Salah

NASA - Jon Devereaux

UDRI - Natasha Voevodin

VLN - William Bloom

Hill AFB - Dave Frederick

Tinker AFB - Van Nguyen

Messier Dowty - Roger Eybel

Boeing Additional Tests

Adhesion
- Chisel
- Flat Peen

Fatigue
- Round Axial
- Flat Axial

Sliding Wear
- Pin-in-Bushing
- Track Roller
- Fretting Wear
Papers/Publications Since IPR 2010


Patents/Patent Applications
US 5,352,266 (1994): Nanocrystalline metals and process of producing the same
## Coating Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Test Method</th>
<th>Applicable Standard</th>
<th>Nanovate CR</th>
<th>EHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Appearance and porosity</td>
<td>Visual and microscopic inspection</td>
<td>N/A</td>
<td>Free from pits, microcracks and pores</td>
<td>Microcracked</td>
</tr>
<tr>
<td>Grain Size</td>
<td>X-Ray Diffractometry</td>
<td>N/A</td>
<td>8-15 nm</td>
<td>-</td>
</tr>
<tr>
<td>Hardness</td>
<td>Vickers Microhardness</td>
<td>ASTM B578</td>
<td>550-600 VHN (as-deposited)</td>
<td>Min. 600 VHN</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>600-750 VHN (heat treated)</td>
<td>-</td>
</tr>
<tr>
<td>Ductility</td>
<td>Bend Test</td>
<td>ASTM B489</td>
<td>2-7%</td>
<td>&lt;1%</td>
</tr>
<tr>
<td>Adhesive Wear</td>
<td>Pin on Disc (Al₂O₃ Ball)</td>
<td>ASTM G99</td>
<td>6-7 x 10⁻⁶ mm³/Nm</td>
<td>9-11 x 10⁻⁶ mm³/Nm</td>
</tr>
<tr>
<td>Coefficient of friction</td>
<td></td>
<td></td>
<td>0.4-0.5</td>
<td>0.7</td>
</tr>
<tr>
<td>Pin Wear</td>
<td></td>
<td></td>
<td>Mild</td>
<td>Severe</td>
</tr>
</tbody>
</table>
## Coating Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Test Method</th>
<th>Applicable Standard</th>
<th>Nanovate CR</th>
<th>EHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abrasive Wear</td>
<td>Taber Wear (CS-17 wheels)</td>
<td>ASTM D4060</td>
<td>17 mg/1000 cycles</td>
<td>4 mg/1000 cycles</td>
</tr>
<tr>
<td>Corrosion</td>
<td>Salt Spray</td>
<td>ASTM B117</td>
<td>0.003” thick Pass 165 hrs</td>
<td>0.003” thick Fail 165 hrs</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.002” thick Protection Rating 7</td>
<td>0.004” thick Protection Rating 2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(ASTM B537) @ 1000 hours</td>
<td>(ASTM B537) @ 1000 hours</td>
</tr>
<tr>
<td>Deposit Stress</td>
<td>Internal Stress Test</td>
<td>N/A</td>
<td>10-15 ksi (Tensile)</td>
<td>Cracked – Exceeds cohesive strength</td>
</tr>
<tr>
<td>Fatigue</td>
<td>Rotating Beam Fatigue</td>
<td>N/A</td>
<td>Comparable to bare at high loads.</td>
<td>Significant debit compared to bare at all loads.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Small debit compared to bare at low loads.</td>
<td>Credit compared to EHC.</td>
</tr>
</tbody>
</table>
Technical Progress

T-45 Pivot Assembly

Plated Area

Plating Rack

Tie Down Ring

Dem/Val Components
Overview of Prior Work

  - Concept Feasibility

  - Industrial scale-up at Integran
  - Process Line NAVAIR JAX

- **Supplemental Risk Reduction DOE (2008)**
  - Optimized Plating Parameters

- **ESTCP/NESDI Project (2009 – 2011)**
  - ESTCP WP-0936 & NESDI #348
  - JTP/DEM Plan Development
  - Process Development
  - Baseline Dem/Val plated
  - Phase I JTP Tests Completed
  - Elsyca modeling for Dem/Val, fatigue rack optimization

660 gal nCoP Plating tank at Integran

250 gal nCoP tank at FRC-SE
Environmental/Cost Benefits

- **Estimated NAVAIR P2 Savings over 10 Yrs**
  (Hexavalent Chromium Plating at Navy FRCs)

  - HAZMAT: *128,930 lbs*
  - HAZ Waste: *348,470 lbs*
  - Cr Rinse: 1,800,000 gals
  - Eng Controls: $1,608,750
  - Regulatory Compliance: $1,100,850

  *Impact of new OSHA Cr\(^{6+}\) regulations drives costs up*

  Waste may continue to drop as a result of decreasing usage of chrome due to increasing regulations.

  **Note:** the above projected savings are assumptions based on FRC-SE data extrapolated to other Navy FRCs. Estimated amounts due to chrome plating based on average Environmental Systems Allocation (ESA) data extrapolated across all FRCs over a 10 yr period.