Electrodeposition of Nanocrystalline Co-P Coatings as a Hard Chrome Alternative

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Report Documentation Page

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Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Hard Chrome Plating
(Why do we use it?)

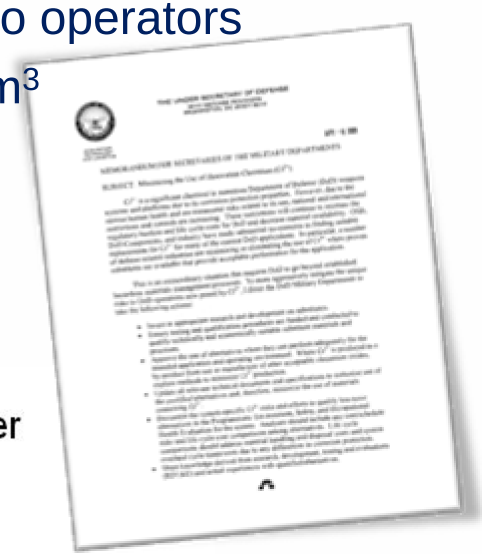
- **Why Chrome plating?**

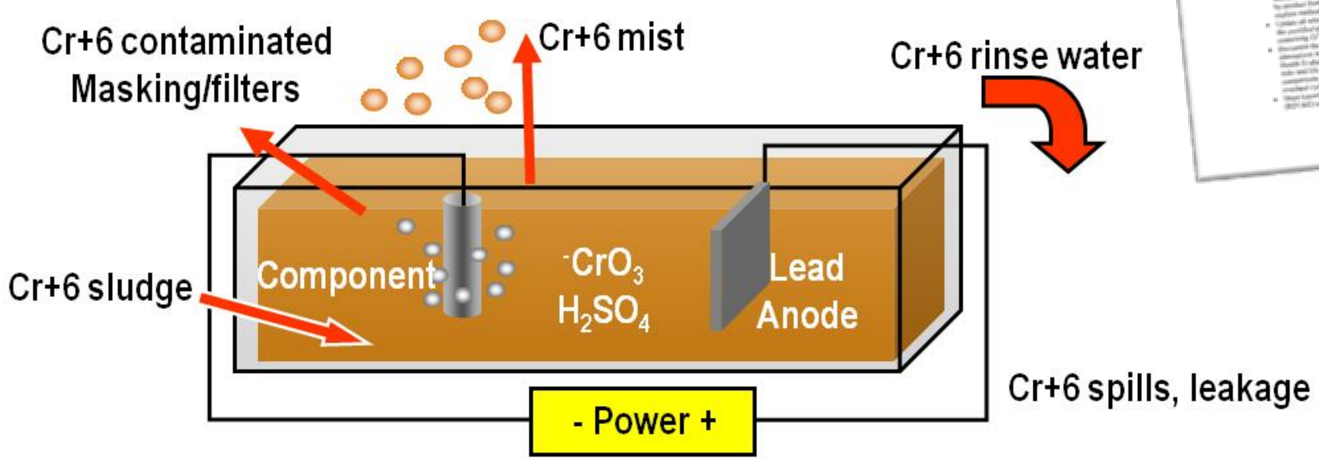
  Engineering hard chrome (EHC) coatings are used extensively in both industry and military applications due to their excellent performance characteristics.
  - Wear
  - Corrosion Resistance
  - Restore Dimensions

- **Where is Chrome Plating Used?**
  - OEM and rebuild/repair
  - Helicopter dynamic components
  - Hydraulic actuators
  - Propeller hubs
  - Gas turbine engines
  - Landing Gear

Hard Chrome Plating
(The Problem)

- **Hard Chrome Plating Environmental & Health Hazards**
  - Hard chrome plating utilizes chromium in the hexavalent state (Cr^{6+})
  - Cr^{6+} is a known carcinogen and poses a health risk to operators
  - OSHA lowered the Cr^{6+} PEL from 52 µg/m^3 to 5 µg/m^3
- **8 Apr 09, Memorandum, DoD Directive**
  - Hexavalent Chromium Management Policy





NAVAIR

Current Alternatives to EHC

- **Line-of-Sight Application (LOS)**
  - Thermal spray
  - HVOF (High Velocity Oxygen Fuel) Coatings

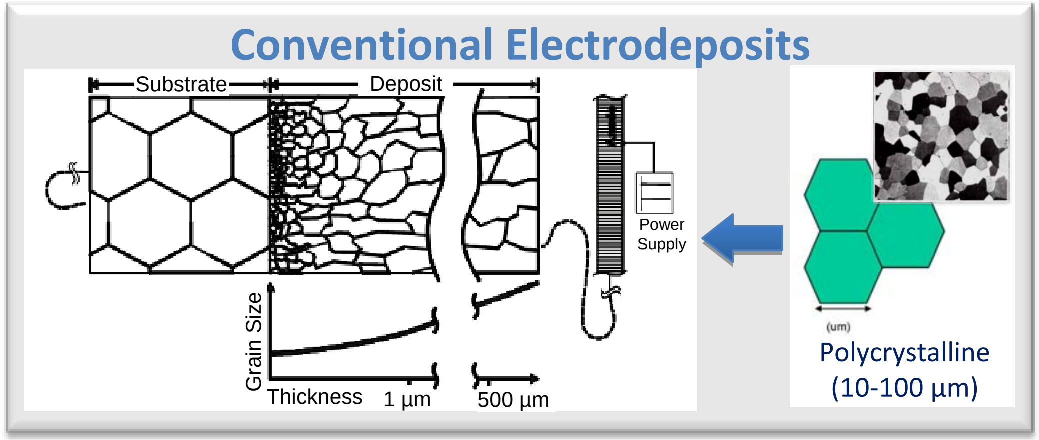
- **Non line-of-sight applications (NLOS)**
  - Ni based electroless (Ni-P and Ni-B) coatings
  - Ni based electrolytic (Ni-W, Ni-Co, Ni-Mo, etc.) coatings
  - Ni listed among EPA's 17 most toxic heavy metals

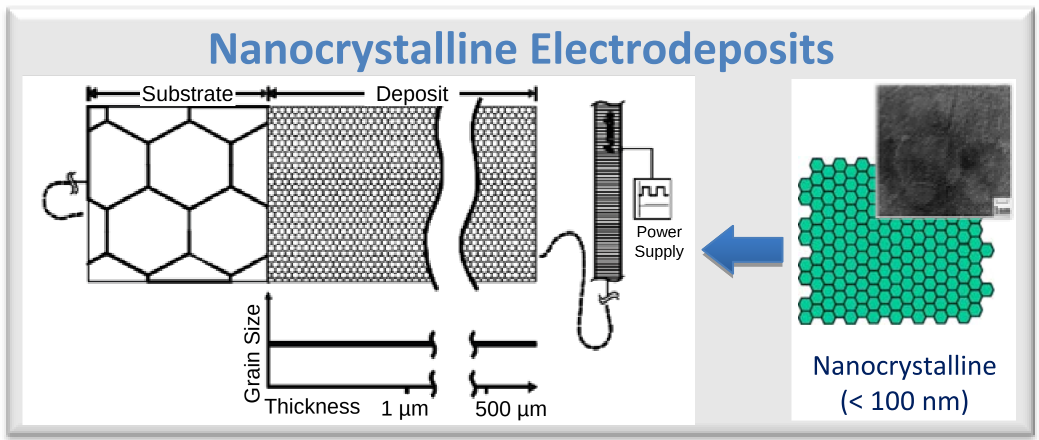
- **Proposed Solution:**
  Nanocrystalline Cobalt Phosphorus (nCoP) electroplating as an alternative to EHC for both LOS and NLOS applications for Depot rework. Co PEL is 20 µg/m^3*

**MERIT policies on Emerging Contaminants per DODI 4715.18 being monitored. Phase I Impact Assessments are planned for manganese and cobalt. Report pending.*

Electrodeposited Nanocrystalline Materials

- **Pulsed Current Waveform Engineering**
  - Favors nucleation of new grains over growth
  - Results in an ultra-fine grain structure
  - Uniform throughout thickness
  - Reduces average Grain Size
- **Leads to unique properties**
  - ↑ Yield Strength, wear, ultimate tensile strength
  - ↓ Coefficient of friction





nCoP (aka Nanovate™ CR) Electrodeposition Process

- **High deposition rate**
  - At 8X faster than Chrome plating / increase throughput
- **High current efficiency**
  - Reduced power consumption (90% reduction)
- **Drop-in technology**
  - Compatible with current EHC plating infrastructure
  - Can be applied to both LOS and NLOS surfaces

	nCoP	EHC
Deposition Method	Electrodeposition (Pulse)	Electrodeposition (DC)
Part Geometries	LOS and NLOS	LOS and NLOS
Efficiency	85-95%	15-35%
Deposition Rate	0.002”-0.008” /hr	0.0005”-0.001” /hr
Emission Analysis	Below OSHA limits	Cr+6

nCoP Properties

nCoP	EHC
	
Cross section of nCoP deposit.	Cross section of EHC deposit.
No pits, cracks or pores.	Microcracking observed.

nCoP Properties

		nCo-P	EHC
Appearance		Pit, Pore, Crack -free	Microcracked
Ductility		2-7%	<1%
Hardness	*As-Deposited*	530-600 VHN	Min. 600 VHN
	Heat Treated	up to 680 VHN	-
Adhesive Wear (Pin-on-disk)	*Wear volume loss*	6-7 x 10^{-6} mm^3/Nm	9-11 x 10^{-6} mm^3/Nm
	Coefficient of friction	0.4-0.5	0.7
	Pin Wear	Mild	Severe
Corrosion	*Salt Spray ASTM B117*	† Protection Rating 8 (1000 h) @ 0.002”	† Protection Rating 2 (1000 h) @ 0.004”
Hydrogen Embrittlement	ASTM F519	Pass with bake	Pass with bake

†*ASTM B537 Rating*

Progress

You Are Here

Program challenges identified

SERDP PP-1152 R&D
- Lab scale development
- Property testing
- Final report available

ESTCP WP-0411 Dem/Val
- Process line (NAVAIR JAX)
- JTP Testing
- Component Plating initiated

Supplemental Risk Reduction
- DOE & Pulsing downselect
- Data acquisition
- Producibility
- Supplemental report - 09/09

ESTCP WP-0936 Dem/Val
- JTP / Dem/val
- Technology integration plan
- Final Report
- Cost/Performance Report

Plating Parameter Downselect

SERDP PP-1152 → ESTCP WP-0411 → Supplemental → ESTCP WP-0936

- **Design of Experiments approach**
  - 2^3 full factorial design

Current Density	Frequency*	Duty Cycle**
1	1	1
1	1	-1
1	-1	1
1	-1	-1
-1	1	1
-1	1	-1
-1	-1	1
-1	-1	-1
0	0	0

$* f = 1/(t_{on}+t_{off})$

$**t_{on}/(t_{on}+t_{off})x100$

Hydrogen Embrittlement Bar

Hydrogen Embrittlement

Appearance

Adhesion

Stress Strip

Internal Stress

Flat Plate

Adhesion	Composition
Appearance	Hardness
Efficiency	Microstructure
Thickness	Plating rate

Plating Parameter Downselect

SERDP PP-1152 | ESTCP WP-0411 | Supplemental | ESTCP WP-0936

- Hydrogen Embritttlement testing (ASTM F519)
  - No post-plating hydrogen embrittlement relief bake (all pass with bake)

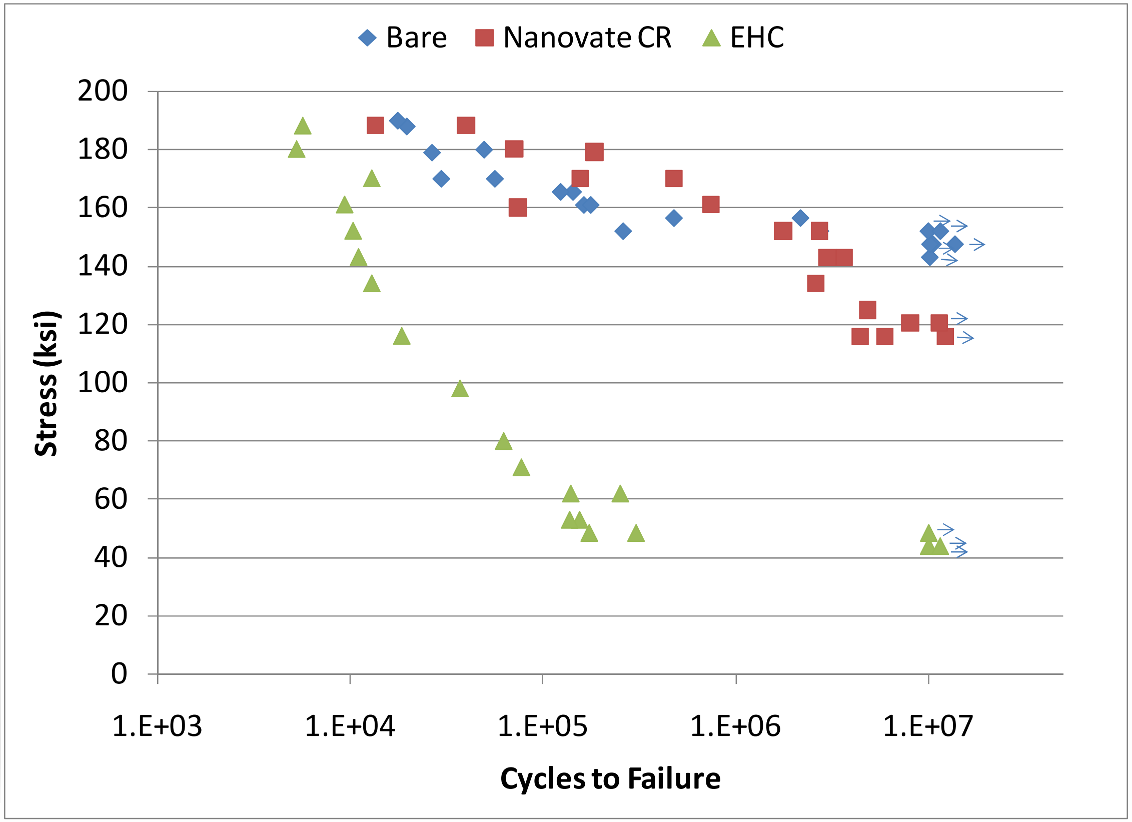
- No statistically significant effect of plating conditions

Current Density	Frequency	Duty Cycle	Time to failure, h			
			Bar 1	Bar 2	Bar 3	Bar 4
1	1	1	40	121	193	193.1
1	1	-1	> 200	> 200	> 200	> 200
1	-1	1	49	57	58	> 200
1	-1	-1	> 200	> 200	> 200	> 200
-1	1	1	136	193	200	> 200
-1	1	-1	80	80	121	193
-1	-1	1	> 200	> 200	> 200	> 200
-1	-1	-1	> 200	> 200	> 200	> 200
0	0	0	80	123	137	> 200

Data Acquisition
(Rotating Beam Fatigue)

SERDP PP-1152 — ESTCP WP-0411 — Supplemental — ESTCP WP-0936

- **Testing with downselected plating conditions**
- Hourglass geometry
- 4340 substrate
  - 260-280 ksi
  - No shot peen



**Unofficial results obtained from supplemental testing using optimized parameters*

Data Acquisition
(Summary)

SERDP PP-1152 | ESTCP WP-0411 | Supplemental | ESTCP WP-0936

- **Testing with downselected plating conditions**

Property	Test	Result
Microstructure	X-ray diffraction	Nanocrystalline
Stress	Stress strips	10-15 ksi (tensile)
Adhesion	Bend test	Pass
Porosity	Microscopy	Fully dense
Hydrogen embrittlement	ASTM F519	Pass
Corrosion	ASTM B117 salt spray 165h	Pass
Hardness	Vicker's Microhardness	560 VHN
Abrasive Wear	Taber	17 mg/1000 cycles
Fatigue	Rotating beam	Comparable to bare Credit vs. EHC

Optimized Pulse Conditions Established

Panel plated using downselected parameters

Productibility

SERDP PP-1152 | ESTCP WP-0411 | Supplemental | ESTCP WP-0936

- **Producibility with downselected plating conditions**
- nCoP applied to internal and outer diameter sections

Internal Diameter Plating
J52 Coupling

Plating area

As-received

nCoP-plated

Outer Diameter Plating
J52 Shaft (section)

As-received

Plating area

nCoP-plated

Rod-Seal Wear
(Leakage, Various O-rings)

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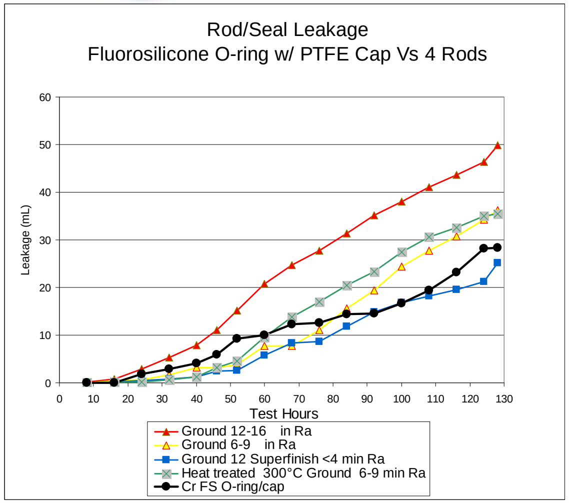
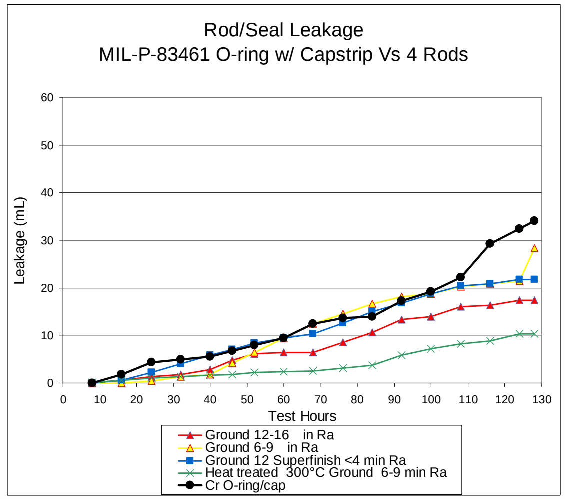
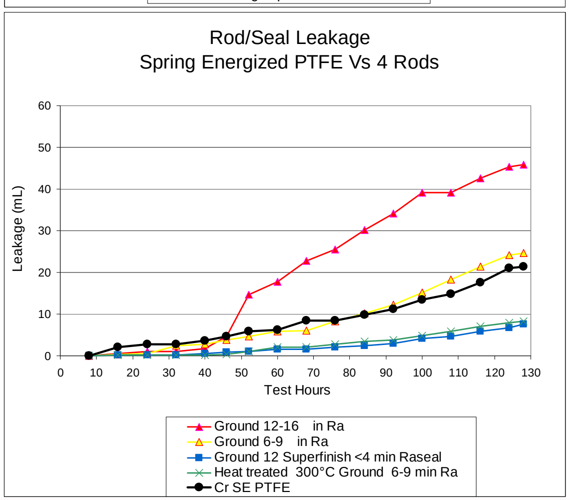
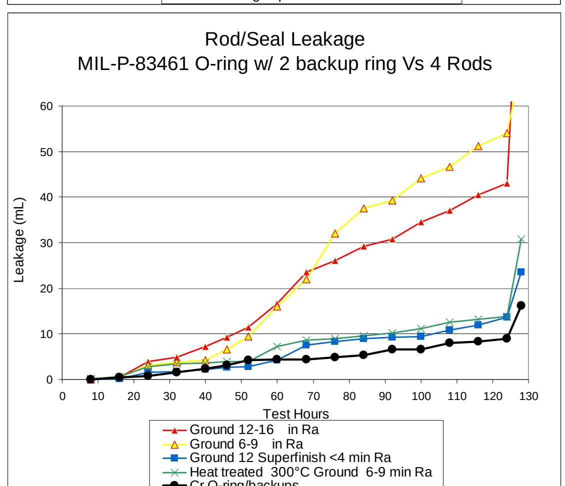








Black lines hard chrome from prior HCAT work

- Different test run
- nCoP roughly comparable with hard chrome
- Ground surfaces higher leakage

Future Work

SERDP PP-1152 → ESTCP WP-0411 → Supplemental → ESTCP WP-0936

- **Demonstration Plan and Joint Test Protocol will be developed by team members**
- Stakeholders:
  - NAVAIR (JAX, PAX, CP, Lakehurst)
  - NAVSEA
  - Integran
  - OEM
- Key JTP Performance Criteria:
  - Coating Properties:
    - Microstructure, % P, Hardness, Residual Stress
  - Coating Performance:
    - Corrosion testing
    - Fatigue testing
    - Wear
    - Hydrogen & Environmental Embrittlement
  - Chemical compatibility tests
  - Rig Testing (where applicable)

U.S. DEPARTMENT OF DEFENSE
Environmental Security Technology Certification Program
(ESTCP)

JOINT TEST PROTOCOL

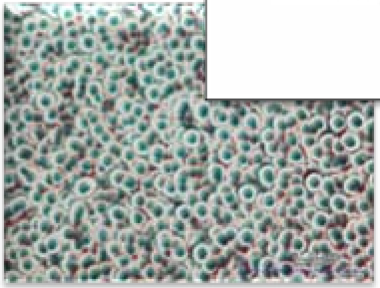
Validation of nano-Co-P Electroplating as an Alternative to Chrome Plate

PART I – COUPON TESTING

Date: March 30, 2005

Prepared By:
Hard Chrome Alternatives Team (HCAT)

ASETS DEFENSE



Demonstration Site

SERDP PP-1152 | ESTCP WP-0411 | Supplemental | ESTCP WP-0936

- **NAVAIR JAX Depot**
  nCoP Dem/Val Process Line
  - 250 gallon nCoP Tank (2.5'x4'x4')
  - 370 gallon Activation Tank (3'x3'x6')
  - Pulse Power Supply (1500A Peak Current)
  - Remote Controller (Touch Screen)

nCoP Dem/Val tank

Power Supply

Remote Controller

Acid/Fluoride Activation tank

Proposed Demo Components

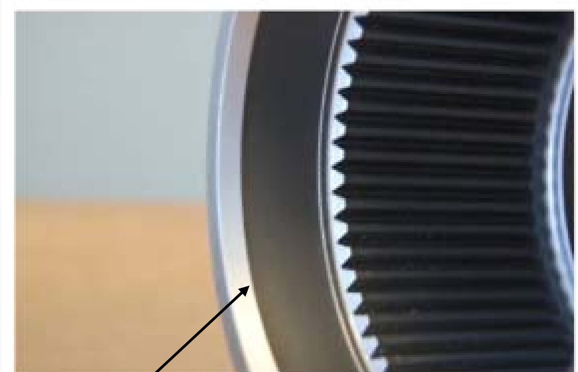
SERDP PP-1152 — ESTCP WP-0411 — Supplemental — ESTCP WP-0936

NAVAIR JAX for Air Vehicle Components

- **J-52 Coupling, Turbine Shaft Actuating Cylinder (for production capability)**

J-52 Coupling, Turbine Shaft
Material: 4340 Steel (AMS 6415)

Demo part shown in rack assembly with titanium basket anode in place



ID area to receive plating

Official part identification pending

Proposed Demo Components

SERDP PP-1152 | ESTCP WP-0411 | Supplemental | ESTCP WP-0936

NAVAIR Lakehurst – Ground Support Equipment

- **Telescoping Hydraulic Cylinder (Spotting Dolly)**

Telescoping Hydraulic Cylinder

Spotting Dolly

Proposed Demo Components

SERDP PP-1152 → ESTCP WP-0411 → Supplemental → ESTCP WP-0936

NAVSEA (NESDI & OSD Leveraged Effort)

- **Marine Corps MK48 LVS (Logistic Vehicle System) Hydraulic Cylinders**
  - Evaluate coatings in accelerated corrosion cabinet (GM9540P) and marine atmospheric test exposures
  - Field test optimum coating systems on MK48 vehicles
  - Develop selection criteria for implementation into system repair / rebuild and spare parts sourcing
  - Reduce corrosion maintenance requirements and repair costs of vehicles

Summary

- **Nanocrystalline Co-P Process (a.k.a. Nanovate™ CR)**
  - Environmentally compliant EHC alternative
  - Process compatible with existing plating infrastructure
  - Reduced energy consumption, increased throughput
- **Nanocrystalline Co-P Properties**
  - Enhanced corrosion and wear
  - Non-embrittling
  - Improved fatigue performance vs. EHC
- **Future work (WP-0936)**
  - Performance testing (JTP)
  - Dem/val at NAVAIR JAX Depot

For more information…

Visit our booth at ASETS Defense

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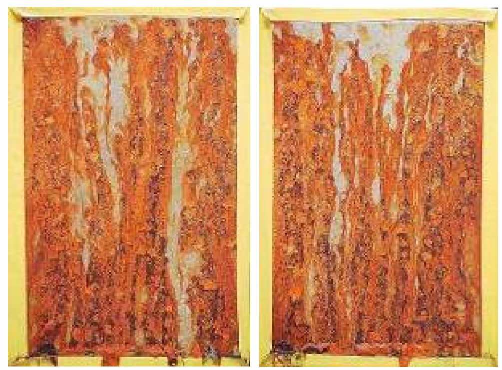
Backup Slides

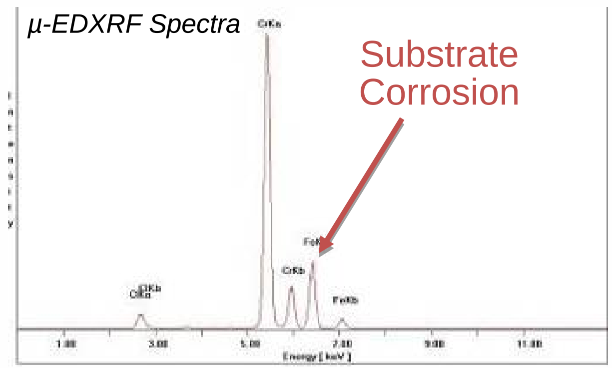
Data Acquisition
(Corrosion)

SERDP PP-1152 · ESTCP WP-0411 · Supplemental · ESTCP WP-0936

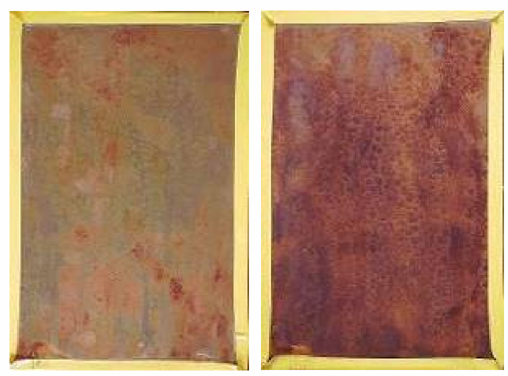
- **Testing with downselected plating conditions**
- ASTM B117 Salt Fog
  - 165 h exposure
- EHC exhibits red rust
- nCoP exhibits coating oxidation
  - No red rust

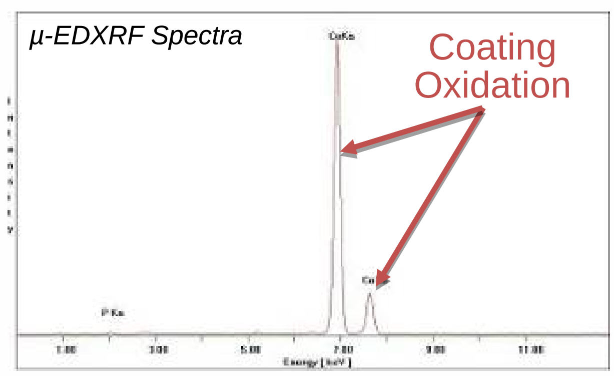
Hard Chrome





nCoP





Corrosion Testing

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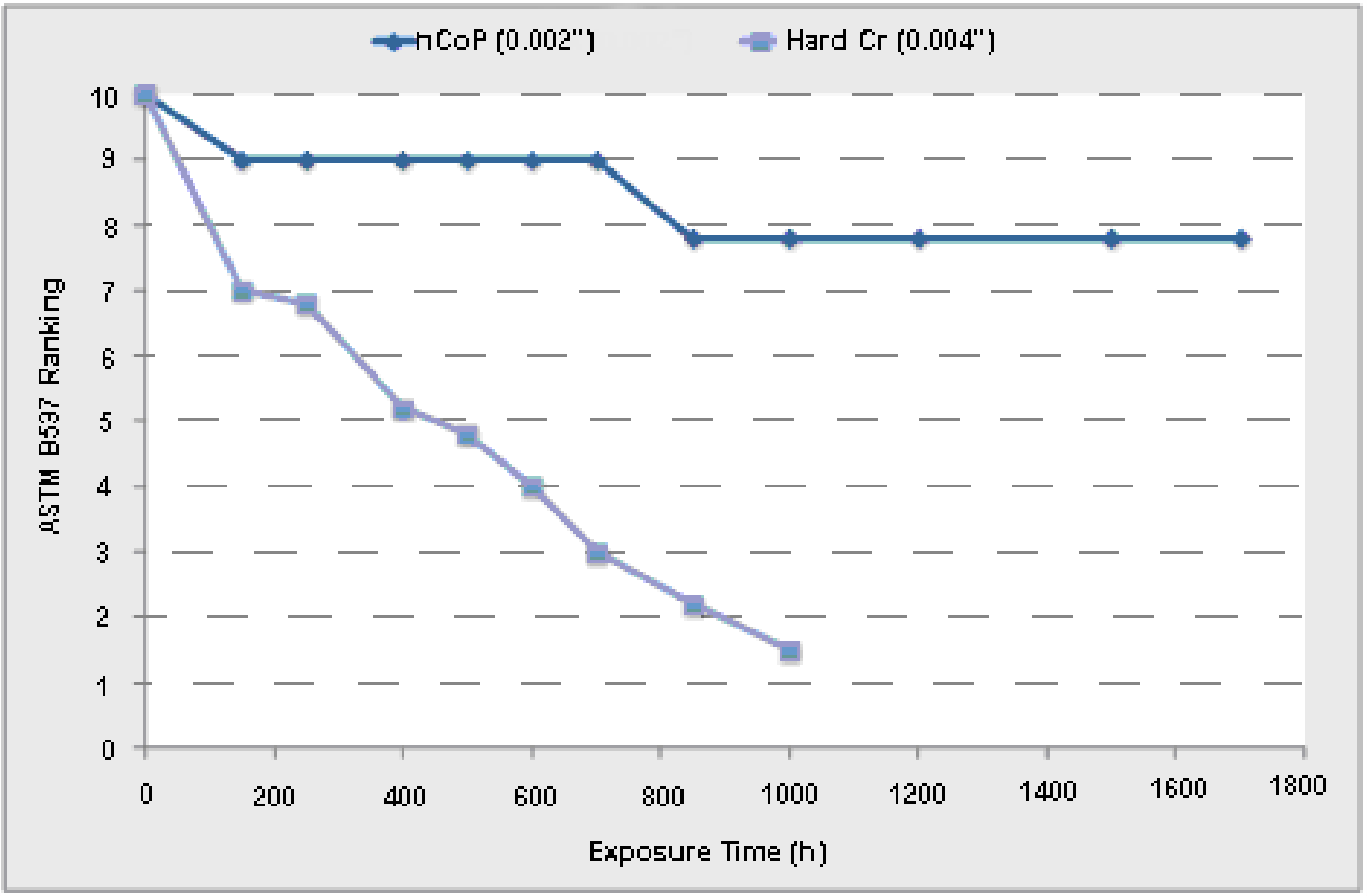
- ASTM B117 Salt Spray, 1000 hrs exposure



Rod-Seal Wear Testing

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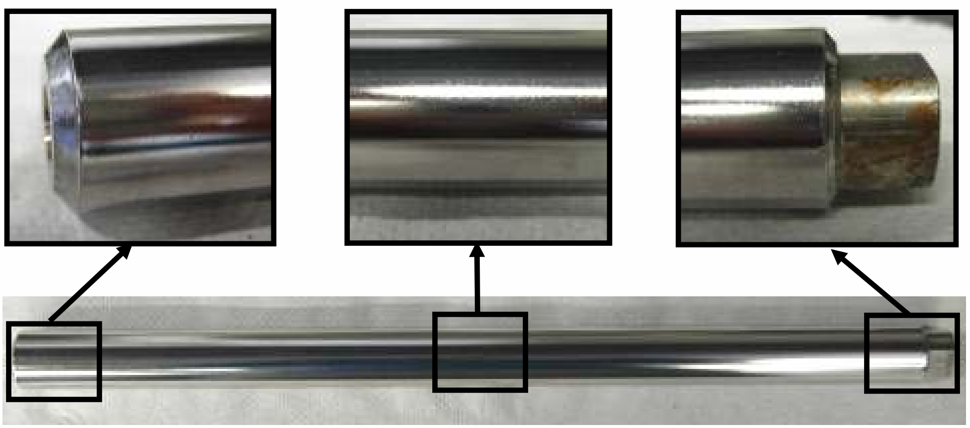
- Four PH 13-8Mo hydraulic actuator rods
  - Plated with 0.006-0.008” nCoP
  - Hydrogen baked (375°F, 23h) or heat treated (300°C, 6 h)
  - Ground to 6-9 µinch, 12-16 µinch or superfinished to Ra < 4 µinch
- Testing conducted at NAVAIR-PAX
  - similar to ID cylinder wear - wear against seals
  - Tests showed nCoP comparable to Cr

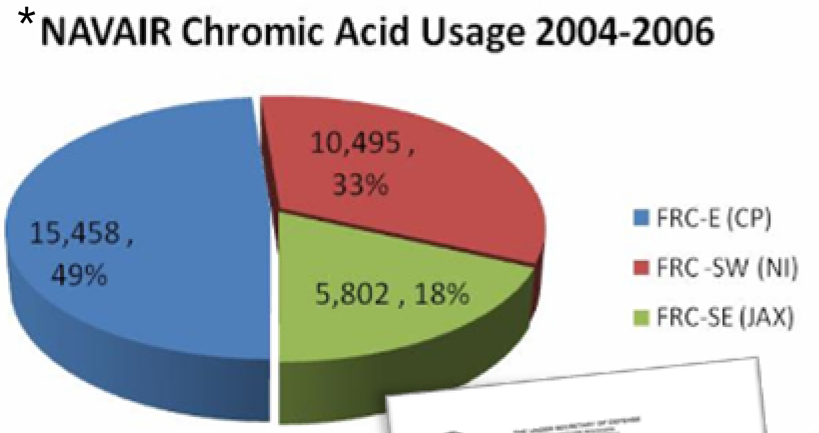


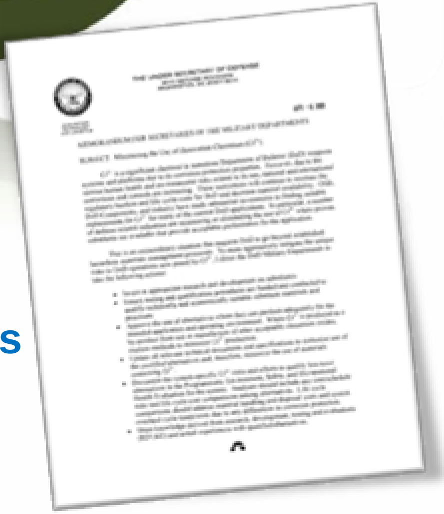
nCoP-coated hydraulic rod

Rod-seal test apparatus

Environmental Driver/Benefit

- **Environmental Benefits**
  - Eliminates chrome plating and all its hazardous waste
  - Eliminates worker exposure to Cr^{+6}
  - Primary cost savings from reduced engineering controls and all required maintenance/monitoring
  - Some savings from reduced power use (more efficient process)
  - Increased throughput and reduced footprint through reduction of process tanks





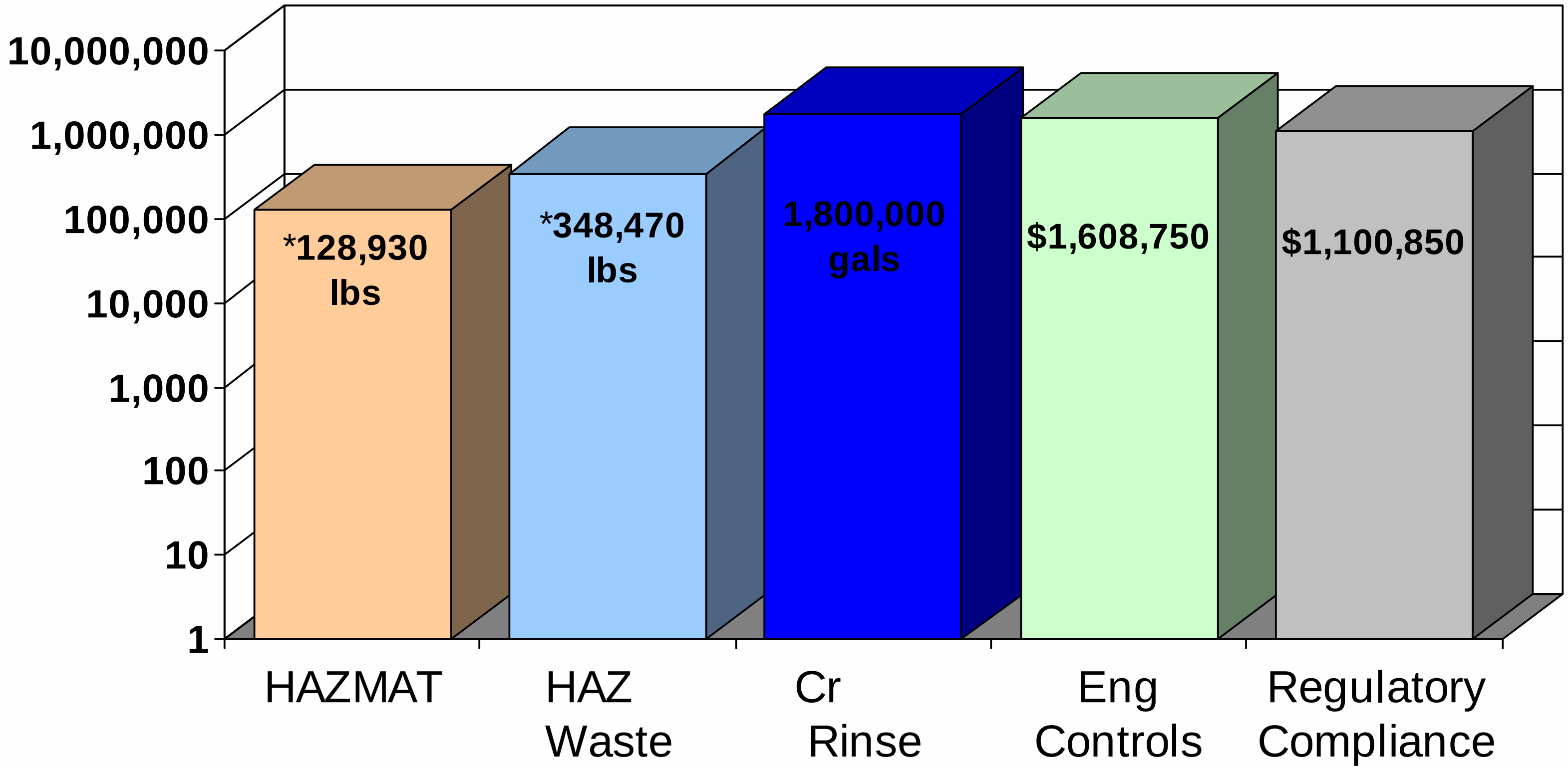
32,000 Gallons

** Data obtained from NAVAIR's Environmental Systems Allocation (ESA) Model. Extend to: Actuators, Landing Gear, Gear and engine journals and wear surfaces on Aircraft, Vehicles & Vessels*

Environmental Driver/Benefit

(Hexavalent Chromium Plating at Navy FRCs)

- **Estimated NAVAIR P2 Savings over 10 Yrs**



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*

IH Assessment at NAVAIR JAX

- NAVAIR-JAX IH assessment on Co emission on the Dem/Val tank.

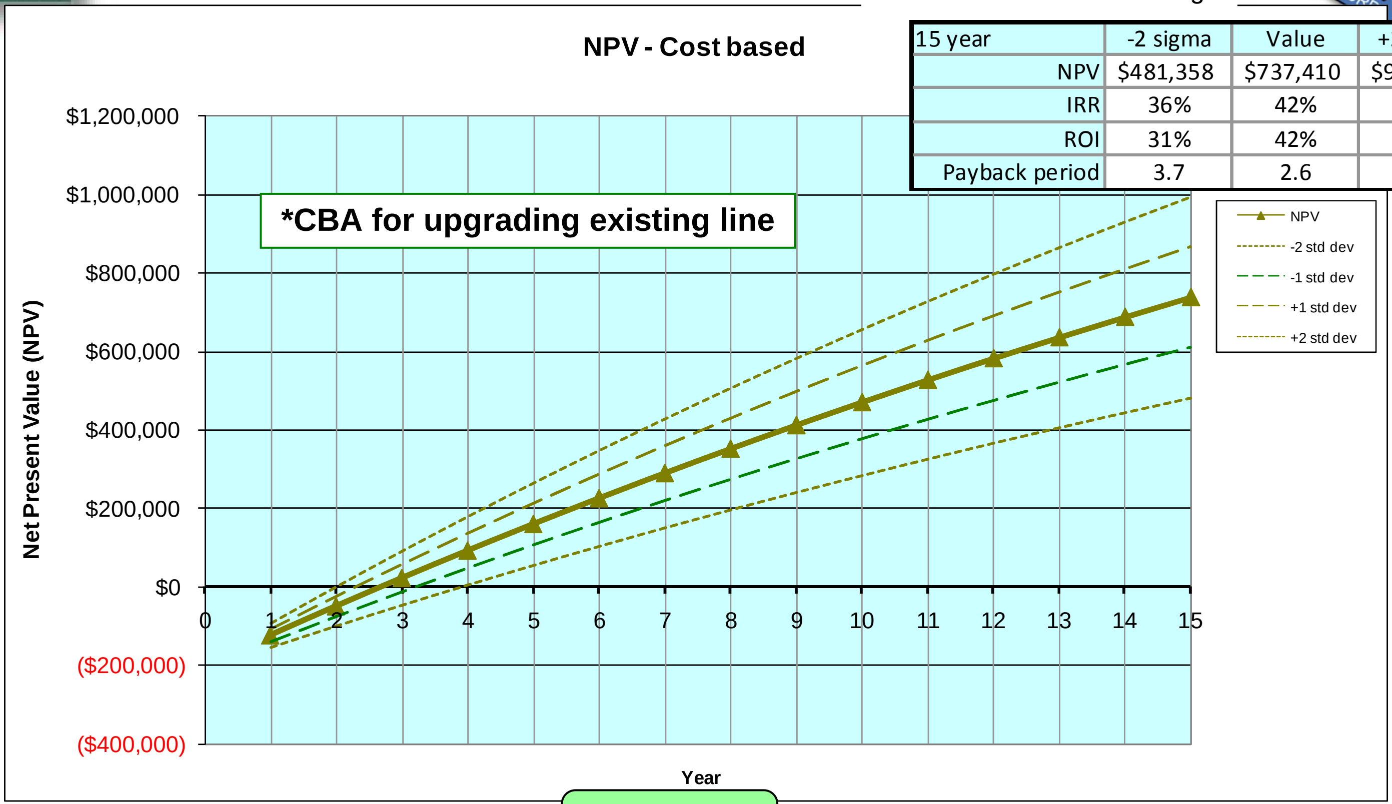
DATE:	PERSONAL SAMPLING RESULTS (8-HR TWAS)	AREA SAMPLING RESULTS (8-HR TWAS)	VENTILATION MEASUREMENTS (TAKEN ON THE PULL SIDE)	DRY BULB READINGS (2)	RELATIVE HUMIDITY (3)
8 Aug 2007	Below the LOD	0.0023 mg/m^3	3519 FPM	Initial: 79.1^{o}F Final: 97.3^{o}F	Initial: 100% Final: 58%
9 Aug 2007	Below the LOD	0.0074 mg/m^3	3545 FPM	Initial: 81.2^{o}F Final: 97.6^{o}F	Initial: 100% Final: 58%
16 Aug 2007	Below the LOD	0.0017 mg/m^3	4001 FPM	Initial: 79.0^{o}F Final: 94.4^{o}F	Initial: 91% Final: 51%
22 Aug 2007	Below the LOD	Below the LOD	4366 FPM	Initial: 78.5^{o}F Final: 95.0^{o}F	Initial: 94% Final: 50%
24 Aug 2007	Below the LOD	Below the LOD	4088 FPM	Initial: 77.5^{o}F Final: 94.2^{o}F	Initial: 100% Final: 58%

Co PEL is 20 μg/m^3

Cost Benefit Analysis

Value based on cost savings

15 year	-2 sigma	Value	+2 sigma
NPV	$481,358	$737,410	$993,463
IRR	36%	42%	47%
ROI	31%	42%	53%
Payback period	3.7	2.6	2.0



*ROI: 42% w/ Payback Period of **2.6 yrs**

	EHC	nCo-P
Labor	$1,365	$1,365
Chemicals	$1,503	$1,585
Water	$6	$62
Electricity	$24	$1

Average cost/item

- → Same labor
- → More expensive chemicals
- → Higher bath temperature
- → Faster, more efficient plating