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"**Award Winning Projects**: Weapons Systems and Platforms"

January 26, 2017

SERDP DOD • EPA • DOE | ESTCP

Welcome and Introductions

Jennifer Nyman, Ph.D.
Webinar Program Coordinator

SERDP DOD • EPA • DOE | ESTCP

Webinar Agenda

- **Webinar Logistics** (5 minutes)

  Dr. Jennifer Nyman, Geosyntec Consultants
- **Overview of SERDP and ESTCP** (5 minutes)

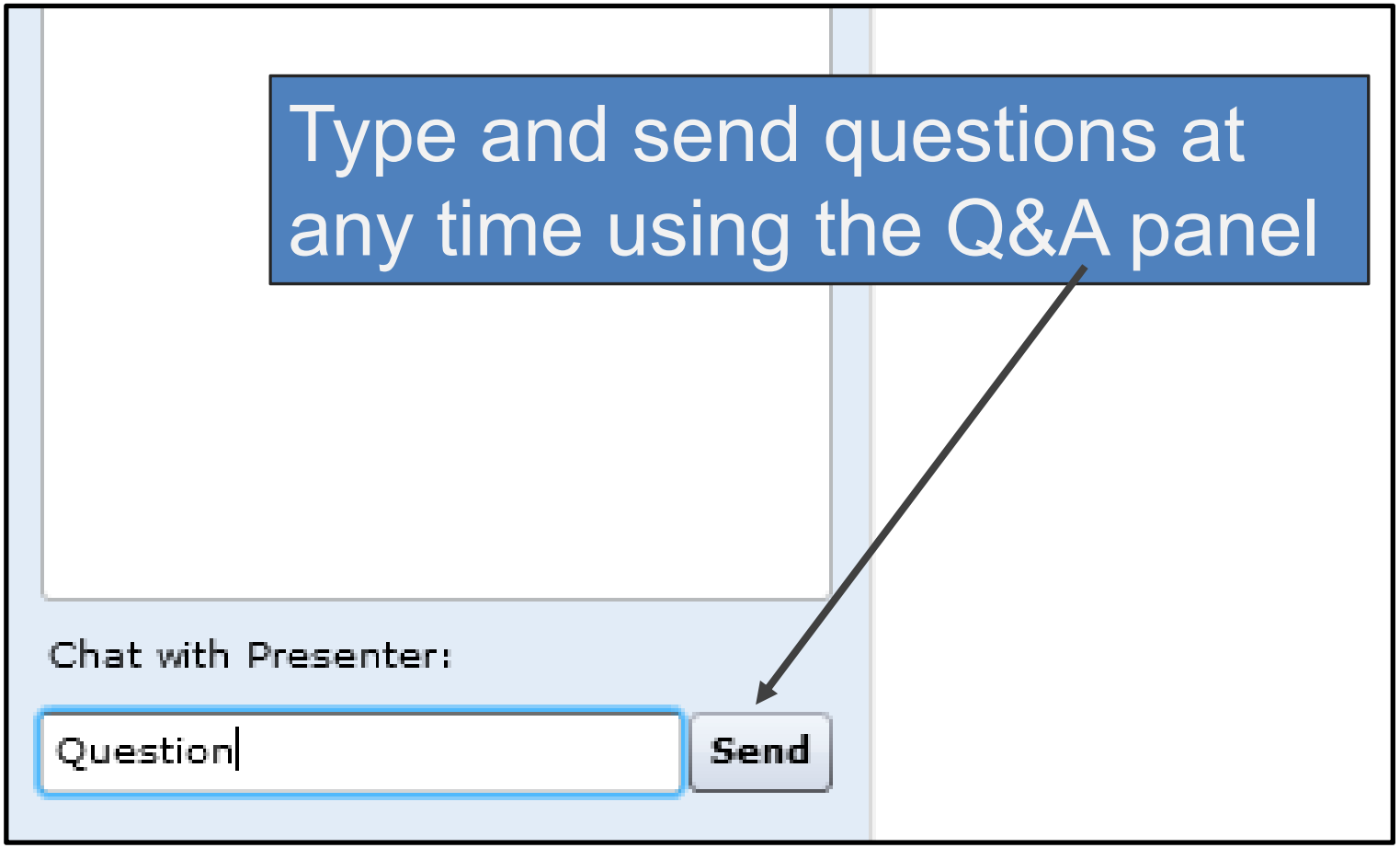
  Dr. Robin Nissan, SERDP and ESTCP
- **Compressor Airfoil Protective Coating for Turbine Engine Durability and Fuel Efficiency** (25 minutes + Q&A)

  Mr. Greg Kilchenstein, Office of the Secretary of Defense

  Mr. Marcio Duffles, MDS Coating Technologies
- **Hydrogen Effects of Common Cadmium Alternatives on Aerospace Grade 4340** (25 minutes + Q&A)

  Mr. Stephen Gaydos, The Boeing Company
- **Final Q&A session**

How to Ask Questions



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SERDP and ESTCP Overview

Robin Nissan, Ph.D.

SERDP and ESTCP, Weapons Systems and Platforms Program Manager

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SERDP

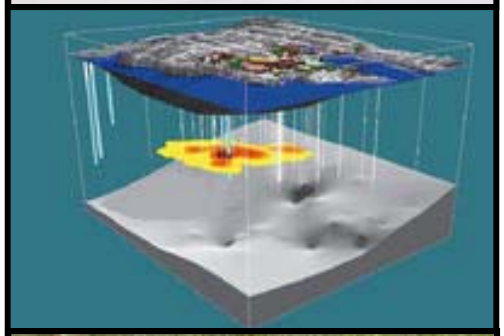
- Strategic Environmental Research and Development Program
- Established by Congress in FY 1991
  - DoD, DOE and EPA partnership
- SERDP is a requirements driven program which identifies high-priority environmental science and technology investment opportunities that address DoD requirements
  - Advanced technology development to address near term needs
  - Fundamental research to impact real world environmental management

ESTCP

- Environmental Security Technology Certification Program
- Demonstrate innovative cost-effective environmental and energy technologies
  - Capitalize on past investments
  - Transition technology out of the lab
- Promote implementation
  - Facilitate regulatory acceptance

Program Areas

1. Energy and Water
2. Environmental Restoration
3. Munitions Response
4. Resource Conservation and Resiliency
5. Weapons Systems and Platforms



Weapons Systems and Platforms

- Major focus areas
  - Surface engineering and structural materials
  - Energetic materials and munitions
  - Noise and emissions
  - Waste reduction and treatment in DoD operations
  - Lead free electronics

SERDP and ESTCP Webinar Series

Date	Topic
February 9, 2017	**Award Winning Projects** Munitions Response
February 23, 2017	**Award Winning Projects** Resource Conservation and Resiliency
March 9, 2017	**Award Winning Projects** Environmental Restoration
March 23, 2017	Monitoring and Risk Assessment of Environmental Risks Posed by Munitions Constituents in Aquatic Systems
April 6, 2017	1,4-Dioxane Impacts and Innovative Cleanup Technologies at DoD Contaminated Sites
May 4, 2017	Novel Coatings Systems for Use as High Performance Chemical Resistant Power Topcoats

For upcoming webinars, please visit

http://serdp-estcp.org/Tools-and-Training/Webinar-Series

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Compressor Airfoil Protective Coating for Turbine Engine Fuel Efficiency

Greg Kilchenstein
Office of the Secretary of Defense

Marcio Duffles
MDS Coating Technologies

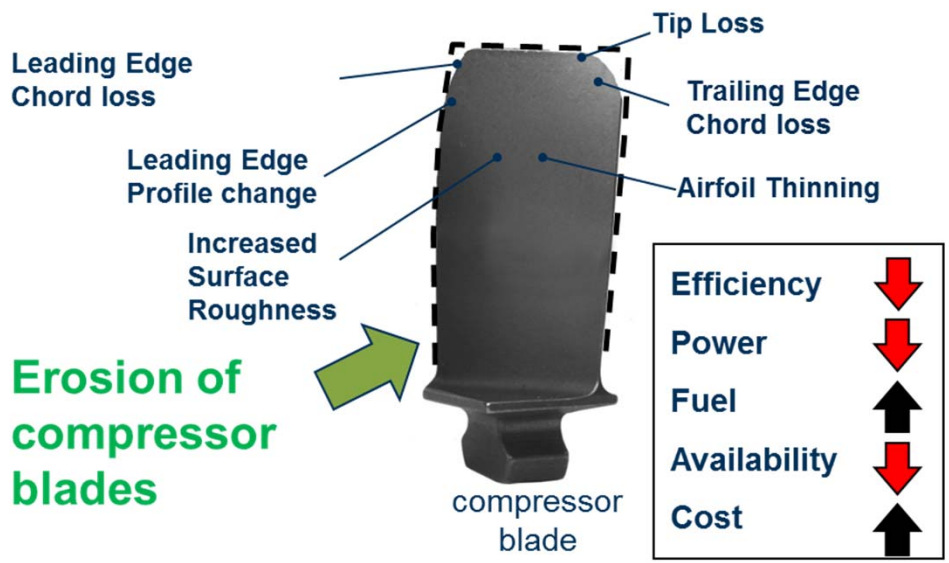
SERDP DOD • EPA • DOE | ESTCP

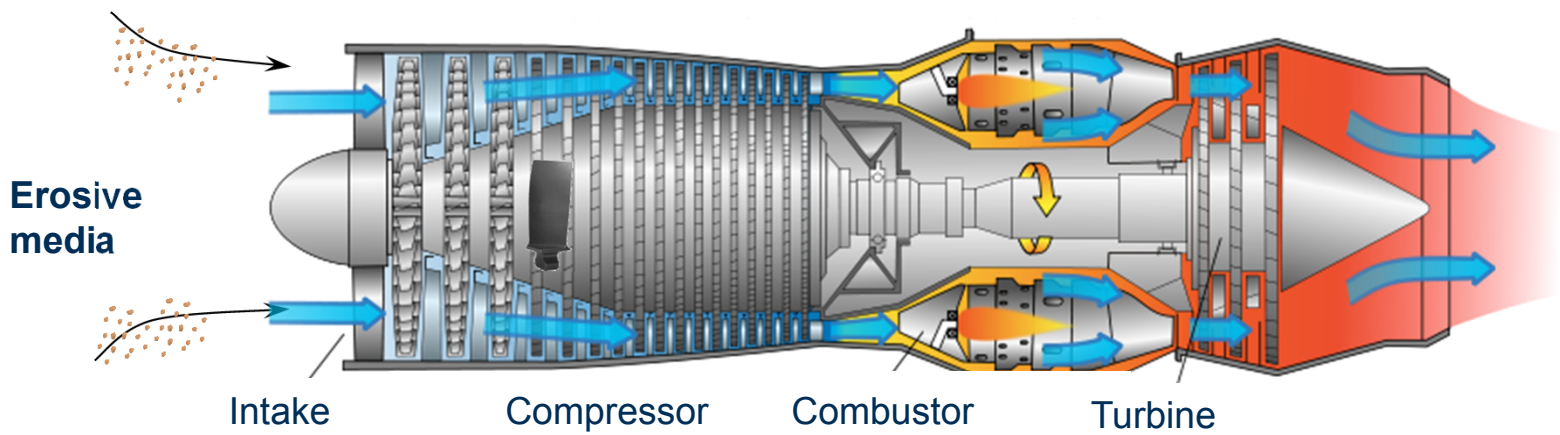
Project Overview

Greg Kilchenstein
Office of the Secretary of Defense

Agenda

- Problem statement
- Background
- Projects
- Conclusions





Gas Turbine Engine

Problem Statement

- DoD consumes >$10B in aviation fuel annually or >250M bbl of oil annually
  - Eroded engine compressor airfoils increase fuel consumption up to 5%
  - Field experience and engine evaluation indicate eroded compressor airfoils on:
    - Fixed wing aircraft
    - Rotary wing aircraft
    - Ground vehicles
- Eroded compressor airfoils increase engine R&O rate and industrial footprint
- Degraded engines emit between 10 to 25% greater pollutants*

** Effects of Engine Aging on Aircraft NOx Emissions*
Lukachko and Waitz, MIT Aero-Environmental Research Lab

Current Approach

- Minimize engine degradation via operational restrictions such as avoiding take-off/landing in unapproved fields
  - Operators cannot always avoid such take-off and landing situations
  - Abrasive particles prevalent throughout the atmosphere
- Particle separators and barrier filters (ground systems and rotary wing only)
  - Approximately 85% efficient
  - Operators routinely bypass/remove protective systems, especially at high altitude operations
  - Fixed-wing aircraft do not operate with filters or separators

Background

CH-53 Desert Operations

- Coated >1,000 T64 engine compressor sets
- >1M operational hours in-theatre
- Coated TOW ~1100 hrs*
  - PMA 261 calculated $120M savings in 2005**
  - Over $1B in savings to date
- Uncoated TOW ~113 hours, ~3 months

Uncoated at 113 hours ~ 2 to 3 months	Coated at 2,022 hours 40 months

* *First 60 uncoated vs. first 60 coated in OIF*

** *Based on reduced frequency of engine repair only, airfoil replacement and other logistics elements not considered*

Background

CH-46 Desert Operations

- Coating implemented in 2005 to enhance durability and TOW
- > 800 T58 compressor sets coated since 2005
- > 300k operational hours in-theatre
  - Uncoated engine avg TOW ~530 hrs*
  - Coated engine avg TOW ~798 hrs**
- Sand ingestion testing → 3% decreased fuel consumption
- 15 uncoated engine blade failures (2003-2008)
- Zero coated engine blade failures

Uncoated blade significant leading edge curl	Coated blade leading edge protection

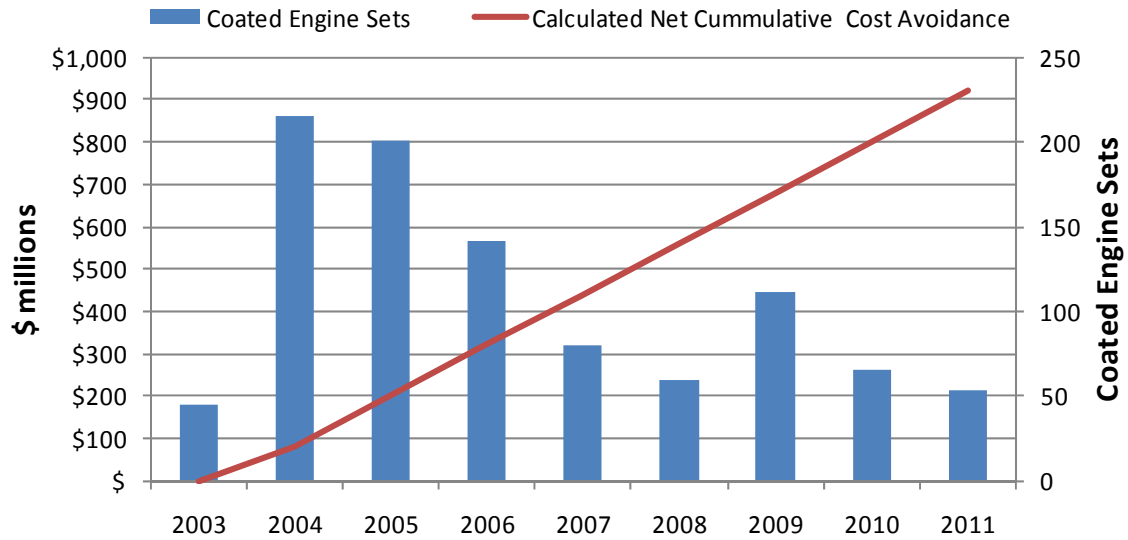
* *Based on PMA-226 engine study data*

** *Based on reduced engine repair frequency only; airfoil replacement and other logistics elements not considered*

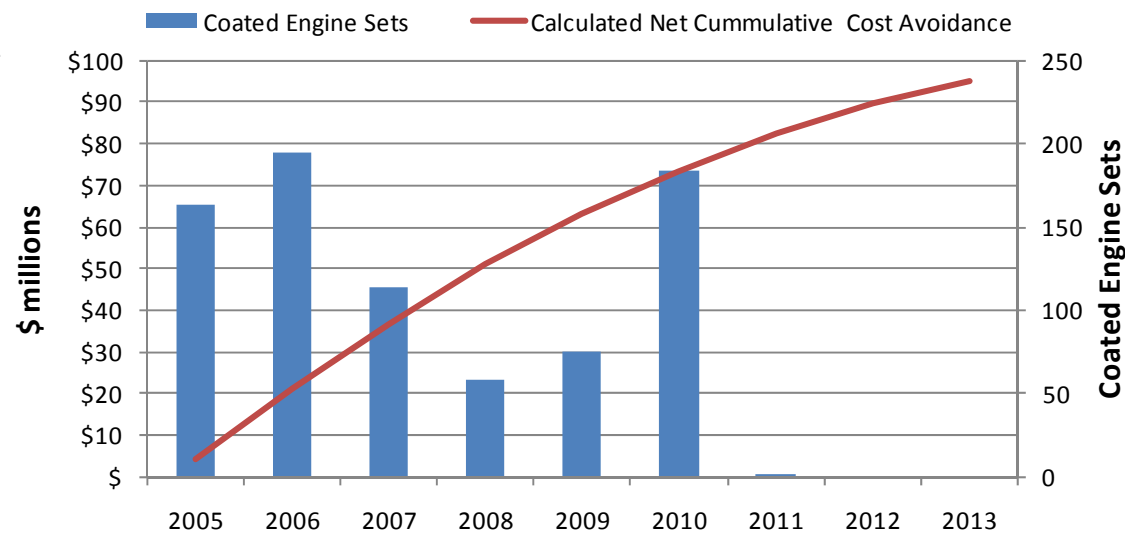
Background

Calculated Net Cumulative Cost Avoidance

CH-53 Desert Operations



CH-46 Desert Operations



Technical Objectives, Demonstration Results and Related Efforts

Marcio Duffles
MDS Coating Technologies

SERDP DOD • EPA • DOE | ESTCP

Technical Objectives

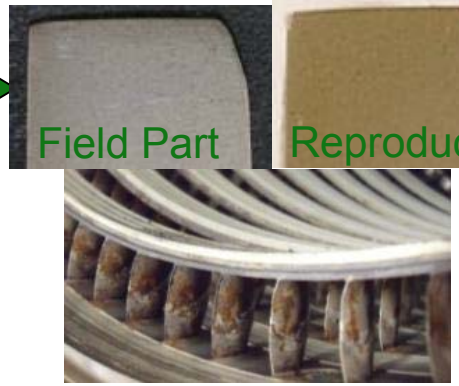
- Define and develop erosion profiles on following engine types
  - T56 (C-130 and E-2)
  - AGT1500 (Abrams M1A tank)
  - T700 (SH-60, HH-60, AH-64)*
  - T55 (CH-47 and MH-47)*
  - V-22 (AE1107C)
- Demonstrate fuel savings, decreased maintenance and industrial footprint and reduced emissions operating with erosion/corrosion resistant coatings
- Scope
  - Engineering analysis
  - Lab/bench testing
  - Full-scale engine testing
  - Field evaluation
  - Modeling and simulation

** Effort expanded to include these engine types*

T56 Demonstration

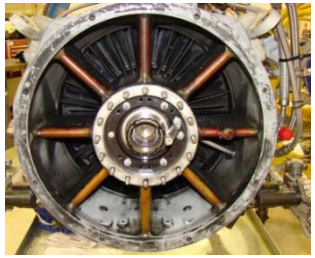
Engineering Investigation of Inducted Engines

Replicate Field Parts in Lab Tests



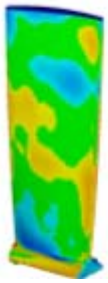
Document Blade Condition

Coat Compressor Set



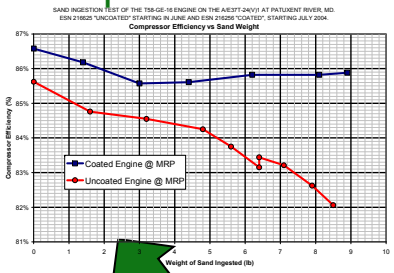
Conduct Engine Testing

Optical Scan New vs. Tested Blades



Computer Modeling

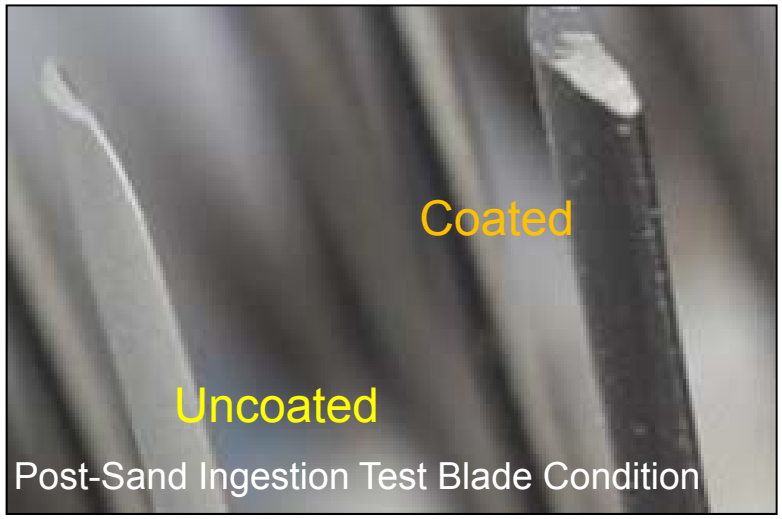
Performance Output



T56 Technical Results

Sand Ingestion Test, Coated versus Uncoated Engines

- Time since overhaul
  - Coated: 1,046 hrs
  - Uncoated: 50 hrs
- ~3X power retention after 135 lbs sand ingested
  - Coated: 102% to 97% shp → 5%
  - Uncoated: 104% to 88% shp → 16%
- 1.5% reduced fuel consumption potential
  - AMC Fuel Efficiency Office analysis
  - Standard Aero Post-Test Performance Analysis
- Standard Aero sustainability report
  - ~5% increase in engine TOW
  - ~20% increase in compressor TOW



T56 Results Analysis

Fuel and Emissions Benefits

- 1-2% less fuel consumption with coated engine
  - USAF C-130 fleets consumes ~200Mgal/year
  - 1% savings = 2Mgal/year or ~$8M/year
  - NAVAIR T56 engine fleet consumes ~62Mgal/year
  - 0.75% savings ~0.5Mgal/year or ~$2M/year
- Each kg fuel not consumed → 3.15 kg CO_2 reduction
  - USAF C-130 fleet → 29.037 metric tonnes CO_2 reduction
  - NAVAIR T56 fleet → 4.5 metric tonnes CO_2 reduction

Estimated savings 6.5M bbl of oil / year

AGT1500 Demonstration

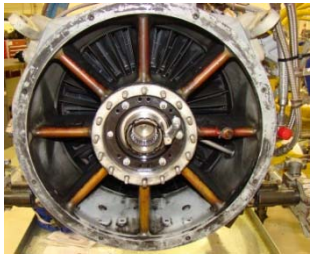
Engineering Investigation of Inducted Engines

Field Eval BCA

Replicate Field Parts in Lab Tests

Document Blade Condition

Coat Compressor Set

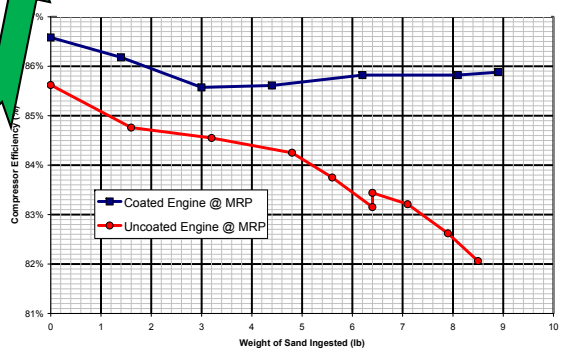


Conduct Engine Testing

Uncoated Engine – April 2012

Coated Engine – June 2012

Performance Output



AGT1500 Demonstration

Coating Configurations

Uncoated Engines

4 parts per stage – BlackGold® v4 LEAP
Remaining parts – Uncoated

Uncoated

Uncoated

Coated Engines

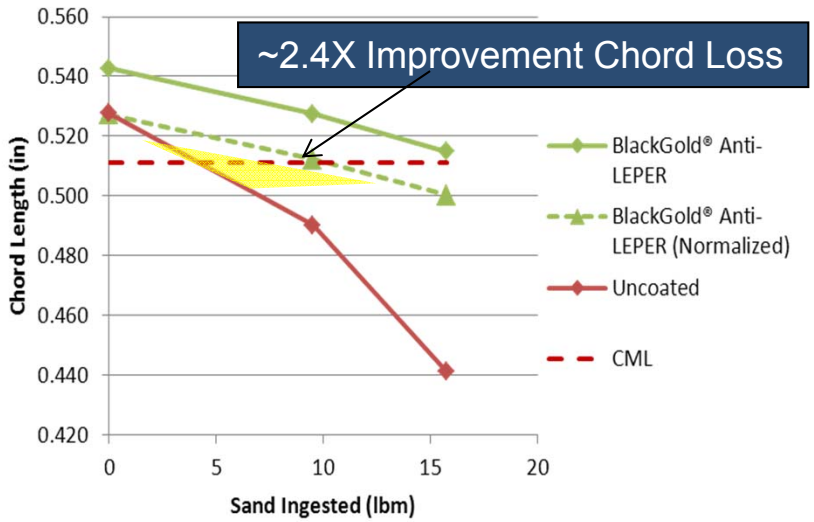
4 parts per stage – BlackGold®v4 LEAP
2 parts per stage* – Uncoated
Remaining parts – BlackGold®v4 Anti-LEPER

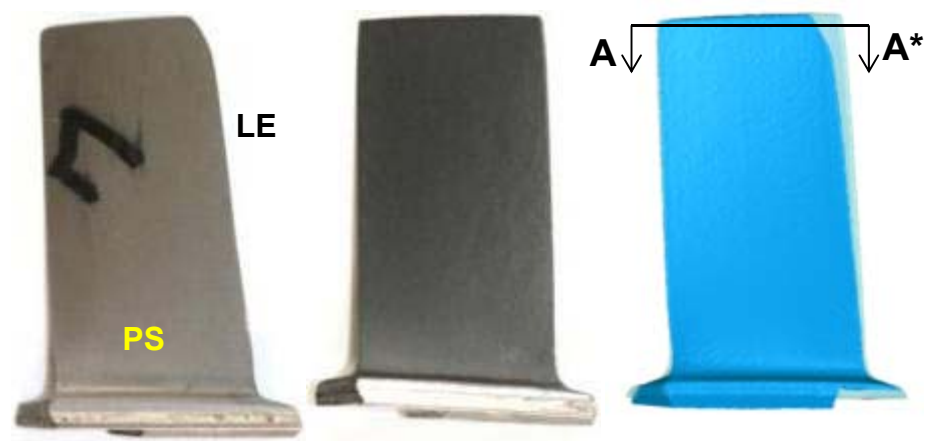
LP02 & LP05: BlackGold®v4 Anti-LEPER
Remaining: Uncoated

**High pressure first stage rotor did not include uncoated parts*

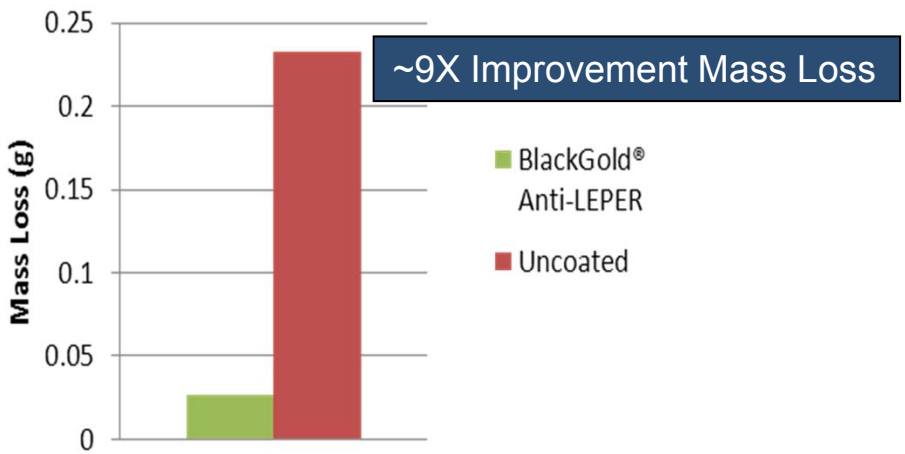
AGT1500 Demonstration

LP05 Airfoil Condition





Uncoated **BlackGold®** **Aligned 3D Models**



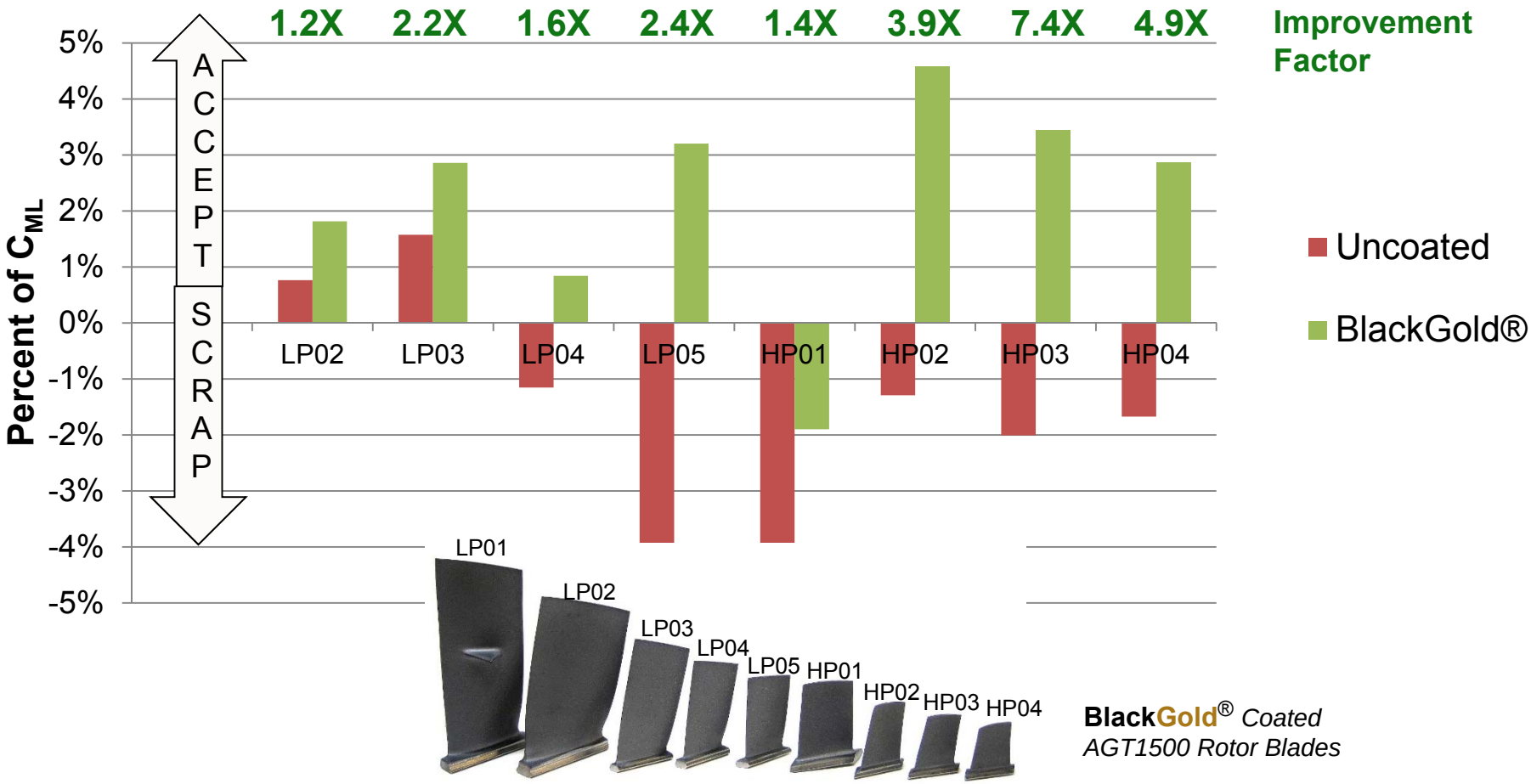
LP05 Section A-A

Uncoated
Coated

*Mass loss after 15.75 lbm; Images and scan after 15.75 lbm

AGT1500 Demonstration

Chord Loss after 9.5 lbm Sand Ingested



BlackGold® *Coated AGT1500 Rotor Blades*

BlackGold® coating delayed parts from reaching Chord Maintenance Limits

AGT1500 Field Service Evaluation

Scope of Work

- Conducted field trials on five coated engines
  - Determine actual durability
  - Performance retention benefits
- Measured uncoated and coated rotor blades during field trials and post tear down inspection
- Determined engine performance (shp and fuel consumption) via engine tests
- Conducted business case required for coating transition

AGT1500 Field Service Evaluation

Service	Location	Eng S/N	FSE Hours	Date Removed
National Guard	Umatilla	AT13F008	393	1-Oct-15
USMC	29 Palms	T12E018	152	21-Jul-14
USMC	29 Palms	T11J026	328	21-Sep-15
Army	YPG	LE94350	277	23-Oct-14
Army	YPG	LE94394	588	5-Nov-15
		Total hours	1738	

Related Efforts

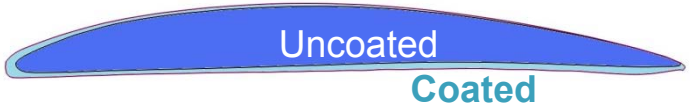
T55 Field Trial Results

- Conducted field service evaluation on one coated engine: T55 for MH-47
  - 138 hours, five hours in desert environment
  - Completed teardown inspection → BlackGold® coated blades provided erosion protection
- Conducted corrosion test
  - Test results approved by Army's Aviation Engineering Directorate
- Completing fatigue tests for final airworthiness certification
  - Transition coating for application on MH-47 helicopters

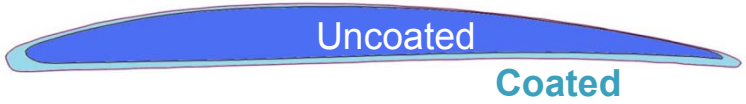
Related Efforts

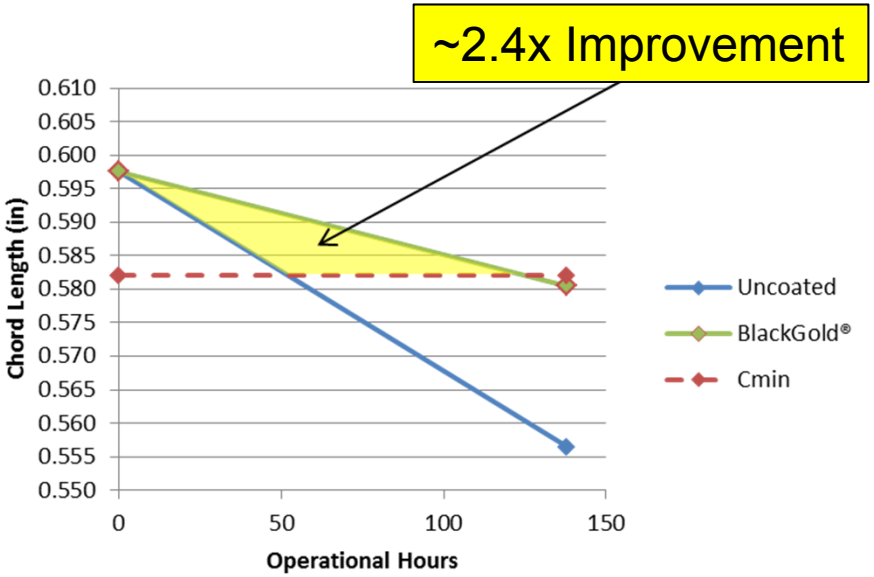
T55 Field Trial Results

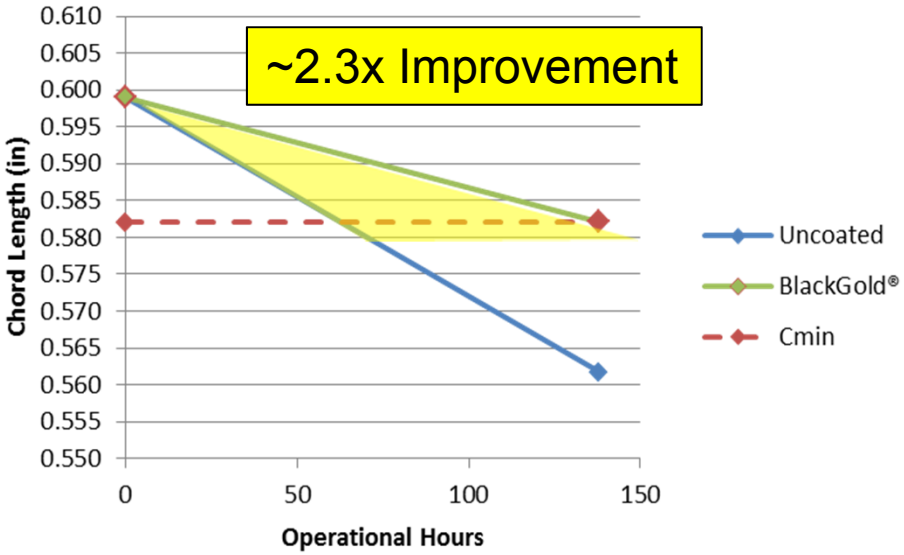
6th Stage



7th Stage

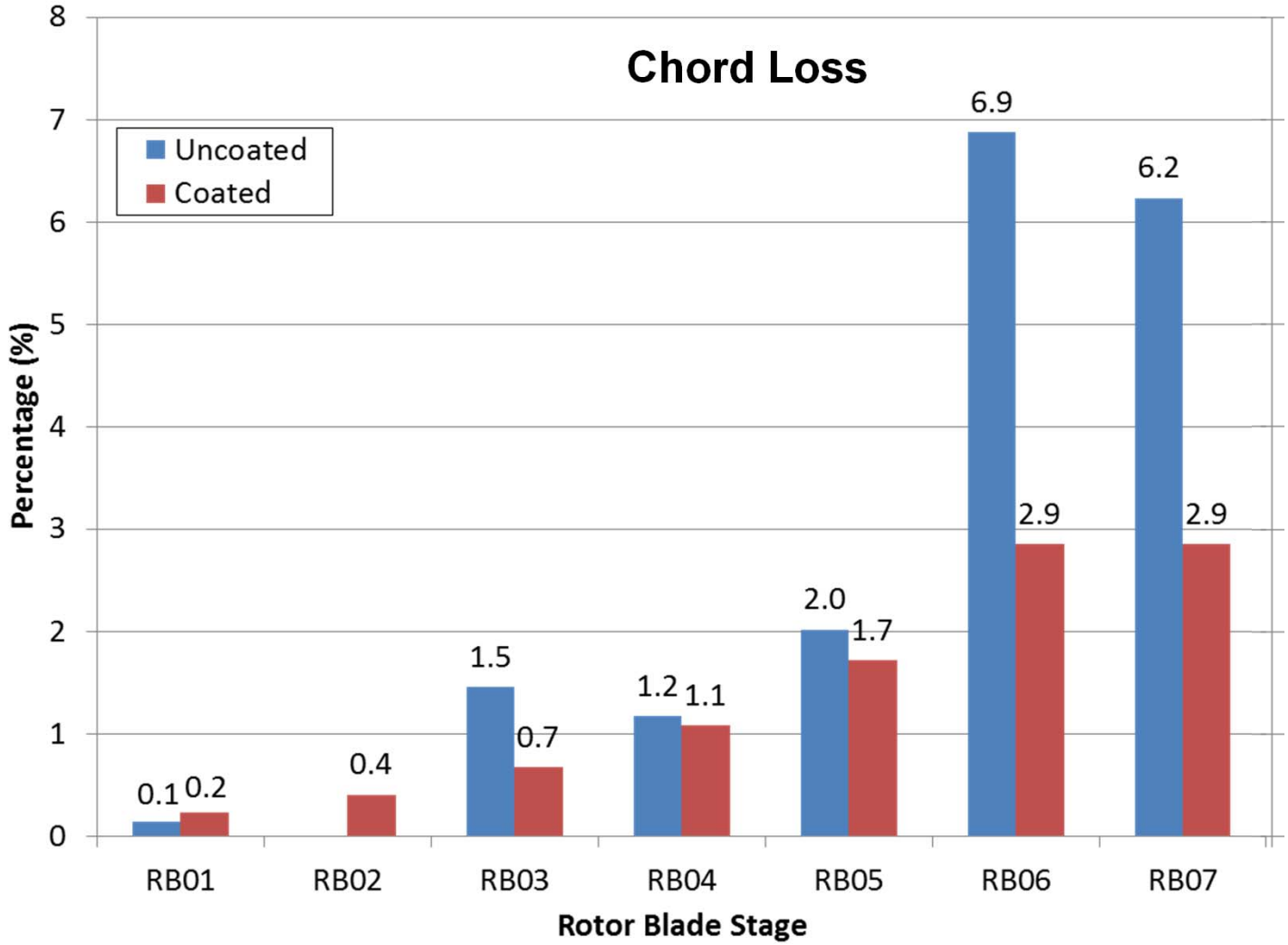






Related Efforts

T55 Field Trial Results



Related Efforts

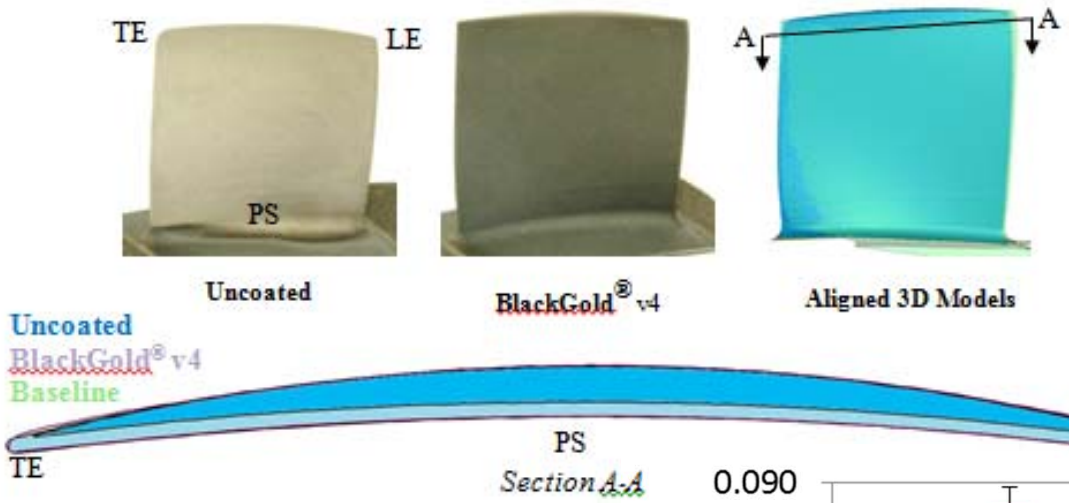
T700 Tests

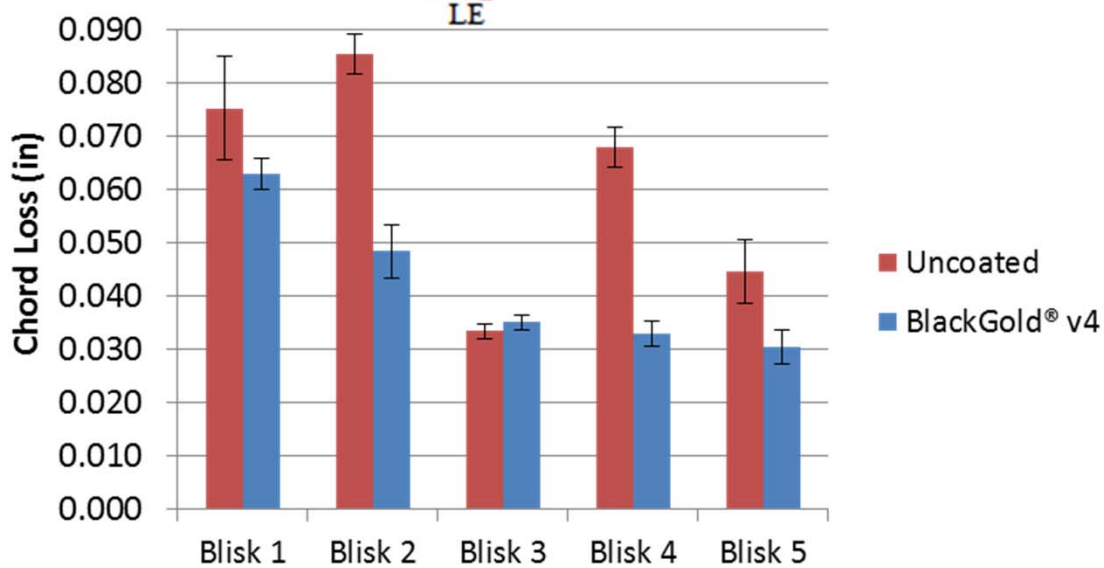
- T700 for SH-60, AH-1Y, UH-1Z, HH-60 and AH-64 helos
- Competed engine sand ingestion test at NAVAIR, 2011
- Completed fatigue tests, 2015
  - Successfully completed 6 of 7 fatigue tests
  - Conducting last fatigue test 1Q, CY17
- NAVAIR conducting accelerated salt water / sand ingestion engine test: 2Q, CY17
  - Serving as Go/No-Go decision for NAVAIR's SH-60 engine fleet
- NAVAIR conducting field trial on 30 coated engine sets for AH-1Z, UH-1Y and SH-60

Related Efforts

T700 Test Results

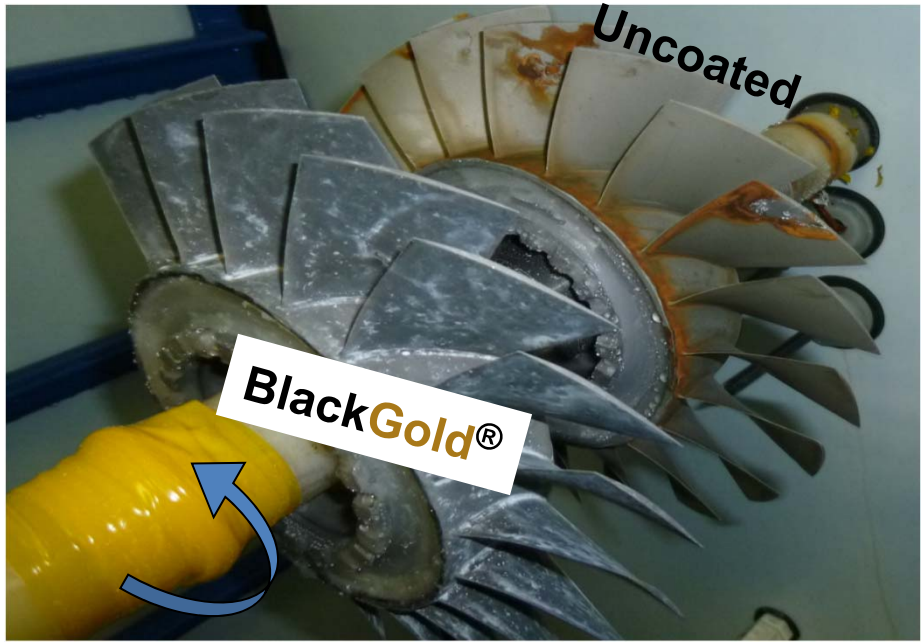
4th Stage Blisk



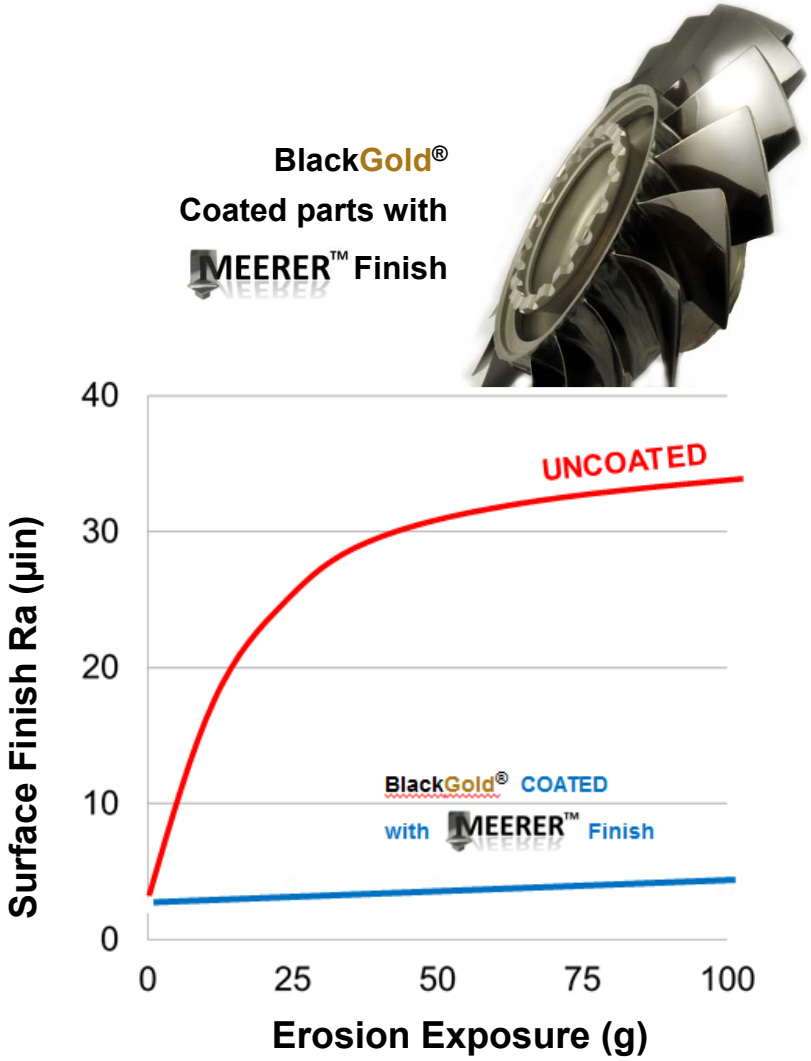


Additional Efforts

T700 Surface Finish Retention



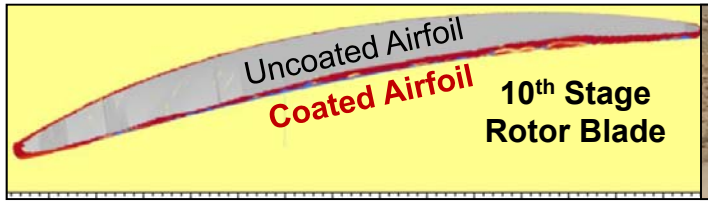
T700 Corrosion Test after 14 days, 5% Salt Fog Exposure



Additional Efforts

AE1107C Field Service Evaluation

- Field trials on BlackGold® coated engines AE1107C for V-22
- Current operations at Canon and Kirtland Air Force Base in arid environments in New Mexico
- High time engines
  - Canon: 412 hrs,10% power margin remaining (average engine TOW ~ 520 hrs)
  - Kirtland:195 hrs, 10% power margin remaining (average engine TOW ~ 220 hrs)
- Analysis of compressor airfoils completed on one engine after scheduled removal
  - Coated airfoils retained surface finish between 15 to 40 µin lower than uncoated airfoils => 0.5% efficiency retention



Summary and Conclusions

Greg Kilchenstein
Office of the Secretary of Defense

SERDP DOD • EPA • DOE | ESTCP

Conclusions

ESTCP seed investment was instrumental

- Led to T56 Series III and IV Transition (USAF and USN)
  - C-130 and E-2C applications
- Proved V-22/A1107 coating potential
  - Justified ONR RIF investment to Field Trial coating
- Initiated USMC and USA evaluation of M1 Tank / AGT 1500 engine
  - Production / transition decision pending
- Facilitated the H-47 Chinook interest and T55 Evaluation
  - Final qualification tests in-process
- Jump-started the H-60 / T700 coating transition program
- DoD-wide adoption underway!
- Coated engines result in significantly reduced industrial footprint, up to 8M less barrels of fuel consumed per year and cleaner air

Acronyms and Symbols

AGT	Advanced gas turbine
AMC	Air Mobility Command
ANAD	Anniston Army Depot
ARD	Arizona road dust
Bbl	Barrel
BCA	Business case analysis
DoD	Department of Defense
NAVAIR	U.S. Naval Air Systems Command
ONR	U.S. Office of Naval Research
R&O	Repair and overhaul
RIF	Rapid Innovation Fund
SIT	Sand ingestion test
TOW	Time on wing
USAF	United States Air Force
USMC	United States Marine Corps

For additional information, please visit

https://www.serdp-estcp.org/Program-Areas/Weapons-Systems-and-Platforms/Surface-Engineering-and-Structural-Materials/Coatings/WP-201009

Speaker Contact Information

gregory.j.kilchenstein.civ@mail.mil; 703-614-0862

marcio.duffles@mdscoating.com; 202-409-1287

SERDP DOD • EPA • DOE | ESTCP

Q&A Session 1

SERDP DOD • EPA • DOE | ESTCP

Hydrogen Effects of Common Cadmium Alternatives on Aerospace Grade 4340

Stephen Gaydos
Boeing Research & Technology
Presenting for: Scott Grendahl
U.S. Army Research Laboratory

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Agenda

- Overall Technical Objective and Approach for 4 Year Test Plan
- Results for FY 10 and FY 11 Work – Select Optimum Test Specimen Type and Steel Alloy for Test Specimen
- Results for FY 12 Work: Identify Preferred Maintenance Chemical for Evaluating Coatings
- Results for FY 13 Work: Evaluate Cadmium Alternative Coatings
- Conclusions and Recommendations

FY = Fiscal Year

Project Team

- Principal Investigator: Scott Grendahl, U.S. Army Research Laboratory, Aberdeen, MD
- The Boeing Company
  - Ed Babcock, Mesa, AZ
  - Stephen Gaydos, St. Louis, MO
  - Joe Osborne, Seattle, WA
  - Stephen Jones, Seattle, WA
  - Shuying Zhu, Seattle, WA
- Chad Hogan, Hill AFB OO-ALC, Ogden, UT
- Richard Green, Green Specialty Services, Ft. Worth, TX
- Dave Kelly, ASKO Plating, Seattle, WA
- ASTM F07.04 Committee on Hydrogen Embrittlement

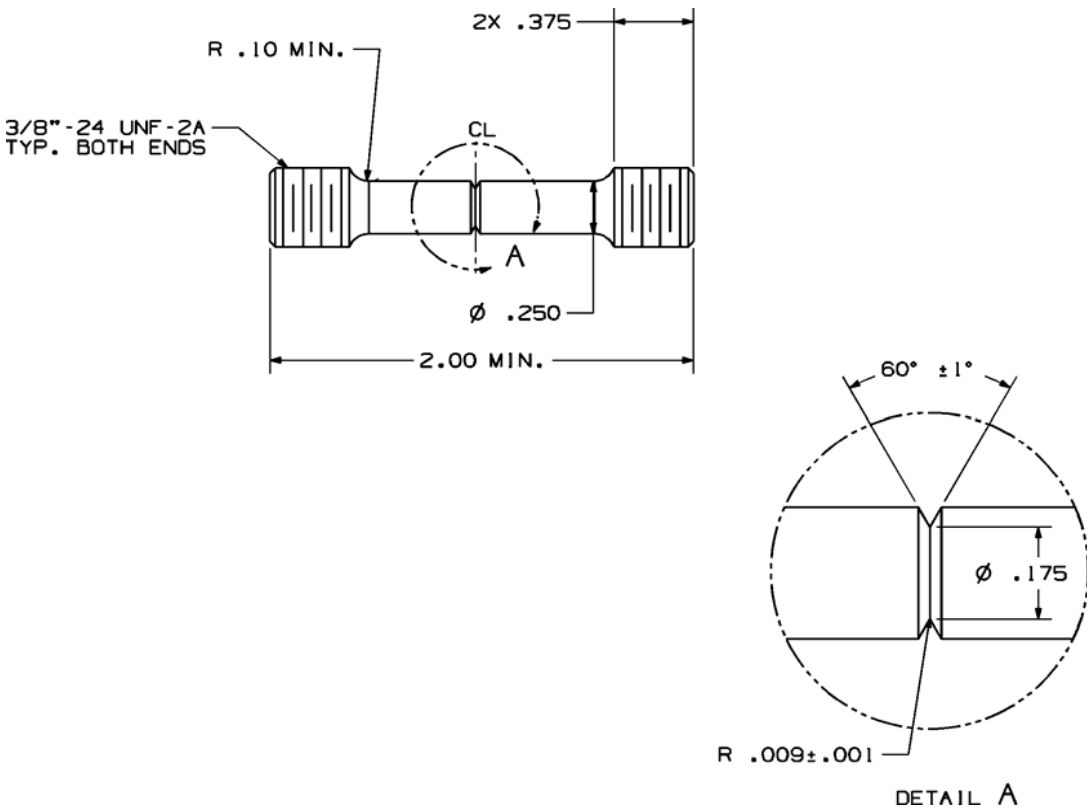
Technical Objective – 4 Year Project

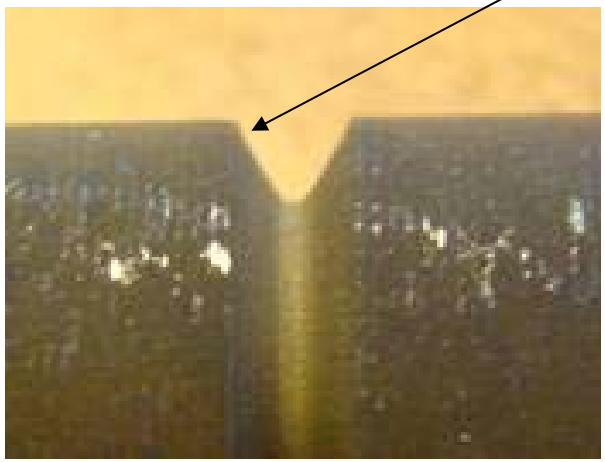
- Increase the implementation and utilization of environmentally friendly maintenance chemicals and cadmium alternatives by alleviating the Hydrogen Effects obstacle
- FY10
  - Life models for air-melted AMS 6415 4340 steel
- FY11
  - Life models for aerospace AMS 6414 grade 4340 steel
- FY12
  - Life models for prospective maintenance chemicals
- FY13
  - Life models for prospective cadmium alternative coatings

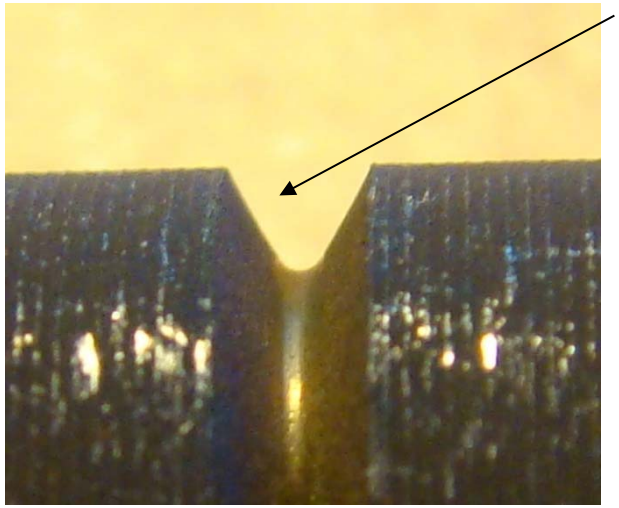
AMS = Aerospace Material Specification

Cadmium Plating HE Specimens

Type 1a.1 Test Specimen

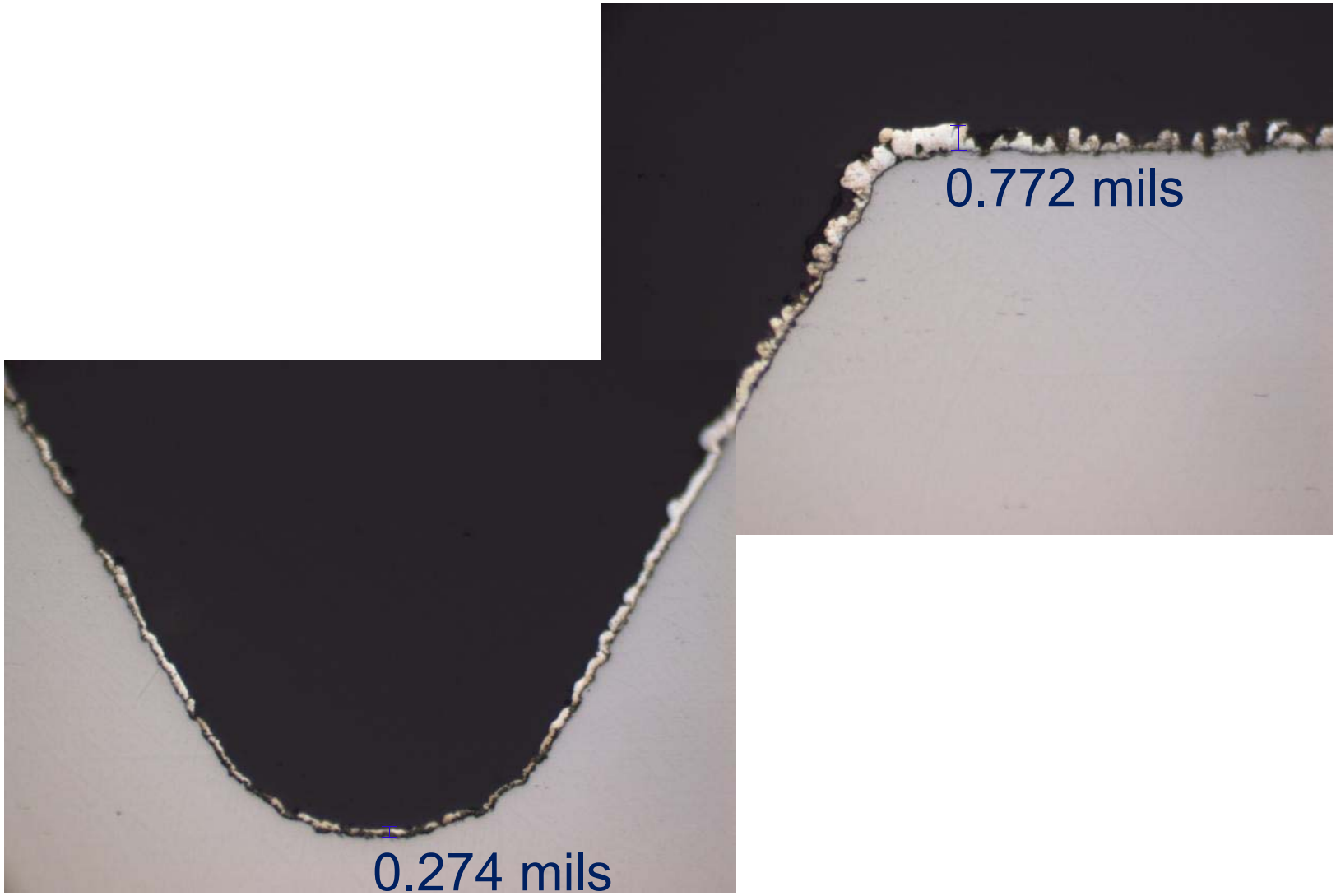






HE = Hydrogen Embrittlement

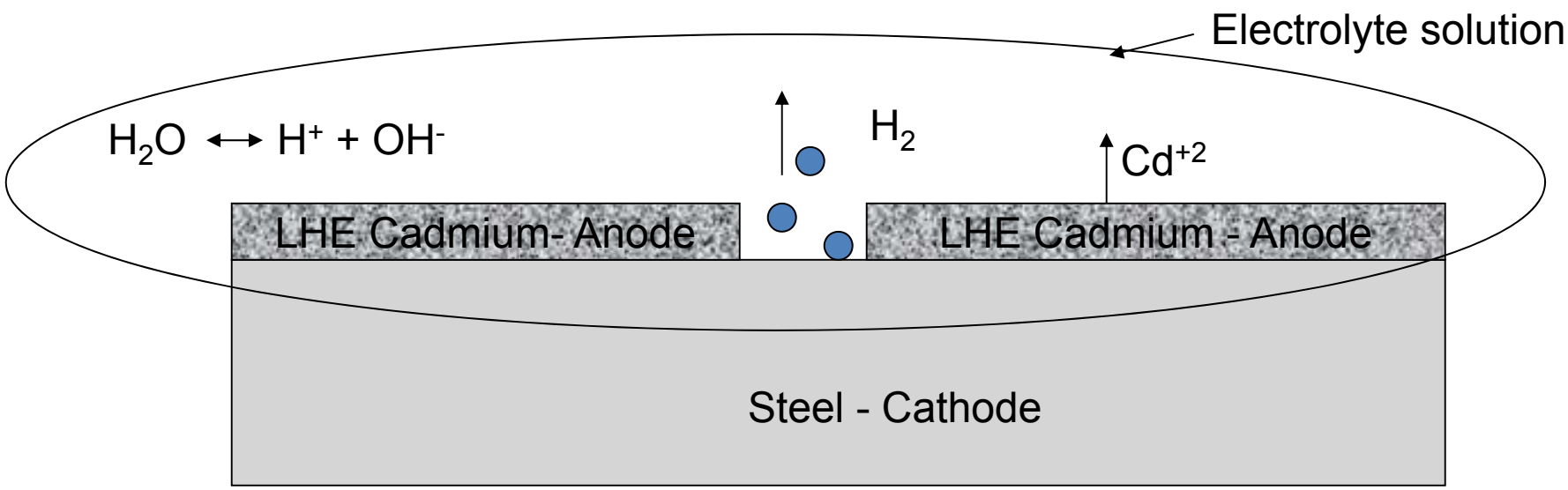
Cadmium Plated Notch



Cadmium (Cd) Protection Mechanism

- Cd is sacrificial to steel; it corrodes to prevent the steel from corroding
- Porous Cd creates microscopic voids or thin areas that allow solutions (electrolyte) to come in contact with steel surface
- Solution forms galvanic cell between steel and Cd; the following reactions occur

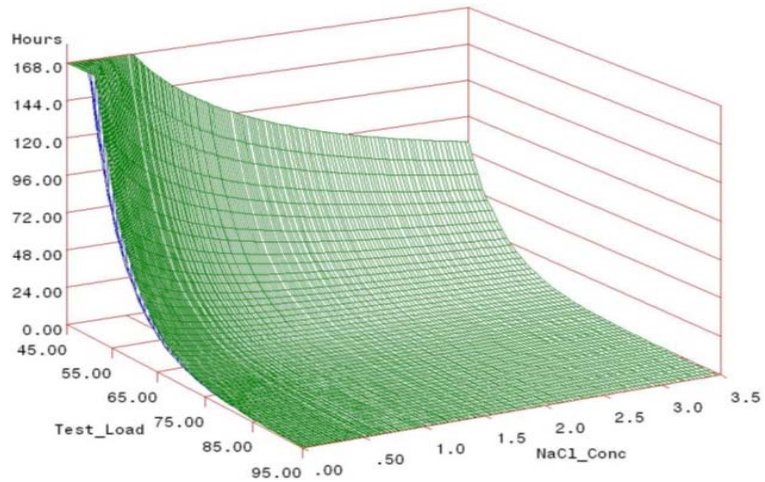
  Anode reaction at Cd: $Cd \rightarrow Cd^{+2} + 2e^-$
  Cathode reaction at Steel: $2H^+ + 2e^- \rightarrow H_2$



Steel is Protected by Formation of Hydrogen!

Technical Approach – Empirical Models

- Traditionally was a pass/fail evaluation
- Failure caused coatings/chemicals not to be implemented
- Models reveal safety zone (below curves)
- Data derived over a range of material strength levels
- Must coat to minimize environmental corrosion and limit H_2 maintenance processes, or accept risk of failure during component life
- Empirical models help answer the common designer question:
  - Does coating on high strength steel cause hydrogen embritlement problems when exposed to maintenance chemicals?



Predicted Median Lifetime Strength=T5 (280 KSI)

Type 1d C-Ring

KSI = Thousand Pounds per Square Inch
H_2 = Hydrogen

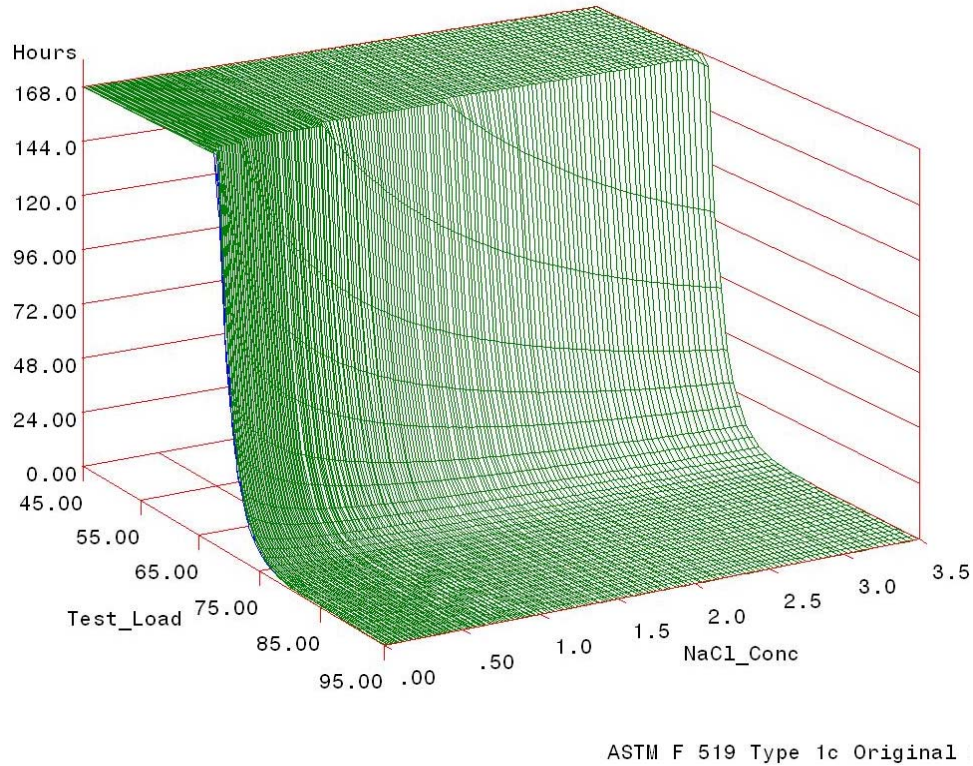
DoE Technical Approach

- HE testing has traditionally been done pass/fail on worst case material
- DoE approach develops life prediction models over a range of material strength, applied stress, and environment
  - 280 ksi 140 to 280 ksi
  - Stress varies with geometry Vs. 40 to 95% NFS
  - Cad plated steel % of NaCl or conc or plating
- Statistical analysis allows a reasonable matrix size while accounting for full spectrum of variables with prediction
  - 5x5x5x5 (625) Vs. 400

DoE = Design of Experiment
NFS = Notch Fracture Strength

DoE Technical Approach

- Material strength (140 - 280 ksi)
- Applied stress (% of NFS)
- Environment
  - Wt.% of NaCl FY11
  - Conc. of chemical FY12
  - Combo coating/ Chemical FY13
- Model yields time to failure (TTF)



Predicted Median Lifetime
Strength=T5 (280 KSI)

DoE Technical Approach

- Linear with center points
- Quadratic
- Confirmation runs
- Base model is developed from linear and quadratic portions
  - ln X =19.01 –11.67*strength -9.93*test_load -0.88*NaCl + offset
  - Run confirmations, then re-compute, then refine model

Condition	-α	-	0	+	+α
Strength (ksi)	140	158	210	262	280
Test Load (% NFS)	35	50	65	80	95
NaCl Concentration (wt% NaCl)	1.25E-05	0.01	0.50	2.36	3.5

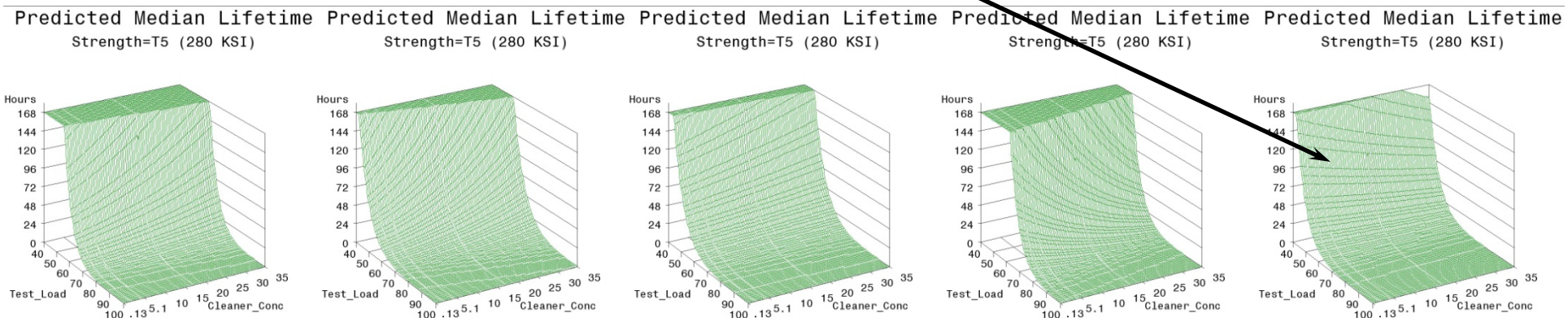
DoE Technical Approach – FY 10 to FY 13

- Air-melt (6415), aerospace grade (6414) models were created for all geometries, heat treats and applied stress (FY 11)
- Explored data to determine best geometry (FY 10) to assess maintenance chemicals, alternative coatings (worst case)
- Assess applicable maintenance chemicals (FY12) and coatings (FY13) in range of concentrations and in combination
- Results provide the airworthiness authorities data to derive which processes (chemicals or coatings) or applications, are deemed safe
- Increase use of alternate chemicals and coatings

Overview of Prior Work

Maintenance Chemical Phase FY12

- Used aerospace grade AMS-6414 material and the Type 1d (ASTM-F-519) specimen
  - AMS 6414 proved more sensitive than AMS 6415 (Results for FY 11)
  - 1d proved more sensitive, more repeatable, easier to test (Results from FY 10)
- Five maintenance chemicals
  - Brulin 815 GD and 1990 GD
  - Cee Bee 300 LFM
  - Calla 602 LF
  - Daraclean 282
- Material strengths between 210 and 280 ksi
- Applied stresses between 35% and 95% of ultimate
- Daraclean 282 proved to be the worst case



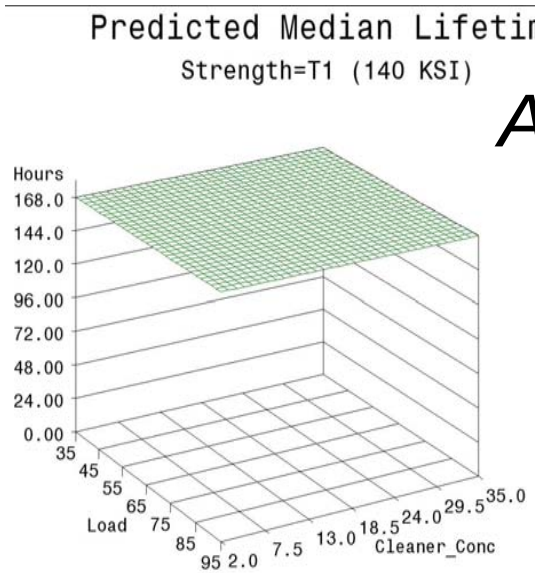
Technical Approach for FY 13

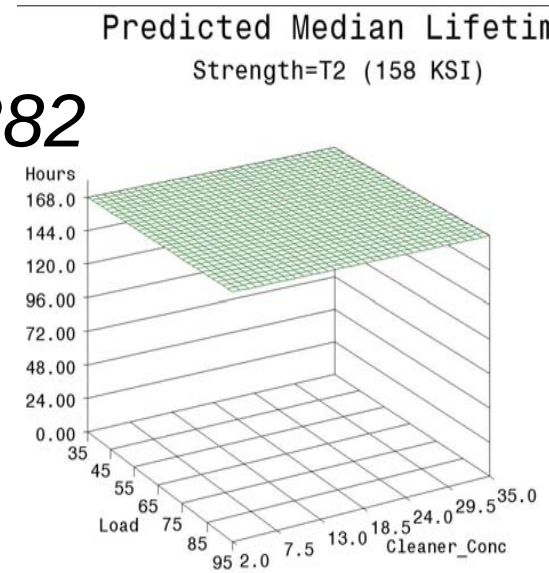
- Coatings phase (FY13) used aerospace grade AMS-6414 material (FY 11) and the Type 1d (FY 10) specimen in combination with Daraclean 282 (FY 12)
- Alternative coatings
  - Dipsol IZ-C17+ Zn-Ni
  - Atotech Alkaline Zn-Ni
  - Alumiplate
  - IVD Aluminum
  - Asko Cd (for comparison)
- Material strengths between 140 and 280 ksi
- Applied stresses between 35% and 95% of ultimate

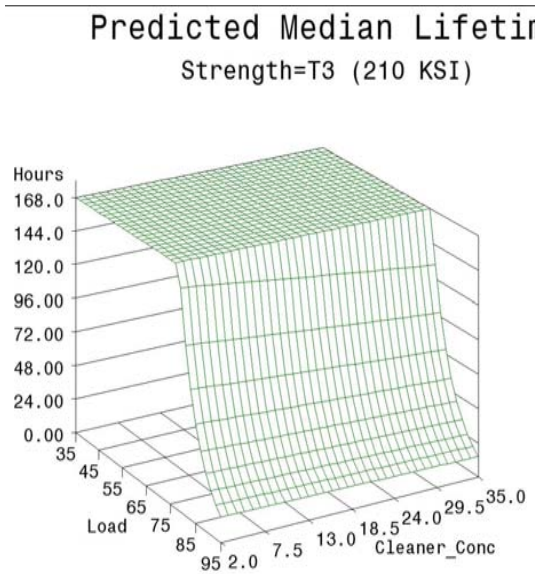
Zn-Ni = Zinc-Nickel
IVD = Ion Vapor Deposition

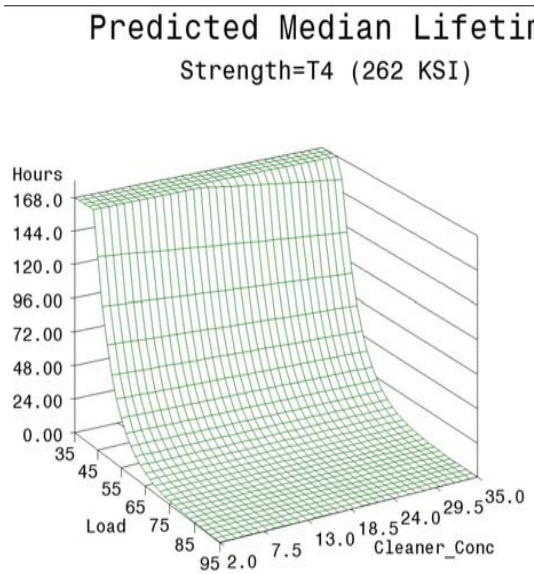
Results

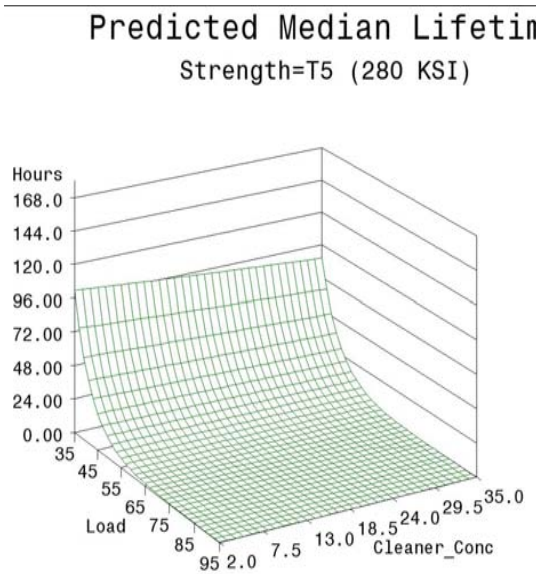
ASKO Cd w/Daraclean 282





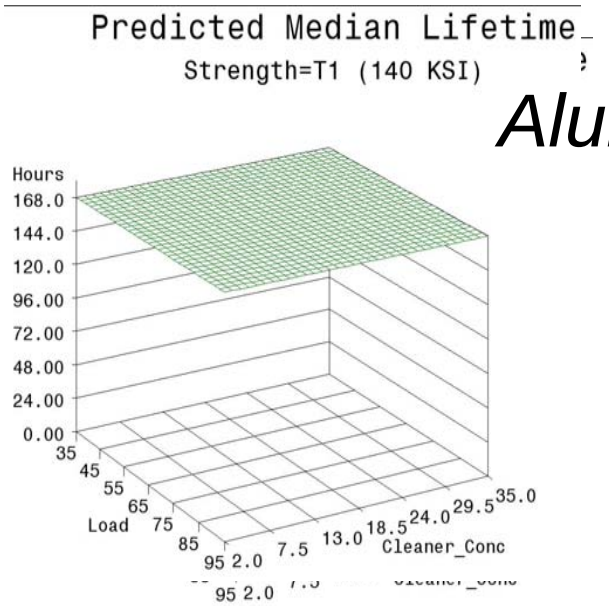


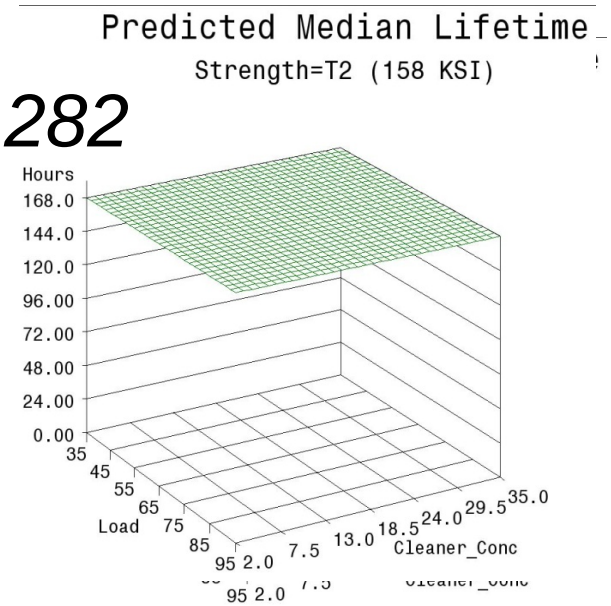


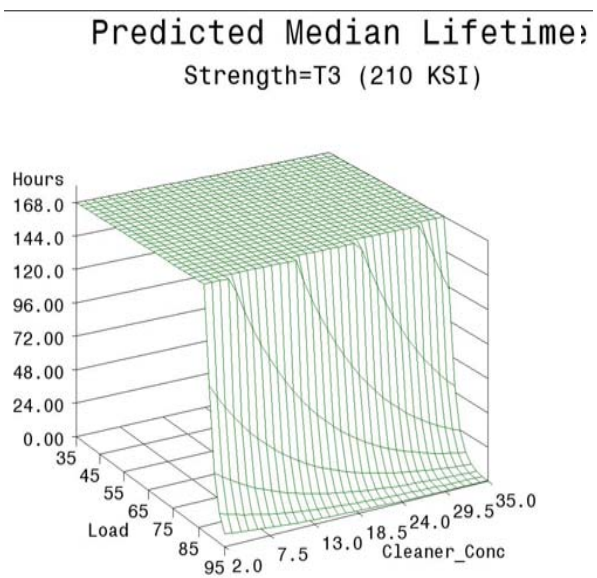


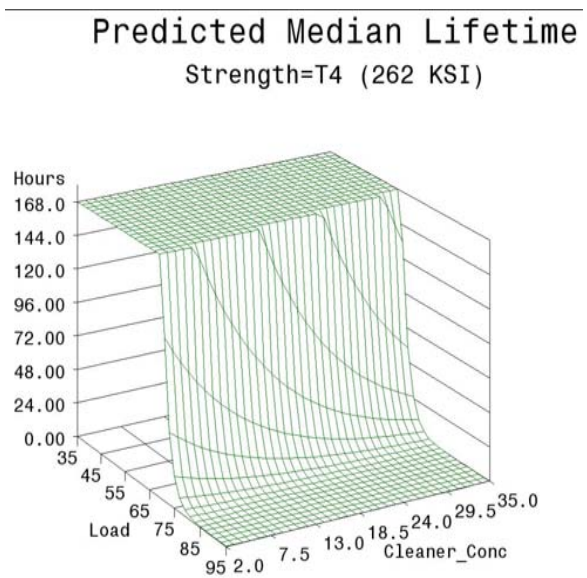
Results

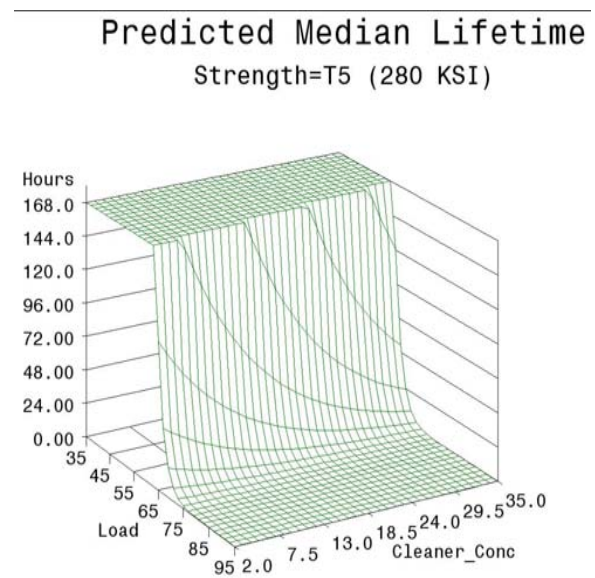
Alumiplate w/Daraclean 282







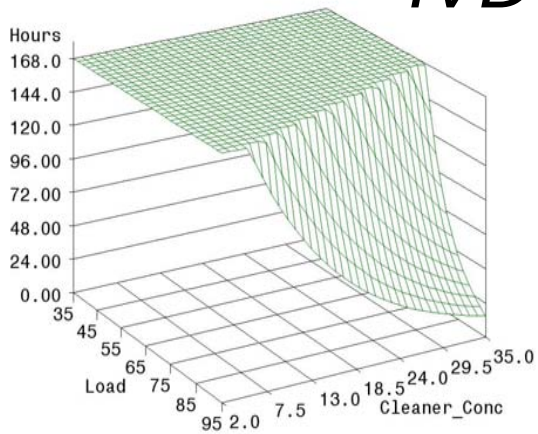




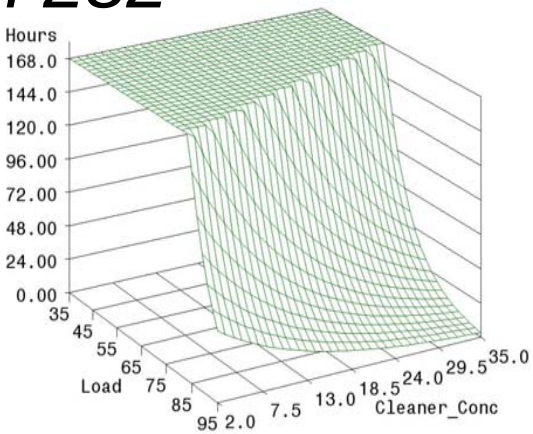
Results

IVD Aluminum w/ Daraclean 282

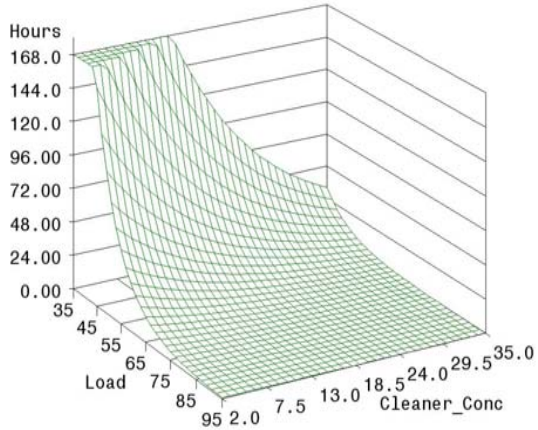
Predicted Median Lifetime
Strength=T1 (140 KSI)



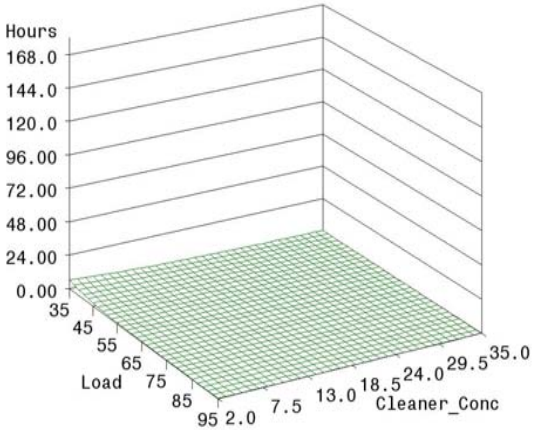
Predicted Median Lifetime
Strength=T2 (158 KSI)



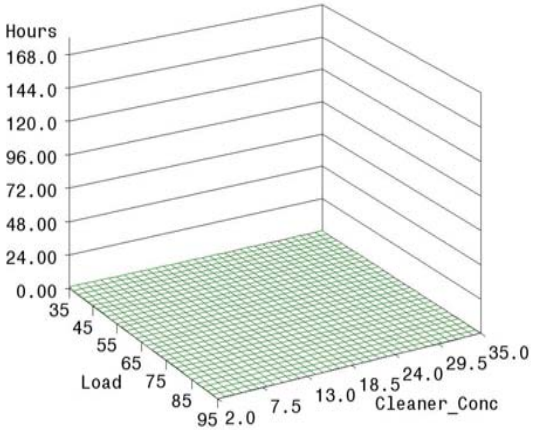
Predicted Median Lifetime
Strength=T3 (210 KSI)



Predicted Median Lifetime
Strength=T4 (262 KSI)

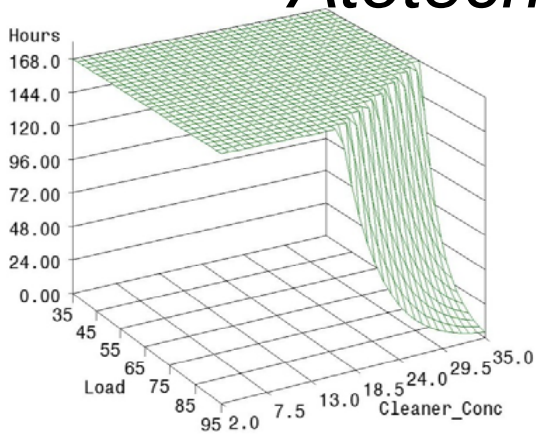


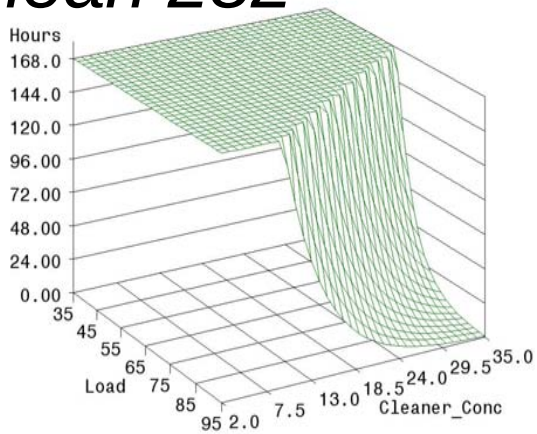
Predicted Median Lifetime
Strength=T5 (280 KSI)

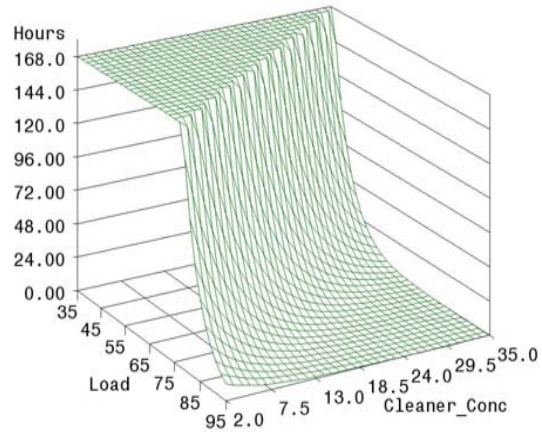


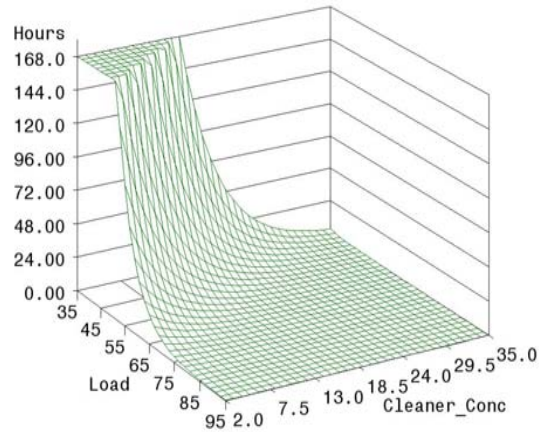
Results

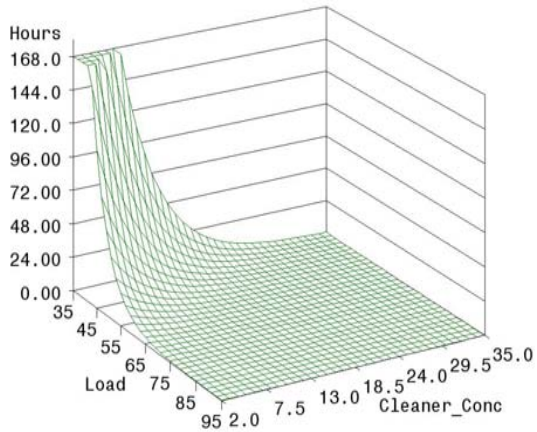
Atotech Alkaline Zn-Ni w/Daraclean 282





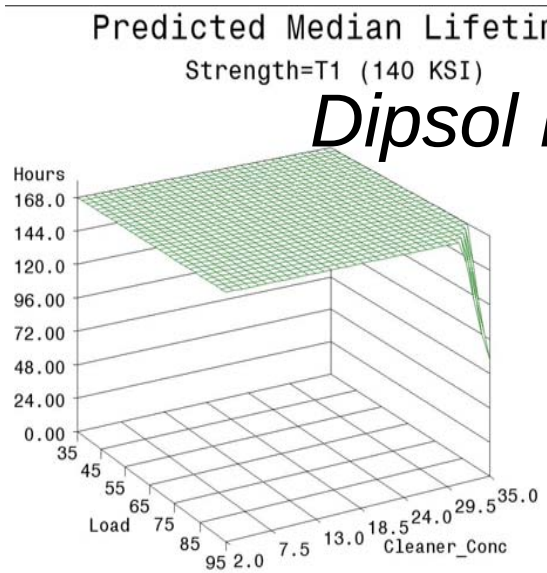


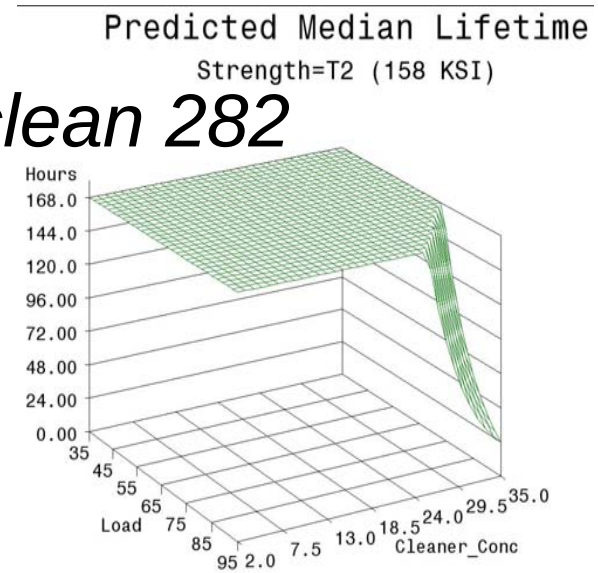


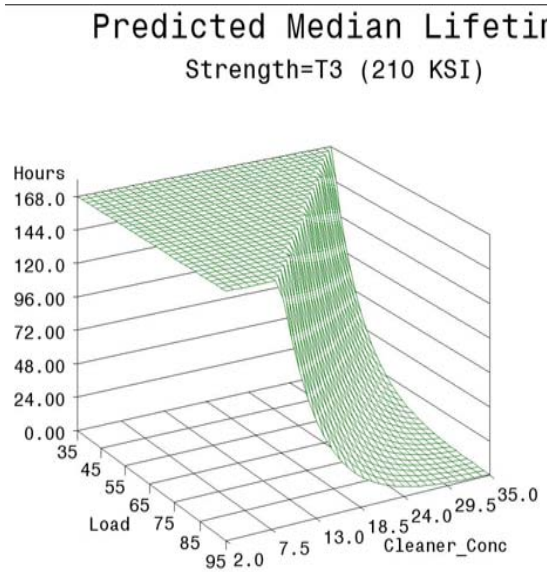


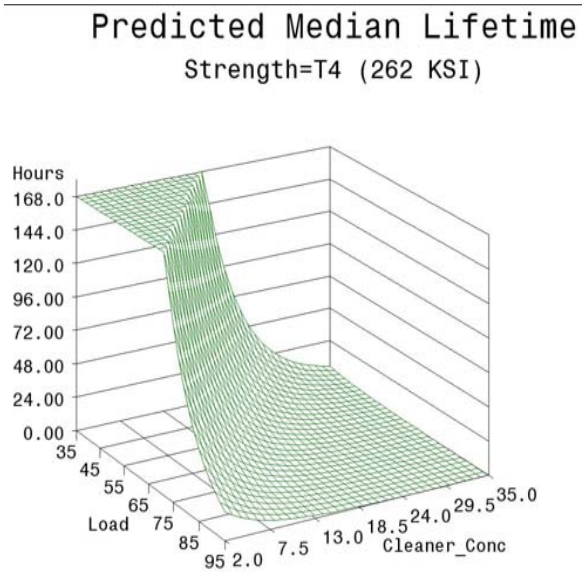
Results

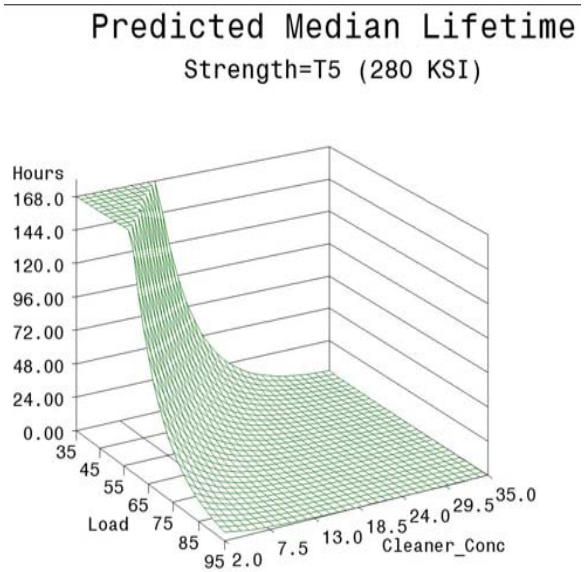
Dipsol IZ C17+ Zn-Ni w/Daraclean 282



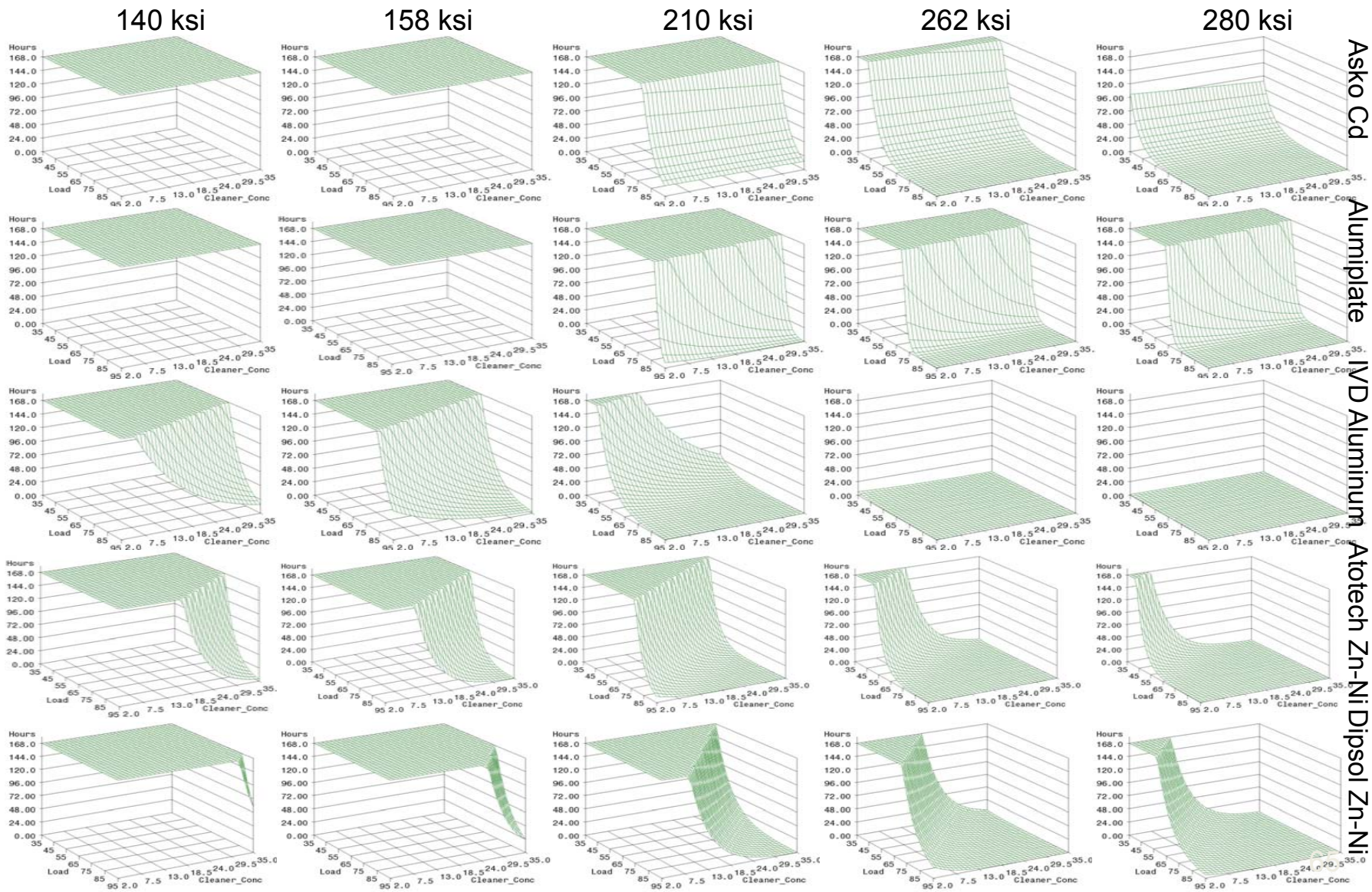








Coating Effects



FY 13 Technical Summary

Hydrogen Effects of Coatings in Daraclean 282

- Baseline ASKO cadmium replicated and verified FY12 results
  - Minimal effects below 200 ksi – Safe zone for Cd in Daraclean 282
- Alternate coatings had stronger dependence on chemical concentration than Cd
  - Alumiplate and IVD had slight dependence
  - Atotech and Dipsol Zn-Ni showed strong dependence
- IVD demonstrated the most hydrogen effects, being effected even at 140 ksi material strength, above 65% test load and above 30% concentration
- Alumiplate showed the least hydrogen effects, good barrier coating
  - Minimal effects below 200 ksi
- Dipsol Zn-Ni appears better than Atotech Zn-Ni
  - Atotech some susceptibility even at 140 ksi
  - Dipsol good above 160 ksi

Conclusions and Recommendations

- Work has been briefed and discussed by ASTM committee F07 on Aerospace and Aircraft, and in detail within subcommittee F07.04 on hydrogen embrittlement
- Changes to F-519 likely upon thorough data review (In Work)
  - Recommended use of Type 1d specimens and AMS 6414 Vac Melt 4340 Steel
- Lifetime prediction models for the targeted maintenance chemicals have been utilized by aviation authorities to alleviate the presently existing bake relief requirement for processes that have failed HE testing
  - Material applications below susceptibility threshold waiver (e.g. 200 ksi)
  - Service stress applications below threshold drawing changes (e.g. below 50% UTS (Ultimate Tensile Strength) at a certain strength level)
- Lifetime prediction models for cadmium alternatives will be transitioned to service use for applications shown to be below the HE susceptibility threshold (e.g. Zn-Ni on 200 ksi steel)
- Commercial partner OEMs will follow guidance from the aviation authority in implementing targeted applications deemed safe

OEM = Original Equipment Manufacturer
Vac = Vacuum

For additional information, please visit

https://www.serdp-estcp.org/Program-Areas/Weapons-Systems-and-Platforms/Surface-Engineering-and-Structural-Materials/WP-2152

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Q&A Session 2

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