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1. DOCUMENT DESCRIPTION

a. TYPE Cost & Performance Report	b. TITLE Replacement of Chromium Electroplating on C-2, E-2, P-3 and C-130 Propeller Hubs Using HVOF Thermal Spray Coatings (PP-9922)
c. PAGE COUNT 41	d. SUBJECT AREA Environmental Security Technology Certification Program

2. AUTHOR/SPEAKER

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3. PRESENTATION/PUBLICATION DATA *(Date, Place, Event)*

4. POINT OF CONTACT

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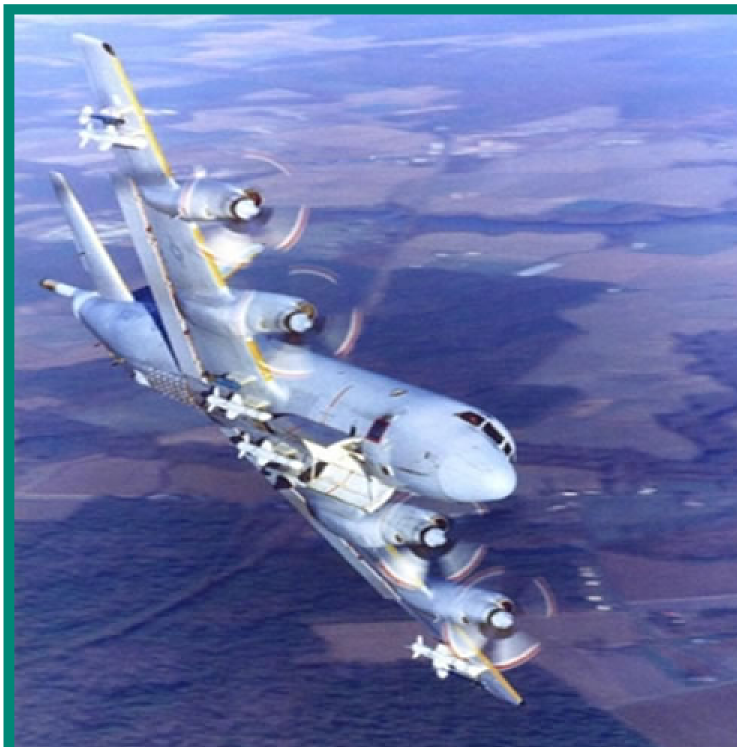
g. SIGNATURE	h. DATE SIGNED *(YYYYMMDD)* 20040116

DD FORM 1910, MAR 1998 (EG) PREVIOUS EDITION MAY BE USED. WHS/DIOR, Mar 98

04-S-0566

ESTCP
Cost and Performance Report

(PP-9922)



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A Replacement of Chromium Electroplating on C-2, E-2, P-3, and C-130 Propeller Hubs Using HVOF Thermal Spray Coatings

March 2004

ENVIRONMENTAL SECURITY
TECHNOLOGY CERTIFICATION PROGRAM

U.S. Department of Defense

COST & PERFORMANCE REPORT
ESTCP Project: PP-9922

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ACRONYMS AND ABBREVIATIONS

ALC	air logistics center
AMS	Aerospace Materials Specification
ANOVA	analysis of variance
ANSI	American National Standards Institute
ASTM	American Society for Testing and Materials
CBA	cost-benefit analysis
CFR	Code of Federal Regulations
Cr	chromium
Cu-Be	copper-beryllium
DARPA	Defense Advanced Research Projects Agency
D-gun	detonation gun
DoD	Department of Defense
DOE	design of experiment
ECAM	Environmental Cost Analysis Methodology
EHC	electrolytic hard chrome
EPA	Environmental Protection Agency
ESOH	environmental, safety, and occupational health
ESTCP	Environmental Security Technology Certification Program
GEAE	GE Aircraft Engines
gph	gallons per hour
GTE	gas turbine engine
HCAT	Hard Chrome Alternatives Team
hex-CR	hexavalent chromium
HVOF	high-velocity oxygen-fuel
IARC	International Agency for Research on Cancer
ID	internal diameter
JG-PP	Joint Group on Pollution Prevention
JTP	Joint Test Protocol
JTR	Joint Test Report
MIL-STD	Military Standard
NADEP-CP	Naval Aviation Depot Cherry Point
NiAl	nickel aluminide
NRL	Naval Research Laboratory

LIST OF ACRONYMS AND ABBREVIATIONS (continued)

OEM	original equipment manufacturer
OSHA	Occupational Safety and Health Administration
PEL	permissible exposure limit
psi	pounds per square inch
PTFE	polytetrafluoroethylene
PVD	physical vapor deposition
SAE	Society of Automotive and Aerospace Engineers
scfh	standard cubic feet per hour
T400	Tribaloy 400
TAT	turnaround time
TBO	time between overhaul
TCLP	Toxicity Characteristic Leaching Procedure
WC/Co	tungsten carbide/cobalt
WR-ALC	Warner-Robins Air Logistics Center

ACKNOWLEDGEMENTS

The financial and programmatic support of the Environmental Security Technology Certification Program (ESTCP), under the direction of Dr. Jeffrey Marqusee, Director, and Mr. Charles Pellerin, Program Manager for Pollution Prevention, is gratefully acknowledged. In addition, the financial and programmatic support of the Joint Group on Pollution Prevention (JG-PP) is also gratefully acknowledged.

The authors would also like to express thanks to the following individuals who made substantial contributions to the execution of the project:

- Mr. Warren Assink and Mr. Gene Jeunelot, Air Force Materiel Command
- Mr. Robert Kestler, Naval Aviation Depot Cherry Point
- Mr. James Hager, Warner-Robins Air Logistics Center
- Mr. Edward Faillace and Mr. Aaron Nardi, Hamilton Sundstrand
- Mr. Jon Devereaux, Naval Aviation Depot Jacksonville
- Mr. Donald Parker, NASA Kennedy Space Center
- Mr. Jerry Schell, GE Aircraft Engines
- Mr. John Sauer, Sauer Engineering
- Mr. Phil Bretz, Metcut Research, Inc.

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Technical material contained in this report has been approved for public release.

1.0 EXECUTIVE SUMMARY

1.1 BACKGROUND

Electrolytic hard chrome (EHC) plating is a technique that has been in commercial production for more than 50 years. It is a critical process used for applying hard coatings to a variety of aircraft components in manufacturing operations and for general rebuild of worn or corroded components removed from aircraft during overhaul. Chromium (Cr) plating baths contain chromic acid, in which the chromium is in the hexavalent state, with hexavalent chromium (hex-Cr) being a known carcinogen. During operation, chrome plating tanks emit a hex-Cr mist into the air, which must be ducted away and removed by scrubbers. Wastes generated from plating operations must be disposed of as hazardous waste, and plating operations must abide by U.S. Environmental Protection Agency (EPA) emissions standards and the Occupational Health and Safety Administration (OSHA) permissible exposure limit (PEL). Recent studies have clearly shown a significant number of deaths at the current PEL of 100 $\mu g/m^3$, prompting OSHA to explore significantly reducing the hex-Cr PEL. A Navy/Industry task group concluded that the cost of compliance for all Navy operations that use hex-Cr (i.e., not just plating) would be more than $10 million to reduce the PEL to less than 5 μg/m[3].

Previous research and development efforts [1,2] had established that high-velocity oxygen-fuel (HVOF) thermal spray coatings are the leading candidates for replacement of hard chrome. HVOF thermal spraying can be used to deposit both metal alloy and ceramic/metal (cermet) such as tungsten carbide/cobalt (WC/Co) coatings that are dense and highly adherent to the base material. They can also be applied to thicknesses in the same range as that currently being used for chrome plating. Currently, there are HVOF thermal spray systems commercially available. Although there are a wide number of applications for these coatings, their qualification as an acceptable replacement for hard chrome plating has not been adequately demonstrated, particularly for fatigue-sensitive aircraft components. The Hard Chrome Alternatives Team (HCAT) was formed to perform the demonstration/validation for the HVOF coatings. After successfully demonstrating HVOF coatings on landing gear components [3], this project demonstrated HVOF coatings on propeller hubs.

1.2 OBJECTIVES OF THE DEMONSTRATION

The objectives were to demonstrate through materials and component testing that the performance of HVOF WC/17Co (83% by weight WC particles in a 17% by weight Co matrix), WC/10Co4Cr, and Tribaloy 800 (T800, composition Co-28Mo-17Cr-3Si) coatings on propeller hub components was equal or superior to that of EHC coatings. Materials testing included axial fatigue, salt-fog corrosion, and sliding wear. Component testing included a rig test on a P-3 low-pitch-stop lever sleeve. In addition, a toxicity characteristic leaching procedure (TCLP) was performed on virgin and spent HVOF powder to ensure that they would not have to be disposed of as hazardous waste.

1.3 REGULATORY DRIVERS

EHC plating operations must comply with the Code of Federal Regulations (CFR) 40 Part 63 (National Emissions Standards for Hazardous Air Pollutants) and 40 CFR Part 50 (National Primary and Secondary Ambient Air Quality Standards). The workplace environment must comply with an OSHA PEL of 100 $\mu g/m^3$ for hex-Cr. As stated above, it is anticipated that the hex-Cr PEL will be significantly reduced. In the Netherlands, there is pending legislation to reduce allowable hex-Cr exposure to 1.5 $\mu g/m^3$ and the United Kingdom's Ministry of Defence is proposing an even stricter standard of 0.5 $\mu g/m^3$. If OSHA adopts a new PEL in this range, the costs associated with EHC plating will significantly increase, and it is possible that EHC plating operations will have to shut down at many Department of Defense (DoD) facilities.

1.4 DEMONSTRATION RESULTS

- **Fatigue.** Cycles-to-failure at different stress levels were measured for fatigue specimens fabricated from 4340 steel and coated with EHC, HVOF WC/17Co, or T800. In general, the average number of cycles-to-failure at any stress level for the WC/17Co-coated specimens was 35% higher than for T800-coated specimens and 95% higher than for EHC-coated specimens; therefore, both types of HVOF coatings passed the acceptance criteria.

- **Wear.** Sliding wear tests were conducted for 4340 steel specimens coated with EHC, hard nickel plate, HVOF WC/17Co, WC/10Co4Cr, or T800, with 4340 steel, Cu-Be alloy, Viton, or 15% glass-filled polytetrafluoroethylene (PTFE) as the counter-face materials. Lubrication was provided by either clean or contaminated oil. In all cases, the performance of the HVOF coatings was at least equivalent to the EHC or hard nickel, and in many cases the performance was superior. Therefore, the HVOF coatings passed the acceptance criteria.

- **Corrosion.** ASTM B117 salt-fog exposure tests were conducted on low-alloy steel specimens coated with hard nickel plate, HVOF WC/17Co, WC/10Co4Cr, or T800. Because it was believed that sufficient corrosion data was already available, EHC-coated specimens were not included in the test matrix. Based on the results of the testing, only the WC/10Co4Cr coatings had performance nearly comparable to the nickel. Comparison to previous testing on EHC indicated that the WC/10Co4Cr was comparable. Therefore, the stakeholders believed these coatings were acceptable substitutes for either EHC or hard nickel.

- **TCLP Testing.** These tests were conducted in accordance with EPA Method 1311 on spent and virgin WC/10Co4Cr, T800, and Tribaloy 400 (T400) powder. The concentrations of chromium and nickel in the leachate were measured, with the results that none of the concentrations were above the regulatory limit. Therefore, these materials would not be classified as hazardous waste by EPA.

- **Rig Testing.** A rig test was conducted at Hamilton Sundstrand on P-3 low-pitch-stop lever sleeves coated with either EHC or HVOF WC/17Co. The test was performed for

75,000 cycles, equivalent to one standard overhaul life. Visual examination of both lever sleeves following the test showed that the EHC sustained mild wear whereas the WC/17Co still looked pristine. Therefore, the HVOF coating passed the acceptance criteria.

- **Cost Assessment.** A detailed cost/benefit analysis was conducted using the Environmental Cost Accounting Methodology (ECAM) [4] at a propeller hub overhaul facility that processes approximately 270 components per year. The results showed that for different scenarios there would be a net annual cost increase of between $2,000 and $26,000 by replacing the EHC process with HVOF. However, overhaul of propeller components is less than 20% of the EHC workload at the facility, and it is believed that if chrome plating were replaced with HVOF on most types of components, cost savings could be realized similar to that calculated for landing gear overhaul operations [3]. Some of these propeller hub components are no longer made and the better wear performance of the HVOF coatings would substantially extend the lives of the existing components, assuring readiness over the coming years.

1.5 STAKEHOLDER/END-USER ISSUES

Based on the favorable materials and component tests, the Navy is proceeding with a flight test on HVOF-coated P-3 propeller hub components. If that is successful, it is anticipated that both Naval Aviation Depot, Cherry Point, NC (NADEP-CP) and Warner-Robins Air Logistics Center, VA (WR-ALC) will implement the technology into production. The HCAT worked with a Society of Automotive and Aerospace Engineers (SAE) aerospace committee to develop and issue specifications for the WC/17Co and WC/10Co4Cr powder, the application of the coatings on high-strength steel, and the grinding of the coatings. These specifications can now be used by any overhaul depot and will result in consistency between facilities with respect to coating properties.

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2.0 TECHNOLOGY DESCRIPTION

2.1 TECHNOLOGY DEVELOPMENT AND APPLICATION

Technology background and theory of operation. HVOF is a standard commercial thermal spray process in which a powder of the material to be sprayed is injected into a supersonic flame of a fuel (usually hydrogen, propylene, or kerosene), as illustrated in Figure 1. The powder particles are accelerated to high speed and soften in the flame, forming a dense, well-adhered coating on the substrate. The coating material is usually a metal or alloy (such as Tribaloy or stainless steel), or a cermet (such as cobalt-cemented tungsten carbide, WC/Co). The technology is used to deposit coatings about 0.003" thick on original equipment manufacturer (OEM) parts, and to rebuild worn components by depositing layers up to 0.015" thick.

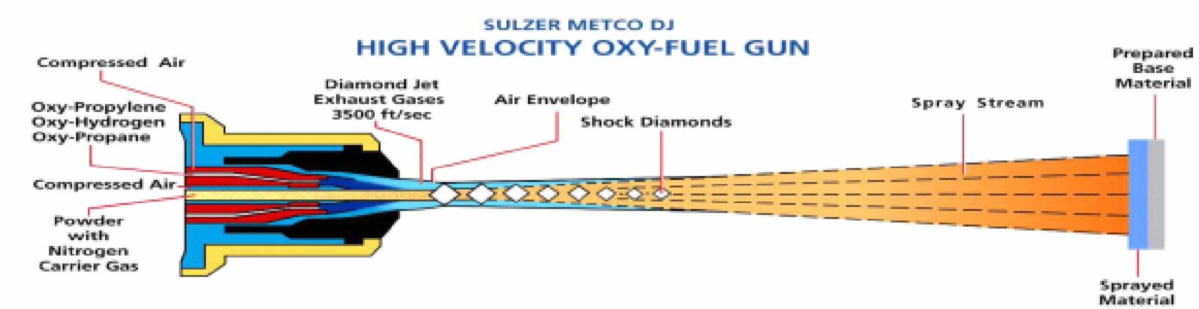


Figure 1. Schematic of HVOF Gun and Process (Sulzer Metco DiamondJet).

Applicability. HVOF was originally developed primarily for gas turbine engine (GTE) applications. The primary thermal spray processes are Flame Spray, Plasma Spray, Arc Spray, HVOF and the recently developed cold spray. The original high velocity spray technology was the pulsed deposition detonation gun (D-gun) developed by Union Carbide (later Praxair). The quality of the wear- and erosion-resistant spray coatings produced by this method was much better than the lower speed methods, and continuous flame HVOF was developed as a competitive response.

The original applications for HVOF were wear components in GTEs, such as shafts and bearing journals. As the availability and use of the technology grew, it began to be applied to a wide range of other types of coatings and applications, including aircraft components such as flap and slat tracks, landing gear and hydraulics for commercial aircraft. It is now being used in many applications outside the aircraft industry, such as industrial rolls and vehicle hydraulics. The original aircraft wear applications, used primarily by Boeing, were for otherwise-intractable spot problems that neither the original alloy nor chrome plate could solve.

The technology can be used to spray a wide variety of alloys and cermets. It is limited for high temperature materials such as oxides, most of which cannot be melted in the flame. The areas to be coated must be accessible to the gun, i.e., they must be line-of-sight.

Material to be replaced. HVOF coatings are used to replace hard chrome plate (especially using carbide cermets and high temperature oxidation-resistant Tribaloys). The combination of HVOF nickel-aluminide (NiAl) with an overlayer carbide is also used to replace the combination sulfamate Ni/hard chrome. HVOF coatings can also be used to replace some hard Ni and electroless Ni coatings on such components as flap tracks and propeller hubs. In the HCAT program, the primary application is hard chrome replacement.

2.2 PROCESS DESCRIPTION

Installation and operation. The HVOF gun can be handheld and used in an open-fronted booth. However, the supersonic gas stream is extremely loud and requires that the operator use very good ear protection. For this reason, the unit is usually installed on a 6-axis robot arm in a soundproof booth, programmed and operated remotely. Most depots already use this type of booth for their existing plasma spray operations. Since the method is frequently used for cylindrical items, the most common arrangement is to rotate the component on a horizontal rotating table and move the gun up and down the axis. This is illustrated in Figure 2, which shows the HVOF spraying of a landing gear inner cylinder. A similar setup would be used for the spraying of cylindrical-shaped propeller hub components such as a lever sleeve.

Figure 2. HVOF Spray of Landing Gear Inner Cylinder.

Facility design. The installation requires the following.

- *A soundproof booth.* Booths are typically 15 feet square with a separate operator control room, an observation window, and a high-volume air handling system drawing air and dust out of the booth through a louvered opening.

- *Gun and control panel.* The gun burns the fuel and oxygen inside its combustion chamber and injects the powder axially into the flame. The gas exits the gun at supersonic speed, while the particles are accelerated to high velocity but usually remain subsonic. The control panel controls the gas flows, cooling water, etc.

- *Powder feeder.* Powder is typically about 60 μm in diameter and is held in a powder feeder, which meters the powder to the gun at a steady rate, carried on a gas stream. Two powder feeders are commonly used to permit changeover from one coating to another without interrupting the spraying.

- *Six-axis industrial robot and controller.* Most installations use an industrial robot to manipulate the gun and ensure even spraying. The robot is often suspended from above to leave the maximum possible floor space for large items.

- *Supply of oxygen.* This is frequently a bulk storage container outside the building. Alternatively, bottled gas can be used but, because of the high usage rate of up to 2,000 standard cubic feet per hour (scfh) (see Table 1), even a standard 12-bottle setup lasts only a few hours in production.

Table 1. Optimized Deposition Conditions for WC-17Co - DJ 2600 and JP 5000 HVOF Guns.

Equipment	**Gun**	Model 2600 hybrid gun	Model 5220 gun with 8"-nozzle
	Console	Model DJC	Model 5120
	Powder feeder	Model DJP powder feeder	Model 5500 powder feeder
Powder feed	**Powder**	Diamalloy 2005	Stark Amperit 526.062
	Powder Feed Rate	8.5 lb/hr	80 gm/min (325 rpm, 6-pitch feeder screw)
	Powder Carrier Gas	Nitrogen	Argon
	Carrier gas pressure	148 pounds per square inch (psi)	50 psi
	Flow rate	28 scfh	15 scfh
Combustion Gases	**Fuel**	Hydrogen	Kerosene, Type 1-K
	Console supply pressure		162-168 psi
	Gun supply pressure	135 psi	121-123 psi
	Flow rate	1229 scfh	5.0 gph
	Oxidizer	Oxygen	Oxygen
	Pressure	148 psi	138-140 psi
	Mass flow	412 scfh	2000 scfh
Gun Compressed Air	**Pressure**	105 psi	
	Mass flow	920 scfh	
Gun Cooling Water Flow	**Flow rate**	5.3-5.7 gallons per hour (gph) (factory set)	8.3-8.7 gph
	Water Temperature to Gun	65-80^{o}F typical (ground water temperature varies)	64-72^{o}F
Specimen Rotation		2,336 rpm for round bars (0.25" dia.) – 1835 in/min surface speed	600 rpm for round bars (0.25" diam.); 144 rpm for rectangular bars (at 6.63" diam.)
Gun Traverse Speed		400 linear in/min for round bars	70 in/min for round bars
Spray Distance		11.5"	18"
Cooling Air	**Pressure**	90-110 psi	90-110 psi
	Location	2 stationary nozzle tips at 6" pointed at coating area	2 gun-mounted air jets at 14"; 1 stationary air jet at 4-6" pointed at coating area

- *Supply of fuel gas or kerosene (bottled or bulk).* Hydrogen is the most common fuel and is supplied in bulk or in bottles. Praxair TAFA guns use kerosene, which is significantly cheaper and less dangerous.

- *Dust extractor and bag-house filter system.* The air extracted from the booth is laden with overspray, particles that have failed to stick to the surface (often 20-50% of the total sprayed). The air is

Figure 3. Air Handler and Dust Filter Installation at NADEP-CP.

blown into a standard bag house, often located outside the building, where the dust is removed (see Figure 3).

- *Dry, oil-free compressed air for cooling the component and gun.* Air cooling prevents the components from being overheated (temperatures must be kept below approximately 400ºF for most high-strength steels).

- *Water cooling for gun.* Most, but not all guns are water cooled.

The facility must be capable of supplying the material pressures and flows shown in Table 1. Standard commercial equipment currently in service already meets these requirements. Equipment vendors are able to supply turnkey systems.

Performance. From Table 1, HVOF guns deliver about 4-5 kg per hour of powder, of which 65% typically enters the coating, for a coating rate of about 3 kg/hour. For a common 0.010" WC/Co rebuild coating (which will be sprayed to a thickness of 0.013-0.015"), an HVOF gun can deposit about 900 in^2/hr. Thus, for example, it is possible to coat a 24"-long, 4"-diameter cylinder in about 30 minutes, compared with about 15 hours for chrome plating.

Specifications. The following specifications and standards apply to HVOF coatings.

- Before the HCAT program, the only aerospace specifications were those issued by original equipment manufacturers (OEM) such as Boeing, whose BAC 5851 thermal spray specification, supported by BMS 10-67G powder specification, is still one of the most quoted standards.

- Aerospace materials specification (AMS) 2447 was developed with the assistance of the HCAT team and issued by SAE in 1998. It is now a widely used standard in the aerospace industry.

- To provide specifications for spraying high strength aircraft steels at depots and vendors, HCAT has worked through SAE to promulgate several standards.

  -AMS 2448, issued in 2003, is a specification for HVOF spraying of high strength steel.
  -AMS 7881 and AMS 7882 are powder specifications that support AMS 2448.
  -An AMS standard for grinding of HVOF coatings will be issued in a few months.

Training. Just as plating shops typically have several personnel who handle masking, racking, demasking, etc., it is common for HVOF shops to have three or four technicians dedicated to masking and spraying. HVOF training is essential and is usually provided by equipment vendors such as Praxair and Sulzer Metco. Training is also available through the Thermal Spray Society. Depot personnel taking part in the HCAT program have been trained by Jerry Schell, a thermal spray coatings expert at GE Aircraft Engines (GEAE). Since thermal spray is a more complex technology than electroplating, plating line personnel cannot be transferred successfully to an HVOF shop without extensive retraining.

Health and safety. The process does not produce air emissions or toxic wastes. Co powder is an International Agency for Research on Cancer (IARC) Group 2B material, which means that "the agent (mixture) is possibly carcinogenic to humans," whereas Cr^{6+} is an IARC Group 1 material, "known to be carcinogenic to humans." However, the OSHA PEL for Co (8-hr time-weighted average) of 0.1 mg(Co)/m^3, is lower than the 1 mg(Cr)/m^3 for metallic chrome and is the same as the 0.1 mg(Cr)/m^3 for Cr^{6+}, and the LD50 toxicity of Co is a factor of 200 lower than Cr. Unlike chrome plating, the Co is not emitted into the air. Excess Co-containing powder is drawn from the spray booth and captured in the bag house. Nevertheless, personnel should wear a dust respirator when handling the powder, working in the booth, or grinding the coating. While the powders are usually about 60μm in diameter, they can break apart on impact, producing 10μm or smaller particles. The American Welding Society recommends the use of a respirator complying with American National Standards Institute (ANSI) Z88.2.

Ease of operation. Since in commercial systems the entire system is programmable, including the gun control and robot, it is generally easy to operate. The operator must create masking (usually shim stock shadow masks) and must develop the correct spray parameters and gun motions. While vendors supply standard operating conditions for different materials, these may have to be optimized experimentally for new materials and powders and must be adjusted for different components to ensure proper coating speed and gun traverse rate. Small diameter components, for example, must be rotated faster than large ones to maintain the same deposition rate and coating structure. In this respect, operating an HVOF system is considerably more complex than electroplating.

2.3 PREVIOUS TESTING OF THE TECHNOLOGY

Before the HCAT program, HVOF technology had been successfully used by Boeing for years for their commercial aircraft and by GEAE for GTEs. From 1993 to 1996, Keith Legg, Bruce Sartwell, GEAE, Cummins Diesel, and Corpus Christi Army Depot conducted an evaluation of chrome alternatives under a project sponsored by the Defense Advanced Research Projects Agency (DARPA). The program evaluated HVOF, physical vapor deposition (PVD) and laser cladding, and concluded that HVOF was the best overall alternative for use in depots and most OEM aircraft applications [2]. At the beginning of the HCAT program, Lufthansa successfully completed flight tests of HVOF coatings on commercial landing gear and Delta Air Lines began to carry out similar flight tests.

2.4 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

Replacing hard chrome plating is much more complex than simply putting down a hard coating. The alternative must not only work technically but must fit with the entire life cycle of use and maintenance, and it must be a reasonable, mature technology for depot use. The advantages and limitations of HVOF are summarized in Table 2.

Table 2. Advantages and Limitations of HVOF as a Chrome Replacement.

Advantages/Strengths	Disadvantages/Limitations
Technical	
Higher hardness, better wear resistance, longer overhaul cycle, less frequent replacement	Brittle, low strain-to-failure, can spall at high load, issue primarily for carrier-based aircraft landing gear
Better fatigue, corrosion, embrittlement	Line-of-sight, cannot coat IDs
Material can be adjusted to match service requirements	More complex than electroplating, requires careful quality control
Depot and OEM fit	
Most depots already have thermal spray expertise and equipment	WC-Co requires diamond grinding wheel. Only HVOF alloys can be plunge ground.
Can coat large areas quickly	
Can be chemically stripped	
Many commercial vendors	
Environmental	
No air emissions, no high volume rinse water	Co toxicity

3.0 DEMONSTRATION DESIGN

3.1 PERFORMANCE OBJECTIVES

The performance objectives were established as a combination of materials testing done on coupons manufactured from the same base materials from which propeller hub components are fabricated and actual component rig testing in which HVOF thermal spray coatings were applied to a specific component that was subjected to a rig test. The materials testing requirements were first established at a stakeholders meeting held at Hamilton Sundstrand in September 1998, from which a draft of a Joint Test Protocol (JTP) was generated. There were numerous revisions generated through conference calls and electronic correspondence, with a final version approved by the Air Force, Navy, and Hamilton Sundstrand in November 1999 [5]. The specific types of materials testing delineated in the JTP were fatigue, wear, and corrosion. A detailed description of these tests can be found in Section 3.6. The performance objectives, also called acceptance criteria, were as follows.

- *Fatigue.* Cycles-to-failure at different stress levels were measured for fatigue specimens coated with hard chrome plate, HVOF WC/17Co or HVOF T800. These data were plotted with stress on the vertical axis and cycles-to-failure on the horizontal axis and smooth curves were fit to the data points (designated S-N curves). If the curves for the HVOF coatings fell on or above those for the hard chrome, then the HVOF coatings were considered to have passed the acceptance criteria. Based on the results of the testing, the acceptance criteria were met.

- *Corrosion.* The American Society for Testing and Materials (ASTM) B117 salt-fog exposure tests were conducted on specimens coated with hard nickel plate, HVOF WC/17Co, WC/10Co4Cr, or T800. Because it was believed that sufficient corrosion data were already available, the corrosion performance of hard chrome plate was not included in the test matrix. The specimens were inspected daily, and it was noted when red rust was first observed. The specimens were removed from the corrosion cabinet when there were more than three corrosion spots or when any one spot was larger than 0.3” in diameter. The acceptance criterion for the HVOF coatings was equivalent performance to the hard nickel. Based on the results of the testing, only the WC/10Co4Cr had performance nearly comparable to the nickel. Comparison to previous testing on hard chrome plate indicated that the WC/10Co4Cr was comparable. Therefore, the stakeholders believed these coatings were acceptable substitutes for either hard chrome or nickel.

- *Wear.* Sliding wear tests were conducted for specimens coated with hard chrome or hard nickel plate, HVOF WC/17Co, WC/10Co4Cr, or T800, with different materials as the mating surfaces. If the average weight loss and wear volume for the HVOF coatings were equal to or less than those for the hard chrome or nickel, the HVOF coatings were considered to have passed the acceptance criteria. Based on the results of the testing, the acceptance criteria were met for the WC/17Co and WC/10Co4Cr coatings.

In addition to these materials tests, TCLP tests were conducted in accordance with EPA Method 1311 on spent and virgin WC/10Co4Cr, T800, and Tribaloy 400 (T400, composition Co-28Mo-8Cr-2Si) powder. The concentrations of chromium and nickel in the leachate were measured, with the results that none of the concentrations were above the regulatory limit. Therefore, these materials would not be classified as hazardous waste by EPA.

Component rig tests were conducted at Hamilton Sundstrand on P3 low-pitch-stop lever sleeves coated with either hard chrome plate or HVOF WC/17Co. The test was performed for 75,000 cycles, which is equivalent to one standard overhaul life. Visual examination of both lever sleeves following the test showed that the hard chrome sustained mild wear whereas the WC/17Co still looked pristine.

3.2 SELECTION OF TEST FACILITY

Navy propeller hub systems are overhauled at the NADEP-CP, and Air Force propeller hub systems are overhauled at WR-ALC. At the beginning of this project neither depot had an HVOF system. In 1996, the Naval Research Laboratory (NRL), using Environmental Security Technology Certification Program (ESTCP) funds, acquired and installed a Sulzer Metco DiamondJet DJ-2600 HVOF system at NADEP-CP. In 1999, the Air Force Materiel Command acquired and installed a DJ-2600 system at WR-ALC. Both systems included a spray booth, powder feeder, and robot on which the HVOF spray gun was mounted, so they were full production systems capable of processing all types of propeller hub components. Training was conducted for personnel at the depots on use of the HVOF systems and quality control procedures.

3.3 TEST FACILITY HISTORY AND CHARACTERISTICS

The lead depot in this project was NADEP-CP in Cherry Point, North Carolina. It has been in existence since the early 1940s and employs 4,100 people. It covers 124 acres and has more than 100 buildings with roughly 1.5 million square feet of space. The depot is the Navy's center of excellence for rotary wing aircraft and provides engineering and logistics support for all Navy helicopters. It performs major airframe modifications and repair for DoD aircraft, including: (1) the AV-8B Harrier, the vertical takeoff and landing tactical attack jet flown by the Marines; (2) the medium-lift transport H46 Sea Knight helicopter; (3) the H-53D Sea Stallion and H53E Super Stallion helicopter; and (4) the Air Force MH-53J helicopter.

The depot also repairs many types of engines, including the T58 used on the H-46, the T400 used on the UH-1 helicopter, the F402 used on the AV-8B, and the T64 used on the CH-53. NADEP-CP performs overhaul and repair of approximately 270 propeller hub systems annually from the P-3, the E-2/C-2, and the C-130. Figure 4 shows a photograph of a P-3 propeller barrel following rework at the depot.

Figure 4. P-3 Propeller Barrel Following Rework at NADEP-CP.

Hard chrome plating is used extensively at NADEP-CP in all of the above repair operations. Several hard chrome plating tanks of differing sizes are maintained for reworking components such as helicopter landing gear, rotor hubs, transmission gears, and engine housings. Plating of propeller hub components is a relatively small portion of the workload, representing less than 20% of the chrome plating operations. Additional operations support hard chrome plating, including stripping, cleaning, grit blasting, oven baking, and inspection. The entire plating process is performed in accordance with Military Standard (MIL-STD) 1501 supported by QQ-C-320.

3.4 PHYSICAL SETUP AND OPERATION

NADEP-CP has one DJ-2600 HVOF thermal spray system that was acquired in this project. The booth, spray gun, and powder feeder were placed into operation first, then the depot acquired a three-axis robot onto which the spray gun was mounted to improve operation. Figure 5 shows the inside of the spray booth, with the robot on the left and the component mounting fixture on the right. In the background is the air handling system that captures any overspray powder. In 2001, the depot acquired and placed into operation a second HVOF system. Both systems are configured for processing components, and no upgrade is required to place them into full production.

Figure 5. Inside of HVOF Spray Booth at NADEP-CP.

3.5 SAMPLING AND MONITORING PROCEDURES

As in all coating methods, the properties and performance of the coating depends on both the coating material and the deposition conditions. Optimal coating properties can therefore be obtained only when critical deposition parameters are in the proper range. In chrome plating, the coating properties are governed primarily by solution chemistry, temperature, and current density. HVOF spraying is more complex to optimize since there are many more variables in the deposition process. For this reason, HVOF coatings were optimized in the HCAT program by a design of experiment (DOE) approach, which permits optimum conditions to be identified from a limited set of test runs, obviating the need for a full test matrix that would entail hundreds of deposition tests.

To optimize a coating, it is important to decide at the outset which property or set of properties is to be optimized. This is especially true for thermal spray coatings where, for example, a coating optimized for minimum wear can demonstrate relatively poor fatigue properties. Within the HCAT program, the fatigue critical nature of applications such as those on landing gear, actuators, and propeller hubs was quickly identified as the major life-limiting characteristics. This did not eliminate the need to evaluate other properties such as corrosion and wear, but coating optimization initially concentrated on fatigue performance. Optimization of the process was carried out for three important reasons:

- To define a thermal spray process that would achieve the desired performance and property goals.

- To establish manufacturing robustness and the process window for a reliable process.

- To understand the process and trends that give an indication of, and can later be used as, a troubleshooting guide; when parameters are identified as significant, these variables will be the first areas of investigation in problem solving.

Although the goal of the DOE studies was the optimization of fatigue performance when a coating is sprayed, only the following measurements can be used for quality control of the process:

- Microstructure (primarily measurement of porosity, unmelted particles, and oxides).

- Hardness (macro and micro).

- Residual stress in the coating as indicated by the curvature of an Almen strip subsequent to coating deposition (compressive residual stress is always desired).

- Substrate temperature during coating application.

- Deposition rate.

These measurements have proved to be adequate for defining the coating for the purpose of quality control. Since the deposition process is known to be uniform and stable if operating parameters are kept constant, the above measurements can be made on test samples set up to see the same deposition conditions as the components to be coated.

The coating DOE studies were performed for the DJ-2600 and the JP-5000 HVOF systems under the leadership of Jerry Schell of GEAE, a specialist in thermal spray and in DOE process optimization, which is used in GE's six-sigma quality program to ensure process robustness. Optimization is typically carried out in a two-level DOE methodology using Minitab software for setting up and analyzing DOEs. This approach uses a fractional factorial array of tests rather than the full factorial array (which would require hundreds of test runs to cover the process parameter space). A standard analysis of variance (ANOVA) method is used to measure the size of the effects (i.e., the importance of the input variables to the responses). On completion of the DOE matrix and its analysis, a set of confirmation runs is usually made about the optimum parameter set to validate the optimization.

Before running the final HVOF optimization DOE, preDOE experiments were run on an iterative basis to determine the limits of the various parameters and which have the most significant effect on the output of the process. Then a DOE matrix was designed. Most final optimization matrices used for HVOF process optimization incorporated 11 factors (input variables such as gas flow and spray distance) and measured eight responses (coating stress, hardness, etc.), with the run parameters chosen in the software to minimize the number of runs (19 runs for an L12 matrix) and avoid confounding (i.e., mixing responses). ANOVA statistical analysis was applied as above, and each variable was assigned a rank as to the effect on the final process output. In subsequent experiments, insignificant variables were eliminated from the analysis and the final outcome was a full parameter set for the process. This type of DOE optimization was carried out at NADEP-CP to provide a process optimized for the equipment used at that facility that was capable of consistently producing functionally equivalent coatings.

Table 3 provides the inputs and outputs for the DOE on HVOF optimization. In general, it was determined that combustion gas and standoff distance were the major factors in the spray process. Microhardness, Almen strip values, and substrate temperature were the critical parameters for control and the obvious areas to investigate in future problem troubleshooting. Related to substrate temperature, it was determined that a continuous infrared temperature measurement during spraying was essential.

Table 3. Inputs and Outputs for Design of Experiment Optimization of HVOF.

Input	Output
Powder size	Hardness
Gas flow	Microstructure
Gas ratio—fuel to oxygen	Almen strip
Spray distance	Tensile stress
Carrier gas flow	Coating deposition rate
Air flow	
Traverse speed	

The optimization process identified the primary and secondary determinants of coating properties, as indicated in Table 4. Details of the results of all DOE analyses, including the optimized parameters for the DJ-2600 system, are presented in the Propeller Hub Joint Test Report (JTR) [6].

Table 4. Primary and Secondary Determinants of Coating Properties.

Property	Primary	Secondary
Almen	Combustion gas/spray distance	Nozzle/powder size
Microhardness	Combustion gas/spray distance	Powder size
Substrate temperature	Combustion gas/spray distance	Nozzle

3.6 ANALYTICAL METHODS

The materials testing requirements and acceptance criteria were delineated in the Joint Test Protocol [5] and will only be summarized here.

3.6.1 Fatigue

Load-controlled constant-amplitude axial fatigue testing was conducted in accordance with ASTM E466-96, and standard S-N curves were generated. Specimens were fabricated from

4340 steel heat treated to a hardness of HRC 40-44 per the Hamilton Sundstrand heat treating specification HS-43. Most of the specimens were in a modified hourglass configuration as shown in Figure 6, with a minimum uncoated gage diameter of 0.2”. Several specimens to receive HVOF coatings were notched as shown in Figure 7, with a stress-intensity factor Kt of 2.7.

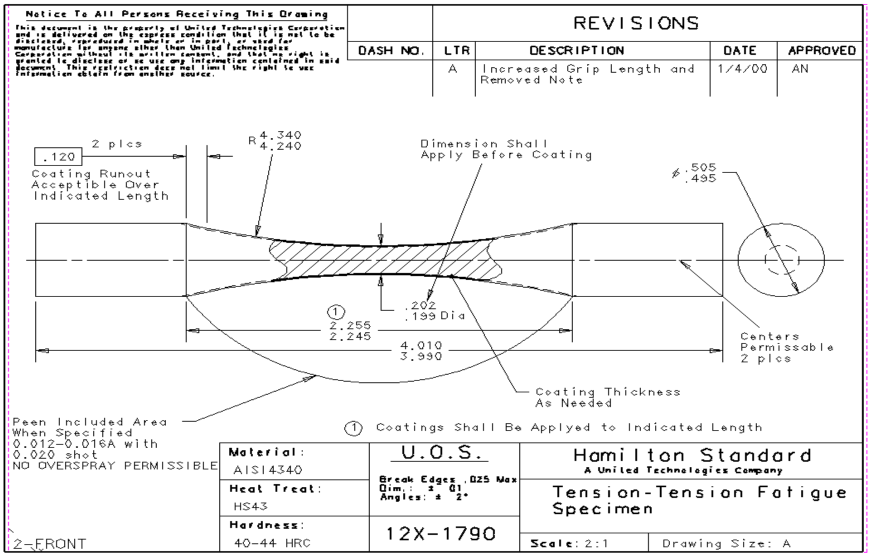


Figure 6. Modified Hourglass Fatigue Specimen.

Before coating application, most specimens were shot-peened, then all were grit-blasted. EHC was applied to some of the specimens in Hamilton Sundstrand’s plating facility in accordance with QQ-C-320 to thicknesses of 0.006”, 0.013”, or 0.018”, and then the coatings were ground to a final thickness of 0.003”, 0.010”, or 0.015”, with an average surface roughness Ra of 16 microinches. HVOF WC/17Co and T800 coatings were deposited in accordance with specification AMS 2447 by Engelhard Surface Technologies. The residual stress in the coatings was controlled by the use of Almen strips, which are normally used with shot-peening. An

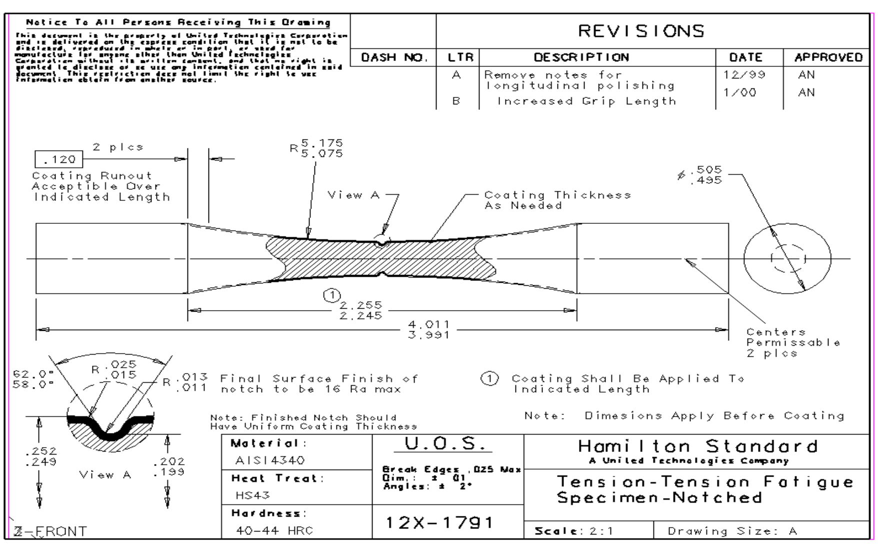


Figure 7. Notched Modified Hourglass Fatigue Specimen.

HVOF coating was sprayed onto an Almen strip immediately before spraying the coating on the fatigue specimens and the strip curvature was measured, with a higher degree of curvature indicating a higher compressive residual stress in the coating. The Almen curvature was specified to be within 0.008” to 0.012” in the JTP, but the actual Almen curvature was approximately 0.020”, indicating a high level of compressive residual stress in the coatings. As-deposited and final thicknesses of the HVOF coatings subsequent to grinding were the same as for the EHC coatings, with a final surface roughness of either 4 or 8 microinches Ra. For the notched specimens, the notch in the base material was machined oversize, the coating was applied, and the final notch contour was then machined into the coating itself. All fatigue measurements were conducted in air. A total of 348 specimens were tested at a stress ratio of R=0.1, meaning they were constantly in tension alternating between the maximum stress and 10% of the maximum stress. Those tested at higher stress levels and thereby expected to fail at a low number of cycles were cycled at 5 Hz. Expected high-cycle fractures were cycled at 59 Hz, with any low-cycle specimen that exceeded 400,000 cycles switched from 5 to 59 Hz.

3.6.2 Wear

The wear performance of various coatings was evaluated using a flat-on-flat reciprocating sliding test developed by Hamilton Sundstrand. The coated specimens consisted of a 0.25”-thick 4340 steel panel, 1.5” wide by 8.0” long, coated on both sides. The counter-face material specimens were 2.0” long, 0.25” wide and 0.125” thick, and consisted of 4340 steel heat treated to 40-44 HRC, a copper-beryllium alloy, a Viton seal, or 15% glass-fiber-filled PTFE. The coatings applied to the panels were EHC deposited in accordance with QQ-C-320, hard nickel plate deposited in accordance with QQ-N-290, and HVOF WC/17Co, WC/10Co4Cr, and T800 all deposited in accordance with AMS 2447. Coating thicknesses subsequent to grinding were 0.003”, with an Ra surface roughness of 4 or 8 microinches for the WC/17Co and WC/10Co4Cr, and 8 or 16 microinches for the other coatings. The wear fixture design shown in Figure 8 allowed for four counter-face specimens to be tested simultaneously with each coated panel.

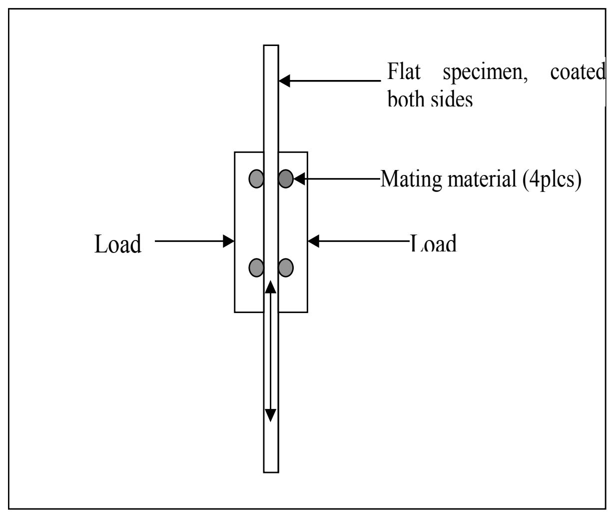


Figure 8. Schematic of Wear Fixture.

Stroke lengths were +/- 0.010” to simulate a dithering action and +/- 0.25” to simulate a longer-stoke sliding action. The dither tests were run for 1 million cycles and the long-stroke tests were run in three increments for 100,000 cycles in each increment. Load levels were 500 or 1,000 pounds for the 4340 steel and copper-beryllium counter-face specimens, 1,000 pounds for the glass-filled PTFE counter-face specimens, and 100 or 200 pounds for the Viton counter-face specimens. All tests were run in the presence of hydraulic oil per MIL-H-83282 and MIL-H-87257. For some tests, contamination consisting of iron oxide, silica sand, and Arizona road dust were added to the MIL-H-83282 to provide abrasive action in addition to the sliding wear.

3.6.3 Corrosion

Corrosion has in general not been a significant concern for the P-3 and E-2 low-pitch-stop sleeve and hub tailshaft since these are bathed in hydraulic fluid during operation. The exception is the E-2 hub rocking lands. This area of the hub is exposed to the outside environment and is therefore susceptible to corrosion attack. The current Hamilton-Sundstrand repair manual allows the use of electrodeposited nickel to restore size when wear is evident. Therefore, it was decided to conduct ASTM B117 salt-fog corrosion testing to compare the level of protection afforded by HVOF coatings compared to nickel plating. Because an extensive amount of corrosion testing had already been conducted on EHC plating in other projects and because nickel was the generally accepted repair process on the component subject to corrosion, it was decided not to include EHC-coated specimens in this test matrix. Low-alloy steel specimens 4” x 6” x 0.040”-thick were fabricated, then grit-blasted before application of the coatings. Nickel plate was deposited to thicknesses of 0.001”, 0.005”, or 0.010” on a first group of nine specimens (three for each thickness) and to thicknesses of 0.003”, 0.007”, or 0.012” on a second group of nine specimens, with the coatings then ground to the same final thickness as the first group with a surface roughness of 16 microinches Ra. HVOF WC/17Co, WC/10Co4Cr, and T800 coatings were applied to the same thicknesses as those for the nickel plate (three specimens for each coating and thickness), with the coatings in the second group ground to the same final thickness as the first group with a surface finish of 8 microinches Ra. This provided for a direct comparison of the corrosion performance of as-deposited coatings to that of ground coatings.

Following application and, for some, grinding of the coatings, the back of each specimen was masked with one piece of 4”-wide red plastic tape, and the edges of the specimen were dipped in red plating lacquer to ensure that only the coating itself would be exposed to the salt fog. This also prevented any galvanic effects between the coated and non-coated areas. The specimens were then placed in an ASTM B-117 salt-fog cabinet. The specimens were inspected daily and test logs were maintained that noted the date when they were placed in the cabinet, the date when red rust was first noted, and the date they were removed from the cabinet. The specimens remained in the cabinet until three or more corrosion spots were noted or when any one spot was larger than 0.3” in diameter. When the specimens were removed from the cabinet, they were cleaned and photographed.

4.0 PERFORMANCE ASSESSMENT

4.1 PERFORMANCE CRITERIA

The performance criteria for all the materials and component testing are delineated in Section 3.1. For all materials testing, the essential criterion was that the performance of specimens coated with HVOF WC/17Co, WC/10Co4Cr, or T800 should be equivalent or superior to the performance of identical specimens coated with EHC, or electrodeposited nickel in the case of corrosion. For fatigue in particular, it is well known that the application of EHC coatings degrades the fatigue performance of high-strength steels. So the issue was whether the HVOF coatings would degrade the performance to a lesser extent or, hopefully, not degrade it at all. Acceptance criteria for the rig test conducted on the P-3 low-pitch-stop lever sleeve were that the HVOF coatings did not show any evidence of delamination, cracking, or extensive wear, and that the performance was equivalent or superior to an EHC-coated lever sleeve in the same rig test.

4.2 PERFORMANCE DATA

All performance data for the materials and component testing is presented in detail in the JTR [6]. Only selective data and summaries are presented here. For a more detailed discussion, refer to the ESTCP Final Report [7].

4.2.1 Materials Testing — Fatigue

The fatigue testing examined the comparative performance between specimens coated with EHC and with HVOF WC/17Co or T800 under the different conditions of specimen preparation (shot-peened or not shot-peened) and coating thickness (0.003”, 0.010”, or 0.015”). Figure 9 shows the data and S-N curves for all coatings applied to shot-peened specimens plus bare non-shot-peened 4340 steel. It can be seen that the fatigue strengths of the WC/17Co-coated specimens

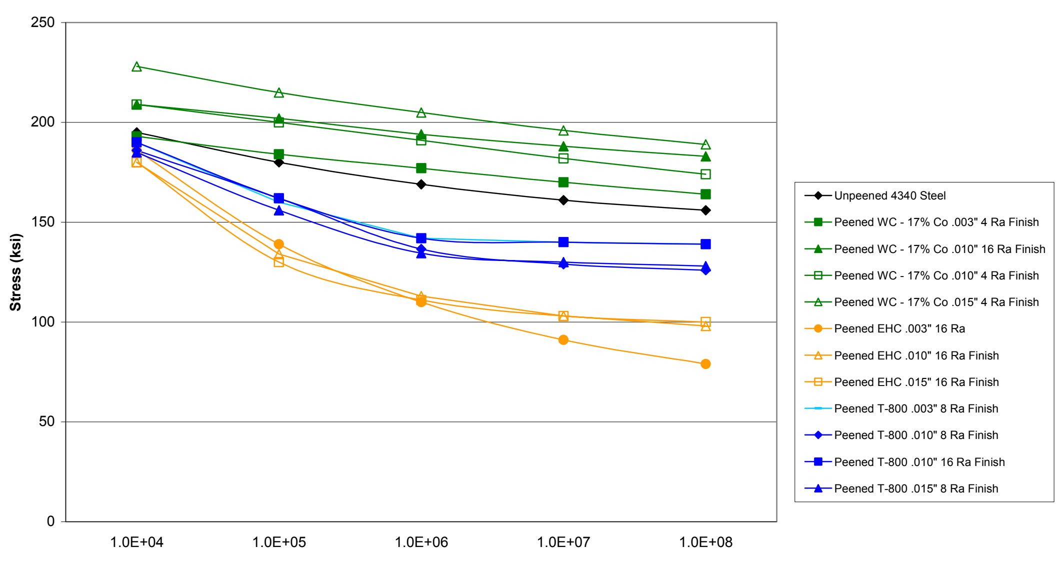


Figure 9. Fatigue Data for Bare 4340 Steel and for Shot-Peened 4340 Specimens Coated with EHC, HVOF WC/17Co, or HVOF T800.

(green) were greater than that for the bare steel. Compared to each other, the fatigue strengths of the T800-coated (blue) and EHC-coated (orange) specimens were approximately 25% and 50% less, respectively, than those for the WC/17Co specimens.

Figure 10 shows the data and S-N curves for all coatings applied to non-shot-peened and notched specimens as well as for the bare, non-shot-peened 4340 steel. It can again be seen that the fatigue strength of the WC/17Co-coated specimens was greater than that of the bare steel. It is also apparent that the fatigue strength of even the notched specimens with the two HVOF coatings exceeded those of the EHC-coated specimens without the notch, which was a surprising result.

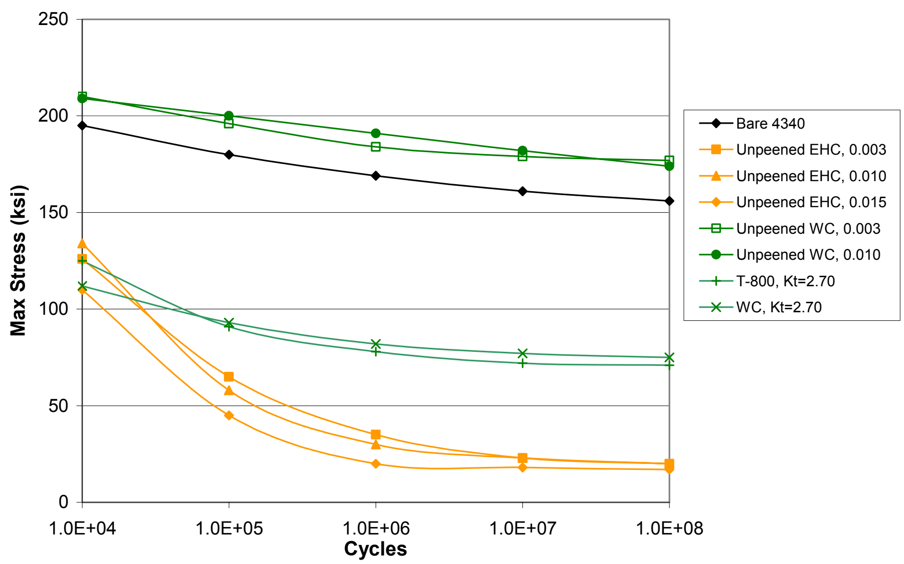


Figure 10. Fatigue Data for Bare 4340 Steel, for Non-Shot-Peened 4340 Specimens Coated with EHC or HVOF WC/17Co, and for Notched Specimens Coated with WC/17Co or T800.

4.2.2 Materials Testing — Wear

Most of the wear tests were conducted on coatings with the rougher surface finish as described in Section 3.6.2 and using the MIL-H-83282 hydraulic oil with and without contamination. Selected wear tests were conducted on coatings with the finer surface finish and using the MIL-H-87257 hydraulic oil. Wear coefficients were determined on the counter-face specimens by measuring weight loss. Because of the difficulty in making wear scar measurements on some of the coated panels and because of the different types of wear noted on the panels, a visual rating method was developed. The scale had a range from one through five, with one corresponding to no wear, two through four corresponding to mild, medium, and severe adhesive or abrasive wear, respectively, and five corresponding to severe pitting of the coating.

Figure 11 shows the wear coefficients for the 4340 steel counter-face specimens sliding against the EHC, WC/17Co, or T800 coatings for a number of different test conditions. The terminology in the labels for the different test conditions on the horizontal axis are as follows: Low or High corresponds to the load that was applied, Dither or Long corresponds to the stroke length, SF indicates coatings with the smoother finish, C indicates the test was done in contaminated oil, and O indicates the test was done in the MIL-H-87257 oil. (See Section 3.6.2 for the details on these conditions.) Figure 12 shows the visual wear ratings for the coated panels sliding against the 4340 counter-face specimens.

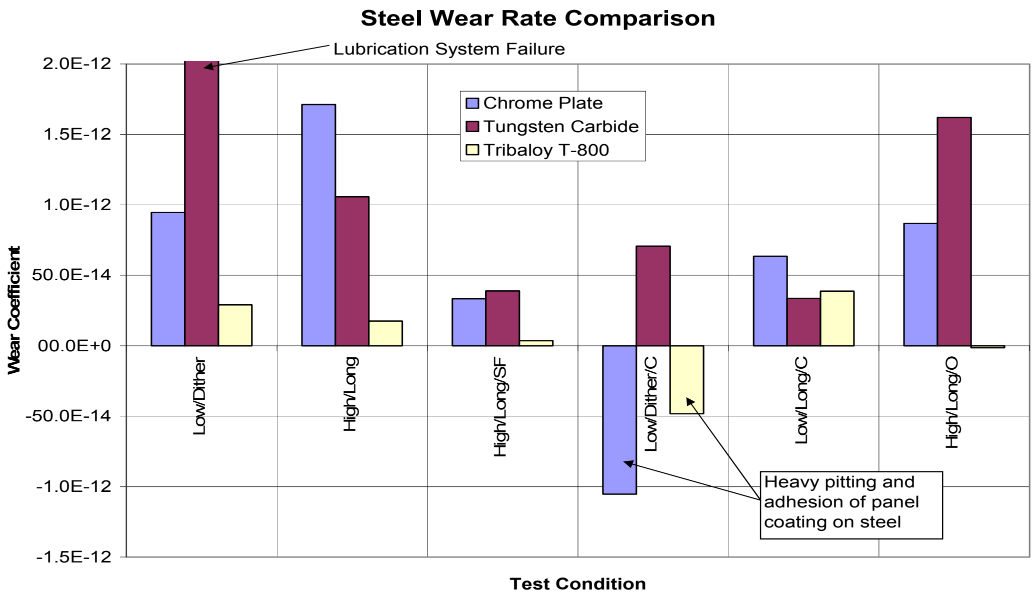


Figure 11. Wear Coefficients for the 4340 Steel Counter-Face Specimens Sliding Against the EHC, WC/17Co, or T800 Coatings for Different Test Conditions.

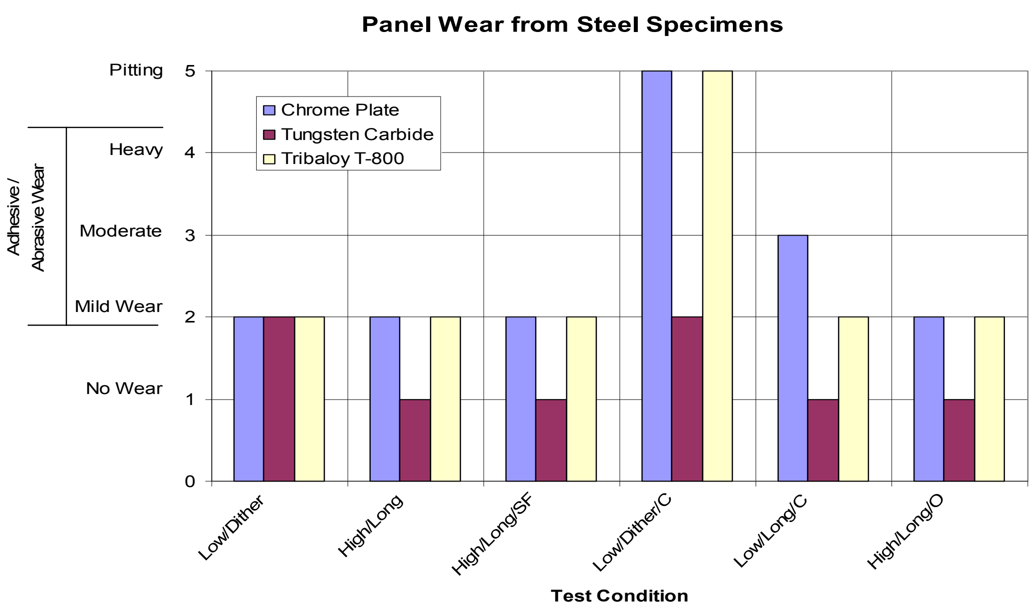


Figure 12. Visual Wear Ratings for the Coated Panels Sliding Against the 4340 Counter-Face Specimens.

Figure 13 shows the wear coefficients for the copper-beryllium (Cu-Be) alloy counter-face specimens sliding against the EHC, WC/17Co, or T800 coatings for different test conditions, and Figure 14 shows the visual wear ratings for the coated panels sliding against the Cu-Be alloy specimens.

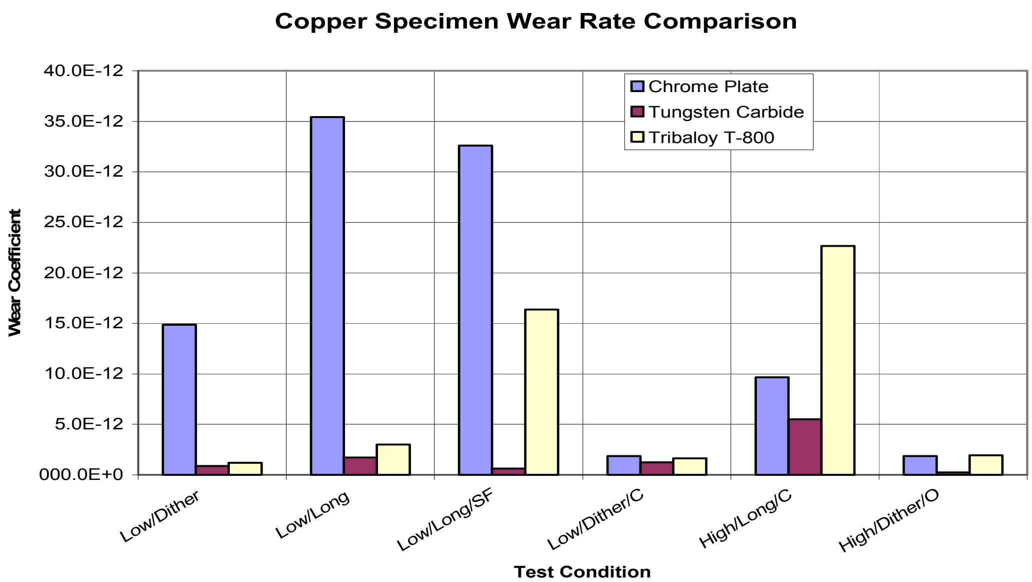


Figure 13. Wear Coefficients for the Cu-Be Alloy Counter-Face Specimens Sliding Against the EHC, WC/17Co, or T800 Coatings for Different Test Conditions.

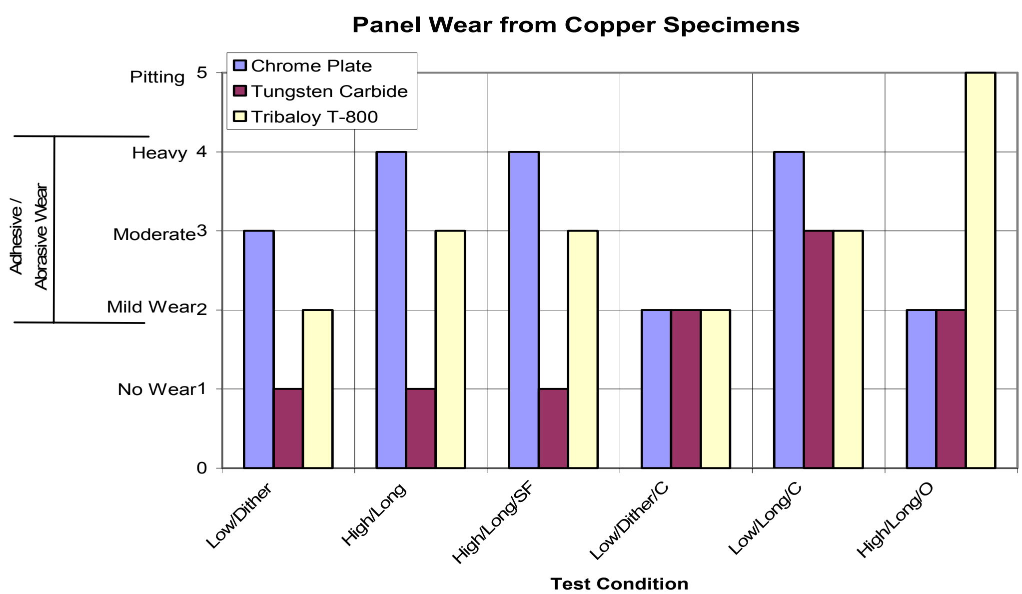


Figure 14. Visual Wear Ratings for the Coated Panels Sliding Against the Cu-Be Alloy Counter-Face Specimens.

There was very little wear on the Viton counter-face specimens sliding against the EHC, WC/17Co, and T800 coatings with the exception of the T800 in the alternative MIL-H-87257 oil where the wear coefficient on the Viton was several orders of magnitude higher. There was no immediate explanation for this result. There was no wear observed on any of the WC/17Co coatings and no wear on most of the EHC and T800 coatings sliding against the Viton. Only mild wear was observed on the EHC and T800 coatings in the contaminated oil test.

Wear tests were performed only for hard-nickel-plated and HVOF WC/10Co4Cr-coated panels sliding against the glass-filled PTFE. In general, the wear coefficients for the PTFE were 50% less when sliding against the WC/CoCr than when sliding against the hard nickel. Similarly, the wear ratings on the coated panels were 50% less for the WC/CoCr than for the hard nickel.

4.2.3 Materials Testing — Corrosion

Figure 15 presents a comparison of 0.001”-thick electrodeposited hard nickel, HVOF WC/17Co, WC/10Co4Cr, and T800 after 8 days of exposure in the B117 salt-fog cabinet. In general, the corrosion performance of the WC/17Co and T800 coatings was significantly worse than the other two coatings at this thickness. Figure 16 presents a comparison of 0.005”-thick hard nickel and WC/17Co after 20 days of exposure.

Figure 15. (Left to right) **Comparison of 0.001”-Thick Electrodeposited Hard Nickel, HVOF WC/17Co, WC/10Co4Cr, and T800; After 8 Days of Exposure in the B117 Salt-Fog Cabinet.**

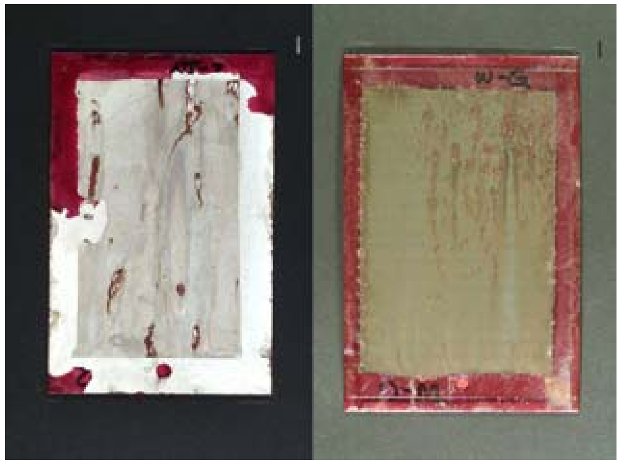


Figure 16. Comparison of 0.005″-Thick Electrodeposited Hard Nickel and HVOF WC/17Co After 20 Days of Exposure in the B117 Salt-Fog Cabinet.

4.2.4 Toxicity Characteristic Leaching Procedure

TCLP testing was performed to determine if production scrap, waste, or used components coated with WC/10Co4Cr, T400, or T800 should be classified as hazardous waste by the EPA and therefore regulated under 40 CFR Part 261 Subpart C. The testing was conducted in accordance with EPA method 1311 using procedures described in the Appendix to the JTR [6]. Hamilton Sundstrand subcontracted the TCLP evaluation to two independent laboratories to compare and validate results. The results are presented in Table 5.

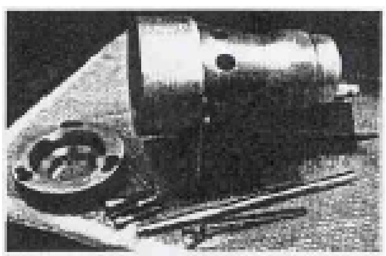
Table 5. Chromium and Nickel Concentrations in TCLP Leachate Solution for Spent and Virgin Powder of WC/10Co4Cr, T400, and T800.

Pretest Condition	Sample	Chromium	Nickel
Spent Solid	T400	0.62 mg/L	0.16 mg/L
	T800	0.41 mg/L	0.07 mg/L
	WC Co Cr	1.00 mg/L	2.92 mg/L
Virgin Powder	T400	0.85 mg/L	0.68 mg/L
	T800	0.34 mg/L	0.20 mg/L
	WC Co Cr	0.76 mg/L	2.14 mg/L

4.2.5 Component Rig Test

The purpose of the component rig test was to assess the durability of the WC/17Co coating on the actual lever support sleeve in a simulated operating environment. This coating was selected based on the favorable results obtained in fatigue and wear testing. Component testing was conducted on sleeves coated with either EHC or the HVOF WC/17Co using an E-2 propeller low pitch stop assembly. Each of the assemblies was installed in the test fixture and actuated using MIL-H-83282 oil at a pressure of 310 psi. The test stand consisted of a holding fixture, controller, counter, and a hydraulic test stand as shown in Figure 17. The number of actuation cycles selected for the test was based on one standard overhaul life, which was estimated at 75,000 cycles. This was based on the following:

- Propeller time between overhaul (TBO) is 7,500 hours (a period established by the Navy for the P-3 propeller system).
- Duration of each flight equals one hour.
- Low-pitch-stop is activated 10 times per flight.



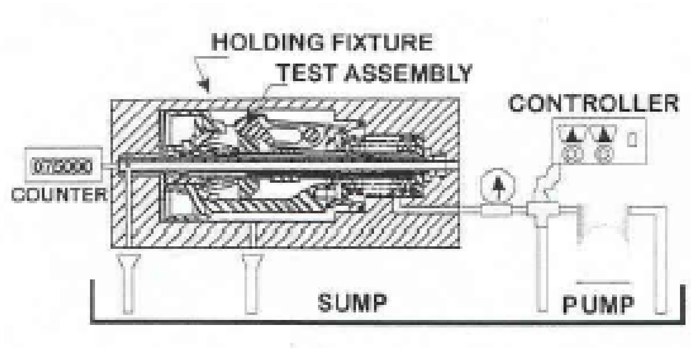


FIGURE 1 HOLDING FIXTURE

FIGURE 2 TEST SCHEMATIC

Figure 17. Photograph of Holding Fixture and Schematic of Entire Test Assembly for Low-Pitch-Stop Lever Sleeve Component Test.

One cycle was counted as the forward and return stroke of the low-pitch-stop piston. The total travel distance of one actuation cycle was approximately 2.06”. The low-pitch-stop assembly was removed at intervals of approximately 7,500 cycles to facilitate inspection of the actuator bore.

On completing testing, both of the low-pitch-stop sleeves and piston rings were visually examined, measured, and surface finish readings taken. The piston rings were also weighed in an attempt to quantify the amount of wear. The wear to the inside diameter was quite minimal and in some cases showed a slight increase in size.

Visually, the internal diameter (ID) of the WC/17Co sleeve appeared unworn, whereas the chrome sleeve showed some initial signs of wear. The wear was minimal and no significant indications of adhesive wear or scoring were present. The piston rings against the WC/17Co and EHC sleeves also showed signs of wear, though not a significant amount. Weight measurements of the piston rings before and after the test showed that weight loss was three times higher running on the EHC sleeve.

Surface measurements taken of the WC/17Co sleeve confirmed the visual results. Pretest and posttest surface finish measurement gave the same reading of 7.2 Ra. The final surface finish measurements of the ID of the EHC sleeve confirmed that surface wear had occurred. At the start of the test, the surface roughness of the EHC sleeve was measured at 2.7 Ra. The surface roughness at the conclusion of testing was measured at 1.4 Ra.

4.3 DATA EVALUATION

For fatigue, it was established that the HVOF WC/17Co-coated specimens demonstrated fatigue strength that was 35% higher than that for the T800-coated specimens and 95% higher than that for the EHC-coated specimens. The fatigue strength of the WC/17Co-coated specimens was actually higher than that for the uncoated 4340 steel, although stress levels were calculated based on the uncoated specimen diameter. The increased fatigue strength of the WC/17Co specimens was thought to be caused by one of the following: a) the ability of the coating itself to carry some of the load, b) the compressive residual stress imparted by the coating application process, or c) some combination thereof. The strength did appear to be directly related to coating thickness so the coating load carrying capability was thought to be the major contributor to this effect. The very low fatigue strength measured for the EHC-coated specimens was partly because they showed evidence of cracks from abusive grinding that created a fatigue strength degradation. However, even using the industry accepted strength knockdown for EHC, the WC/17Co was still far superior. The WC/17Co and T800 coatings underwent the same grinding process, so an unforeseen benefit from this work is that the WC/17Co can withstand a level of abusive grinding that would be detrimental to chrome plate without the adverse effect on fatigue strength. One other result from the fatigue studies was that there was minimal effect on the fatigue strength of the WC/17Co- and T800-coated specimens by shot-peening the specimens before the coating application. The use of shot-peening is so ingrained in the industry that it is unlikely that HVOF coatings would be used without it. Nevertheless, this shows that HVOF performance will be adequate even when the shot-peening is done improperly or not at all.

For wear, somewhat different results were obtained for studies of the EHC, WC/17Co, and T800 coatings sliding against the different counter-face materials.

- For 4340 steel counter-faces, the wear coefficients were comparable when mated against either EHC or WC/17Co, whereas they were lower when mated against T800 for all cases except in the contaminated oil. There was either mild or no wear on the coatings in noncontaminated oil. In contaminated oil, the EHC and T800 coatings exhibited significant pitting whereas the WC/17Co exhibited only mild wear.

- For the Cu-Be alloy counter-faces, the wear coefficients were lower against the WC/17Co coatings under all test conditions than against either the EHC or T800 coatings. The WC/17Co coating exhibited far lower wear than either the EHC or T800 coatings under all test conditions. The T800 coatings outperformed the EHC coatings under all long-stroke sliding conditions, whereas the reverse was true for all dithering conditions.

- For the Viton counter-faces, there was generally little wear against any of the coatings, although the wear coefficients were slightly lower for the WC/17Co coatings. There was no visible wear on the coatings tested in noncontaminated oil. In contaminated oil, very light scratches were observed on the EHC and T800 coatings, whereas none were observed on the WC/17Co.

- For the 15% glass-filled PTFE counter-faces, the wear coefficients were slightly lower against the WC/10Co4Cr than against the EHC. The EHC coatings exhibited early stages of abrasion at the outline of the PTFE specimens, whereas the WC/10Co4Cr coatings exhibited only oil staining at the contact point.

- For corrosion, for the 0.001"-thick coatings, the nickel plate provided the greatest level of protection to the base steel. Among the HVOF coatings, the WC/10Co4Cr performed fairly well, with the WC/17Co and T800 demonstrating poor performance. As the thickness of the coatings was increased, the performance of the WC/10Co4Cr and WC/17Co improved markedly such that the difference between them and the nickel plate was less pronounced. The T800 coating tended to "bleed" rust from many different areas dispersed over the coating surface, due most likely to the higher porosity level in the coating, allowing multiple paths for the corrosive media to reach the substrate. The WC17Co and WC/10Co4Cr coatings corroded in one or two specific locations. In general, the ground coatings demonstrated poorer corrosion resistance than the as-deposited coatings. The performance of WC/10Co4Cr was considered adequate for its use as a Ni replacement, allowing both Cr and Ni to be replaced on the same component.

The results of the TCLP testing on virgin and spent WC/10Co4Cr, T400, and T800 powder indicated that the chromium and nickel concentrations in the leachate were below the regulatory limit. Based on the results, these materials would not be classified as hazardous waste by the EPA.

The component rig test on the low-pitch-stop lever sleeve demonstrated that the wear of the HVOF WC/17Co coating was less than for the baseline EHC coating. The WC/17Co-coated bore produced less wear on the mating piston ring than the EHC coating. Based on these test results, Hamilton Sundstrand recommends WC/17Co as a replacement for EHC on the ID of this component for the P-3 and E-2 propeller hubs.

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5.0 COST ASSESSMENT

5.1 COST REPORTING

To quantify the economic feasibility of implementing HVOF WC/Co for propeller hub repair, a cost-benefit analysis (CBA) was performed focusing on a military propeller hub repair facility [8].

Information about current hard chrome electroplating operations at the repair facility was used to estimate the economic impact that may be expected if some hard chrome electroplating is replaced by HVOF WC/Co.

Data collection and financial analyses of the data were performed using the Joint Group on Pollution Prevention (JG-PP) methodology, which is based on the ECAM. In accordance with this methodology, baseline process flow diagrams associated with current hard chrome electroplating processes were developed (see Figure 18).

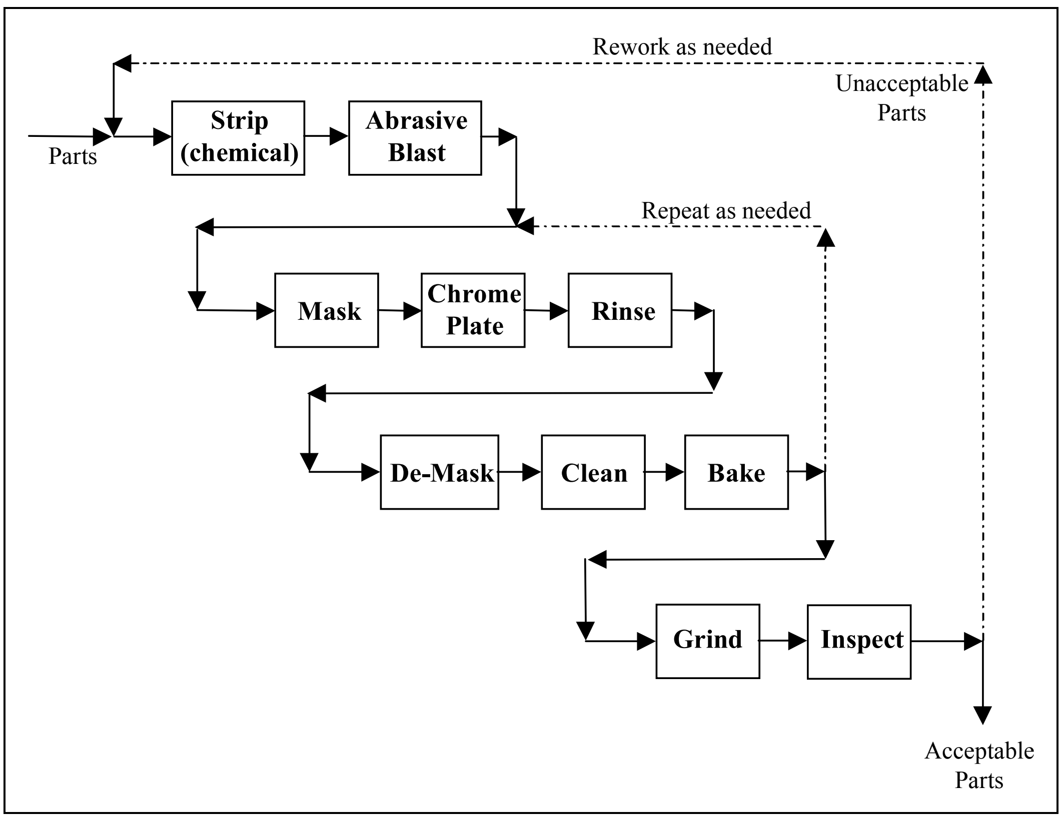

Figure 18. Hard Chrome Plating Process Flow at the Repair Facility.

Data collection forms were developed to collect information on the baseline hard chrome electroplating operations, and a site visit was performed to collect the data. Information was collected in accordance with the ECAM methodology. During the site visit, interviews were held with plating engineers, operators, chemists, supervisors, environmental engineers, the environmental management team, safety personnel, and other employees throughout the facility. The information gathered during the site visit was supplemented with correspondence after the visit. Where available, material usage rates and costs, labor hours, and waste treatment and disposal costs were identified. Where data were not available, values were assumed based on data from other facilities and using engineering judgment. Environmental, safety, and occupational health (ESOH) activity costs were also obtained where available, or estimated.

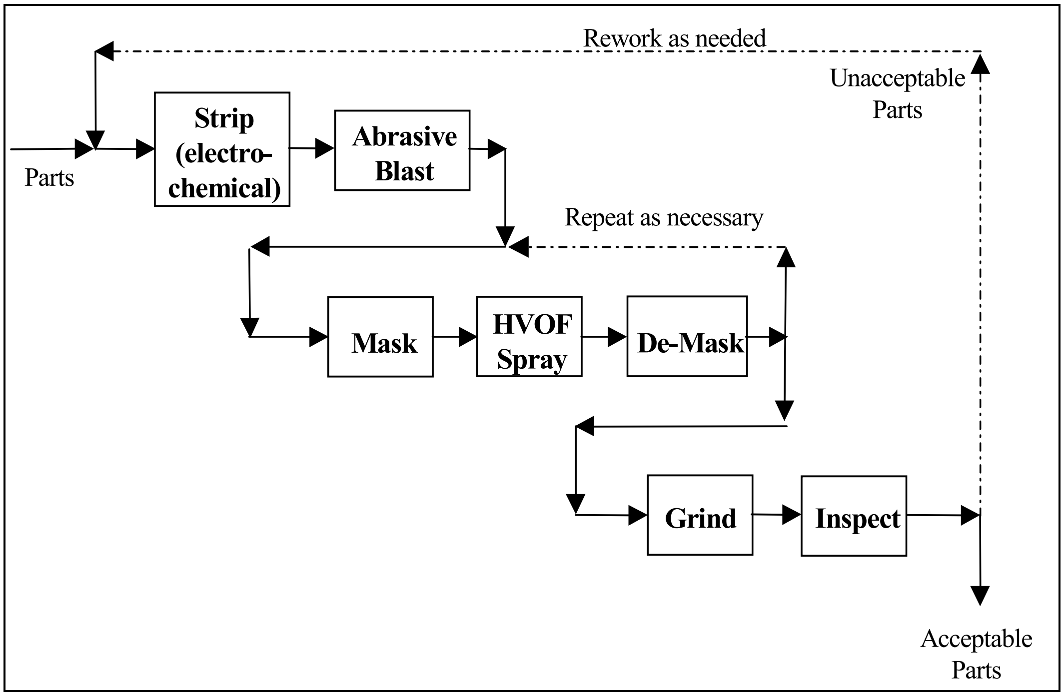

Figure 19. HVOF Process Flow at the Repair Facility.

The collected operating information was used to estimate the potential financial impact of the project, in accordance with the ECAM methodology. A process flow diagram relating to the application of WC/Co by HVOF developed to aid in analysis of the data is shown in Figure 19.

As with Figure 18, rework steps are included because aircraft propeller hubs may be processed more than once to achieve desired coating thickness on specific areas of each component, and because some components may be improperly coated and require rework. Several scenarios were considered and are summarized in Table 6.

Scenario 1 (base scenario). Overhaul cycle unchanged, no changes in regulations or environmental and ESOH costs.

Scenario 2. Same assumptions as Scenario 1 plus: OSHA regulations reduce chrome PEL to the range 0.5-5 $\mu gm/m^3$. Overhaul cycle time increased 50% due to better HVOF wear performance. This reduces the number of propeller hubs overhauled annually.

Scenario 2a. Same as Scenario 2, but 150% increase in service life (overhaul cycle time).

Scenario 3. Same assumptions as Scenario 2 plus: Incorporates a 5-day decrease in turnaround time (TAT) and therefore lower inventory cost.

Scenario 3a. Same as Scenario 3 but 17-day reduction in TAT.

Table 6. Assumptions for Different Scenarios (Years 7-15).

Item	EHC	Scen 1	Scen 2	Scen 2a	Scen 3	Scen 3a
Overhaul cycle	7 yr	7 yr	10.5 yr	17.5 yr	10.5 yr	17.5 yr
# Overhauls/year	270	270	170	100	170	100
Turnaround time					-5 days	-17 days
Chrome PEL	100 μgm/m^3	100 μgm/m^3	0.5-5 μgm/m^3	0.5-5 μgm/m^3	0.5-5 μgm/m^3	0.5-5 μgm/m^3

Table 7 shows some cost factors included in the analysis (the CBA did not include all data for competitive reasons). It was assumed that the labor cost of $97/hr would be the same for chrome plating and HVOF. The costs listed in the table for chemicals, utilities, and ESOH costs are associated with chrome plating. The cost of installing electrolytic stripping tanks for HVOF was not included in the capital cost. It was assumed that the additional cost of diamond grinding wheels for HVOF grinding would be offset by their longer life.

Table 7. Some Costs Included in Analysis.

Item	Value
Labor cost	$97/hr
Chemicals	$789/yr
Utilities	$1,236/yr
ESOH costs	$44,120/yr
HVOF WC-Co 0.017" thick	$84/hub
HVOF utilities	$6.5/hub
HVOF masking and fixturing	+$410/yr
Spray booth time	40 min/hub

5.2 COST ANALYSIS

The analysis produced the results of Table 8 and Table 9 for the different scenarios. Note that, for each scenario, the cost avoidance was negative, i.e., the adoption of HVOF was estimated to increase the overhaul cost. Because of this, the standard value estimates (Net Present Value, Internal Rate of Return, Return on Investment) were not calculated, while Payback Period would, of course, be meaningless. Even though these could not be calculated, it is relevant to provide information on the capital cost of implementing an HVOF facility. Such a cost is dependent on whether the facility already has air handling equipment in place for capturing the overspray powder. If that is the case, then the cost of implementing an HVOF system similar to the one at NADEP-CP would be approximately $500,000. If the facility needed to install air handling equipment, then the total cost would be approximately $800,000.

Table 8. Estimated Annual Cost Avoidance (Scenarios 1, 2, and 3).

Category	Scenario 1	Scenario 2	
		Years 1-6	Years 7-15
Parts/year hard chrome electroplated without HVOF implementation	270	270	270
Parts/year coated with HVOF Wc/Co after HVOF implementation	250	250	170
Annual operating cost avoidance			
Labor	$0	$0	$0
Materials and utilities	($26,000)	($26,000)	($17,000)
ESOH activities			
Waste disposal	$340	$340	$340
Other ESOH activities	$0	$510	$400
Total	**($26,000)**	**($25,000)**	**($16,000)**
Additional cost avoidance due to reduced TAT (Scenario 3)	N.A.	$5,600	$3,700
Total Scenario 3	**N.A.**	**($19,000)**	**($12,000)**

Values in "( )" indicate negative values, or loss. All values are rounded to two significant digits.
N.A. = Not applicable

Table 9. Estimated Annual Cost Avoidance (Scenarios 1, 2a, and 3a).

Category	Scenario 1	Scenario 2a [a]	
		Years 1-6	Years 7-15
Parts/year hard chrome electroplated without HVOF implementation	270	270	270
Parts/year coated with HVOF WCCo after HVOF implementation	250	250	100
Annual operating cost avoidance			
Labor	$0	$0	$0
Materials and utilities	($26,000)	($27,000)	($11,000)
ESOH activities			
Waste disposal	$340	$340	$340
Other ESOH activities	$0	$510	$400
Total	**($26,000)**	**($26,000)**	**($10,000)**
Additional cost avoidance due to reduced TAT (Scenario 3a [b])	N.A.	$19,000	$7,600
Total Scenario 3a [b]	**N.A.**	**($7,000)**	**($2,400)**

a Scenario 2a incorporates the effects of more stringent OSHA requirements for chrome exposure and a 150% increase of WC/Co coating lifetime over electroplated chrome.

b Scenario 3a incorporates the effects of 17-day reduction in TAT of HVOF application of WC/Co compared to hard chrome electroplating.

5.3 COST COMPARISON

This cost analysis was performed in 1999. A more recent CBA performed at a landing gear overhaul facility [9] showed that the 15-year net present value of implementing HVOF in place of hard chrome plating was approximately $2,000,000. This raises the issue of why a positive return-on-investment would be obtained at the landing gear facility whereas a negative one was obtained for the propeller hub facility. At the landing gear facility, HVOF could replace approximately 75% of the chrome plating workload, and the number of components processed annually would be considerably higher than at the propeller hub facility where overhaul of those types of components represents only 10% of the chrome plating workload. The replacement of a large portion of the chrome plating operations results in substantial savings in areas such as waste disposal, plating tank maintenance, and worker safety monitoring. Replacing only a small fraction of the chrome plating workload does not lead to equivalent savings and is very inefficient. It can be concluded that any CBA performed at a repair facility that applies hard chrome plating to many different types of components should take into account all of them that could be replaced with HVOF and not just a small segment in order to achieve the most accurate picture of potential cost savings.

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6.0 IMPLEMENTATION ISSUES

6.1 COST OBSERVATIONS

A major contributor to HVOF process cost is the cost of spray powder. Spray efficiency is an important contributor to this cost since any powder that does not stick (i.e. becomes overspray) is lost and goes into the filter system. Therefore, optimizing the process for spray efficiency would have a major impact on long-term cost. This is likely to be a cost-effective process improvement.

In the long term, it is also possible to use a different, less expensive powder. However, in this case, since the longevity of the coating is critical to this weapons system, this would only lead to a net saving if the performance of the new coating is essentially the same as that of WC/Co. It would also lead to additional qualification costs.

A primary reason for adopting HVOF in place of hard chrome on these components is that some of them are no longer manufactured, and they can only be overhauled a limited number of times before they must be scrapped. Replacements can only be obtained from dwindling inventories or by cannibalizing other aircraft. The only alternative would be to have new items manufactured, which would likely cost significantly more than their current $98,000 price because of the costs of retooling for limited production runs. With its significantly longer wear life, HVOF will reduce the number of overhaul cycles in the remaining aircraft life, hopefully avoiding the costs of new components or the need to take aircraft out of service. This is likely to be a major cost benefit as well as being a critical readiness issue.

Based on the materials and component testing, it has been recommended that both chrome and nickel plate be replaced by HVOF coatings on the 5460 hubs used for the E-2/C-2. These are one-piece components that can be coated in a single spray run. This eliminates not one, but two electrochemical processes, together with all their masking, processing, and embrittlement relief operations. This should result in additional cost savings not factored into the CBA performed in 1999.

6.2 PERFORMANCE OBSERVATIONS

The JTR showed that, in fatigue and wear testing, the HVOF WC/Co coatings were significantly better than hard chrome and would be a suitable replacement for EHC in the repair of the low-pitch-stop lever sleeve and hub tail shaft for 54H60 and 54460 propellers.

In corrosion testing, which was compared with the Ni plate currently used for repair of rocking lands on 54460 propeller hubs, Ni performed best, followed by WC/CoCr, Tribaloy-800, then WC/Co. Nevertheless, WC/CoCr corrosion performance was considered adequate for its use as a replacement for Ni plating as well as EHC plating, further reducing the environmental impact of propeller hub overhaul. Since WC/CoCr showed significantly better wear performance, both in reduced component wear and reduced seal material wear, it was expected to provide a significant benefit in reduced depot and field maintenance.

Because of the findings in the Landing Gear JTR concerning spalling at high stress, Hamilton-Sundstrand recommended additional fatigue testing to ensure that this is not a problem for propeller hubs. (It is not expected to be a problem since these components are not subject to high bending stresses.) This additional testing is ongoing.

The HVOF coatings tested in the JTP were sprayed with unusually high compressive stress. Hamilton Sundstrand recommended that comparisons be made with performance of coatings deposited by other vendors. Presumably, NADEP-CP would also spray with a lower compressive stress. The primary effect of this is on fatigue, where high compressive stress improves fatigue life. However, excessive compressive stress carries with it the danger of inducing too high a tensile stress in the substrate, with a potential for enhanced crack propagation in the substrate and reduced fatigue. Therefore, since fatigue was not an issue, HVOF coatings should still have better fatigue performance than EHC even with a lower residual stress in the HVOF coating.

The performance of the rig tests on the low-pitch-stop lever sleeve confirmed the observations of the coupon tests. The HVOF coated components, as well as their matching components, showed no wear or very slight wear, whereas chrome showed low but noticeable wear. Therefore, it is anticipated that, in common with other components, the overhaul frequency could probably be reduced, with a cycle time from 1.5 to 4 times longer.

6.3 SCALE-UP ISSUES

The HVOF systems currently in operation at aerospace-qualified HVOF vendors and at the NADEPs and air logistics centers (ALC) are full-production systems with fixturing for manipulation of various types of components and robots on which the HVOF spray guns are mounted. The original spray booth at NADEP CP that was acquired using ESTCP funds has now been supplemented by an additional, similar booth acquired by NADEP to meet demand. These two booths are expected to be used for processing propeller hub components, landing gear, and other items for fixed-wing and rotary-wing aircraft.

WR-ALC is responsible for a high volume of C-130 propeller system overhauls and now has a production-capable HVOF system that is anticipated to be used for processing C-130 propeller components.

Hamilton Sundstrand purchases its HVOF services from various commercial vendors such as Engelhard's local spray shop in Windsor Locks, Connecticut. These commercial shops already use full-scale HVOF equipment.

6.4 LESSONS LEARNED

It is instructive that the program led not only to an EHC replacement, but to an alternative to Ni plating repair. Although Ni is not yet as high on the list of environmentally unacceptable materials as Cr, it is a toxic 17 material that is coming under increasing regulation. The usage of HVOF in this instance, using a different coating material than that used for EHC, shows the power of the HVOF technology. Not only can HVOF replace Cr, but it can also replace other materials. Furthermore, both materials can be sprayed on the same part in a single spray run simply by automatically switching powder feeders, without the need for recleaning, remasking, rebaking for embrittlement relief, and all the other requirements of two separate electroplating processes.

This suggests that, when replacing one process with another, especially with one as general as HVOF, additional process modifications should be explored that will eliminate other environmentally unsound processes while reducing the total overhaul cost.

6.5 END USER/OEM ISSUES

This program involved a system that was important primarily to two DoD repair facilities and one OEM, making it relatively easy to formulate a test plan and carry out the work. It required close collaboration between the OEM and the maintenance depot — an arrangement that worked very well.

One of the key end user/OEM issues is the availability of standards and specifications related to the powder used for HVOF coatings, application procedures for the coatings, and grinding procedures for the coatings. Standards and specifications were not developed specifically for the propeller hub project, but in the landing gear project, the HCAT worked with the SAE Aerospace Metals Engineering Committee to develop four separate specifications in these areas. Those related to powder and coating deposition were completed and forwarded to SAE Aerospace Materials Committee B, who approved them in February 2003. The following are the designations:

- AMS 2448 – “Application of Tungsten Carbide Coatings on Ultra-High-Strength Steels, High-Velocity Oxygen/Fuel Process”

- AMS 7881 – “Tungsten Carbide-Cobalt Powder, Agglomerated and Sintered”

- AMS 7882 – “Tungsten Carbide-Cobalt Chromium Powder, Agglomerated and Sintered”

In addition, United Technologies Hamilton Sundstrand has developed HS 4412 for application of HVOF thermal spray coatings in place of EHC.

A specification for grinding and superfinishing the coatings has been drafted and is in the approval process. All these specifications can now be used by any manufacturing or overhaul depot and their use will result in consistency between facilities with respect to coating properties.

P-3 flight testing is to start shortly, and qualification procedures are beginning. NAVAIR has stated that a 6-month trouble-free flight test will suffice for qualification. A supplement to the JTR will be issued when flight testing is complete. This same technology will then be implemented at WR-ALC, where a larger number of C-130 propeller hubs are overhauled.

The primary factor likely to slow implementation at the depot is obtaining final NAVAIR approval for a change in repair specifications. Unlike Ogden ALC, which is the cognizant authority able to authorize repair changes for landing gear, NADEP-CP must obtain NAVAIR authorization for the repair. However, since the program was done in very close collaboration with the OEM, Hamilton Sundstrand, and much of the testing was done by the manufacturer, there should be no issue with the manufacturer endorsing the change. Indeed, as pointed out above, NAVAIR has agreed to a limited flight test for final qualification. Since Hamilton Sundstrand intends to adopt the technology on new components, any new purchases will already incorporate HVOF, with HVOF being the OEM-specified repair as well.

6.6 APPROACH TO REGULATORY COMPLIANCE AND ACCEPTANCE

The principal environmental and worker safety issues associated with HVOF thermal spraying are air emissions containing overspray particles and the noise of the gun itself. All the depots involved in the HCAT project already had other types of thermal spray equipment in operation, such as flame or plasma spray, and therefore they had the appropriate air handling equipment (e.g., exhaust hoods and bag houses) available and also had the appropriate air permits to cover operation of the HVOF systems.

The equipment was installed in a soundproof booth, with robotic arm and computer control. This ensured that, as in the other depots, there is no operator exposure to noise or dust generated during spraying.

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APPENDIX A

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