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Environmental Security Technology Certification Program (ESTCP)

Final Report

Validation of HVOF Thermal Spray Coatings as a Replacement for Hard Chrome Plating on Hydraulic/Pneumatic Actuators

Project WP-0038

July 27, 2006

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14. ABSTRACT

Hard chromium plating is extensively used by military maintenance depots to provide wear and/or corrosion resistance or to restore dimensional tolerance to components. However, chrome plating utilizes hexavalent chromium which is a highly toxic carcinogen, and increasingly stringent regulations are making chrome plating more expensive for the DOD. This document constitutes the Final Report on a project to qualify high-velocity oxygen-fuel (HVOF) thermal spray coatings as a replacement for hard chrome plating on hydraulic actuator components. Extensive fatigue, salt-fog corrosion and environmental embrittlement tests were performed on several HVOF coatings compared to hard chrome plating. For fatigue and embrittlement tests, the HVOF coatings were equivalent or superior to hard chrome. For corrosion, the HVOF coatings were inferior. Functional rod/seal testing demonstrated superior performance of HVOF coatings sliding against standard actuator seals. The Air Force performed extensive successful qualification testing of actuators containing HVOF-coated components.

15. SUBJECT TERMS

Thermal spray; HVOF thermal spray; hydraulic actuators; WC/Co coatings; WC/CoCr coatings; Hard chromium plating; Fatigue; Corrosion; Wear

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EXECUTIVE SUMMARY

Background: Electrolytic hard chrome (EHC) plating is a technique that has been in commercial production for over 50 years. It is a critical process that is used both for applying hard coatings to a variety of aircraft components in manufacturing operations and for general re-build of worn or corroded components that have been removed from aircraft during overhaul. Chromium plating baths contain chromic acid, in which the chromium is in the hexavalent state, with hexavalent chromium (hex-Cr or Cr^{6+}) 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 Occupational Safety and Health Administration (OSHA) permissible exposure limits (PEL).

High-velocity oxygen-fuel (HVOF) thermal spray technology can be used to deposit both metal alloy coatings and ceramic/metals (cermets) such as tungsten carbide/cobalt (WC/Co) that are dense and highly adherent to the base material. Previous research, development and validation efforts had established HVOF thermal spray coatings as the leading candidates for replacement of hard chrome. This led to industry acceptance of HVOF WC/CoCr and WC/Co in place of hard chrome for landing gear, to the point that all landing gear on new aircraft designs (including the Airbus 380, Boeing 787, F-35, X-45) are now specified with HVOF. In addition, in overhaul operations these coatings can be built up to thicknesses needed for dimensional restoration, as is currently done with EHC.

HVOF systems are commercially available and installed in several depots, and there are numerous commercial vendors supplying the OEM community. Although HVOF coatings are now coming into wide use for landing gear, their qualification as an acceptable replacement for hard chrome plating on actuators has not been adequately demonstrated. The Hard Chrome Alternatives Team (HCAT) was formed to perform the demonstration/validation for the HVOF coatings.

Objectives of the Demonstration: The objectives were to demonstrate, through coupon testing, functional rig testing and delta qualification testing of actual hydraulic actuators, that HVOF coatings have equivalent or better performance than EHC coatings. In addition, rig tests were conducted to compare the performance of different surface finishes in order to establish the best surface finish specification.

Regulatory Drivers: EHC plating operations must comply with 40 Code of Federal Regulations (CFR) Part 63 (National Emissions Standards for Hazardous Air Pollutants) and 40 CFR Part 50 (National Primary and Secondary Ambient Air Quality Standards). Recent studies have clearly shown that there are a significant number of excess deaths at the current PEL of 52 $\mu g/m^3$ of Cr^{6+}. In February, 2006, OSHA promulgated a new Cr^{6+} exposure limit (PEL) of 5 $\mu g/m^3$, with an Action Level of 2.5 $\mu g/m^3$, an order of magnitude below the previous standard of 52 $\mu g/m^3$. A Navy/Industry task group concluded in a 1995 study that the cost of compliance for all Navy operations that utilize hex-Cr (i.e., not just plating) would be about $5 million annually at a PEL of 5 $\mu g/m^3$.

Air sampling by the Navy showed that a very large number of operations, including chrome plating, painting and depainting, sanding and corrosion control, would all exceed the Action Level – some by a wide margin. The costs of meeting the PEL are likely to be very high at some Department of Defense (DOD) facilities.

Demonstration Results:

Substrates were 4340 high strength steel, (180-200 ksi ultimate tensile strength (UTS)), PH15-5 stainless steel (155 ksi UTS) and Ti-6Al4V (130 ksi UTS). HVOF coatings were WC/10Co4Cr, Cr_3C_2/20(80Ni-20Cr) and Tribaloy 400 (T400, nominal composition 57Co-28.5Mo-8.5Cr-3.0Ni-3.0Si)

- Fatigue: All HVOF coatings on 4340 and PH15-5 steel were equal to or better than EHC, with T400 having significantly better fatigue. There was some cracking of the HVOF coatings at the highest loads as well as at the highest cycles. Spalling of the HVOF coatings occurred on 4340 at the highest load (160ksi) and at the highest cycles (9.5 million cycles). There was cracking, but no spalling, on the PH15-5 specimens. The data on Ti-6Al4V were unreliable since neither the EHC nor the HVOF coatings adhered properly – EHC because of inadequate activation and HVOF because the surface was not grit blasted so as to avoid embedding grit particles. All the EHC coatings on Ti-6Al4V spalled, while the HVOF coatings also spalled over some of their range.
- Salt Fog Corrosion (ASTM 1,000 hour B117): As in previous tests, the EHC coatings in general provided somewhat better appearance rankings than HVOF coatings. Thicker EHC or HVOF coatings did not in general provide any better protection. Both rods and flat panels were evaluated, with no consistent performance differences between them. Previous HVOF EHC replacement projects determined that there is very poor correlation between the standard B117 cabinet testing of HVOF and EHC coatings and their actual performance in beach exposure and in service. Since the B117 corrosion behavior on the substrates in this testing is similar to what has been seen in other evaluations, it is expected that the service performance of HVOF coatings on these substrates is likely to be better than that of EHC, just as it is on 300M and fully hardened 4340.
- Fluid Immersion: The coatings were tested for weight loss and roughening in a wide variety of commonly-used cleaners, etchants, hydraulic fluids, fuels and other chemicals likely to be encountered during MRO or in service. WC/CoCr and Cr_3C_2/NiCr were not affected by any of these chemicals, while T400 showed slight attack by strong cleaners and reactive chemicals. The one exception was that the Co-containing coatings, WC/CoCr and T400, were both strongly attacked by bleach (sodium hypochlorite). Bleach is not an approved MRO chemical, but is sometimes used as a disinfectant on commercial aircraft during disease outbreaks. Cr_3C_2/NiCr was unaffected.
- Environmental Embrittlement (200 hour ASTM F519): None of the coatings, including EHC, caused environmental embrittlement (re-embrittlement) in DI water or 5% NaCl solution.
- Functional Rod-Seal Testing: Testing was run by NAVAIR, Patuxent River,

using HVOF WC/CoCr with different surface finishes, using actuator speeds and temperatures intended to simulate service conditions. Several seals from different manufacturers were tested – O-ring with capstrip, O-ring with two backup rings, fluorosilicone O-ring with PTFE cap and spring energized PTFE. In almost all cases the HVOF coatings gave significantly less leakage than the EHC, the only exception being a seal system of an O-ring with two backups, where the performance of HVOF and EHC was the same. Surprisingly, the ground (not superfinished) rods had the least leakage of all. However, they did smooth out over time, whereas the superfinished rods showed only very faint scratches. (The EHC coated rods showed considerable scratching.) There was very little seal damage or rod damage, especially when using superfinished coatings. Tape superfinished coatings performed slightly better than stone superfinished. Overall the best performance was for a superfinished rod with either a MIL-P-83461 O-ring with PTFE cap strip or spring energized PTFE seals with backup ring.

- Component Testing and Qualification: Testing of actuators with HVOF-coated rods was carried out by the Oklahoma City Air Logistics Center Airborne Accessories Directorate Avionics and Accessories Division (OC-ALC/LGERC). Flight control actuators, utility actuators and snubbers were tested, with test components chosen to permit qualification of additional components by similarity. Overall, actuators with HVOF-coated rods were found to perform as well as or better than those with EHC-coated rods, although in some cases different seals were required. A number of actuators have passed rig tests and are going into service testing. Actuators tested were: C130 Rudder Booster Actuator, A-10 Aileron Actuator, C/KC-135 Aileron Snubber (passed testing, to be service tested); B-1 Horizontal Stabilizer (endurance testing successful, no service tests needed, drawings updated, Tech Order and stocklist updates in progress); B-1 Pitch/Roll SCAS (testing in progress); F-15 Pitch/Roll Channel Assembly (to be tested); T-38 Aileron (testing successful); C-130 Ramp and C-KC-135 Main Landing Gear Actuators (passed testing with change to seal specification, to be service tested); C/KC-135 Main Landing Gear Door (qualified for service testing); Navy F/A-18 C/D Stabilator and Trailing Edge Flap (same leakage as EHC, but fewer scratches, Engineering Change Proposal validated).

Cost/Benefit Analysis (CBA): A CBA was conducted at a facility that overhauls aircraft components including landing gear and actuators and which currently utilizes hard chrome plating on many components. For replacement of the chrome plating with HVOF thermal spray coatings on the combined landing gear and actuator workload, the analysis predicted a 15 year NPV of $18 million, which rose to $25 million when performance improvements were added. Taking into account the new OSHA Cr^{6+} PEL raised the payback slightly, but a major contributor to economic payback is the improved performance afforded by HVOF, which reduces the need for stripping and replacing rod coatings. This also directly reduces waste streams.

Stakeholder and End-User Issues: HVOF coatings on actuator rods will generally work better than EHC, with less leakage and lower wear of both rod and seal. However, the rod should be superfinished and the seal may need to be changed to an energized PTFE design.

During the most recent European outbreak of hoof-and-mouth disease, aircraft wheels were sprayed with bleach to inhibit the spread of the disease. Test results clearly showed that bleach will dissolve Co-containing coatings such as WC/CoCr, which could lead to fluid loss, seal damage, or even stress-corrosion cracking. An alternative disinfectant should be used in place of bleach for aircraft landing gear, wheels and brakes.

It is clear from testing performed in this project that if Ti alloys are to be HVOF-coated they should be grit blasted, although this should probably be done at an angle and at a lower pressure than usual to avoid embedding grit. This is in accord with current industry practice on components such as titanium flap tracks.

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List of Acronyms/Symbols

ALC	Air Logistics Center
AFB	Air Force Base
AMS	Aerospace Materials Specification
ANOVA	analysis of variables
ANG	Air National Guard
ANSI	American National Standards Institute
ASTM	American Society for Testing and Materials
BAC	Boeing Aircraft Corporation
BMS	Boeing Materials Specification
CAA	Clean Air Act
CBA	cost/benefit analysis
CCAD	Corpus Christi Army Depot
CFR	Code of Federal Regulations
CWA	Clean Water Act
DI	deionized
DOD	Department of Defense
ECAM	Environmental Cost Analysis Methodology
EHC	electrolytic hard chrome
EPA	Environmental Protection Agency
ESTCP	Environmental Security Technology Certification Program
FPI	fluorescent penetrant inspection
FTE	full-time equivalent
GEAE	GE Aircraft Engines
GTE	gas turbine engine
HA	hydraulic actuator
HCAT	Hard Chrome Alternatives Team
HEPA	high-efficiency particulate arresting
hex-Cr	hexavalent chromium
HV	Vickers hardness number
HVOF	high-velocity oxygen-fuel
IARC	International Agency for Research on Cancer
ID	internal diameter
IRR	internal rate-of-return
JG-PP	Joint Group on Pollution Prevention
JTP	joint test protocol
ksi	thousands of pounds per square inch
Kt	stress intensity factor

MRO	maintenance, repair and overhaul
NADEP-CP	Naval Air Depot Cherry Point
NADEP-JAX	Naval Air Depot Jacksonville
NAVAIR	Naval Air Systems Command
NAVSEA	Naval Sea Systems Command
NDI	non-destructive inspection
NPV	net present value
OC-ALC	Oklahoma City Air Logistics Center
OD	outside diameter
OEM	original equipment manufacturer
OO-ALC	Ogden Air Logistics Center
OSHA	Occupational Safety and Health Administration
PEL	permissible exposure limit
PEWG	Propulsion Environmental Working Group
PPE	personal protective equipment
PRCA	pitch/roll channel assembly
psi	pounds per square inch
PTFE	designation for Teflon
QC	quality control
Ra	arithmetic average surface roughness
RCRA	Resource Conservation and Recovery Act
Rp	maximum peak height in surface profile
rpm	rotations per minute
RSL	rising step load
Rz	10-point average of highest peaks and lowest valleys
SAE	Society of Automotive and Aerospace Engineers
scfh	standard cubic feet per hour
SEM	scanning electron microscopy
T400	Tribaloy 400
TETA	triethylenetramine
TO	technical order
Tp	bearing ratio in surface profile
TRI	toxic release inventory
TWA	time-weighted average
UTS	ultimate tensile strength

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1. Background and Introduction

The replacement of hard chrome plating in aircraft manufacturing activities and maintenance depots is a high priority for the U.S. Department of Defense (DOD). Hard chrome plating is a technique that has been in commercial production for over 50 years and is a critical process that is used both for applying hard coatings to a variety of aircraft components in manufacturing operations and for general re-build of worn or corroded components that have been removed from aircraft during overhaul. In particular, chrome plating is used extensively on hydraulic actuator (HA) components such as piston rods. Chromium plating baths contain chromic acid, in which the chromium is in the hexavalent state, with hexavalent chromium (hex-Cr) being a known carcinogen having a level of toxicity greater than arsenic or cadmium. 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 EPA emissions standards and OSHA permissible exposure limits (PEL).

A significant lowering of the hex-Cr PEL would most likely have the greatest cost impact on military and commercial repair facilities. Such a change has been expected since the mid 1990's. But it was only in 2004 that OSHA began the process to issue a new PEL as a result of a lawsuit filed in 2002 by a citizens group and union that petitioned OSHA to issue a lower PEL, and a subsequent ruling by a Federal District Court upholding the petition [1]. The court ruling required OSHA to publish a new draft hex-Cr PEL in the Federal Register no later than October 2004. Public review and hearings would be conducted in 2005, with a final rule issued in January 2006. In October 2004 OSHA proposed a new PEL of 1 $\mu g/m^3$ with a 0.5 $\mu g/m^3$ action level, which represents almost a two-order-of-magnitude reduction from the current PEL of 52 $\mu g/m^3$. The expected compliance costs in all industries including electroplating, welding, painting and chromate production was estimated to be \$226 million. On 28 February 2006 the final rule was promulgated at 5 $\mu g/m^3$, with an action level of 2.5 $\mu g/m^3$. While this is a factor of five higher than the initial proposed rule, it will effectively require that facilities maintain a level close to 1 $\mu g/m^3$ in order to stay below the action level. The difficulty and cost of doing this will be substantial.

As stated above, a change in the hex-Cr PEL has been expected since the mid 1990's. In anticipation of the change, in 1995 a Navy/Industry task group under the coordination of the Naval Sea Systems Command studied the technical and economic impact of a reduction in the hex-Cr PEL [2]. At the time, a reduction in the 8-hour time-weighted average (TWA) from the existing 100 $\mu g/m^3$ to between 0.5 and 5.0 $\mu g/m^3$ was being considered. The Navy/Industry task group performed the following tasks:

- Identified the manufacturing and repair operations, materials and processes that are used in Navy ships, aircraft, other weapons systems and facilities where worker exposure to hex-Cr would be expected
- Developed data on current worker exposure levels to hex-Cr using OSHA Method 215
- Estimated the technical and economic impact of the anticipated reductions in hex-

Cr exposure on Navy ships, aircraft, other weapons systems and facilities

- Identified future actions required to comply with the anticipated PEL reductions

The following operations within the Navy were identified as having the potential for exposing workers to hex-Cr:

- Metal cleaning (including abrasive blasting and grinding) of chromate-coated materials
- Electroplating of chromium
- Painting and application of chromate paints and coatings
- Welding, thermal spraying and thermal cutting

The following conclusions were reached by the task group:

1. Regulated areas for hex-Cr would have to be created in much greater numbers than have been required for cadmium or lead exposure
2. Local exhaust ventilation, which is the presently available engineering control, is not completely effective in reducing exposure to below 0.5 $\mu g/m^3$ for many operations or even below 5 $\mu g/m^3$ in some cases
3. The inability of engineering controls to consistently reduce worker exposure below the anticipated PEL levels will significantly increase the use of respirators
4. The costs of reducing the hex-Cr PEL will include costs for training, exposure monitoring, medical surveillance, engineering controls, personal protective equipment, regulated areas, hygiene facilities, housekeeping and maintenance of equipment. There will also be costs due to reduced efficiency of not only the operations involving hex-Cr but adjacent operations and personnel as well.
5. The estimated costs for compliance with a PEL of 0.5 $\mu g/m^3$ at Navy facilities include an initial, one-time cost of about $22,000,000 and annual costs of about $46,000,000 per year.
6. The estimated costs for compliance with a PEL of 5.0 $\mu g/m^3$ at Navy facilities include an initial, one-time cost of about $3,000,000 and annual costs of about $5,000,000 per year
7. In addition to the greatly increased cost that would be associated with chrome plating, turnaround times for processing of components would be significantly increased as well, impacting mission readiness.

Based on the projections of the metal finishing industry and the study conducted by NAVSEA in 1995, it is clear that a reduction of the hex-Cr PEL to a 5 $\mu g/m^3$, although higher than the original proposed level, will greatly increase the cost and processing times associated with hard chrome plating within DOD.

Previous research and development efforts had established that high-velocity oxygen-fuel (HVOF) thermal spray coatings are the leading candidates for replacement of hard chrome [3,4]. Using commercially available thermal spray systems, HVOF thermal spraying can be used to deposit both metal alloy and ceramic/metal (e.g., WC/Co) coatings that are dense and highly adherent to the base material. They also can be applied to thicknesses in the same range as that currently being used for chrome plating.

In order to conduct the advanced development work required for qualification of the HVOF coatings, a project titled, "Tri-Service Dem/Val of Chromium Electroplating Replacements," principally sponsored by the Environmental Security Technology Certification Program (ESTCP), was established in March 1996. A project team, designated the Hard Chrome Alternatives Team (HCAT) was established to execute the project. From 1996 to early 1998, the HCAT acquired and installed HVOF thermal spray systems at the Naval Aviation Depot in Cherry Point, North Carolina (NADEP-CP) and the Corpus Christi Army Depot (CCAD). It also performed some generic fatigue and corrosion testing on HVOF WC/17Co and Tribaloy 400 coatings compared to electrolytic hard chrome (EHC) coatings. In general, the performance of the HVOF coatings was superior to that of the EHC coatings.

While these studies were valuable, it was realized in early 1998 that because hard chrome plating was being used on such a wide variety of aircraft components, it would be impossible to develop one test plan or conduct one series of tests that would address all materials and component qualification requirements. It was therefore decided to develop separate projects related to categories of aircraft components onto which hard chrome was being used. At the same time, the DOD Joint Group on Pollution Prevention (JG-PP) decided to partner with the HCAT on development and execution of the various projects. JG-PP is chartered by the Joint Logistics Commanders to coordinate joint service pollution prevention activities during the acquisition and sustainment of weapons systems. It was jointly determined by the HCAT and JG-PP that the first projects to be executed would be on landing gear and propeller hubs, with projects on hydraulic actuators and helicopter dynamic components to come later. The landing gear and propeller hub projects have now been completed with extensive materials testing generally showing that HVOF coatings such as WC/17Co demonstrate performance superior in fatigue and wear to EHC coatings. Mixed results were obtained for corrosion, with the HVOF coatings superior in atmospheric testing but inferior in salt fog cabinet testing. Rig and flight tests on WC/17Co-coated components showed acceptable performance for the HVOF coatings and, in many cases, superior performance to what would be expected had the components been coated with EHC. As a result of these projects, HVOF is being implemented at a number of Air Force and Navy repair facilities for processing of landing gear and propeller hub components. Final reports on both of these efforts have been issued as archival publications [5,6].

The HCAT in partnership with the DOD Propulsion Environmental Working Group (PEWG) executed a project on qualifying HVOF thermal spray coatings as an EHC replacement on gas turbine engine (GTE) components. Extensive materials and component testing was performed, with the result that HVOF WC/Co has been qualified on several TF33 components and is currently being implemented at Oklahoma City ALC (OC-ALC). It is expected that HVOF coatings on additional components from other engines will be qualified and implemented at OC-ALC as well. A final report on this project has been issued as an archival publication [7].

As mentioned above, the qualification of HVOF thermal spray coatings to replace EHC plating on hydraulic actuators represented the third joint HCAT/JG-PP project. Table 1-1 summarizes the current applications for EHC plating on actuator components and the current specifications used for that application. The execution of the project to qualify the HVOF coatings to replace EHC involved development of materials testing requirements, functional rod/seal test requirements, delta qualification testing on actuators, and a cost/benefit analysis. Stakeholders from the three services, aircraft OEMS, and actuator and seal manufacturers were brought together at a meeting to develop a Materials Joint Test Protocol (JTP) that covered all of the materials test requirements [8]. In addition, a test plan for the functional rod/seal testing to be conducted at NAVAIR Patuxent River was also developed. The Cognizant Authority for actuators within the Air Force, located at Tinker Air Force Base, together with their contractor ARINC developed delta qualification and service implementation test plans for qualification of HVOF WC/CoCr coatings.

This Final Report provides detailed information on all work performed under the project.

Section 2 provides a description of HVOF thermal spray technology including a discussion of the advantages and disadvantages of the technology for EHC replacement.

Section 3 presents results for all of the work performed under the Materials JTP including a description of the coatings deposition parameters plus results of the fatigue, corrosion, fluid immersion and environmental hydrogen embrittlement studies.

Section 4 presents results for the functional rod/seal testing performed at NAVAIR Patuxent River.

Section 5 presents an overview of the Air Force delta qualification and service testing. As of this writing, much of the work is continuing, so the results cover work performed through January 2006.

Section 6 presents the results of a cost/benefit analysis for replacement of EHC with HVOF thermal spray coatings for processing hydraulic actuator components at a DOD repair facility.

Finally, Section 7 discusses issues associated with implementation of thermal spray technology at hydraulic actuator repair facilities.

In this report there are a number of references to specific standards related to coatings deposition, materials processing, and materials testing. These are listed in Table 1-2.

Table 1-1 Summary of Targeted Process, Applications and Specifications

Target HazMat	Current Process	Application	Current Specifications	Candidate Parts/ Substrates
Hexavalent Chromium	Hard Chromium Electro-plating	Rebuilding Worn Components Wear-resistant Coating Corrosion-resistant Coating	DOD-STD-2182 MIL-C-20218F MIL-STD-1501C QQ-C-320B AMS 2408	Flight-control and utility hydraulic actuators

Table 1-2 Applicable Materials Processing, Coating Deposition, and Test Standards.

ASTM E466:	Standard Practice for Fatigue testing
ASTM E606:	Standard Practice for Strain Controlled Fatigue Testing
ASTM B117:	Standard Practice for Salt Spray (fog) Apparatus, Operating
Boeing Aircraft Corporation (BAC) Standards:	
BAC 5851:	Deposition of HVOF thermal spray coatings
Military Specifications:	
MIL-H-6875:	Heat Treatment of 4340 Steel
MIL-STD-1501C:	Chromium Plating Low Embrittlement, Electrodeposition
MIL-STD-866:	Grinding of Chrome Plated Steel and Steel Parts Heat Treated to 180,000 psi or over
MIL-STD-1504:	Abrasive Blasting
QQ-C-320B:	Chromium Plating (Electrodeposited)
QQ-N-290:	Sulfamate Nickel Plating
SAE Standards:	
AMS-2432:	Shot Peening, Computer Controlled
AMS-5604:	Heat Treatment of 17-4PH Steel
AMS-5660:	Heat Treatment of IN-901 Alloy
AMS-6875:	Heat treating of high strength Steels
GE Aircraft Engine (GEAE) Specifications:	
C50TF103, Class B:	Forging of IN-718
C50TF58, Class A:	Forging of A-286
C50TF53, Class A or B:	Forging and heat treatment of AM-355
C50TF37, Class B:	Heat treatment for IN-718
C50TF20, Class A:	Heat treatment for A-286
C50TF50-S8:	Heat treatment and carburization of 9310
Word Drawing 4013195-990:	Low-stress grinding of materials

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2. Technology Description

2.1. Technology Development and Application

Technology background and theory of operation: High-velocity oxygen-fuel (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). The powder particles are accelerated to high speed and soften in the flame, forming a dense, well-adhered coating on the substrate (see Figure 2-1). The coating material is usually a metal or alloy (such as Tribaloy or stainless steel), or ceramic particles in a metal matrix, designated 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.

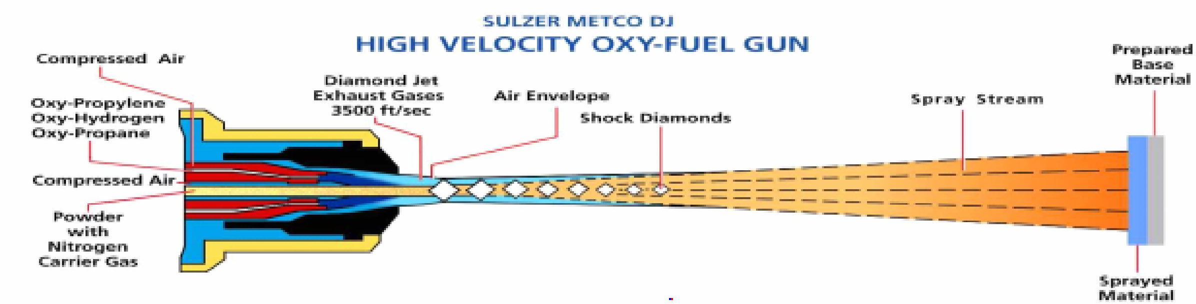

Figure 2-1 Schematic of HVOF Gun and Process (Sulzer Metco DiamondJet)

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 a variety of 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, primarily used 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 EHC plating (especially using carbide cermets and high temperature oxidation-resistant Tribaloys). The combination of HVOF 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 hand-held 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 six-axis robot arm in a sound-proof 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 2-2 which shows the HVOF spraying of a landing gear inner cylinder. A similar setup would be used for the spraying of hydraulic actuator piston rods.

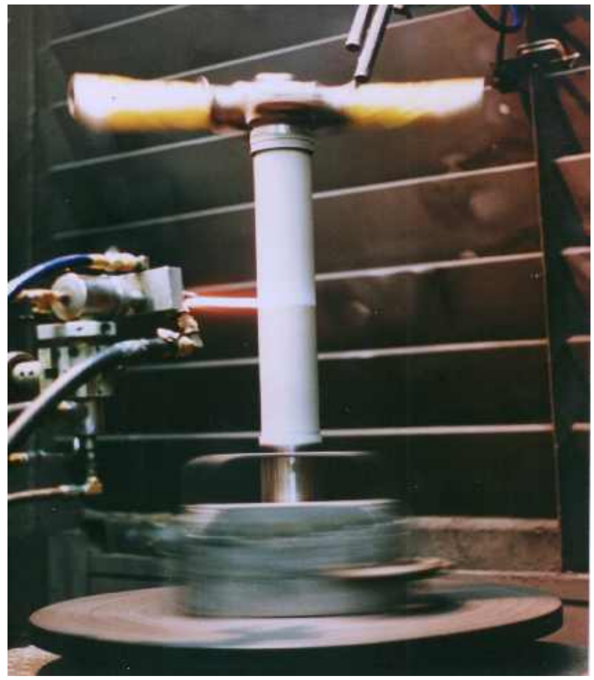

Figure 2-2 HVOF Spray of Landing Gear Inner Cylinder

Facility Design: The installation requires:

- 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 60μm 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.
- 6-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 scfh, even a standard 12-bottle setup lasts only a few hours in production.
- Supply of fuel gas or kerosene (bottled or bulk). Hydrogen is the most common fuel, supplied in bulk or in bottles. Praxair (TAFA) guns use kerosene, which is significantly cheaper and less dangerous. There are also systems that utilize natural gas which is considerably less expensive.
- 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 blown into a standard bag house, often located outside the building, where the dust is removed.
- Dry, oil-free compressed air for cooling the component and gun. Air cooling prevents the components being overheated (temperatures must be kept below about 400°F for most high strength steels).
- Water cooling for gun. Not all guns are water cooled, but most are.

Table 2-1 provides examples of optimized parameters for deposition of WC/17Co on high-strength steel using two standard, readily available HVOF thermal spray systems, the DiamondJet DJ-2600 manufactured by Sulzer Metco and the JP-5000 manufactured by Praxair TAFA. It should be pointed out that there are many companies that are capable of providing complete turnkey HVOF systems.

Performance: From Table 2-1, HVOF guns deliver about 4-5 kg of material per hour, of which 65% typically enters the coating, for a coating rate of about 3 kg/hour. For a common 0.010”-thick WC/Co rebuild coating (which will be sprayed to a thickness of 0.013”-0.015” and ground to final dimension), an HVOF gun can deposit about 900 in^2/hr. This permits the coating of the outside diameter of a 25”-long, 4”-diameter cylinder in about 30 minutes, compared with about 12 hours for chrome plating.

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

- Prior to the HCAT program, the only aerospace specifications were those issued by OEMs 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.
- In order to provide specifications for spraying high strength aircraft steels at depots and vendors, HCAT has worked through the Society of Automotive and Aerospace Engineers (SAE) to promulgate several standards:
    - AMS 7881 is a powder specification for WC/Co and AMS 7882 is a powder specification for WC/CoCr that were both issued in April 2003.
    - AMS 2448 is a specification describing procedures for spraying WC/Co

and WC/CoCr coatings using HVOF onto high-strength steel that was issued in August 2004

AMS 2449 is a specification describing procedures for low-stress grinding of HVOF WC/Co and WC/CoCr coatings that was issued in August 2004

Table 2-1 Optimized Deposition Conditions for WC/17Co - DJ 2600 and JP 5000 HVOF Systems

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 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 gph (factory set)	8.3-8.7 gph
	Water Temperature to Gun:	65-80°F typical (ground water, temp varies)	64-72°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

Training: Just as plating shops typically have several personnel who handle masking, racking, demasking, etc., it is common for HVOF shops to have 3 or 4 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.

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 (8hr TWA) of 100 μg/m^3 is lower than the 1000 μg/m^3 for metallic chromium, but is substantially higher than the current 5 μg/m^3 for Cr^{6+}. 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 60 μm in diameter, they can break apart on impact, producing 10 μm 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. Advantages and Limitations of the Technology

Replacing hard chrome plating is a great deal more complex than simply putting down a hard coating. The alternative must not only work technically, but it 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 2-2.

Table 2-2 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
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. Materials Testing

3.1. Development of Materials JTP

Required testing and performance objectives under the JTP consisted of materials testing performed on coupons manufactured from representative materials from which EHC-plated hydraulic actuator components are fabricated. A stakeholders meeting was held in October 2003 in Los Angeles to discuss the testing requirements and create a first draft of the JTP. There were numerous revisions generated through electronic correspondence among the stakeholders, with a final version [8] approved in 2004. The stakeholders who were involved in the JTP development were:

NAVAIR Patuxent River

NADEP Jacksonville

NADEP Cherry Point

Oklahoma City ALC (Cognizant AF Engineering Authority for actuators)

Ogden ALC

Propulsion Environmental Working Group (PEWG)

Boeing Long Beach

Parker Hannifin

Smiths Aerospace Actuation Systems

Shamban Aerospace Seals

HR Textron

Moog Aircraft Group

Saint-Gobain Performance Plastics

Greene Tweed & Co.

CoorsTek

The specific types of materials tests delineated in the JTP were fatigue, corrosion, fluid immersion and environmental hydrogen embrittlement. A detailed description of these tests with the results can be found later in this section. The performance objectives, also called acceptance criteria, were as follows:

Fatigue: Cycles-to-failure at different stress or strain levels were measured for fatigue specimens coated with either EHC or an HVOF coating. These data were plotted with stress/strain on the vertical axis and cycles-to-failure on the horizontal axis and smooth curves were fit to the data points. If the curves for the thermal spray coatings fell on or above those for the EHC, then the thermal spray coatings were considered to have passed the acceptance criteria.

Corrosion: American Society for Testing and Materials (ASTM) B117 salt-fog exposure tests were conducted on specimens coated with EHC and various HVOF coatings. Protection ratings were determined in accordance with ASTM specifications. If the average ratings for the HVOF coatings were greater than or equal to those for EHC, then the thermal spray coatings were considered to have passed the acceptance criteria.

Fluid immersion: Steel specimens coated with several different HVOF coatings were immersed for specified periods of time. If no visible chemical attack or weight-loss was observed, then the coatings were considered to have passed the acceptance criteria.

Environmental hydrogen embrittlement: ASTM F519 Type 1a.2 notched specimens were coated with EHC or various HVOF coatings and then a cut was made at the base of the notch exposing the base material. The specimens were then immersed in deionized water or a 5% NaCl solution and loaded to 45% of the notch fracture strength. If the specimens did not fracture after 200 hours of immersion, then they were considered to have passed the acceptance criteria.

3.2. Substrate Material Selection

The stakeholders selected three alloys, 4340 steel, PH15-5 stainless steel and Ti-6Al-4V, as the base materials for evaluating the HVOF coatings compared to EHC plating. These alloys were viewed as being most representative of the alloys used in hydraulic actuators on which EHC is currently applied. The composition of the alloys is given in Table 3-1.

Table 3-1 Composition of Alloys Selected for Testing

Composition in Weight %												
Alloy	**Ni (+Co)**	**Cr**	**Fe**	**Mo**	**Nb+ Ta**	**Ti**	**Al**	**C**	**Mn**	**Cu**	**Si**	**V**
4340	1.75	0.8	95.8	0.25	----	----	----	0.40	0.70	----	0.3	----
PH15-5	3.5-5.5	14.0-15.5	~ 75	-----	0.15-0.45	----	----	0.07	1.00	2.5-4.5	1.00	----
Ti-6Al-4V	----	----	0.13	----	----	~ 90	6.0	0.04	----	----		4.0

Table 3-2 provides the tensile strength values for each alloy which defines the type of heat treatment to which each alloy was subjected.

Table 3-2 Tensile Strength Values for Each Alloy

Material	Tensile Strength
4340	180-200 ksi
PH15-5	155 ksi (condition H1025)
Ti-6Al-4V	130 ksi (annealed condition)

3.3. Coatings Selection, Deposition and Characterization

3.3.1. Coatings Selection

The stakeholders selected three HVOF thermal spray coatings to be compared to EHC plating for the materials tests. These were:

WC/10Co4Cr

Cr_3C_2/20(80Ni-20Cr)

Tribaloy 400 (nominal composition 57Co-28.5Mo-8.5Cr-3.0Ni-3.0Si)

3.3.2. Surface Preparation

In general, test specimens were fabricated and shot-peened in one facility and then transported to the facility performing the coating application. The surfaces of the test specimens onto which the coatings were to be applied were shot peened using cut wire (CW-14) to an intensity of 8-10A in accordance with AMS-2432 under computer control with 100% surface coverage. The Ti-6Al-4V specimens were cleaned with nitric acid immediately following shot peening.

At the coating facility, the surfaces of the test specimens onto which the coatings were to be applied were grit blasted not more than 2 hours prior to coating deposition. Surfaces to receive EHC plating were grit blasted with #13 glass bead in accordance with AMS-QQ-C-320. Surfaces to receive the HVOF coatings were grit blasted with 54-60 mesh aluminum oxide at 40-60 psi at a 90º angle of impingement in accordance with MIL-STD-1504. A uniform standoff distance of 4-6 inches was used. **The Ti-6Al-4V was not grit blasted due to concerns about embedded grit creating stress risers that could affect mechanical properties such as fatigue.** The Ti-6Al-4V was cleaned with acetone immediately prior to coating application.

3.3.3. Chrome Plating and Surface Finishing

The EHC coatings were deposited in accordance with MIL-STD-1501D (Class 2, Type II), supported by AMS-QQ-C-320. There was no interfacial layer between the specimen and EHC coating. No sealer was applied to the EHC. Table 3-3 indicates the EHC plating parameters.

Table 3-3 EHC Plating Parameters

Parameter	Condition
CrO_3	225-270 gm/l
SO_4	2.25-2.70 gm/l
Anode	Lead
Current Density	360 A/ft^2
Bath Temp	130-140°F
Deposition Rate	0.001” per hour

The as-deposited thickness was at least 0.002” greater than the final required thickness. Subsequent to application, each specimen was baked at 375º F for 23 hours to remove any hydrogen. Then the coating was ground to final dimension with and Ra surface finish of 12-16 microinches using low-stress grinding techniques in accordance with MIL-STD-866.

3.3.4. HVOF Coating Deposition and Surface Finishing

The HVOF coatings were applied to test specimens within 30 minutes after grit blasting. They were applied using a Sulzer Metco Diamondjet hybrid HVOF thermal spray gun in accordance with Boeing Specifications BAC 5851, Class 2, with the types as indicated in Table 3-4. Uniform deposition conditions were utilized for all specimens. Air cooling and/or built in pause times off the specimen as required were utilized to ensure the surface temperature did not exceed 375°F for all specimens. To ensure uniform internal stress in the coatings, initial depositions were made on Almen N strips, with the deposition parameters adjusted such that the Almen N values as indicated in Table 3-4 were obtained.

Table 3-4 HVOF Coating Deposition Specifications and Almen N Strip Values

Coating	Spec.	Almen N range
WC-10Co4Cr	BAC 5851, Class 2, Type XVII	4-12
Co-28 Mo-8 Cr-2 Si (Tribaloy T-400)	BAC 5851, Class 2, Type XV, optimized per HCAT specs	4-12
Cr_3C_2-20/Ni-Cr	BAC 5851, Class 2, Type XVI	4-12

Prior to application of the actual coating, the specimens were preheated using the HVOF gun to a temperature sufficient to remove all moisture. The substrate preheat temperature did not exceed 375°F. The temperature on the surface of the specimens was measured using a laser sighted infrared thermometer with adjustable emissivity (0.1 to 0.99) and response time of less than 1 second. The measurement was made one spot removed from the trailing edge of the plume path as it traversed the area being coated. To avoid oxidation, the Ti-6Al-4V specimens were not preheated.

Air cooling was used to ensure the specimen surface temperature did not exceed 375°F. The angle of incidence of the spray plume to the surface of the specimen was maintained at 90º, although for small cylindrical specimens such as fatigue bars, the plume width was greater than the diameter of the gage section, so the particles were impinging on the surface at variable angles.

The as-deposited thickness of the HVOF coatings was generally 0.003”-0.004” greater than the final required thickness. After deposition, the coatings were ground with a diamond abrasive wheel to 8-10 Ra (10-14 Ra for T400) using low-stress grinding techniques in accordance with specification BAC 5855 with the following modifications:

> Paragraph 8.3.b.(1): If the excess coating thickness is less than 0.004”, then rough grinding is not required. A minimum of 0.002 inch stock removal (per side, or 0.004 inch on diameter) is required for finish grinding. The finishing in-feeds shall not exceed a maximum of 0.0005 inch for 100 or 120 grit, 0.0004 inch for 150 grit, 0.0003 inch for 180 grit, 0.0002 inch for 220 grit, or 0.0001 inch for 320 or 400 grit.

Paragraph 8.3.b.(3): Use a finishing cross feed or traverse rate of 1/8 to 1/12 wheel width per workpiece revolution.

Paragraph 8.3.c.(4): Hardness – L, M, N, P or R

Paragraph 8.3.d: When grinding ID or OD surfaces, the work should have a speed of 50 to 100 surface feet per minute.

For those coatings where superfinishing was specified, SupFina equipment was used. After low stress grinding the coating to an 8-10 Ra finish, it was superfinished using a 2.25” wide two diamond stone.

Table 3-5 summarizes all of the surface preparation, coating deposition and finishing requirements.

Table 3-5 Summary of Specimen Preparation, Coating, and Finishing Requirements.

#	Process	Process conditions	Notes
1	**Specimen preparation**		
1.1	Nital etch	MIL-STD-867	For grind burns
1.2	Hydrogen bake	375°F for 23 hours	
1.3	Shot peen	Shot peen per AMS-2432: 100% coverage, 8-10A, S110, wrought steel shot. For Ti6Al4V clean with nitric acid after peening.	Computer control
1.4	Clean		Within 4 hours prior to coating; use nitric acid on Ti alloy
1.5	Mask		All surfaces not to be blasted or coated
2	**Chrome plate**		
2.1	Grit blast	QQ-C-320: # 13 glass bead or 220 grit aluminum oxide	Within 2 hours prior to coating; do not grit blast Ti alloy – clean with acetone
2.2	Specification	MIL-STD-1501, plus QQ-C-320	
2.3	Thickness	0.002" – 0.004" thicker than final ground finish	±0.0005" of final thickness if to be tested in as-plated condition
2.4	Sublayer	None, unless otherwise specified	Ni underlayer may be specified
2.5	Hydrogen bake	375°F for 23 hours	
2.6	Sealer	None, unless otherwise specified	Vacuum impregnation or wipe-on wipe-off sealer may be specified
3	**HVOF spray**		
3.1	Grit blast	MIL-STD-1504: 54-60 mesh aluminum oxide, 40-60 psi, 90°	Do not grit blast Ti alloy – clean with acetone.
3.2	Equipment	HVOF gun	Any commercial unit
3.3	Specifications	BAC 5851 Class 2: WC/CoCr Type XVII T-400 Type XV Cr_3C_2-20/Ni-Cr Type XVI	Almen N number Carbides: 4-12 compressive T400: 6-12 compressive
3.4	Preheat	No more than 375°F	To remove moisture
3.5	Cooling	Air cool to maintain below 375°F	IR pyrometer required
3.6	Spray geometry	90° ±5° where possible; not <45°	
3.7	Spray QC samples	Include with each spray run	Same spray conditions as test specimens
4	**Surface Finish**		
4.1	Grind	MIL-STD-866 low-stress grinding: EHC: 12-16 microinch Ra HVOF: 8-10 microinch Ra, diamond T400: 10-14 microinch Ra	Infeeds < 0.0005" for 100/120 grit, 0.0004" for 150grit, 0.0003" for 180 grit, 0.0002" for 220 grit, 0.0001" for 320/400 grit
4.2	Superfinish	Supfina or equivalent stone, 2-4 microinch Ra.	

The deposition of the HVOF coatings onto various test specimens was performed by Hitemco, Inc. Table 3-6 indicates the exact deposition parameters that were used.

Table 3-6 HVOF Deposition Parameters

Parameter	WC/CoCr	Cr_3C_2/NiCr	T-400
Fuel	Hydrogen	Hydrogen	Hydrogen
Fuel flow rate	1214 scfh	1450 scfh	1420 scfh
Fuel pressure	135 psi	140 psi	150 psi
Oxidizer	Oxygen	Oxygen	Oxygen
Ox. flow rate	388 scfh	489 scfh	388 scfh
Ox. pressure	150 psi	170 psi	150 psi
Carrier gas	Nitrogen	Nitrogen	Nitrogen
CG pressure	148 psi	150 psi	140 psi
Powder feed rate	8.5 lbs/hr	10 lbs/hr	6.3 lbs/hr
Spray distance	11 inches	9 inches	10 inches

Because of the small diameter of the gage area, the spraying of fatigue specimens required a special configuration. Figure 3-1 shows the setup that was used, with a small metal bar simulating the fatigue specimen. A shadow mask with aperture was used to ensure the coating was only deposited as a "patch" in the gage area. To achieve a linear spray rate approximately equivalent to what would be used on a larger component required rotating the fatigue specimens at a very high rotational velocity. In general, the rotational velocity ranged from 130 to 190 surface-feet-per-minute which corresponded to a rotational velocity ranging from 2000 to 3000 rpm.

The surface temperature of the specimens was measured during HVOF coating deposition using an infrared pyrometer. Figure 3-2 shows a typical temperature chart obtained during the spraying, with the incursions occurring due to the spray plume moving on and off the specimen.

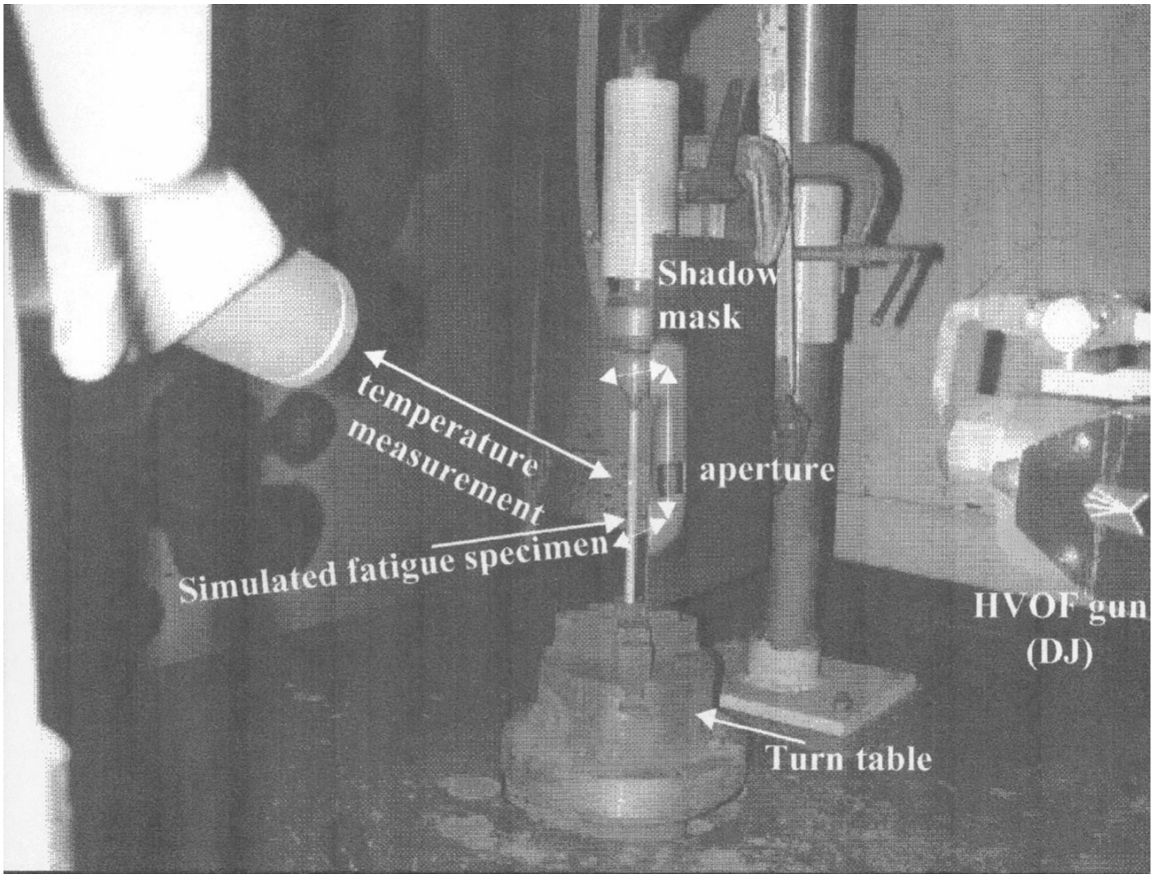

Figure 3-1 Photograph of the Setup Used for HVOF spraying of HVOF Fatigue Specimens

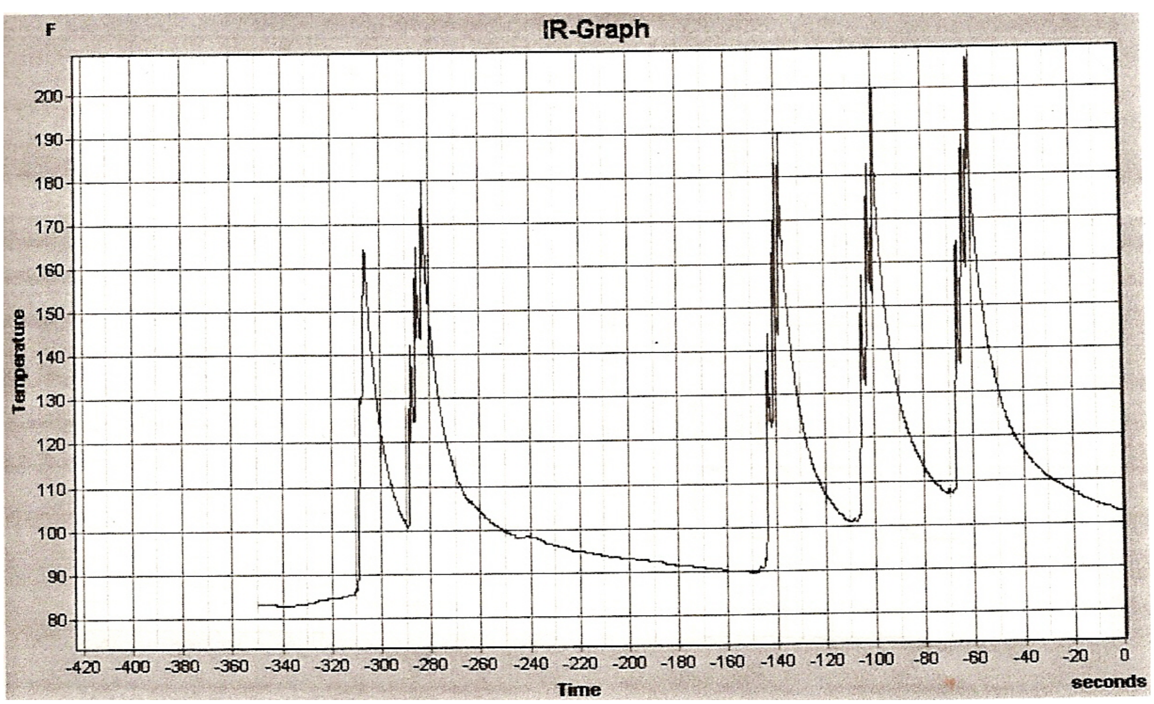

Figure 3-2 Typical Temperature Chart for HVOF Spraying of Fatigue Specimens.

3.3.5. HVOF Coating Characterization

Prior to each HVOF run, Hitemco deposited the HVOF coatings onto test coupons and characterized the coatings to ensure they were meeting the required characteristics and properties. Cross-section metallography was used to measure the porosity and amount of oxides in the coatings. Figure 3-3, Figure 3-4 and Figure 3-5 show typical cross-section micrographs of the WC/CoCr, Cr_3C_2/NiCr and T-400 coatings, respectively.

Figure 3-3 Cross-section Micrograph of Typical HVOF WC/CoCr Coating

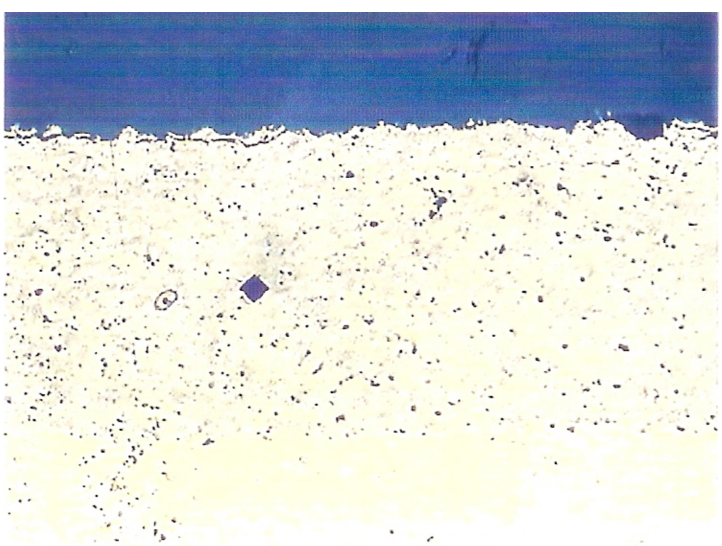

Figure 3-4 Cross-section Micrograph of Typical HVOF Cr3C2/NiCr Coating

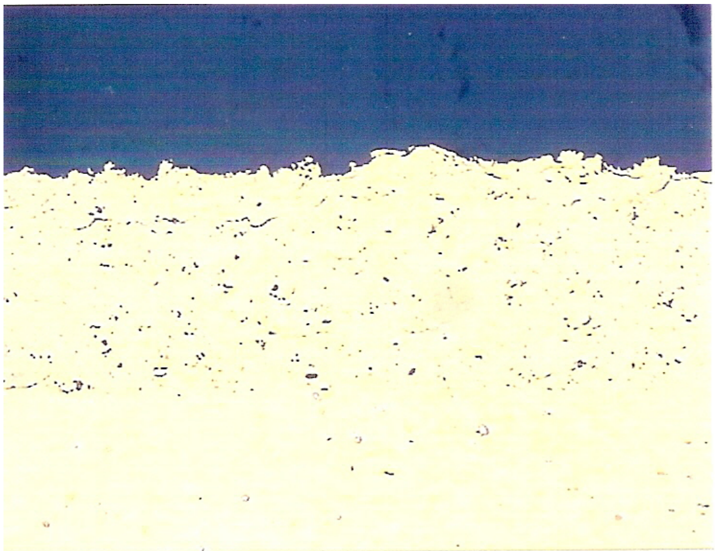

Figure 3-5 Cross-section Micrograph of Typical HVOF T-400 Coating

The Vickers microhardness of each coating was measured using an indenter load of 100 grams. Multiple measurements were taken across the surface and an average microhardness was computed. Adhesion bond strength measurements were taken in accordance with ASTM C-633. The strength of the epoxy was determined to be between 10,500 and 11,500 psi. For all HVOF coating adhesion measurements, the failure occurred in the epoxy, indicating that the coating bond strength exceeded 10,500 psi.

As indicated above, Almen N strips were used as a quality control method for determining the internal stress in the coatings. In all cases the internal stress was compressive. The specific methodology for spraying the Almen N strips was provided in the Materials JTP [8]. For different thickness coatings, Almen N numbers were normalized to a thickness of 0.005”.

Table 3-7 provides average values for oxide content, porosity, microhardness and Almen N values for each of the three HVOF coatings. By way of comparison, the Vickers microhardness for the EHC used in these studies ranged from 900-930 HV.

Table 3-7 Results of Measurements of Oxide Content, Porosity, Microhardness and Almen N Strip Values.

Parameter	WC/CoCr	Cr_3C_2/NiCr	T-400
Oxide Content	< 1% @ 200X	< 1% @ 200X	< 1% @ 200X
Porosity	< 1% @ 400X	1.0 – 1.5% @ 400X	< 1% @ 400X
Microhardness	1150 HV	1115 HV	650 HV
Almen N	10.5	5.7	9.3

3.4. Fatigue Testing

3.4.1. Data Summary

Table 3-8 Quick Reference to Primary Fatigue Data.

Material	Fatigue curve	Photos
4340		
Uncoated	Figure 3-7, Figure 3-8, Figure 3-10	
EHC	Figure 3-7, Figure 3-8, Figure 3-10	
WC/CoCr	Figure 3-7	
Cr_3C_2/NiCr	Figure 3-8	Figure 3-9
T400	Figure 3-10	
PH15-5		
Uncoated	Figure 3-11, Figure 3-13, Figure 3-15	
EHC	Figure 3-11, Figure 3-13, Figure 3-15	
WC/CoCr	Figure 3-11	Figure 3-12
Cr_3C_2/NiCr	Figure 3-13	Figure 3-14
T400	Figure 3-15	
Ti-6Al4V		
Uncoated	Figure 3-16, Figure 3-19, Figure 3-21	
EHC	Figure 3-16, Figure 3-19, Figure 3-21	Figure 3-17
WC/CoCr	Figure 3-16	Figure 3-18
Cr_3C_2/NiCr	Figure 3-19	Figure 3-20
T400	Figure 3-21	Figure 3-22

Click blue links to jump to data.

3.4.2. Test Rationale

The purpose of fatigue testing is to evaluate the effect of the coating on the fatigue of the underlying material, in particular comparing it with the fatigue debit induced by hard chrome plate. In addition, coatings must maintain their integrity under expected service conditions (i.e. not delaminate during testing at stresses seen in service, although delamination may occur on failure or at stresses in excess of service stresses).

Previous data has shown that HVOF coatings crack when their strain-to-failure is exceeded (typically at about 0.7% strain). Coatings tend to spall at a somewhat higher stress. Since actuator alloys are typically heat treated to have lower ultimate stress than landing gear alloys, yet have essentially the same elastic modulus, high strain effects such as coating integrity and spalling should be less significant for actuators. *Nevertheless, for safety and completeness, spalling checks were incorporated into the actuator fatigue JTP.*

Because the heat treatments, even for the same alloys, are typically different for actuators and landing gear, full data sets were required for all of the substrate/coating combinations.

3.4.3. Specimen Fabrication and Coating

All fatigue specimens were fabricated from round bar taken from the same heat treating lot for each material. Specimens were in the form of a standard hourglass bar, 0.25-inch gage diameter (see Figure 3-6). Specimens were shot peened to AMS 2432 under

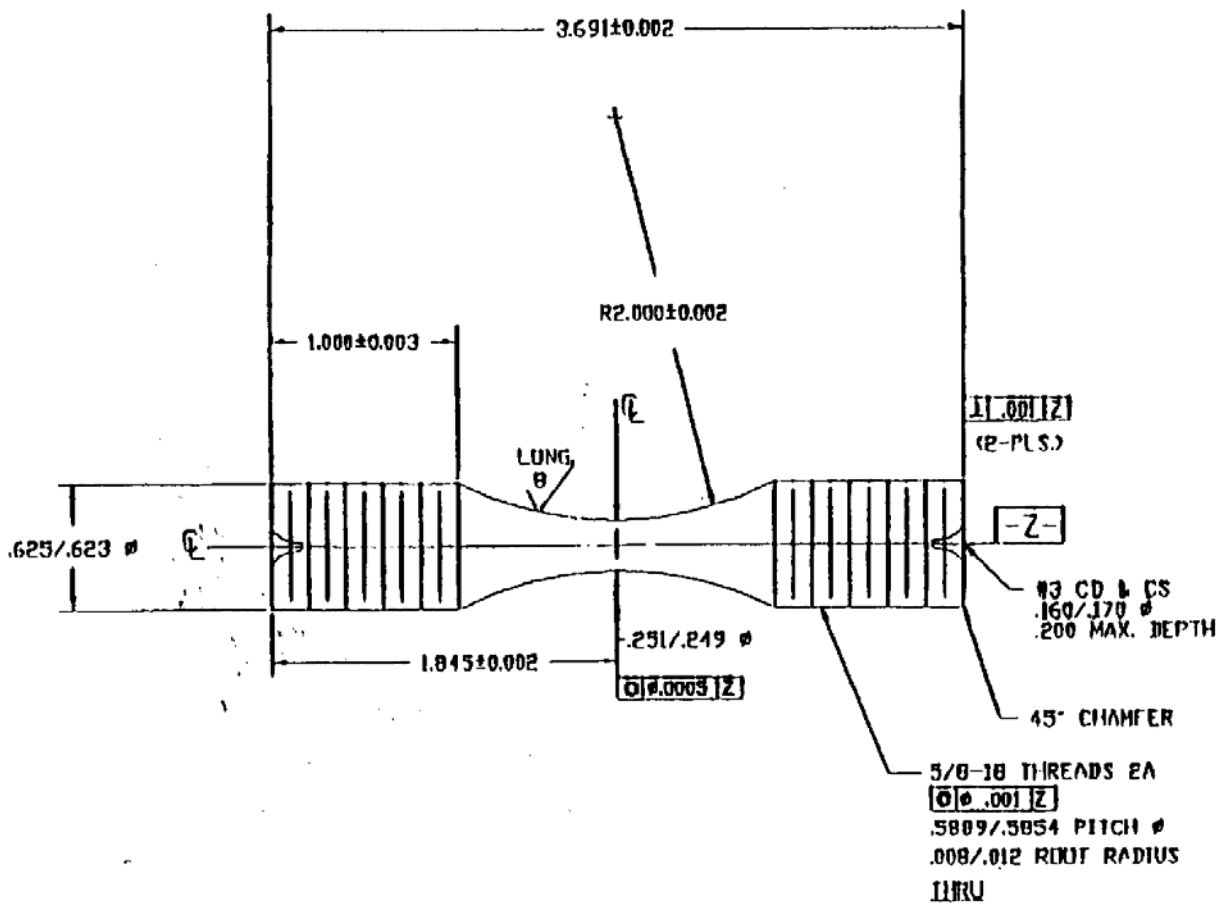

Figure 3-6. Hourglass fatigue specimen – ¼ “ diameter.

computer control to 100% surface coverage using 8-10A, S110, wrought steel shot.

Coating deposition was carried out as described in Section 3.3. Grit blasting was performed prior to HVOF spraying on all except the Ti-6Al4V substrates, as shown in

Table 3-9. Spraying was carried out over the gage length using the arrangement shown in Figure 3-1, and coatings were ground to a final thickness of 0.004" and a finish of 8-10 microinches Ra.

Table 3-9 Grit blasting requirements.

Coating	Blast medium	Spec	Notes
EHC	180-220 grit aluminum oxide or #13 glass beads	QQ-C-320	
HVOF on 4340 and PH15-5	54-60 mesh aluminum oxide	MIL-STD-1504	40-60 psi, 90°
HVOF on Ti-6Al4V	None		Clean with acetone only

3.4.4. Test Methodology

Load-controlled constant amplitude axial fatigue testing was conducted in accordance with ASTM E466-96 under the following conditions:

- Baselines – standard S-N curves for uncoated and hard chrome plated specimens
- Data at 10 points for all coated specimens. Loads were spread between the maximum used for the uncoated curves and the runout load.
- R ratio: R=-1
- Environment: Laboratory air at ambient temperature

Stress levels: Uncoated specimens were first run at the following loads to determine the stress-strain curve for each substrate:

- High load – approximately 85% of Fty (yield)
- Low load – A load at which the uncoated specimen fatigue life was approximately 10^6 cycles (runout defined as 10^7 cycles).
- Intermediate loads –Loads spread between the high and low load, usually with one point per load, but no more than two points per load.

During testing specimen surfaces were examined visually at approximately 25%, 50% and 75% of expected life, and finally after failure. Notations were made in the test data when cracking or spalling was observed. The surfaces were photographed if there was evidence of spalling. Not all surfaces showing cracking were photographed, but photographs were intended to show typical surface conditions. Note that, because cracking of these materials can be difficult to see, the fact that there was no notation does not necessarily imply that there was no cracking. Since spalling can be seen clearly, all spalls should have been recorded.

3.4.5. Test Results

The fatigue curves are plotted below for each substrate/HVOF coating combination, compared with the hard chrome fatigue curve and the uncoated points. The hard chrome curve is least squares fitted through the non-runout points. Points associated with photographs are indicated by a caption with a photograph number. (A notation with no number means that there was no accompanying photograph.)

3.4.5.1. 4340 substrate

HVOF WC/CoCr: The fatigue data are shown in Figure 3-7. The HVOF curve is essentially identical to that for EHC. No photographs of specimen surfaces were taken for this coating as there was only one HVOF spall, which occurred essentially at runout.

HVOF Cr_3C_2/NiCr : The fatigue data are shown in Figure 3-8. The HVOF curve is essentially identical to that for EHC, with one point somewhat low. Cracking of the HVOF coating was observed at runout at the lowest load, while spalling occurred in the highest stress region prior to failure at the highest load (Figure 3-9).

HVOF Tribaloy 400: The fatigue data are shown in Figure 3-10. The HVOF data are above those for EHC, especially at high cycles. No cracking or spalling was reported.

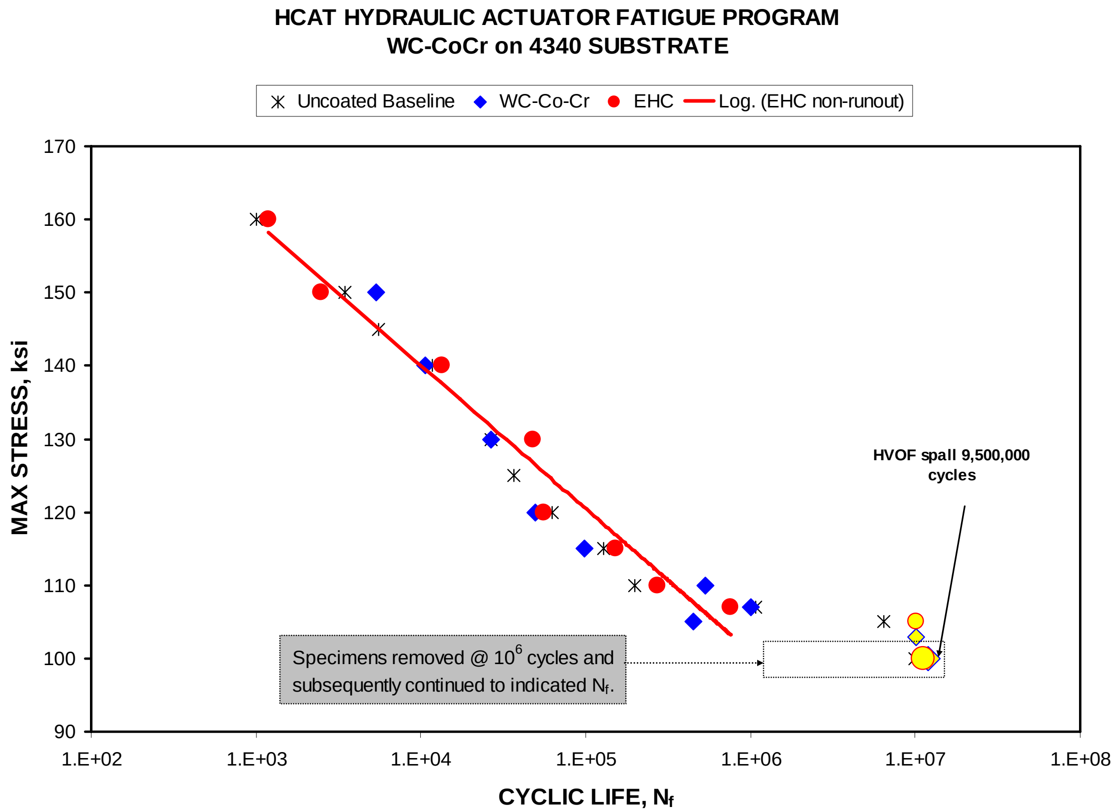

Figure 3-7. Fatigue curves - 4340 steel, HVOF WC/CoCr vs EHC, room temperature, R=-1. (Note: 100 ksi stress is equivalent to 0.34% strain.)

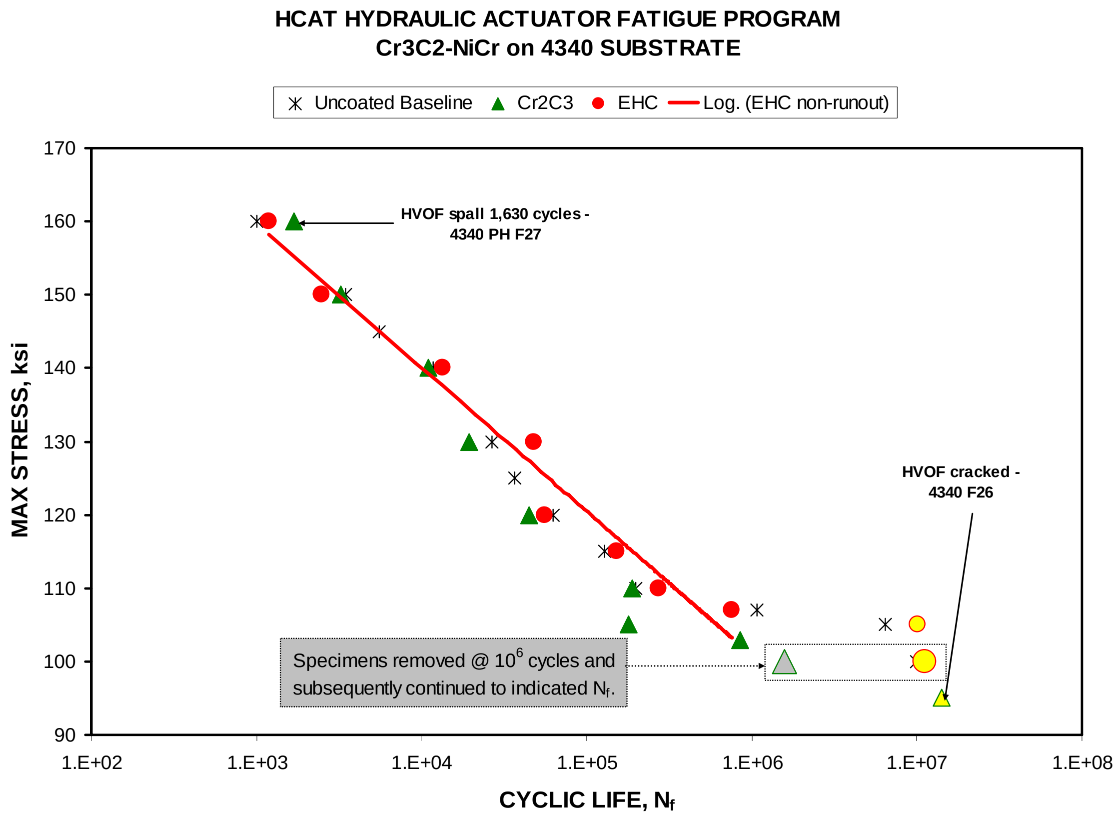

Figure 3-8. Fatigue curves – 4340 steel, HVOF Cr_3C_2/NiCr vs EHC, room temperature, R=-1.

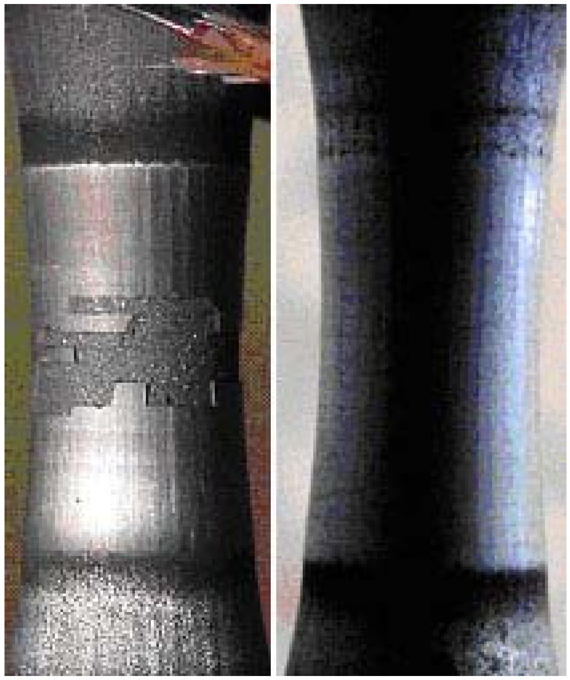

Figure 3-9. HVOF Cr_3C_2/NiCr 0.004" thick on 4340. Left 4340-F27, 160 ksi, 1,630 cycles; right 4340-F26, 95 ksi, ~14,153,000 cycles.

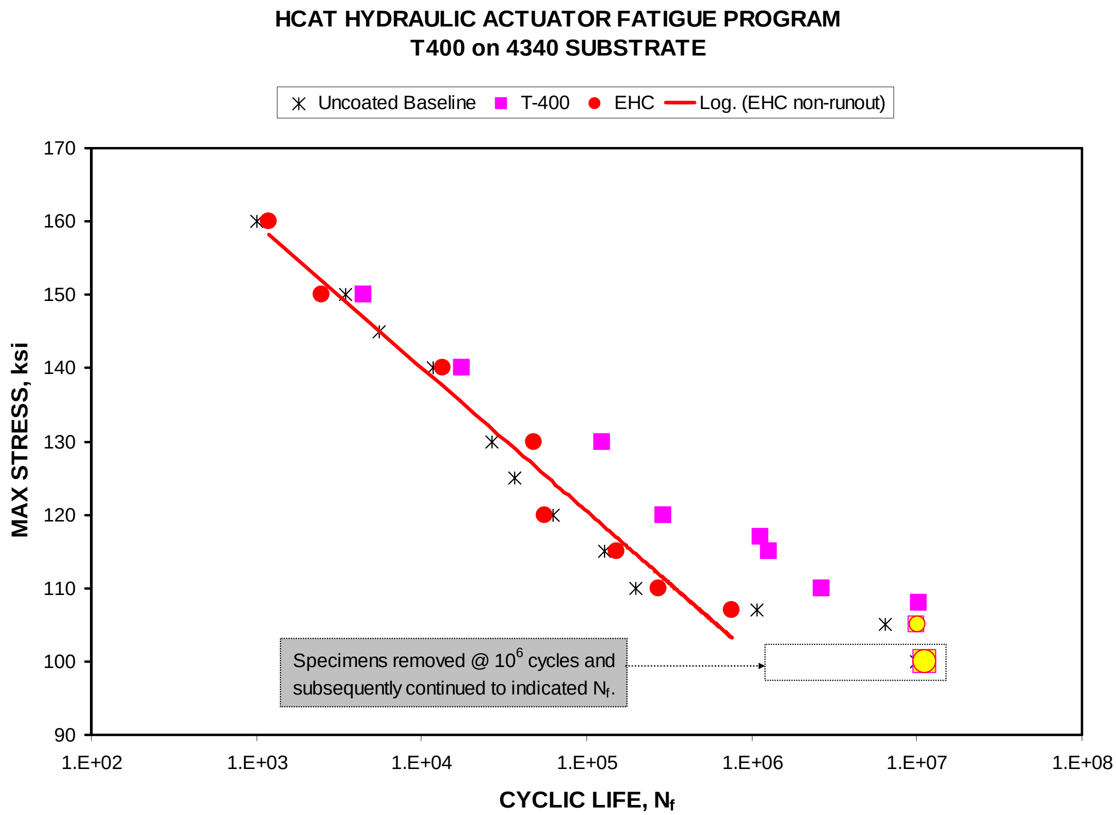

Figure 3-10. Fatigue curves - 4340 steel, HVOF Tribaloy 400 vs EHC, room temperature, R=-1.

3.4.5.2. PH15-5 substrate

HVOF WC/CoCr: The fatigue data are shown in Figure 3-11. The HVOF curve is slightly above that for EHC. Cracking of the coating was observed above 1,000,000 cycles, but no spalling (see Figure 3-12).

HVOF Cr_3C_2/NiCr : The fatigue data are shown in Figure 3-13. The HVOF curve is essentially identical to that for EHC. Cracking was observed at approximately 6,000,000 cycles (Figure 3-14).

HVOF Tribaloy 400: The fatigue data are shown in Figure 3-15. The HVOF curve is significantly above that for EHC. No cracking or spalling was observed.

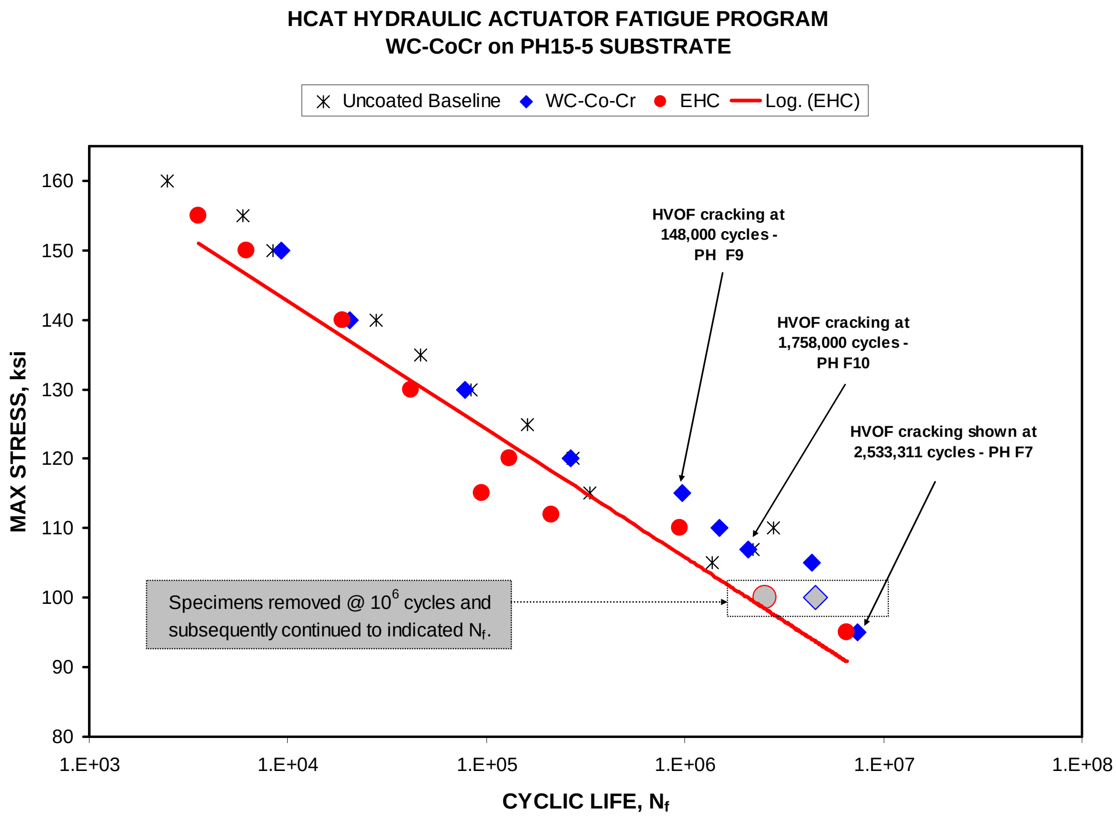

Figure 3-11. Fatigue curves – PH15-5, WC/CoCr vs EHC, room temperature, R=-1. (Note: 100 ksi stress is equivalent to 0.35% strain.)

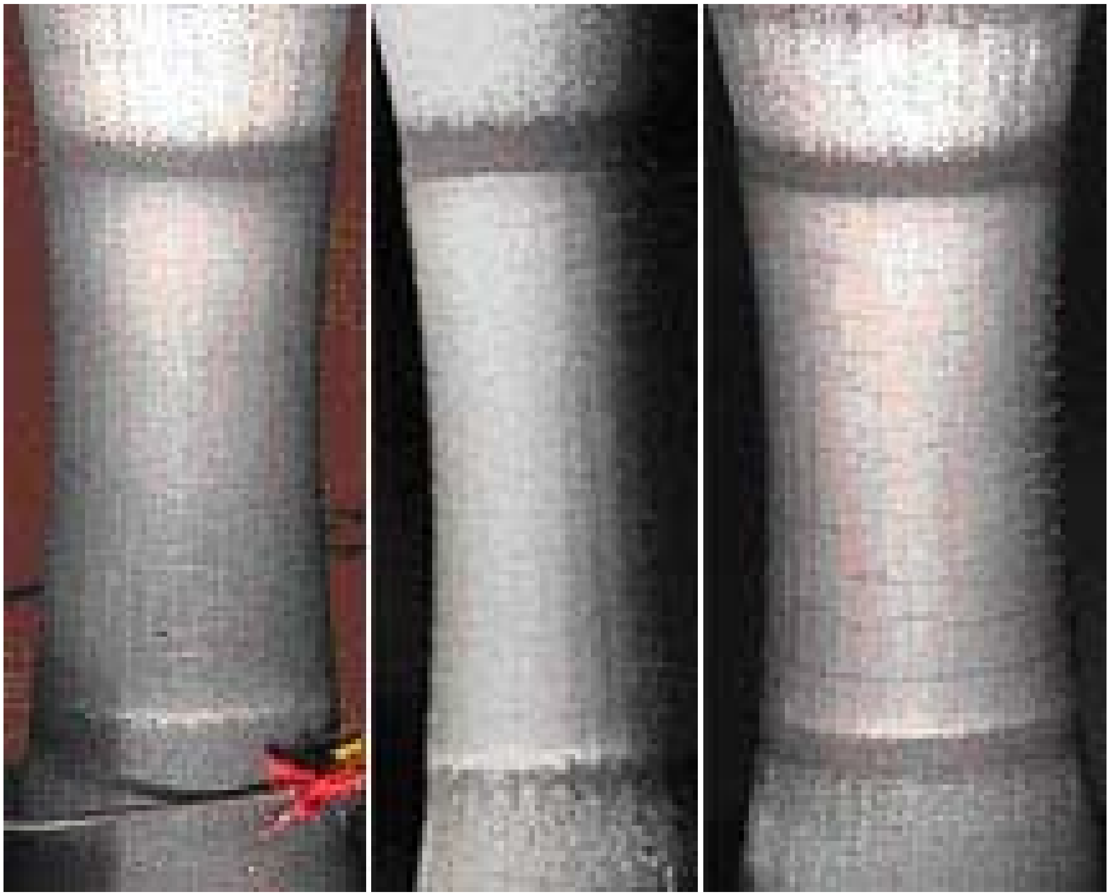

Figure 3-12. HVOF WC/CoCr 0.004” thick. Left PH F9, 85 ksi, 2,753,298 cycles; center PH F10, 107 ksi, 1,758,629 cycles; right PH F7, 95 ksi, 2,533,311 cycles.

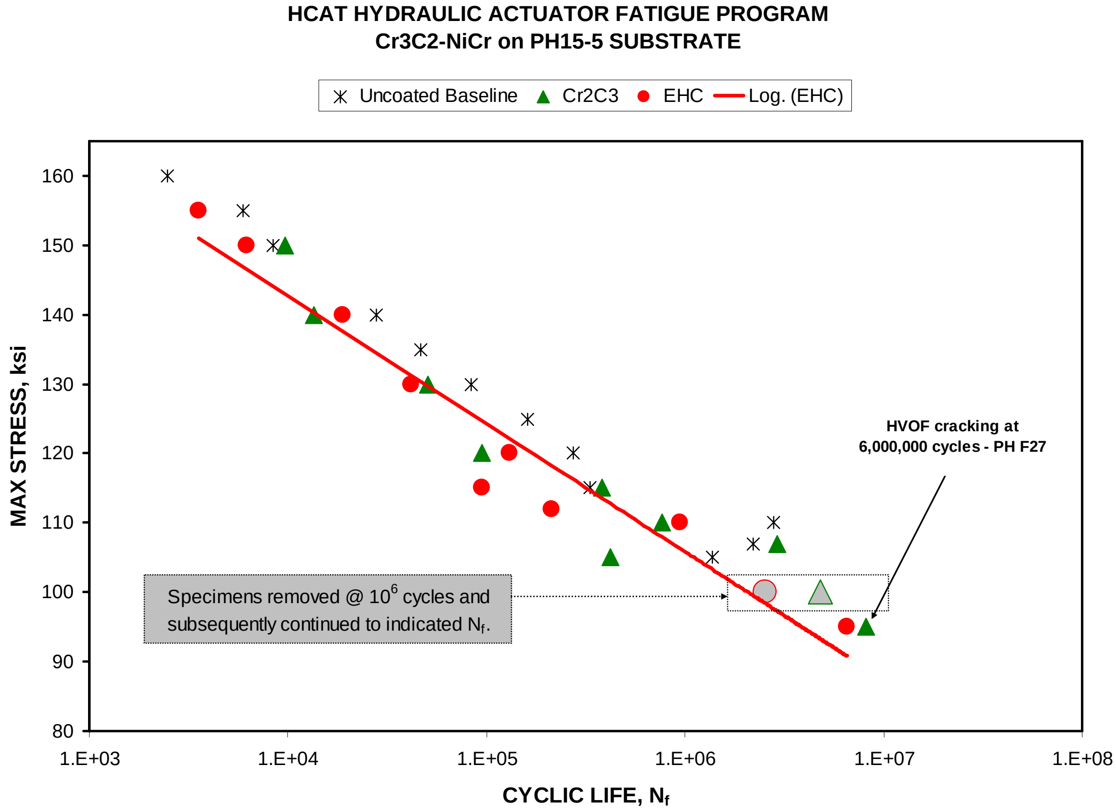

Figure 3-13. Fatigue curves – PH15-5, Cr_3C_2/NiCr vs EHC, room temperature, R=-1.

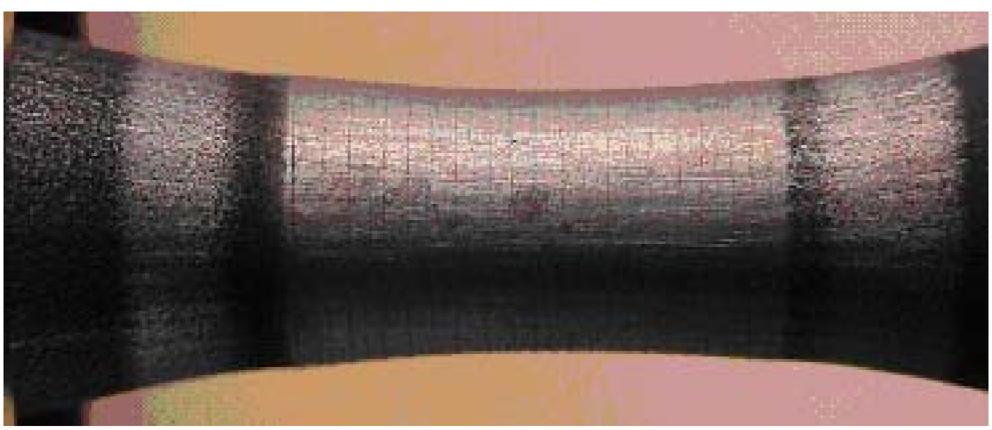

Figure 3-14. HVOF Cr_3C_2/NiCr 0.004" thick, 95 ksi, approximately 6,000,000 cycles, showing cracking. (Photo PH F27.)

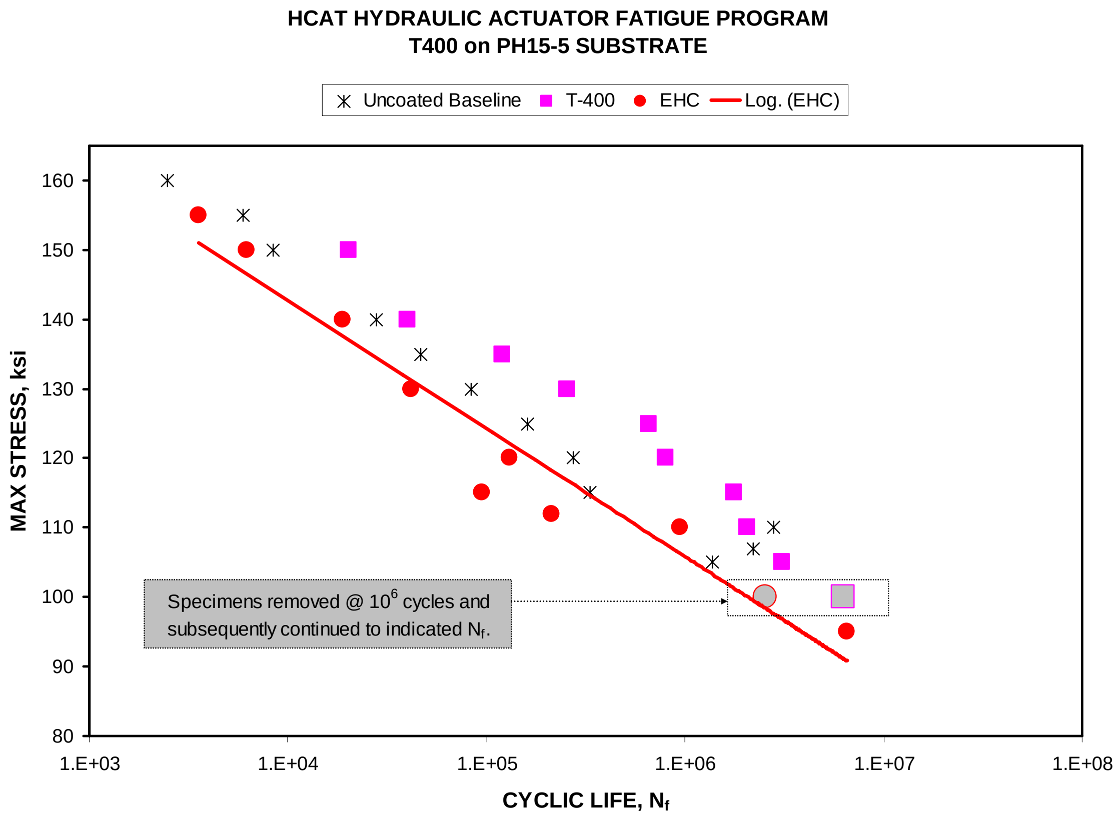

Figure 3-15. Fatigue curves – PH15-5, Tribaloy 400 vs EHC, room temperature, R=-1.

3.4.5.3. Ti-6Al 4V substrate

There were many spalling failures of both EHC and HVOF coatings due to inadequate surface preparation (discussed in Section 3.4.6). In the following fatigue curves the light gray circles represent the points at which spalling was observed for EHC, while the other light-colored symbols show the spalling points for the different HVOF coatings.

EHC: The fatigue data are shown in detail in Figure 3-16, which shows both coating failure and specimen failure loads. Pictures of a number of the specimens are shown in Figure 3-17, chosen to illustrate typical coating failures. Note that the EHC coating spalled well before failure for most specimens.

HVOF WC/CoCr: The fatigue data are shown in Figure 3-16. The HVOF curve is essentially similar to or above that for EHC below 10^6 cycles, but drops well below it above this load. Pictures of specimens showing cracking or spalling are provided in Figure 3-18.

HVOF Cr_3C_2/NiCr: The fatigue data are shown in Figure 3-19. The HVOF curve is well below that for EHC, diverging at higher cycles. The HVOF specimen that showed cracking is shown in Figure 3-20.

HVOF Tribaloy 400: The fatigue data are shown in Figure 3-21. The HVOF curve is essentially identical to that for EHC. The HVOF specimens showing cracking and spalling are shown in Figure 3-22.

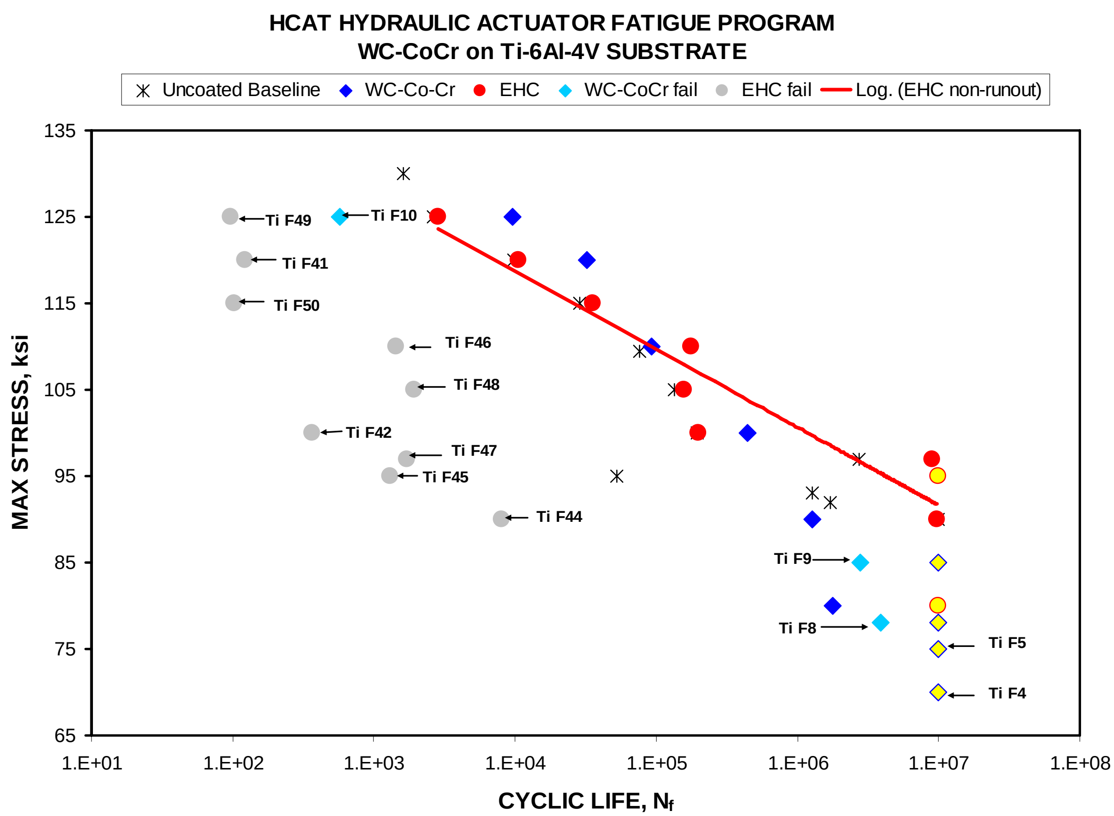

Figure 3-16. Fatigue curves – Ti-6Al 4V, WC/CoCr vs EHC, room temperature, R=-1. Light colored points show when spalling occurred for EHC (circles) and WC/CoCr (diamonds). (Note: 100 ksi is equivalent to 0.63% strain.)

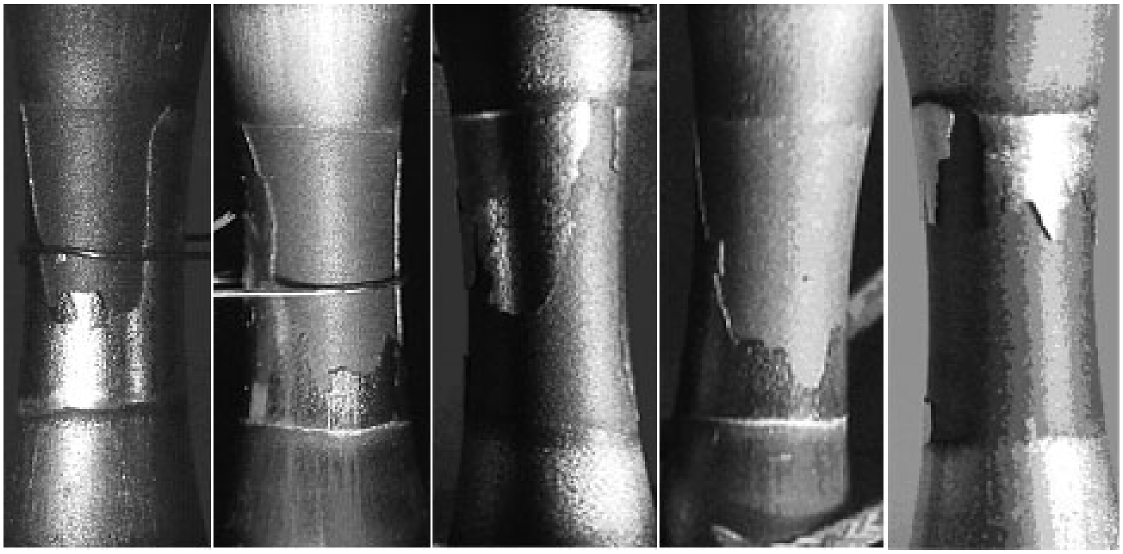

Figure 3-17. Spalling of selected EHC on Ti-6Al4V. Left to right – Ti-F49 (125 ksi, 97 cycles), Ti-F41 (120 ksi, 122 cycles), Ti-F46 (110 kai, 1,425 cycles), Ti-F42 (100 ksi, 365 cycles), Ti F44 (90 ksi, 8,102 cycles).

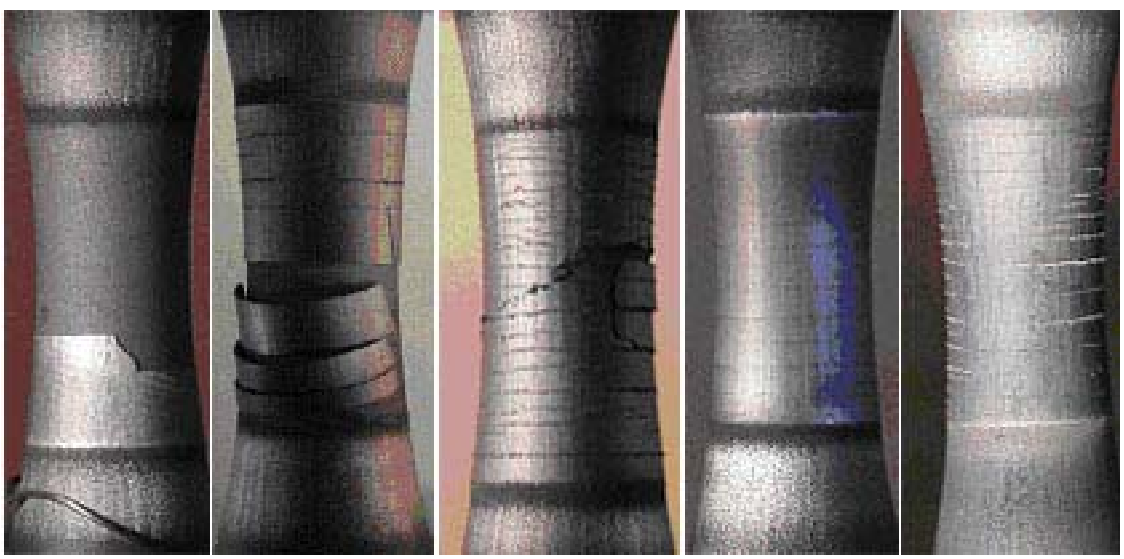

Figure 3-18. Cracking and spalling of HVOF WC/CoCr on Ti-6Al4V. Left to right – Ti-F10 (125 ksi, 575 cycles), Ti-F9 (85 ksi, 2,753,298 cycles), Ti-F8 (78 ksi, 3,930,130 cycles), Ti-F5 (75 ksi, 405,776 cycles), Ti F4 (70 ksi, 2,846,017 cycles).

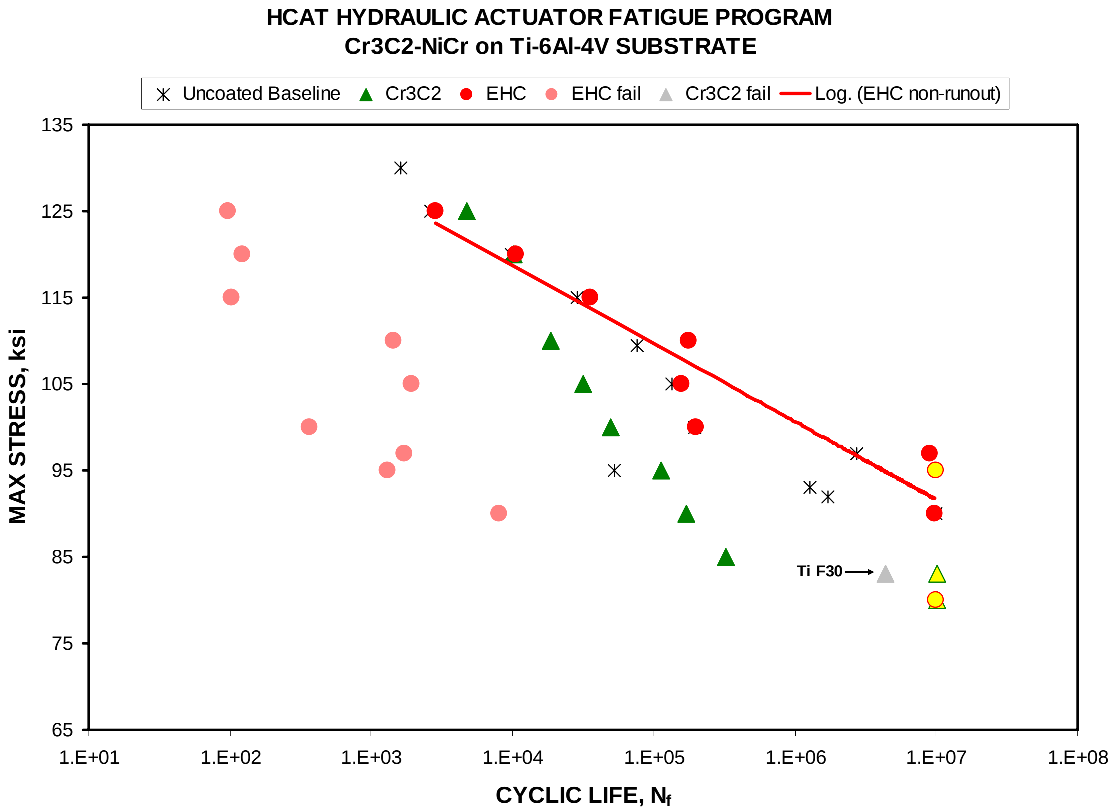

Figure 3-19. Fatigue curves – Ti-6Al 4V, Cr_3C_2/NiCr vs EHC, room temperature, R=-1.

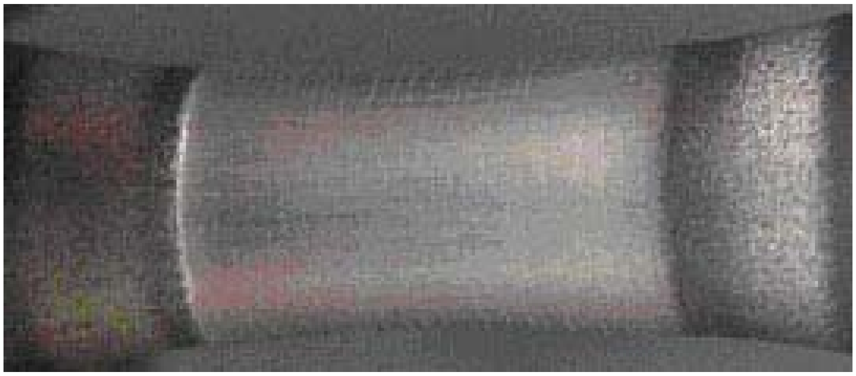

Figure 3-20. HVOF Cr_3C_2/NiCr 0.004" thick, 4,370,038 cycles at 83 ksi, R=-1. (Photo Ti F30.)

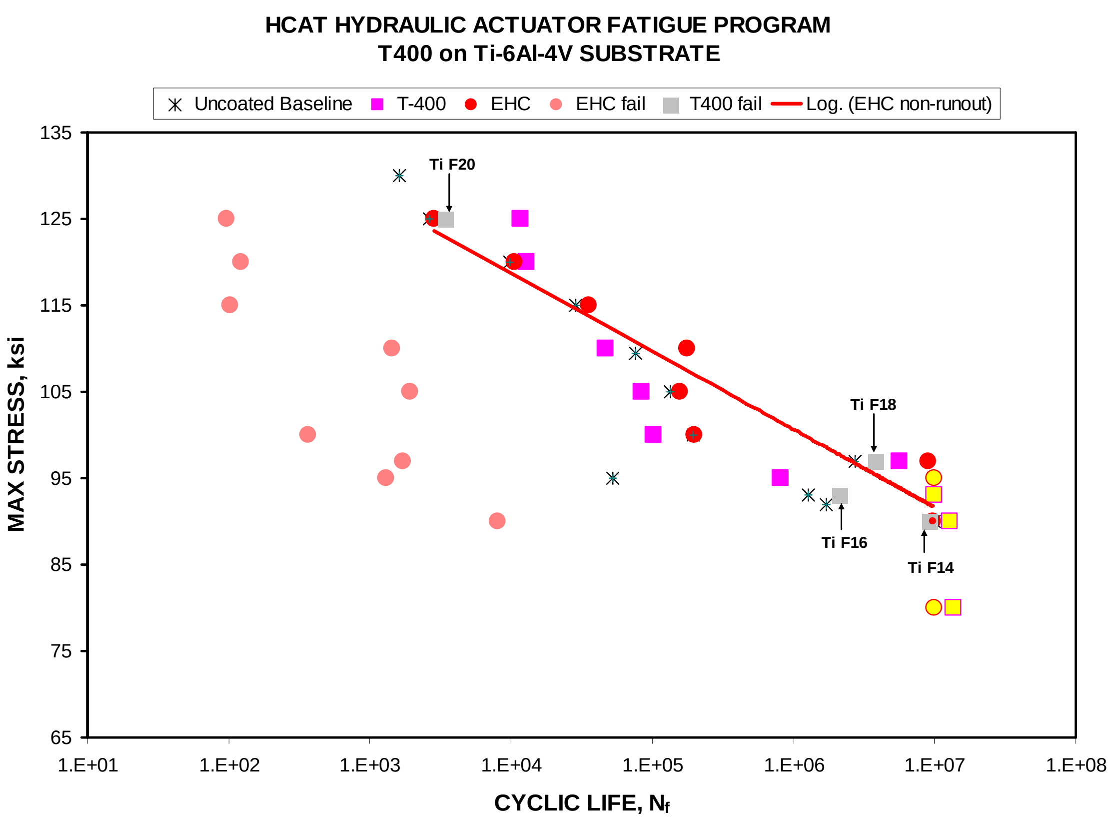

Figure 3-21. Fatigue curves – Ti-6Al 4V, Tribaloy 400 vs EHC, room temperature, R=-1.

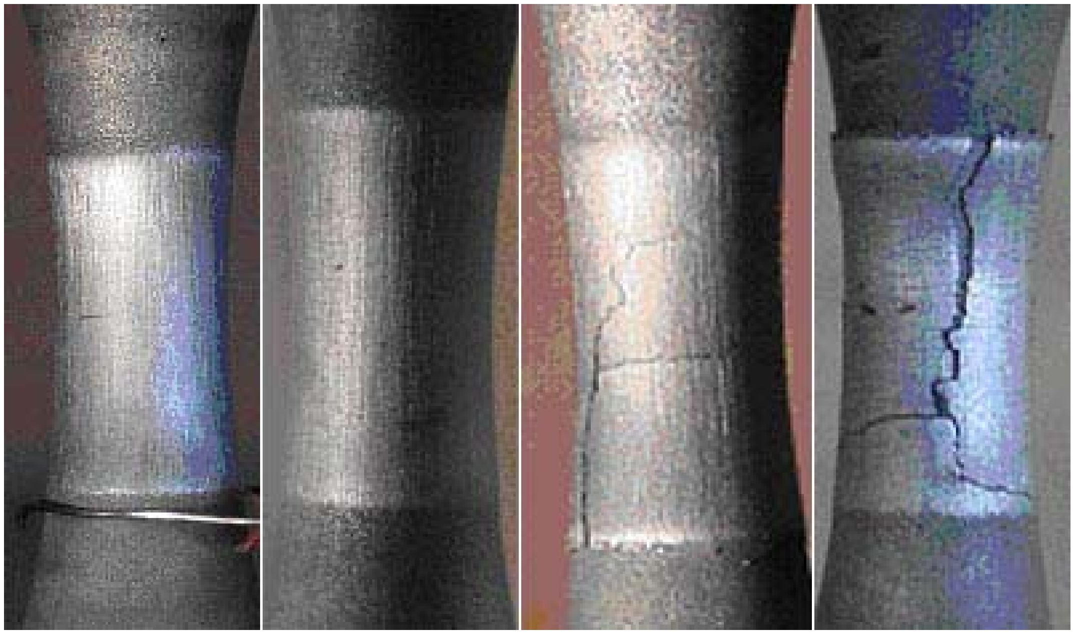

Figure 3-22. Cracking and spalling of HVOF Tribaloy 400 on Ti-6Al4V. Left to right – Ti-F20 (125 ksi, 1.500 cycles), Ti-F18 (97 ksi, 3,819,214 cycles), Ti-F16 (93 ksi, 2,112,425 cycles), Ti-F14 (90 ksi, 9,183,469 cycles).

3.4.6. Discussion

Table 3-10 provides a summary of all material/coating combinations for which coating cracking or spalling was observed.

Table 3-10 Cracking and spalling loads for tested coatings.

Material	Load (ksi)	Cycles	Cracks	Spalls
4340				
WC/CoCr	103	9,500,000		X
Cr_3C_2/NiCr	160	1,630		X
	95	14,153,000	X	
T400			none	none
PH15-5				
WC/CoCr	85	2,753,298	X	
	107	1,758,629	X	
	95	2,533,311	X	
Cr_3C_2/NiCr	95	~6,000,000	X	
T400			none	none
Ti-6Al4V				
EHC	125-90	97-8,102		X
WC/CoCr	125	575		X
	85	2,573,298		X
	78	3,930,130		X
	75	405,776	X	
	70	2,846,017	X	
Cr_3C_2/NiCr	83	4,370,038	X	
T400	125	1,500	X	
	97	3,819,214	X	
	93	2,112,425		X
	90	9,183,469		X

3.4.6.1. 4340 substrate

EHC: Specimens coated with EHC showed essentially the same fatigue as uncoated, shot peened material, i.e. there was no fatigue debit. A fatigue debit is expected for high strength heat treats of 4340 steel, but evidently for this lower strength heat treat any fatigue debit is reclaimed by the shot peening stress.

HVOF WC/CoCr: Specimens coated with HVOF WC/CoCr had fatigue equivalent to

EHC coated specimens (Figure 3-7). Spalling was reported for only one coating and that was essentially at runout. Otherwise, no cracking or spalling of the coatings was observed.

HVOF Cr_3C_2/NiCr: Specimens coated with HVOF Cr_3C_2/NiCr had fatigue equivalent to EHC coated specimens (Figure 3-8). However, it is possible that the fatigue limit was somewhat lower for the HVOF coated specimens (95 ksi for HVOF versus 105 ksi for EHC). Establishing the fatigue limit accurately would require a significant number of additional high cycle tests.

One HVOF Cr_3C_2/NiCr specimen spalled at high stress (160 ksi), with delamination around most of the circumference in the highest stress (central) region of the specimen (Figure 3-9). At very high cycles, some coating cracking was observed. The crack pattern was difficult to see (Figure 3-9), but was typical of that observed with HVOF coatings – faint circumferential cracks at a fairly regular spacing. However, there was no evidence of spalling at this low load.

Tribaloy 400: Specimens coated with HVOF T400 showed somewhat better fatigue than those coated with EHC, and even higher than uncoated material, especially at high cycles (Figure 3-10). This is probably a result of the compressive stress in the coating. The fatigue limit appeared to be approximately 105 ksi – essentially equivalent to hard chrome. There was no sign of cracking or spalling of the HVOF T400.

Overall the behavior of HVOF coatings on 4340 substrates was similar to that seen in other applications, except that there was essentially no fatigue debit for either hard chrome or HVOF, whereas on higher strength steels fatigue of EHC coated specimens tends to have a larger debit that that of HVOF coated materials.

3.4.6.2. PH15-5 substrate

EHC: EHC coating caused a small fatigue debit (Figure 3-11).

HVOF WC/CoCr: The fatigue curve for HVOF WC/CoCr was essentially equivalent to the uncoated material (Figure 3-11). Above about 1,000,000 cycles the coatings exhibited cracking that appeared to become somewhat more obvious at higher cycles (Figure 3-12). However, there was no evidence of spalling.

HVOF Cr_3C_2/NiCr: The fatigue curve for HVOF Cr_3C_2/NiCr coated specimens was essentially equivalent to that of EHC coated materials (Figure 3-13). Cracking of the coating was observed at the highest cycles (Figure 3-14).

Tribaloy 400: As with 4340 substrates, the fatigue curve for T400 coated material was significantly higher than that of both the EHC coated and the uncoated material (Figure 3-15). No cracking or spalling was observed.

Overall the behavior of the HVOF coatings was similar to that seen on other substrates.

3.4.6.3. Ti-6Al4V substrate

EHC: The EHC coating showed spalling on almost all specimens. Titanium alloys are known to be very hard to plate because of the difficulty in activating them effectively. Inadequate activation produces a plating with poor adhesion, which is clearly seen in the data of Figure 3-16 and the photographs of Figure 3-17. The EHC spalled well before failure, with the coating delaminating over most of its surface. Clearly this type of coating would not be acceptable on aerospace components.

The fatigue curve for the EHC specimens was essentially the same as for the uncoated material, presumably at least in part because the specimens were effectively uncoated once the coating spalled. There was one outlier in the fatigue data for the uncoated material at 95 ksi, but there was no evident reason for this.

HVOF WC/CoCr: Fatigue of the HVOF WC/CoCr specimens was essentially similar to or above that of EHC coated and uncoated material at lower cycles, but fell below the EHC curve above 10^6 cycles (Figure 3-16). However the HVOF coatings showed far more spalling than with the other substrates (Figure 3-18). Below 75 ksi (at runout) the specimens cracked but did not spall. Between 75 and 85 ksi (10^6 – 10^7 cycles) there was cracking and spalling. At the highest load (125 ksi) the coating spalled over most of its area at 575 cycles. Between the highest load and the high cycle region Metcut did not report any cracking or spalling.

HVOF Cr_3C_2/NiCr: The fatigue curve showed a fatigue debit for the HVOF coating that was significantly below that for EHC, especially at high cycles (Figure 3-19). This was the only case of an HVOF fatigue debit that placed the fatigue curve below that of EHC over most of the range. However, since the hard chrome spalled, the "EHC curve" is unreliable and may simply be the curve for the uncoated material as noted above. Thus we cannot tell if the HVOF curve falls below the curve for an unspalled EHC coating. Cracking of the HVOF coating was seen only at the highest life (Figure 3-20).

HVOF Tribaloy 400: The fatigue curve for HVOF T400 material was essentially equivalent to that of EHC coated specimens. Cracking was observed at 3,380 cycles at the highest stress (125 ksi), and again above 10^6 cycles (below 100 ksi). The high cycle crack pattern was unusual in that a large crack appeared that was longitudinal rather than circumferential. This type of behavior has occasionally been seen in other coating materials, and we believe it to be a result of Poisson ratio contraction of the specimen diameter on tensile stress.

The spalling seen with the EHC coatings is clearly the result of inadequate activation. As a result it is not possible to know what the EHC curve actually is, since it could be significantly different from the uncoated material. As a result we cannot say whether the HVOF coatings cause more or less fatigue than EHC.

We believe that the relatively poor spalling performance of the HVOF coatings on T-6Al4V is due to the surface preparation prior to coating. The method agreed to in the JTP avoided grit blasting (which is standard practice in HVOF coating) so as to prevent grit embedding in the surface. Subsequent discussions with other spray shops have shown that many shops do grit blast, but at a lower gas pressure (lower particle velocity) and at an angle, both of which tend to prevent grit embedding. As a result they are able to achieve good adhesion of the HVOF coating in production on Ti alloy substrates such as flap tracks.

3.4.7. Conclusions

For 4340 and PH15-5, the fatigue performance of the HVOF coatings was equal or superior to that for EHC. The only spalling seen with HVOF coatings (other than one sample with WC/CoCr at runout) was for Cr_3C_2/NiCr at high stress. Other HVOF coatings developed circumferential cracks at high cycles. This type of coating cracking has been observed to occur in HVOF coated landing gear without causing deleterious performance results, such as leakage, corrosion or seal damage.

The data for Ti-6Al4V demonstrate the need for development of proper grit blasting procedures, which are clearly essential for proper adhesion. Even with this poor preparation, however, the HVOF coatings spalled only at the top and bottom of the curve (high stress or high cycles), showing cracking but no spalling over most of the range.

For 4340 and PH15-5 steels, it was concluded that the fatigue data show that the HVOF coatings meet the JTP pass criterion of being better than or equal to hard chrome.

Both the EHC and HVOF data for Ti-6Al4V are unreliable because of inadequate surface preparation. Even with this, WC/CoCr performed well except at high load or high cycles ($>10^6$). If HVOF (especially coatings other than WC/CoCr) is to be considered for use on Ti-6Al4V actuator components, the fatigue data should be retaken with adequate surface preparation for both the EHC and the thermal spray.

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3.5. Corrosion (ASTM B117)

Table 3-11 Quick Reference to Primary Corrosion Data.

Item	Item Number
Appearance ratings for panels, grouped by substrate material	Figure 3-26
Appearance ratings for panels, grouped by coating material	Figure 3-27
Appearance ratings for rods, grouped by substrate material	Figure 3-28
Appearance ratings for rods, grouped by coating material	Figure 3-29

Click blue links to jump to data

3.5.1. Specimen Fabrication and Coating

Flat Panel Specimens

Flat panels, 3" x 4" x ¼"-thick, were fabricated from each of the alloys indicated in Section 3.2. One face of each panel was ground to a surface finish of 32-64 microinches Ra. Then each ground face was shot peened, grit blasted, and coated with either EHC or an HVOF coating as described in Section 3.3. Only WC/CoCr and T400 HVOF coatings were applied to the panels.

For EHC deposition, a l"-wide area at the bottom of each panel was masked such that the coated area was 3" x 3", with coating applied to both faces and the edges. HVOF coatings were applied on the ground 3" x 4" face only.

Figure 3-23 Photograph of four EHC-coated panels subsequent to grinding but prior to application of the epoxy resin.

As-deposited coating thicknesses were either 0.007" or 0.013". Subsequent to deposition, each coating was ground to a final thickness of either 0.004" (± 0.0005") or 0.010" (± 0.0005"), with an Ra surface finish of 12-16 microinches for EHC, 10-14 microinches for the HVOF T400, and 8-10 microinches for the WC/CoCr. Figure 3-23 shows four of the EHC-coated panels subsequent to grinding.

Just prior to initiating the corrosion test, the reverse side and edges of each panel were coated with an inert epoxy resin to ensure that only the one coated face was exposed to the corrosive media. On the EHC-coated panels, the 1” x 3” non-coated area on the front face was also coated with the epoxy. Note that the epoxy extended beyond the edges onto the coated front face for about 0.25” to ensure that there were no edge effects.

Table 3-12 provides a listing of each corrosion panel, indicating panel number, coating and final coating thickness.

Rod Specimens

One-inch-diameter, six-inch-long rods were fabricated from each of the alloys indicated in Section 4.2. The curved surface on each rod was ground to a surface finish of 32-64 microinches Ra. Then the curved surface was shot peened, grit blasted, and coated with either EHC or an HVOF coating as described in Section 4.3. Figure 3-24 is a schematic of the rod, indicating the areas that were shot-peened, grit blasted and coated.

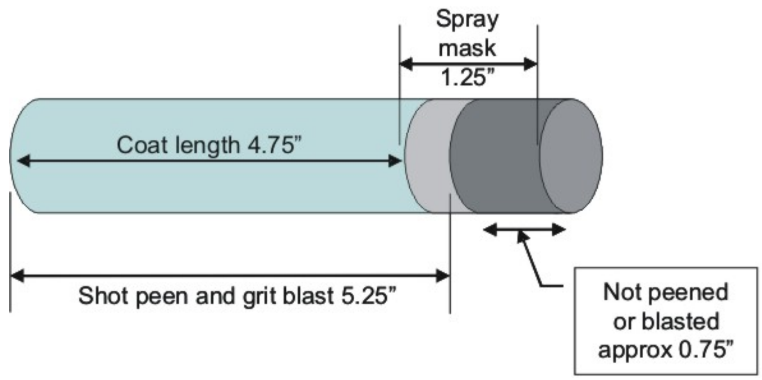


Figure 3-24 Schematic of the Corrosion Rods, indicating the areas that were shot-peened, grit-blasted, and coated.

As-deposited coating thicknesses were either 0.007” or 0.013”. Subsequent to deposition, each coating was ground to a final thickness of either 0.004” (± 0.0005”) or 0.010” (± 0.0005”), with an Ra surface finish of 12-16 microinches for EHC, 10-14 microinches for the HVOF T400, and 8-10 microinches for the WC/CoCr and Cr_3C_2/NiCr. There were two 0.013”-thick EHC coatings on 4340 that were ground excessively to final thicknesses of 0.007” (± 0.005”). Subsequent to grinding, three of the WC/CoCr coatings on 4340 were superfinished, with an Ra surface finish of 2-4 microinches.

Just prior to initiating the corrosion test, the flat ends and a 1.5” length at the bottom of each rod were coated with an inert epoxy resin to ensure that only the coated areas were exposed to the corrosive media.

Table 3-13 provides a listing of each corrosion rod, indicating rod number, coating and final coating thickness.

Table 3-12 List of Coated Panels for Corrosion Testing. (First column is panel number, with "PH" indicating a PH15-5 substrate, and "Ti" indicating a Ti-6Al-4V substrate)

Substrate	Coating	Ground Coating Thickness
PH-C1	WC/CoCr	0.004"
PH-C2	WC/CoCr	0.004"
PH-C5	WC/CoCr	0.010"
PH-C6	WC/CoCr	0.010"
Ti-C1	WC/CoCr	0.004"
Ti-C2	WC/CoCr	0.004"
Ti-C5	WC/CoCr	0.010"
Ti-C6	WC/CoCr	0.010"
4340-C1	WC/CoCr	0.004"
4340-C2	WC/CoCr	0.004"
4340-C5	WC/CoCr	0.010"
PH-C17	T400	0.004"
PH-C18	T400	0.004"
PH-C21	T400	0.010"
PH-C22	T400	0.010"
Ti-C17	T400	0.004"
Ti-C18	T400	0.004"
Ti-C21	T400	0.010"
Ti-C22	T400	0.010"
4340-C21	T400	0.010"
4340-C22	T400	0.010"
PH-C25	EHC	0.004"
PH-C26	EHC	0.004"
PH-C28	EHC	0.010"
PH-C29	EHC	0.010"
Ti-C25	EHC	0.004"
Ti-C26	EHC	0.004"
Ti-C28	EHC	0.010"
Ti-C29	EHC	0.010"
4340-C25	EHC	0.010"
4340-C26	EHC	0.004"
4340-C29	EHC	0.004"
4340-C30	EHC	0.010"

Table 3-13 List of Coated Rods for Corrosion Testing. (SF indicates that the coating was superfinished)

Substrate	Coating	Ground Coating Thickness
PH15-5-1	EHC	0.004”
PH15-5-2	EHC	0.010”
Ti6-4-1	EHC	0.004”
Ti6-4-2	EHC	0.010”
4340-1	EHC	0.010”
4340-2	EHC	0.010”
4340-5	EHC	0.007”
4340-6	EHC	0.007”
PH15-5-4	WC/CoCr	0.004”
PH15-5-6	WC/CoCr	0.010”
Ti6-4-4	WC/CoCr	0.004”
Ti6-4-6	WC/CoCr	0.010”
4340-9	WC/CoCr	0.004”
4340-10	WC/CoCr	0.004”
4340-11	WC/CoCr	0.004”
4340-12	WC/CoCr	0.004”
4340-19	WC/CoCr	0.010”
4340-16	WC/CoCr (SF)	0.004”
4340-17	WC/CoCr (SF)	0.010”
4340-21	WC/CoCr (SF)	0.010”
PH15-5-8	Cr_3C_2/NiCr	0.004”
PH15-5-10	Cr_3C_2/NiCr	0.010”
Ti6-4-8	Cr_3C_2/NiCr	0.004”
Ti6-4-10	Cr_3C_2/NiCr	0.010”
4340-23	Cr_3C_2/NiCr	0.004”
4340-25	Cr_3C_2/NiCr	0.010”
PH15-5-12	T400	0.004”
PH15-5-14	T400	0.010”
Ti6-4-12	T400	0.004”
Ti6-4-14	T400	0.010”
4340-27	T400	0.004”
4340-29	T400	0.010”

3.5.2. Corrosion Test Results

All specimens were cleaned in accordance with ASTM G1 prior to corrosion testing. The test chamber was a standard salt fog exposure chamber manufactured by Auto Technology Company. The specimens were placed into the chamber in holders that maintained them at an angle of 25º from the vertical. They were then subjected to a constant 5% NaCl salt fog environment at 35º C (95º F) in accordance with ASTM B117. Figure 3-25 is a photograph of the panel and rod specimens inside the salt fog chamber.

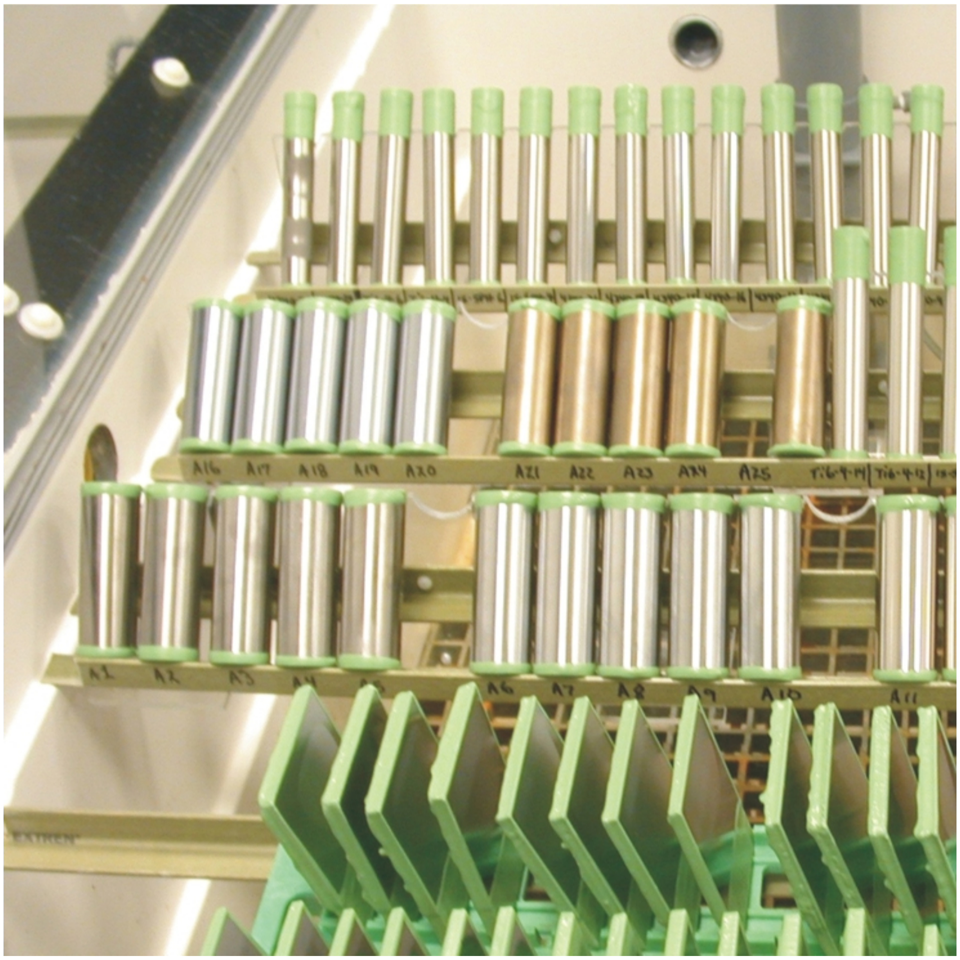


Figure 3-25 Photograph of EHC- and HVOF-coated panels and rods mounted in salt fog chamber.

During the testing, the specimens were removed from the chamber, photographed, and evaluated at 0, 125, 250, 375, 500, 625, 750, 875, and 1000 hours of exposure. Evaluations were conducted in accordance with ASTM B537. This specification assigns ratings of 0 to 10 (10 being best, 0 being worst) for two aspects of observed coating performance. "Protection" is determined by how well the coating protects the substrate from corrosion. "Appearance" incorporates the protection aspect but also accounts for other visual aspects of corrosion performance (staining, dripping, etc.) that might be considered detrimental but not a protection defect. Table 3-14 indicates what rating is assigned based on what percentage of the surface area has visible corrosion.

Table 3-14 Corrosion rating per ASTM B537-70.

Defect area (%)	Rating
0	10
>0 – 0.1	9
>0.1 – 0.25	8
>0.25 – 0.5	7
>0.5 - 1	6
>1 – 2.5	5
>2.5 – 5	4
>5 – 10	3
>10 – 25	2
>25 – 50	1
>50	0

The appearance ratings for the panels after 1000 hours of salt fog exposure are presented in Figure 3-26. The data is grouped by substrate material and also indicates the coating thickness for each panel. The corrosion performance of the EHC-coated panels for all three substrate materials was superior to that of the two HVOF coatings. The average rating for the EHC-coated PH15-5 panels was 9.5, followed by the EHC-coated Ti-6Al-4V with an average rating of 7.1 and the EHC-coated 4340 with an average rating of 7.0. The performance of the T400 coatings on all three substrates was almost comparable to that of the EHC coatings, with an average rating of 7.8 on Ti-6Al-4V, 6.8 on PH15-5 and 6.5 on 4340. The WC/CoCr coatings appeared to provide somewhat less protection, with an average 5.0 rating on PH15-5, 3.6 on Ti-6Al-4V and 2.8 on 4340.

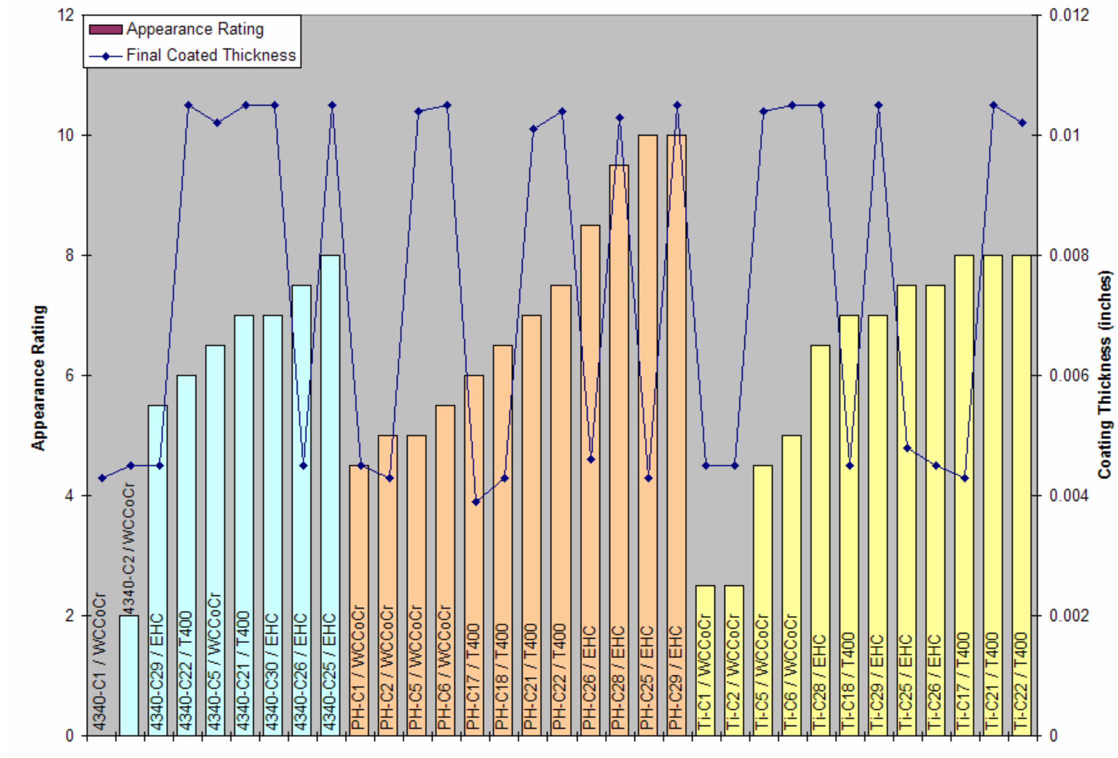


Figure 3-26 Appearance ratings and coating thicknesses for EHC- and HVOF-coated panels, grouped by substrate material, and shown from worst to best corrosion performance within each substrate group.

Figure 3-27 presents the appearance ratings and coating thicknesses for the panels grouped by coating. In terms of correlation with coating thickness, it was apparent that for the WC/CoCr coatings on 4340 and Ti-6Al-4V, the 0.010”-thick coatings provided substantially better corrosion protection than the 0.004”-thick coatings. However, for all other coating/substrate combinations, there appeared to be no significant correlation between coating thickness and corrosion performance.

Figure 3-28 presents the appearance ratings and coating thicknesses for the rods grouped by substrate material and Figure 3-29 presents the appearance ratings and coating thicknesses for the rods grouped by coating. The corrosion performance of the EHC-coated panels for all three substrate materials was again superior to that of the three HVOF coatings, with an average rating of 10 on PH15-5, 9.7 on 4340 and 8.8 on Ti-6Al-4V. The performance of the HVOF Cr_3C_2/NiCr coatings was only slightly less than for the EHC, with average ratings of 8.8 on Ti-6Al-4V, 8.0 on 4340 and 6.8 on PH15-5. The performance of the WC/CoCr coatings was almost comparable to the Cr_3C_2/NiCr, with average ratings of 7.0 on PH15-5, 6.7 on Ti-6Al-4V and 5.4 on 4340. The corrosion performance of the T400 coatings on the rods was inferior to the other coatings, with average ratings of 6.0 on PH15-5, 6.5 on Ti-6Al-4V and 3.5 on 4340.

As with the panels, there was an indication that the coating performance of the 0.010”-thick WC/CoCr coatings was superior to that of the 0.004”-thick coatings on 4340 but there was no other correlation between coating thickness and corrosion performance. It did appear that the corrosion performance of the superfinished WC/CoCr coatings was somewhat superior to the ground coatings.

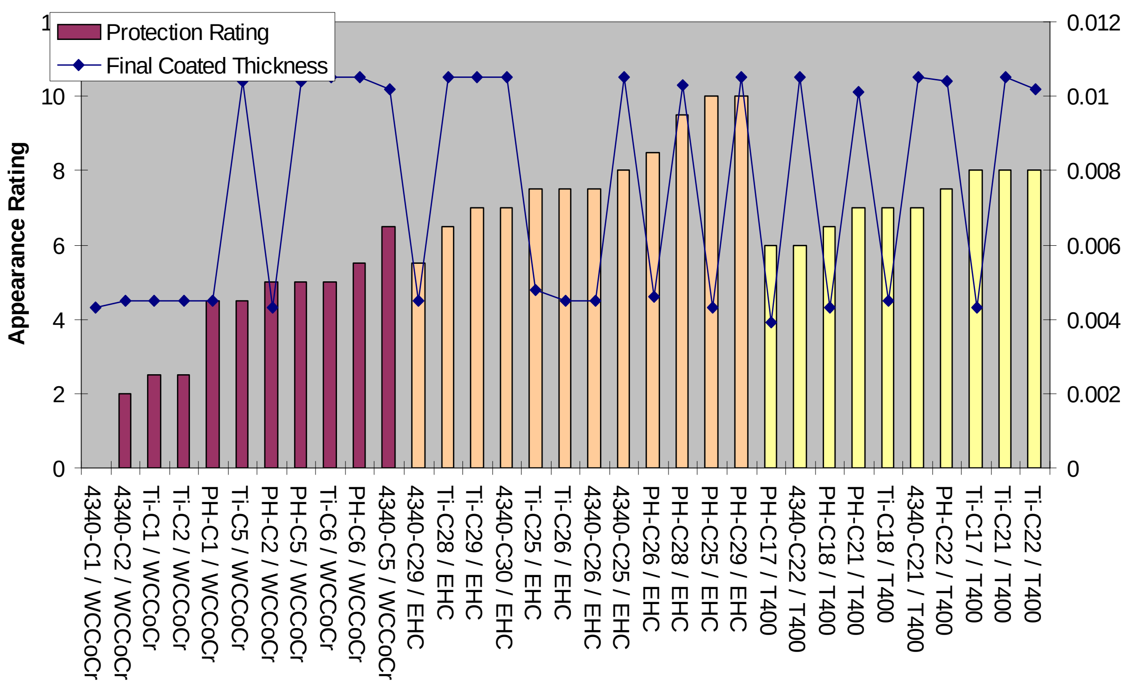


Figure 3-27 Appearance ratings and coating thicknesses for EHC- and HVOF-coated panels, grouped by coating material, and shown from worst to best corrosion performance within each coating group.

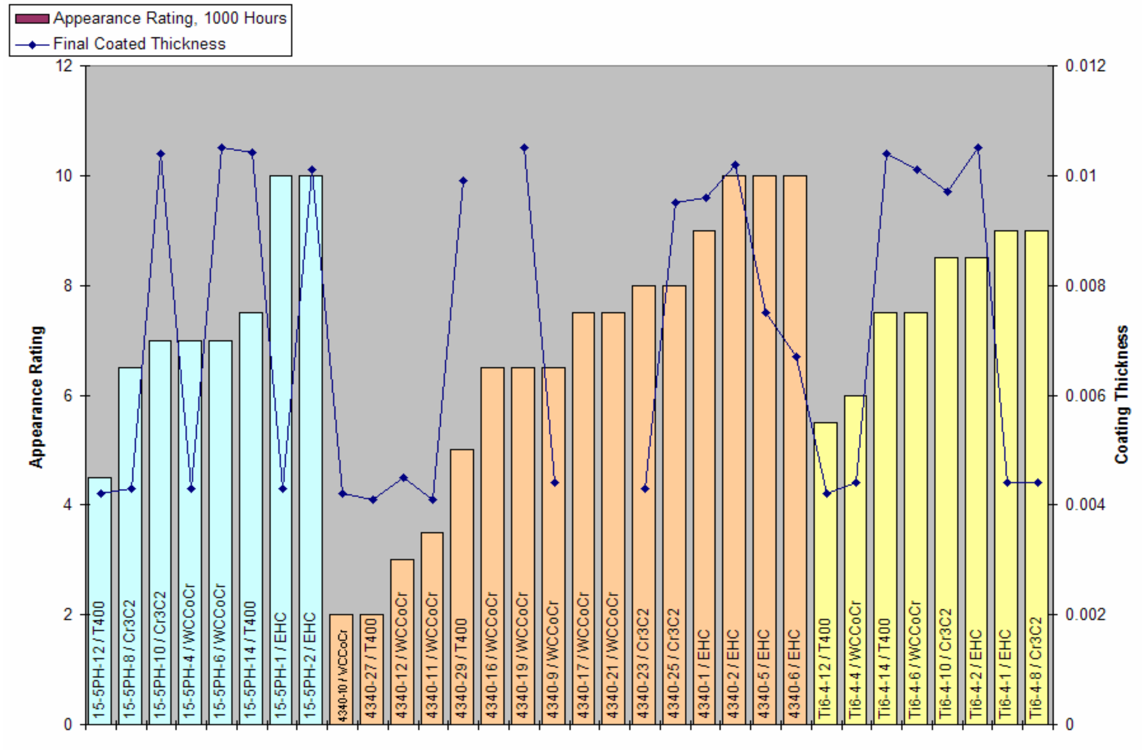


Figure 3-28 Appearance ratings and coating thicknesses for EHC- and HVOF-coated rods, grouped by substrate material, and shown from worst to best corrosion performance within each substrate group.

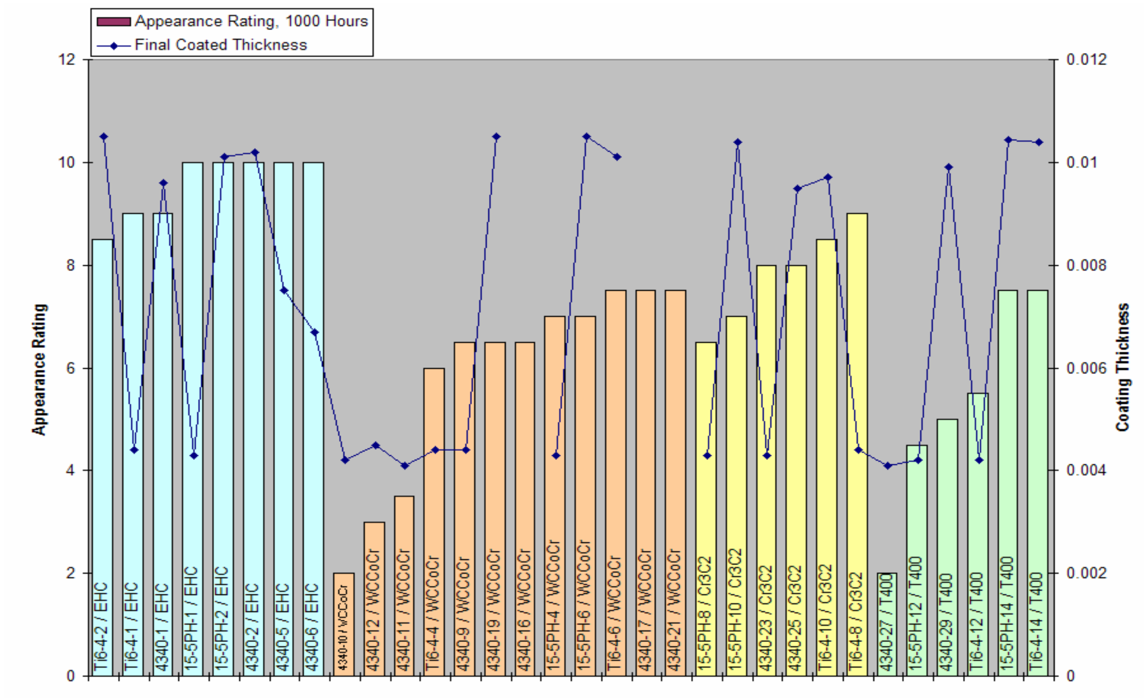


Figure 3-29 Appearance ratings and coating thicknesses for EHC- and HVOF-coated rods, grouped by coating material, and shown from worst to best corrosion performance within each coating group.

In summary, the corrosion performance of the EHC coatings was somewhat better than for any of the HVOF coatings on the three substrate materials, results that are similar to previous B117 salt fog corrosion studies comparing the performance of various HVOF coatings to EHC coatings. In this study, the results were not consistent between the panels and rods, with the T400 coatings generally showing the best performance on the panels and the worst performance on the rods. The performance of the WC/CoCr coatings was significantly better on the rods than on the panels. In addition, it appeared that superfinishing slightly improved the corrosion performance of the WC/CoCr.

3.5.3. Conclusions

In general, it can be concluded that the HVOF coatings investigated in this study did not meet the acceptance criteria. These corrosion test results are consistent with those obtained in previous HVOF thermal spray chrome replacement projects [5, 6, 7] where most of the HVOF carbide or tribaloy coatings demonstrated inferior performance to EHC coatings, especially on low-alloy steel substrates, in cabinet salt fog testing. However, as pointed out in the landing gear report [5], the cabinet salt fog test results have been contradicted by other types of tests. For example, HVOF WC/17Co coatings demonstrated significantly superior performance to EHC coatings on 4340 steel in three-year beach atmospheric corrosion testing. In addition, it was reported that field trials of a WC/17Co-coated P3 main landing gear piston showed no evidence of corrosion or other degradation after four years service [5]. As of the date of this report, that piston is still in service after six years and more than 6400 landings with no evidence of coating degradation.

3.6. Fluid Immersion

3.6.1. Data Summary

Table 3-15 Quick Reference to Primary Fluid immersion Data.

Item	Item Number
Mass loss for immersion	Table 3-17
Mass loss grouped by fluid type	Table 3-18
Surface roughness changes resulting from immersion	Table 3-19

Click blue links to jump to data

3.6.2. Rationale

In order to utilize HVOF thermal spray coatings instead of EHC plating on hydraulic actuator components, stakeholders must consider coating compatibility with all fluids that come into contact with the coating during manufacture, service and maintenance. These include lubricating oils, hydraulic fluids, solvents, and cleaning compounds, as well as greases used for preservation and operation, and deicing fluids used in the airfield. The coating should be inert to the working fluids or greases, and not crack, flake, pit, soften or separate under any expected conditions of fluid or grease exposure. To adequately assess the performance of coatings under simulated real-life conditions, the fluid or grease immersion temperature should be similar to the actual usage temperature and the test specimens should be either fully submerged or partially submerged in the fluid, reflecting their usual service or maintenance conditions. In developing the JTP, the stakeholders did not require immersion testing of EHC coatings since there was already ample operating experience that indicated that EHC was not affected by the fluids tested.

3.6.3. Specimen Preparation and Test Procedures

For the fluid immersion tests, 1”-diameter 4340 steel rod was cut into disks 0.05” thick, with both faces of each disk ground to a surface finish of 32-64 microinches Ra. Because the immersion tests were only to assess the behavior of the coatings under exposure, the substrates were not shot peened. Both faces of each disk were grit blasted and then coated with HVOF WC/CoCr, Cr_3C_2/NiCr, or T400 using the parameters as specified in Section 4.3. The nominal as-deposited coating thicknesses were 0.0055” for all coatings. The coatings were not ground prior to the fluid immersion tests.

The following fluids were specified in the JTP for immersion testing:

1. MIL-PRF-83282 hydraulic fluid
2. Skydrol AS1241 Type 4 hydraulic fluid
3. Non-destructive inspection (NDI) fluorescent penetrant dye, ARDROX 985-P14

4. Propylene glycol, commonly used for de-icing procedures
5. Nital etchant, a 4% by volume mixture of nitric acid in alcohol
6. Ammonium persulfate etchant, 10% by weight mixture with water
7. MIL-C-87937 cleaner, d-limonene based, mixed one part cleaner to two parts water
8. Oakite 90 cleaner, mixed 8.5 ounces per gallon of water
9. Chlorine bleach, sodium hypochlorite, common household bleach mixed 60% with water to yield a solution of approximately 3% by volume NaOCl
10. Cee-Bee J-84A, a high pH, heavy duty degreaser, mixed 8.5 ounces per gallon of water
11. Turco Vitro-Klene heavy duty soak cleaner, mixed 8.5 ounces per gallon of water
12. JP-5 jet fuel

Since the edges of the disks were not coated, it was necessary to seal them with a material that would not be attacked by the different fluids. Dow Epoxy Resin 324 hardened with triethylenetetramine (TETA) had been found to be resistant to common solvents, cleaners and chemical etchants. To evaluate the epoxy resistance for this study, specimens of cartridge brass and 316 stainless steel, approximately 1 inch square, were prepared and coated with the epoxy around the edges, and then weighed. Subsequently, the specimens were soaked at ambient temperature overnight for approximately 20 hours in five representative liquids: hydraulic fluid, JP-5, isopropanol, propylene glycol, and J-84 cleaner and then weighed. The weight loss was insignificant and, based on visual examination, there was no evidence of attack of the epoxy by any of the fluids.

To further evaluate the potential effects of the fluids on the epoxy, a 316 stainless steel specimen with the edges coated with the epoxy were prepared, weighed, and immersed in the fluids together with the HVOF-coated disks.

For the HVOF-coated disks, the edge around each specimen was coated with the epoxy such that it extended slightly onto the coating on each face, with the epoxy allowed to cure overnight at room temperature. Then photographs were taken at the approximate center of each specimen at 25X optical magnification.

Any chemical attack on the HVOF coatings caused by fluid immersion would likely be manifested as changes in the surface roughness. Therefore, the surface roughness near the center of each specimen was measured with a Mahr Perthometer S2 digital profilometer.

Subsequent to the profilmetry measurements, the specimens were individually cleaned in an ultrasonic cleaner, soaking each specimen for one to three minutes in isopropanol during the ultrasonic agitation. Upon removal from the ultrasonic cleaner, a jet of clean, dry air was used to blow off the isopropanol. Then each specimen was dried in open air for one to three minutes and weighed. The mass balance was a Mettler AE-200-S with 0.1 mg readability and reproducibility, and with a linearity of ±0.3 mg.

Two specimens of each of the three coating groups were tested in each fluid. With 12 fluids, this resulted in a total of 72 specimens being evaluated. Table 3-16 lists the specimen number, the HVOF coating on the specimen and the test fluid in which the specimen was immersed.

Stainless steel spring-clips were fastened to each specimen to hold them upright during immersion. Then each specimen was placed in a lidded, individual glass jar containing one of the test fluids under the conditions described below.

Fluid #1: MIL-PRF-83282 Hydraulic Fluid. The specimens were positioned individually in the jars and then fluid added to accurately immerse half of the specimen. These jars were held 500 hours at 70°C in a precision convection oven.

Fluid #2: Skydrol AS1241 Type 4 Hydraulic Fluid. The specimens were positioned individually in the jars and then fluid added to accurately immerse half of the specimen. These jars were held 500 hours at 70°C in a precision convection oven.

Fluid #3: Non-destructive Inspection (NDI) Fluorescent Penetrant Dye, ARDROX 985 P14. The specimens were completely immersed in the penetrant for 1 hour at ambient temperature, approximately 23°C.

Fluid #4: Propylene Glycol. Conditioned air was used to equilibrate the propylene glycol at 20°C. The specimens were completely immersed in the fluid for 1 hour at that temperature.

Fluid #5: Nital Etchant. The specimens were completely immersed in the etchant for 6 minutes at ambient temperature.

Fluid #6: Ammonium Persulfate Etchant. The specimens were completely immersed in the etchant for 6 minutes at ambient temperature.

Table 3-16 Specimen number, coating, and immersion fluid for all tests.

Specimen Number	Coating	Solvent	Specimen Number	Coating	Solvent
1	Triballoy-400	Not Tested	39	WC/CoCr	Propylene Glycol
2	Triballoy-400	JP-5	40	WC/CoCr	Propylene Glycol
3	Triballoy-400	Cee-Bee J-84A	41	WC/CoCr	Not Tested
4	Triballoy-400	Cee-Bee J-84A	42	WC/CoCr	Oakite 90
5	Triballoy-400	MIL-PRF-83282 Hydrualic Fluid	43	WC/CoCr	Oakite 90
6	Triballoy-400	Chlorine Bleach	44	WC/CoCr	MIL-C-87937 Cleaner
7	Triballoy-400	Skydrol	45	WC/CoCr	MIL-C-87937 Cleaner
8	Triballoy-400	Turco Vitro-Klene	46	WC/CoCr	Chlorine Bleach
9	Triballoy-400	Oakite 90	47	WC/CoCr	Cee-Bee J-84A
10	Triballoy-400	Skydrol	48	WC/CoCr	Cee-Bee J-84A
11	Triballoy-400	MIL-PRF-83282 Hydrualic Fluid	49	WC/CoCr	JP-5
12	Triballoy-400	Oakite 90	50	WC/CoCr	Chlorine Bleach
13	Triballoy-400	Turco Vitro-Klene	51	CrC/NiCr	Turco Vitro-Klene
14	Triballoy-400	Propylene Glycol	52	CrC/NiCr	Turco Vitro-Klene
15	Triballoy-400	Propylene Glycol	53	CrC/NiCr	JP-5
16	Triballoy-400	Ammonium Persulfate Etchant	54	CrC/NiCr	JP-5
17	Triballoy-400	Ammonium Persulfate Etchant	55	CrC/NiCr	Cee-Bee J-84A
18	Triballoy-400	Chlorine Bleach	56	CrC/NiCr	Cee-Bee J-84A
19	Triballoy-400	MIL-C-87937 Cleaner	57	CrC/NiCr	Skydrol
20	Triballoy-400	JP-5	58	CrC/NiCr	Skydrol
21	Triballoy-400	NDI Flourescent Penetrant Dye	59	CrC/NiCr	MIL-PRF-83282 Hydrualic Fluid
22	Triballoy-400	NDI Flourescent Penetrant Dye	60	CrC/NiCr	MIL-PRF-83282 Hydrualic Fluid
23	Triballoy-400	MIL-C-87937 Cleaner	61	CrC/NiCr	Chlorine Bleach
24	Triballoy-400	Nital Etchant	62	CrC/NiCr	Chlorine Bleach
25	Triballoy-400	Nital Etchant	63	CrC/NiCr	Propylene Glycol
26	WC/CoCr	Ammonium Persulfate Etchant	64	CrC/NiCr	Oakite 90
27	WC/CoCr	Ammonium Persulfate Etchant	65	CrC/NiCr	Oakite 90
28	WC/CoCr	Nital Etchant	66	CrC/NiCr	MIL-C-87937 Cleaner
29	WC/CoCr	Nital Etchant	67	CrC/NiCr	MIL-C-87937 Cleaner
30	WC/CoCr	Turco Vitro-Klene	68	CrC/NiCr	Propylene Glycol
31	WC/CoCr	Turco Vitro-Klene	69	CrC/NiCr	NDI Flourescent Penetrant Dye
32	WC/CoCr	MIL-PRF-83282 Hydrualic Fluid	70	CrC/NiCr	NDI Flourescent Penetrant Dye
33	WC/CoCr	MIL-PRF-83282 Hydrualic Fluid	71	CrC/NiCr	Ammonium Persulfate Etchant
34	WC/CoCr	JP-5	72	CrC/NiCr	Ammonium Persulfate Etchant
35	WC/CoCr	NDI Flourescent Penetrant Dye	73	CrC/NiCr	Nital Etchant
36	WC/CoCr	NDI Flourescent Penetrant Dye	74	CrC/NiCr	Not Tested
37	WC/CoCr	Skydrol	75	CrC/NiCr	Nital Etchant
38	WC/CoCr	Skydrol			

Fluid #7: MIL-C-87937 Cleaner, d-Limonene Based. The jars were filled with sufficient fluid to completely immerse the specimens. The jars were placed in a constant temperature bath at 50º C long enough to warm the fluid to that temperature and then the specimens were added to the fluid for a total immersion time of 6 hours.

Fluid #8: Oakite 90. The jars were filled with sufficient fluid to completely immerse the specimens. The jars were placed in a constant temperature bath at 50º C long enough to warm the fluid to that temperature and then the specimens were added to the fluid for a total immersion time of 6 hours.

Fluid #9: Chlorine Bleach, sodium hypochlorite. Conditioned air was sufficient to equilibrate the bleach solution at 20º C. Then the specimens were completely immersed in the bleach for 6 hours.

Fluid #10: Cee-Bee J-84A. The jars were filled with sufficient fluid to completely immerse the specimens. The jars were placed in a constant temperature bath at 50º C long enough to warm the fluid to that temperature and then the specimens were added to the fluid for a total immersion time of 6 hours.

Fluid #11: Turco Vitro-Klene. The jars were filled with sufficient fluid to completely immerse the specimens. The jars were placed in a constant temperature bath at 50º C long enough to warm the fluid to that temperature and then the specimens were added to the fluid for a total immersion time of 6 hours.

Fluid #12: JP-5 Jet Fuel. The specimens were positioned individually in the jars and then fluid was added to accurately immerse half of the specimen. The jars were held 500 hours at 40º C in a constant temperature bath. The jars were placed inside a fume hood to exhaust any vapors.

After the prescribed immersion times, each specimen was removed from its jar and excess fluid was wiped off with a paper towel. Then each specimen was thoroughly rinsed with isopropanol and dried with a jet of clean, dry air. The ARDROX penetrant was rinsed with water rather than isopropanol. Water rinsing was used to remain consistent with NDI procedures. After cleaning, each specimen was allowed to dry in open air for one to three minutes and then weighed using the procedure for the pre-test weighing. Further, each specimen was reweighed after drying in open air for approximately 48 hours. Finally, each specimen was photographed at 25X, similar to the pre-test photographs and then the surface roughness measurements were repeated.

3.6.4. Immersion Test Results

Table 3-17 presents the weight measurements and calculated weight gain or loss for each specimen, grouped by type of coating. Table 3-18 presents the same data, except grouped by fluid. This table also presents the weight gain/loss data for the stainless steel specimens with the epoxy on the edges (designated by an S specimen number).

Table 3-19 presents the results for the surface profile measurements before and after the immersion tests. Because of the statistical uncertainty in the surface profilometry, a criteria was established that if a change in Ra value was less than 20%, then it would be considered to represent “no change” as a result of the immersion.

Table 3-17 Mass values before and after immersion testing, grouped by coating type.

Specimen #	Coating Type	Pre Test Mass (g)	Test Fluid	Initial Post Test Mass (g)	After Extended Air-Dry Mass (g)	Initial Post Test Mass Change (g)	After Extended Air-Dry Mass Change (g)
1	T-400		Not Tested				
2	T-400	6.2807	JP-5 Jet Fuel	6.2826	6.2818	0.0019	0.0011
3	T-400	6.1966	Cee-Bee J-84A	6.1951	6.1943	-0.0015	-0.0023
4	T-400	6.2200	Cee-Bee J-84A	6.2188	6.2180	-0.0012	-0.0020
5	T-400	6.1723	Hydraulic Fluid	6.1746	6.1747	0.0023	0.0024
6	T-400	6.2507	Chlorine Bleach	6.2540	6.2528	0.0033	0.0021
7	T-400	6.2428	Skydrol	6.2536	6.2535	0.0108	0.0107
8	T-400	6.1953	Turco Vitro-Klene	6.1952	6.1937	-0.0001	-0.0016
9	T-400	6.1896	Oakite 90	6.1903	6.1895	0.0007	-0.0001
10	T-400	6.2607	Dkydrol	6.2700	6.2796	0.0093	0.0189
11	T-400	6.2363	MIL-PRF-83282 Hydraulic Fluid	6.2375	6.2380	0.0012	0.0017
12	T-400	6.1880	Oakite 90	6.1870	6.1861	-0.0010	-0.0019
13	T-400	6.2712	Turco Vitro-Klene	6.2714	6.2700	0.0002	-0.0012
14	T-400	6.2741	Propylene Glycol	6.2731	6.2727	-0.0010	-0.0014
15	T-400	6.2838	Propylene Glycol	6.2834	6.2829	-0.0004	-0.0009
16	T-400	6.2848	Ammonium Persulfate	6.2837	6.2833	-0.0011	-0.0015
17	T-400	6.2644	Ammonium Persulfate	6.2630	6.2630	-0.0014	-0.0014
18	T-400	6.2449	Chlorine Bleach	6.2287	6.2242	-0.0162	-0.0207
19	T-400	6.2765	MIL-C-87937 Cleaner	6.2790	6.2767	0.0025	0.0002
20	T-400	6.3001	JP-5 Jet Fuel	6.3020	6.3001	0.0019	0.0000
21	T-400	6.2906	Flourescent Penetrant Dye	6.2905	6.2903	-0.0001	-0.0003
22	T-400	6.1861	Flourescent Penetrant Dye	6.1861	6.1857	0.0000	-0.0004
23	T-400	6.1695	MIL-C-87937 Cleaner	6.1710	6.1691	0.0015	-0.0004
24	T-400	6.2959	Nital Etchant	6.2974	6.2959	0.0015	0.0000
25	T-400	6.1638	Nital Etchant	6.1651	6.1637	0.0013	-0.0001
Average Mass		6.2391		6.2397	6.2392	0.0006	0.0001

Table 3-17 (continued)

Specimen #	Coating Type	Pre Test Mass (g)	Test Fluid	Initial Post Test Mass (g)	After Extended Air-Dry Mass (g)	Initial Post Test Mass Change (g)	After Extended Air-Dry Mass Change (g)
26	WC/CoCr	7.0356	Ammonium Persulfate	7.0361	7.0353	0.0005	-0.0003
27	WC/CoCr	7.1543	Ammonium Persulfate	7.1542	7.1537	-0.0001	-0.0006
28	WC/CoCr	6.9513	Nital Etchant	6.9533	6.9515	0.0020	0.0002
29	WC/CoCr	6.8621	Nital Etchant	6.8637	6.8622	0.0016	0.0001
30	WC/CoCr	7.0319	Turco Vitro-Klene	7.0351	7.0320	0.0032	0.0001
31	WC/CoCr	7.1918	Turco Vitro-Klene	7.1956	7.1921	0.0038	0.0003
32	WC/CoCr	7.0192	Hydraulic Fluid	7.0244	7.0249	0.0052	0.0057
33	WC/CoCr	6.9622	Hydraulic Fluid	6.9681	6.9684	0.0059	0.0062
34	WC/CoCr	6.9982	JP-5 Jet Fuel	7.0029	6.9990	0.0047	0.0008
35	WC/CoCr	7.1219	Flourescent Penetrant Dye	7.1255	7.1240	0.0036	0.0021
36	WC/CoCr	7.1393	Flourescent Penetrant Dye	7.1421	7.1408	0.0028	0.0015
37	WC/CoCr	7.0596	Skydrol	7.0776	7.0774	0.0180	0.0178
38	WC/CoCr	7.0491	Skydrol	7.0696	7.0696	0.0205	0.0205
39	WC/CoCr	7.0029	Propylene Glycol	7.0032	7.0027	0.0003	-0.0002
40	WC/CoCr	7.0878	Propylene Glycol	7.0882	7.0879	0.0004	0.0001
41	WC/CoCr		Not Tested				
42	WC/CoCr	6.9515	Oakite 90	6.9530	6.9519	0.0015	0.0004
43	WC/CoCr	6.9603	Oakite 90	6.9616	6.9609	0.0013	0.0006
44	WC/CoCr	7.0005	MIL-C-87937 Cleaner	7.0099	7.0063	0.0094	0.0058
45	WC/CoCr	6.9687	MIL-C-87937 Cleaner	6.9765	6.9727	0.0078	0.0040
46	WC/CoCr	6.9691	Chlorine Bleach	6.9480	6.9470	-0.0211	-0.0221
47	WC/CoCr	6.9508	Cee-Bee J-84A	6.9531	6.9514	0.0023	0.0006
48	WC/CoCr	6.9660	Cee-Bee J-84A	6.9681	6.9658	0.0021	-0.0002
49	WC/CoCr	7.1083	JP-5 Jet Fuel	7.1132	7.1095	0.0049	0.0012
50	WC/CoCr	6.8975	Chlorine Bleach	6.8788	6.8773	-0.0187	-0.0202
Average Mass		7.0183		7.0209	7.0193	0.0026	0.0010

Table 3-17 (continued)

Specimen #	Coating Type	Pre Test Mass (g)	Test Fluid	Initial Post Test Mass (g)	After Extended Air-Dry Mass (g)	Initial Post Test Mass Change (g)	After Extended Air-Dry Mass Change (g)
51	CrC/NiCr	6.2294	Turco Vitro-Klene	6.2312	6.2299	0.0018	0.0005
52	CrC/NiCr	6.2226	Turco Vitro-Klene	6.2247	6.2232	0.0021	0.0006
53	CrC/NiCr	6.1394	JP-5 Jet Fuel	6.1413	6.1399	0.0019	0.0005
54	CrC/NiCr	6.1531	JP-5 Jet Fuel	6.1548	6.1531	0.0017	0.0000
55	CrC/NiCr	6.1909	Cee-Bee J-84A	6.1922	6.1916	0.0013	0.0007
56	CrC/NiCr	6.2713	Cee-Bee J-84A	6.2729	6.2720	0.0016	0.0007
57	CrC/NiCr	6.1503	Skydrol	6.1727	6.1723	0.0224	0.0220
58	CrC/NiCr	6.2633	Skydrol	6.2590	6.2587	-0.0043	-0.0046
59	CrC/NiCr	6.3263	Hydraulic Fluid	6.3284	6.3289	0.0021	0.0026
60	CrC/NiCr	6.2407	Hydraulic Fluid	6.2420	6.2424	0.0013	0.0017
61	CrC/NiCr	6.1991	Chlorine Bleach	6.1994	6.1992	0.0003	0.0001
62	CrC/NiCr	6.2912	Chlorine Bleach	6.2914	6.2913	0.0002	0.0001
63	CrC/NiCr	6.2665	Propylene Glycol	6.2670	6.2664	0.0005	-0.0001
64	CrC/NiCr	6.3429	Oakite 90	6.3441	6.3436	0.0012	0.0007
65	CrC/NiCr	6.3043	Oakite 90	6.3060	6.3052	0.0017	0.0009
66	CrC/NiCr	6.3546	MIL-C-87937 Cleaner	6.3606	6.3567	0.0060	0.0021
67	CrC/NiCr	6.2818	MIL-C-87937 Cleaner	6.2883	6.2847	0.0065	0.0029
68	CrC/NiCr	6.3262	Propylene Glycol	6.3259	6.3257	-0.0003	-0.0005
69	CrC/NiCr	6.2600	Flourescent Penetrant Dye	6.2606	6.2603	0.0006	0.0003
70	CrC/NiCr	6.4065	Flourescent Penetrant Dye	6.4068	6.4063	0.0003	-0.0002
71	CrC/NiCr	6.2238	Ammonium Persulfate	6.2238	6.2236	0.0000	-0.0002
72	CrC/NiCr	6.2318	Ammonium Persulfate	6.2316	6.2316	-0.0002	-0.0002
73	CrC/NiCr	6.2930	Nital Etchant	6.2930	6.2928	0.0000	-0.0002
74	CrC/NiCr	Not Tested					
75	CrC/NiCr	6.3175	Nital Etchant	6.3182	6.3176	0.0007	0.0001
Average Mass		6.2619		6.2640	6.2632	0.0021	0.0013

Table 3-18 Mass values before and after immersion testing, grouped by fluid type

Specimen #	Coating Type	Pre Test Mass g	Test Fluid	Test Temp. °C	Test Duration hours	Initial Post Test Mass g	After Extended Air-Dry Mass g	Initial Post Test Mass Change	After Extended Air-Dry Mass Change
5	T-400	6.1723	1	70	500	6.1746	6.1747	0.0023	0.0024
11	T-400	6.2363	1	70	500	6.2375	6.2380	0.0012	0.0017
32	WC/CoCr	7.0192	1	70	500	7.0244	7.0249	0.0052	0.0057
33	WC/CoCr	6.9622	1	70	500	6.9681	6.9684	0.0059	0.0062
59	CrC/NiCr	6.3263	1	70	500	6.3284	6.3289	0.0021	0.0026
60	CrC/NiCr	6.2407	1	70	500	6.2420	6.2424	0.0013	0.0017
			Hydraulic fluid				Max Change	0.0059	0.0062
							Min Change	0.0012	0.0017
							Avg Change	0.0030	0.0034
S1		2.4125	1	70	500	2.4109	2.4114	-0.0016	-0.0011
7	T-400	6.2428	2	70	500	6.2536	6.2535	0.0108	0.0107
10	T-400	6.2607	2	70	500	6.2700	6.2796	0.0093	0.0189
37	WC/CoCr	7.0596	2	70	500	7.0776	7.0774	0.0180	0.0178
38	WC/CoCr	7.0491	2	70	500	7.0696	7.0696	0.0205	0.0205
57	CrC/NiCr	6.1503	2	70	500	6.1727	6.1723	0.0224	0.0220
58	CrC/NiCr	6.2633	2	70	500	6.2590	6.2587	-0.0043	-0.0046
			Skydrol				Max Change	0.0224	0.0220
							Min Change	-0.0043	-0.0046
							Avg Change	0.0128	0.0142
S4		2.8717	2	70	500	2.8406	2.8404	-0.0311	-0.0313
21	T-400	6.2906	3	23	1	6.2905	6.2903	-0.0001	-0.0003
22	T-400	6.1861	3	23	1	6.1861	6.1857	0.0000	-0.0004
35	WC/CoCr	7.1219	3	23	1	7.1255	7.1240	0.0036	0.0021
36	WC/CoCr	7.1393	3	23	1	7.1421	7.1408	0.0028	0.0015
69	CrC/NiCr	6.2600	3	23	1	6.2606	6.2603	0.0006	0.0003
70	CrC/NiCr	6.4065	3	23	1	6.4068	6.4063	0.0003	-0.0002
			NDI Penetrant				Max Change	0.0036	0.0021
							Min Change	-0.0001	-0.0004
							Avg Change	0.0012	0.0005
S13		2.4224	3	23	1	2.4204	2.4203	-0.0020	-0.0021
14	T-400	6.2741	4	20	1	6.2731	6.2727	-0.0010	-0.0014
15	T-400	6.2838	4	20	1	6.2834	6.2829	-0.0004	-0.0009
39	WC/CoCr	7.0029	4	20	1	7.0032	7.0027	0.0003	-0.0002
40	WC/CoCr	7.0878	4	20	1	7.0882	7.0879	0.0004	0.0001
63	CrC/NiCr	6.2665	4	20	1	6.2670	6.2664	0.0005	-0.0001
68	CrC/NiCr	6.3262	4	20	1	6.3259	6.3257	-0.0003	-0.0005
			Propylene glycol				Max Change	0.0005	0.0001
							Min Change	-0.0010	-0.0014
							Avg Change	-0.0001	-0.0005
S12		2.4241	4	20	1	2.4225	2.4224	-0.0016	-0.0017
24	T-400	6.2959	5	23	0.1	6.2974	6.2959	0.0015	0.0000
25	T-400	6.1638	5	23	0.1	6.1651	6.1637	0.0013	-0.0001
28	WC/CoCr	6.9513	5	23	0.1	6.9533	6.9515	0.0020	0.0002
29	WC/CoCr	6.8621	5	23	0.1	6.8637	6.8622	0.0016	0.0001
73	CrC/NiCr	6.2930	5	23	0.1	6.2930	6.2928	0.0000	-0.0002
75	CrC/NiCr	6.3175	5	23	0.1	6.3182	6.3176	0.0007	0.0001
			Nital				Max Change	0.0020	0.0002
							Min Change	0.0000	-0.0002
							Avg Change	0.0012	0.0000
S15		2.1495	5	23	0.1	2.1498	2.1496	0.0003	0.0001
16	T-400	6.2848	6	23	0.1	6.2837	6.2833	-0.0011	-0.0015
17	T-400	6.2644	6	23	0.1	6.2630	6.2630	-0.0014	-0.0014
26	WC/CoCr	7.0356	6	23	0.1	7.0361	7.0353	0.0005	-0.0003
27	WC/CoCr	7.1543	6	23	0.1	7.1542	7.1537	-0.0001	-0.0006
71	CrC/NiCr	6.2238	6	23	0.1	6.2238	6.2236	0.0000	-0.0002
72	CrC/NiCr	6.2318	6	23	0.1	6.2316	6.2316	-0.0002	-0.0002
			Ammonium persulfate				Max Change	0.0005	-0.0002
							Min Change	-0.0014	-0.0015
							Avg Change	-0.0004	-0.0007
S14		2.4045	6	23	0.1	2.4004	2.4003	-0.0041	-0.0042

Table 3-18 continued

Specimen #	Coating Type	Pre Test Mass g	Test Fluid	Test Temp. °C	Test Duration hours	Initial Post Test Mass g	After Extended Air-Dry Mass g	Initial Post Test Mass Change	After Extended Air-Dry Mass Change
19	T-400	6.2765	7	50	6	6.2790	6.2767	0.0025	0.0002
23	T-400	6.1695	7	50	6	6.1710	6.1691	0.0015	-0.0004
44	WC/CoCr	7.0005	7	50	6	7.0099	7.0063	0.0094	0.0058
45	WC/CoCr	6.9687	7	50	6	6.9765	6.9727	0.0078	0.0040
66	CrC/NiCr	6.3546	7	50	6	6.3606	6.3567	0.0060	0.0021
67	CrC/NiCr	6.2818	7	50	6	6.2883	6.2847	0.0065	0.0029
			d-limonene cleaner				Max Change	0.0094	0.0058
							Min Change	0.0015	-0.0004
							Avg Change	0.0056	0.0024
S10		3.1654	7	50	6	3.1639	3.1621	-0.0015	-0.0033
9	T-400	6.1896	8	50	6	6.1903	6.1895	0.0007	-0.0001
12	T-400	6.1880	8	50	6	6.1870	6.1861	-0.0010	-0.0019
42	WC/CoCr	6.9515	8	50	6	6.9530	6.9519	0.0015	0.0004
43	WC/CoCr	6.9603	8	50	6	6.9616	6.9609	0.0013	0.0006
64	CrC/NiCr	6.3429	8	50	6	6.3441	6.3436	0.0012	0.0007
65	CrC/NiCr	6.3043	8	50	6	6.3060	6.3052	0.0017	0.0009
			Oakite 90				Max Change	0.0017	0.0009
							Min Change	-0.0010	-0.0019
							Avg Change	0.0009	0.0001
S7		2.3754	8	50	6	2.3750	2.3746	-0.0004	-0.0008
6	T-400	6.2507	9	20	6	6.2540	6.2528	0.0033	0.0021
18	T-400	6.2449	9	20	6	6.2287	6.2242	-0.0162	-0.0207
46	WC/CoCr	6.9691	9	20	6	6.9480	6.9470	-0.0211	-0.0221
50	WC/CoCr	6.8975	9	20	6	6.8788	6.8773	-0.0187	-0.0202
61	CrC/NiCr	6.1991	9	20	6	6.1994	6.1992	0.0003	0.0001
62	CrC/NiCr	6.2912	9	20	6	6.2914	6.2913	0.0002	0.0001
			bleach (NaOCl)				Max Change	0.0033	0.0021
							Min Change	-0.0211	-0.0221
							Avg Change	-0.0087	-0.0101
S11		2.8651	9	20	6	2.8613	2.8609	-0.0038	-0.0042
3	T-400	6.1966	10	50	6	6.1951	6.1943	-0.0015	-0.0023
4	T-400	6.2200	10	50	6	6.2188	6.2180	-0.0012	-0.0020
47	WC/CoCr	6.9508	10	50	6	6.9531	6.9514	0.0023	0.0006
48	WC/CoCr	6.9660	10	50	6	6.9681	6.9658	0.0021	-0.0002
55	CrC/NiCr	6.1909	10	50	6	6.1922	6.1916	0.0013	0.0007
56	CrC/NiCr	6.2713	10	50	6	6.2729	6.2720	0.0016	0.0007
			J-84A				Max Change	0.0023	0.0007
							Min Change	-0.0015	-0.0023
							Avg Change	0.0008	-0.0004
S8		2.3202	10	50	6	2.3179	2.3175	-0.0023	-0.0027
8	T-400	6.1953	11	50	6	6.1952	6.1937	-0.0001	-0.0016
13	T-400	6.2712	11	50	6	6.2714	6.2700	0.0002	-0.0012
30	WC/CoCr	7.0319	11	50	6	7.0351	7.0320	0.0032	0.0001
31	WC/CoCr	7.1918	11	50	6	7.1956	7.1921	0.0038	0.0003
51	CrC/NiCr	6.2294	11	50	6	6.2312	6.2299	0.0018	0.0005
52	CrC/NiCr	6.2226	11	50	6	6.2247	6.2232	0.0021	0.0006
			Vitro-Klene				Max Change	0.0038	0.0006
							Min Change	-0.0001	-0.0016
							Avg Change	0.0018	-0.0002
S9		2.2756	11	50	6	2.2751	2.2745	-0.0005	-0.0011
2	T-400	6.2807	12	40	500	6.2826	6.2818	0.0019	0.0011
20	T-400	6.3001	12	40	500	6.3020	6.3001	0.0019	0.0000
34	WC/CoCr	6.9982	12	40	500	7.0029	6.9990	0.0047	0.0008
49	WC/CoCr	7.1083	12	40	500	7.1132	7.1095	0.0049	0.0012
53	CrC/NiCr	6.1394	12	40	500	6.1413	6.1399	0.0019	0.0005
54	CrC/NiCr	6.1531	12	40	500	6.1548	6.1531	0.0017	0.0000
			JP5 fuel				Max Change	0.0049	0.0012
							Min Change	0.0017	0.0000
							Avg Change	0.0028	0.0006
S6		2.2861	12	40	500	2.2856	2.2859	-0.0005	-0.0002
1	T-400	6.2679	NA						
41	WC/CoCr	7.1104	NA						
74	CrC/NiCr	6.3326	NA						

Table 3-19 Surface roughness measurements for each specimen before and after immersion testing.

Specimen Number	Coating	Solvent	Pre-Immersion Measurements				Post-Immersion Measurements				Change			
			Ra (μin)	Rz (μin)	Rp (μin)	Rsk (-)	Ra (μin)	Rz (μin)	Rp (μin)	Rsk (-)	Ra (μin)	Rz (μin)	Rp (μin)	Rsk (-)
1	Triballoy-400	Not Tested	149.1	942.5	463.9	0.1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2	Triballoy-400	JP-5	169.1	983.0	477.2	0.1	161.9	952.7	483.3	0.1	-7.2	-30.3	6.1	0
3	Triballoy-400	Cee-Bee J-84A	169.8	992.8	533.2	0.3	124.5	745.9	474.5	0.6	-45.3	-246.9	-58.7	0.3
4	Triballoy-400	Cee-Bee J-84A	148.4	1023.5	542.3	0.4	171.7	991.6	536.9	0.3	23.3	-31.9	-5.4	-0.1
5	Triballoy-400	MIL-PRF-83282 Hydrualic Fluid	166.0	1078.2	600.1	0.6	139.2	902.7	500.4	0.5	-26.8	-175.5	-99.7	-0.1
6	Triballoy-400	Chlorine Bleach	159.7	972.4	516.9	0.2	243.1	1470.9	713.8	0.5	83.4	498.5	196.9	0.3
7	Triballoy-400	Skydrol	154.5	953.4	480.0	0.1	214.5	1109.5	623.4	0.8	60	156.1	143.4	0.7
8	Triballoy-400	Turco Vitro-Klene	161.7	957.6	485.4	0.4	172.9	1115.7	685.1	1.0	11.2	158.1	199.7	0.6
9	Triballoy-400	Oakite 90	217.6	1150.6	641.6	0.5	188.8	1097.9	595.4	0.5	-28.8	-52.7	-46.2	0
10	Triballoy-400	Skydrol	171.4	1010.7	558.2	0.7	151.4	942.4	528.3	0.6	-20	-68.3	-29.9	-0.1
11	Triballoy-400	MIL-PRF-83282 Hydrualic Fluid	184.1	1067.1	606.4	0.2	173.6	970.5	454.7	0.2	-10.5	-96.6	-151.7	0
12	Triballoy-400	Oakite 90	151.0	997.6	604.9	1.0	174.3	1085.3	582.4	0.5	23.3	87.7	-22.5	-0.5
13	Triballoy-400	Turco Vitro-Klene	173.0	1105.4	591.3	0.5	171.7	999.6	496.9	0.3	-1.3	-105.8	-94.4	-0.2
14	Triballoy-400	Propylene Glycol	163.7	1065.6	585.9	0.5	169.5	1050.1	601.1	0.5	5.8	-15.5	15.2	0
15	Triballoy-400	Propylene Glycol	166.4	994.8	485.9	0.2	184.7	1043.4	567.6	0.4	18.3	48.6	81.7	0.2
16	Triballoy-400	Ammonium Persulfate Etchant	157.0	965.7	539.1	0.5	196.7	1200.0	674.6	0.8	39.7	234.3	135.5	0.3
17	Triballoy-400	Ammonium Persulfate Etchant	173.0	981.0	544.9	0.3	160.7	940.5	484.8	0.3	-12.3	-40.5	-60.1	0
18	Triballoy-400	Chlorine Bleach	188.4	1125.1	612.4	0.2	619.6	2880.2	1412.0	0.2	431.2	1755.1	799.6	0
19	Triballoy-400	MIL-C-87937 Cleaner	169.8	1027.5	558.6	0.6	154.8	1014.9	561.9	0.8	-15	-12.6	3.3	0.2
20	Triballoy-400	JP-5	146.2	897.0	468.2	0.2	180.4	1118.9	607.9	0.4	34.2	221.9	139.7	0.2
21	Triballoy-400	Penetrant Dye	187.0	1123.7	693.5	1.0	191.5	1271.3	767.4	0.8	4.5	147.6	73.9	-0.2
22	Triballoy-400	Penetrant Dye	171.0	1001.5	578.8	0.6	152.4	930.5	461.8	0.2	-18.6	-71	-117	-0.4
23	Triballoy-400	MIL-C-87937 Cleaner	176.8	1016.1	547.5	0.5	161.6	902.9	502.1	0.2	-15.2	-113.2	-45.4	-0.3
24	Triballoy-400	Nital Etchant	179.2	961.4	509.2	0.5	192.4	1112.8	664.8	0.9	13.2	151.4	155.6	0.4
25	Triballoy-400	Nital Etchant	149.3	882.7	431.4	0.2	169.0	1015.6	505.2	-0.1	19.7	132.9	73.8	-0.3

Table 3-19 continued

Specimen Number	Coating	Solvent	Pre-Immersion Measurements				Post-Immersion Measurements				Change			
			Ra (µin)	Rz (µin)	Rp (µin)	Rsk (-)	Ra (µin)	Rz (µin)	Rp (µin)	Rsk (-)	Ra (µin)	Rz (µin)	Rp (µin)	Rsk (-)
26	WC/CoCr	Ammonium Persulfate Etchant	95.9	632.5	311.5	-0.1	105.8	637.6	323.0	0.2	9.9	5.1	11.5	0.3
27	WC/CoCr	Ammonium Persulfate Etchant	118.3	706.0	358.1	0.0	111.8	723.8	347.6	0.0	-6.5	17.8	-10.5	0
28	WC/CoCr	Nital Etchant	107.6	651.2	333.2	0.0	126.8	716.7	342.3	0.0	19.2	65.5	9.1	0
29	WC/CoCr	Nital Etchant	106.0	707.2	375.5	0.3	107.9	619.8	327.8	0.0	1.9	-87.4	-47.7	-0.3
30	WC/CoCr	Turco Vitro-Klene	128.0	815.6	423.8	0.1	100.5	660.1	318.9	-0.4	-27.5	-155.5	-104.9	-0.5
31	WC/CoCr	Turco Vitro-Klene	125.4	705.4	368.9	0.2	98.2	604.7	321.9	0.3	-27.2	-100.7	-47	0.1
32	WC/CoCr	MIL-PRF-83282 Hydrualic Fluid	117.6	717.2	390.0	0.2	111.9	710.6	378.7	0.2	-5.7	-6.6	-11.3	0
33	WC/CoCr	MIL-PRF-83282 Hydrualic Fluid	109.1	700.7	365.0	0.5	105.4	651.8	304.9	-0.2	-3.7	-48.9	-60.1	-0.7
34	WC/CoCr	JP-5	115.6	684.2	369.8	0.4	117.9	719.8	368.0	0.1	2.3	35.6	-1.8	-0.3
35	WC/CoCr	NDI Flourescent Penetrant Dye	109.6	747.5	350.4	-0.3	96.8	612.8	301.4	-0.1	-12.8	-134.7	-49	0.2
36	WC/CoCr	NDI Flourescent Penetrant Dye	106.9	644.5	325.7	0.1	118.6	664.8	323.2	0.0	11.7	20.3	-2.5	-0.1
37	WC/CoCr	Skydrol	113.6	632.9	313.5	0.2	97.8	639.9	331.7	0.0	-15.8	7	18.2	-0.2
38	WC/CoCr	Skydrol	104.1	588.6	292.6	-0.1	114.3	755.3	368.8	-0.2	10.2	166.7	76.2	-0.1
39	WC/CoCr	Propylene Glycol	109.4	652.8	330.4	0.0	113.9	713.4	366.1	0.0	4.5	60.6	35.7	0
40	WC/CoCr	Propylene Glycol	108.1	685.8	366.2	0.2	114.4	695.5	395.9	0.4	6.3	9.7	29.7	0.2
41	WC/CoCr	Not Tested	150.2	1005.5	494.4	-0.1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
42	WC/CoCr	Oakite 90	98.5	652.3	327.6	0.0	115.9	726.0	404.8	0.2	17.4	73.7	77.2	0.2
43	WC/CoCr	Oakite 90	108.7	664.6	343.0	0.2	97.3	630.1	305.0	0.3	-11.4	-34.5	-38	0.1
44	WC/CoCr	MIL-C-87937 Cleaner	115.0	711.7	423.8	0.8	109.2	708.5	392.5	0.4	-5.8	-3.2	-31.3	-0.4
45	WC/CoCr	MIL-C-87937 Cleaner	123.1	703.3	333.9	-0.1	105.9	612.8	302.6	0.1	-17.2	-90.5	-31.3	0.2
46	WC/CoCr	Chlorine Bleach	119.6	683.7	330.3	-0.1	96.6	610.0	322.7	0.4	-23	-73.7	-7.6	0.5
47	WC/CoCr	Cee-Bee J-84A	103.8	648.7	337.8	0.1	112.9	715.2	379.3	0.3	9.1	66.5	41.5	0.2
48	WC/CoCr	Cee-Bee J-84A	102.9	588.0	298.7	0.2	103.4	663.9	339.2	-0.1	0.5	75.9	40.5	-0.3
49	WC/CoCr	JP-5	103.7	578.3	282.1	-0.1	97.5	615.9	312.5	0.0	-6.2	37.6	30.4	0.1
50	WC/CoCr	Chlorine Bleach	110.0	693.1	369.7	0.4	113.5	706.5	363.9	-0.1	3.5	13.4	-5.8	-0.5

Table 3-19 continued

Specimen Number	Coating	Solvent	Pre-Immersion Measurements				Post-Immersion Measurements				Change			
			Ra (µin)	Rz (µin)	Rp (µin)	Rsk (-)	Ra (µin)	Rz (µin)	Rp (µin)	Rsk (-)	Ra (µin)	Rz (µin)	Rp (µin)	Rsk (-)
51	CrC/NiCr	Turco Vitro-Klene	122.2	718.9	375.6	0.2	120.7	816.0	459.5	0.3	-1.5	97.1	83.9	0.1
52	CrC/NiCr	Turco Vitro-Klene	120.1	880.1	543.8	0.7	139.3	825.1	412.0	0.2	19.2	-55	-131.8	-0.5
53	CrC/NiCr	JP-5	118.7	780.0	415.9	0.3	121.9	771.6	389.5	0.4	3.2	-8.4	-26.4	0.1
54	CrC/NiCr	JP-5	106.1	667.7	336.3	0.3	119.3	709.1	385.9	0.5	13.2	41.4	49.6	0.2
55	CrC/NiCr	Cee-Bee J-84A	138.9	885.3	486.8	0.4	125.4	734.0	383.6	0.3	-13.5	-151.3	-103.2	-0.1
56	CrC/NiCr	Cee-Bee J-84A	138.0	814.4	423.0	0.3	102.1	672.2	346.9	0.1	-35.9	-142.2	-76.1	-0.2
57	CrC/NiCr	Skydrol	107.7	648.0	332.5	0.2	123.3	776.2	416.9	0.3	15.6	128.2	84.4	0.1
58	CrC/NiCr	Skydrol	113.5	708.9	364.9	0.3	126.2	751.1	402.4	0.2	12.7	42.2	37.5	-0.1
59	CrC/NiCr	MIL-PRF-83282 Hydrualic Fluid	120.7	773.8	434.5	0.3	120.7	741.6	357.2	0.0	0	-32.2	-77.3	-0.3
60	CrC/NiCr	MIL-PRF-83282 Hydrualic Fluid	118.6	710.2	395.7	0.4	127.3	788.1	451.2	0.4	8.7	77.9	55.5	0
61	CrC/NiCr	Chlorine Bleach	120.1	722.3	415.0	0.3	133.7	819.8	420.1	0.4	13.6	97.5	5.1	0.1
62	CrC/NiCr	Chlorine Bleach	128.1	791.4	409.6	0.3	122.4	776.0	420.9	0.4	-5.7	-15.4	11.3	0.1
63	CrC/NiCr	Propylene Glycol	127.5	761.6	419.8	0.2	116.8	735.2	418.0	0.5	-10.7	-26.4	-1.8	0.3
64	CrC/NiCr	Oakite 90	115.7	704.6	350.2	0.1	129.1	838.3	450.2	0.3	13.4	133.7	100	0.2
65	CrC/NiCr	Oakite 90	128.2	789.9	455.1	0.5	120.9	724.1	362.4	0.2	-7.3	-65.8	-92.7	-0.3
66	CrC/NiCr	MIL-C-87937 Cleaner	113.4	693.6	336.6	0.1	118.3	726.1	392.8	0.3	4.9	32.5	56.2	0.2
67	CrC/NiCr	MIL-C-87937 Cleaner	128.1	769.8	408.3	0.3	120.7	710.7	394.0	0.4	-7.4	-59.1	-14.3	0.1
68	CrC/NiCr	Propylene Glycol	115.1	739.6	392.1	0.4	143.2	848.4	489.2	0.4	28.1	108.8	97.1	0
69	CrC/NiCr	NDI Flourescent Penetrant Dye	104.0	640.9	343.4	0.3	118.1	700.4	359.6	0.3	14.1	59.5	16.2	0
70	CrC/NiCr	NDI Flourescent Penetrant Dye	144.5	872.6	469.9	0.2	126.8	802.6	449.2	0.6	-17.7	-70	-20.7	0.4
71	CrC/NiCr	Ammonium Persulfate Etchant	131.9	801.1	456.7	0.4	117.9	721.5	387.7	0.3	-14	-79.6	-69	-0.1
72	CrC/NiCr	Ammonium Persulfate Etchant	132.3	740.4	382.1	0.1	123.4	697.4	378.5	0.3	-8.9	-43	-3.6	0.2
73	CrC/NiCr	Nital Etchant	113.5	659.9	340.0	0.0	122.1	822.5	452.5	0.4	8.6	162.6	112.5	0.4
74	CrC/NiCr	Not Tested	117.6	751.5	420.2	0.5	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
75	CrC/NiCr	Nital Etchant	120.5	741.2	399.8	0.4	132.1	849.5	459.1	0.2	11.6	108.3	59.3	-0.2

The following observations were made with respect to the immersion tests.

<u>Fluid #1:</u> MIL-PRF-83282 Hydraulic Fluid

- Mass change after immersion: Increase, due to fluid retention.
- Mass change after extended air-dry: Further increase, apparent moisture absorption.
- Visual examination comparison before and after immersion: No change.
- Surface roughness measurement: No change.

Examination of the 50% immersed specimens revealed no observable difference between the immersed half and the non-immersed half. The MIL-PRF-83282 hydraulic fluid wicked up the surface of the specimens, and appeared to wet the entire exposed surface. The fluid retention is explainable by the surface characteristics and porosity of the coatings. These specimens were held at 70°C for three weeks, and it is likely that they were well desiccated. Hydraulic fluid is generally hygroscopic, and moisture absorption in retained hydraulic fluid would explain the further mass gain after open air exposure.

<u>Fluid #2:</u> Skydrol AS1241 Type 4 Hydraulic Fluid

- Mass change after immersion: Invalid results.
- Mass change after extended air-dry: Invalid results.
- Visual examination comparison before and after immersion: No change.
- Surface roughness measurement: No change.

Examination of the 50% immersed specimens revealed no observable difference between the immersed half and the non-immersed half. The Skydrol hydraulic fluid was not included in the pre-test epoxy evaluation with the stainless steel and brass specimens, and it proved to soften and loosen some of the epoxy during the 500 hour elevated temperature soak. This unforeseen occurrence invalidates the mass difference measurements for specimens in the Skydrol fluid. Apparently, the epoxy tended to absorb the Skydrol fluid for a net mass gain. Specimen number 58 was anomalous in that it lost mass. Presumably, some of the epoxy was lost, but this loss was not obvious. Visually, there appeared to be no degradation of the coating.

<u>Fluid #3:</u> Non-destructive Inspection (NDI) Fluorescent Penetrant Dye, ARDROX 985 P14

- Mass change after immersion: Increase, due to fluid retention.
- Mass change after extended air-dry: Decreased approaching zero net change.
- Visual examination comparison before and after immersion: No change.
- Surface roughness measurement: No change.

Tribaloy-400 and CrC/NiCr were essentially unaffected by ARDROX. WC/CoCr appeared to retain the fluid, which appeared to evaporate with further air dry. Overall, ARDROX had no effect on these coatings in this test.

<u>Fluid #4:</u> Propylene Glycol

- Mass change after immersion: Negligible change.
- Mass change after extended air-dry: Slight decrease.
- Visual examination comparison before and after immersion: No change.

- Surface roughness measurement: No change.

Propylene glycol had no effect on the coatings in this test.

<u>Fluid #5:</u> Nital Etchant

- Mass change after immersion: Slight increase.
- Mass change after extended air-dry: Decreased to essentially no mass change.
- Visual examination comparison before and after immersion: No change.
- Surface roughness measurement: No change.

Nital etchant had no effect on the coatings in this test.

<u>Fluid #6:</u> Ammonium Persulfate Etchant

- Mass change after immersion: Negligible change.
- Mass change after extended air-dry: Slight decrease.
- Visual examination comparison before and after immersion: No change.
- Surface roughness measurement: No change.

Ammonium persulfate may have attacked the Tribaloy-400 coating since there was a consistent mass loss. However, the loss was small and inconclusive. Visual examination revealed no change due to exposure. Likewise, there was no change in the surface roughness measurements.

<u>Fluid #7:</u> MIL-C-87937 Cleaner, d-Limonene Based

- Mass change after immersion: Increase, due to fluid retention.
- Mass change after extended air-dry: Substantial decrease.
- Visual examination comparison before and after immersion: No change.
- Surface roughness measurement: No change.

Though the coatings appeared to have some tendency to retain the fluid on the surface, the fluid tended to evaporate readily. Otherwise, there was no observed effect of this fluid on the coatings in this test.

<u>Fluid #8:</u> Oakite 90

- Mass change after immersion: Slight increase.
- Mass change after extended air-dry: Decreased to approximately no-change.
- Visual examination comparison before and after immersion: No change.
- Surface roughness measurement: No change.

Oakite 90 may have attacked the Tribaloy-400 coating, but the loss was small and inconclusive. Visual examination revealed no change due to exposure, and there was no change in the surface roughness measurements.

<u>Fluid #9:</u> Chlorine Bleach, Sodium Hypochlorite

- Mass change after immersion: Decreased significantly.
- Mass change after extended air-dry: Further decrease, perhaps loose particles lost.
- Visual examination comparison before and after immersion: Obvious degradation.
- Surface roughness measurement: Obvious surface effect and roughening of the Tribaloy-400.

The bleach solution aggressively attacked WC/CoCr, and the effect was visually obvious, both during the immersion and after cleaning. The bleach solution attacked the cobalt-containing Tribaloy-400 even more aggressively than the WC/CoCr. The Tribaloy-400 coating was aggressively attacked in the bleach solution. Gas evolved at the surface and boiled away rapidly. Specimen 6 and specimen 18 were affected equally, but only specimen 18 exhibited the anticipated mass loss. Visual evidence suggested that the corrosion products adhered and built-up on specimen 6. The corrosion products appeared to remain loose on specimen 18, and possibly loose particles fell off the specimen before the final weighing. Specifically, specimen 18 had a mass loss of 16.2 mg after immersion and cleaning, but it had a mass loss of 20.7 mg after the extended air-dry period. Particle loss would seem necessary to explain the 4.5 mg extra loss, which was triple the loss likely due to evaporation of retained fluids on the other five bleach-soaked specimens. There was substantial roughening of the surface on the Tribaloy-400 but surprisingly there was little change in the surface roughness on the WC/CoCr even though there was substantial mass loss.

The bleach had little effect on CrC/NiCr, which contained no cobalt.

Fluid #10: Cee-Bee-J-84A

- Mass change after immersion: Slight increase.
- Mass change after extended air-dry: Decreased to approximately no-change.
- Visual examination comparison before and after immersion: No change.
- Surface roughness measurement: No change.

Cee-Bee J-84A may have attacked the Tribaloy-400 coating, but the loss was small and inconclusive. Visual examination revealed no change due to exposure, and there was no change in the surface roughness measurements.

Fluid #11: Turco Vitro-Klene

- Mass change after immersion: Slight increase.
- Mass change after extended air-dry: Decreased to approximately no-change.
- Visual examination comparison before and after immersion: No change.
- Surface roughness measurement: No change.

Turco Vitro-Klene may have attacked the Tribaloy-400 coating, but the loss was small and inconclusive. Visual examination revealed no change due to exposure, and there was no change in the surface roughness measurements.

Fluid #12: JP-5 Jet Fuel

- Mass change after immersion: Increased.
- Mass change after extended air-dry: Decreased to approximately no-change.
- Visual examination comparison before and after immersion: No change.
- Surface roughness measurement: No change.

Examination of the 50% immersed specimens revealed no observable difference between the immersed half and the non-immersed half. JP-5 jet fuel had no effect on these coatings in this test.

3.6.5. Analysis of Results

The only effect evident from visual inspection, surface roughness, and the mass measurements was the effect of the bleach (NaOCl) solution on the two cobalt-containing coatings, Tribaloy-400 and WC/CoCr, specimen numbers 6, 18, 46, and 50. Visual inspection identified both coupons of both coatings to have had significant coating alteration. Figure 3-30 presents photographs of specimens 6 and 18. The field-of-view width was approximately 5/8 inch. The images are presented here at approximately 5X. Figure 3-31 is the same view for specimens 46 and 50.

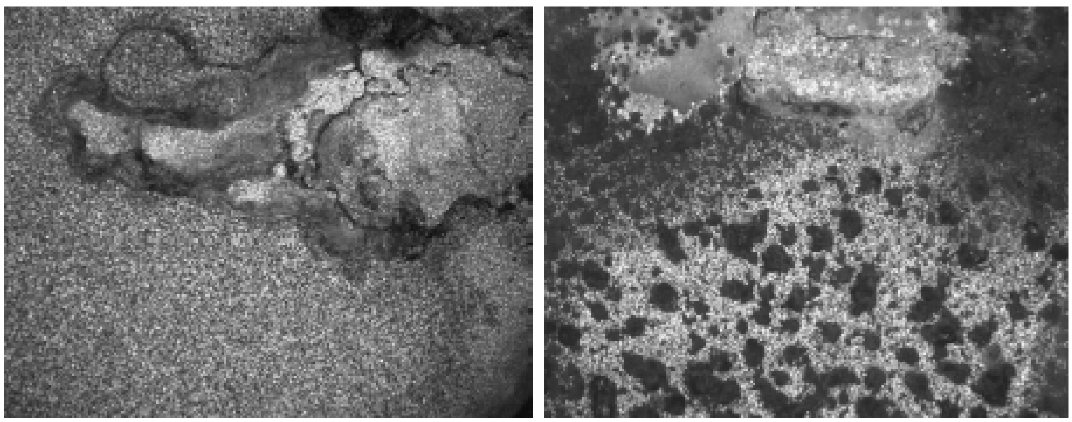


Figure 3-30 Fluid immersion specimens #6 (left) and #18 (right) with T400 coatings showing degradation after immersion in chlorine bleach.

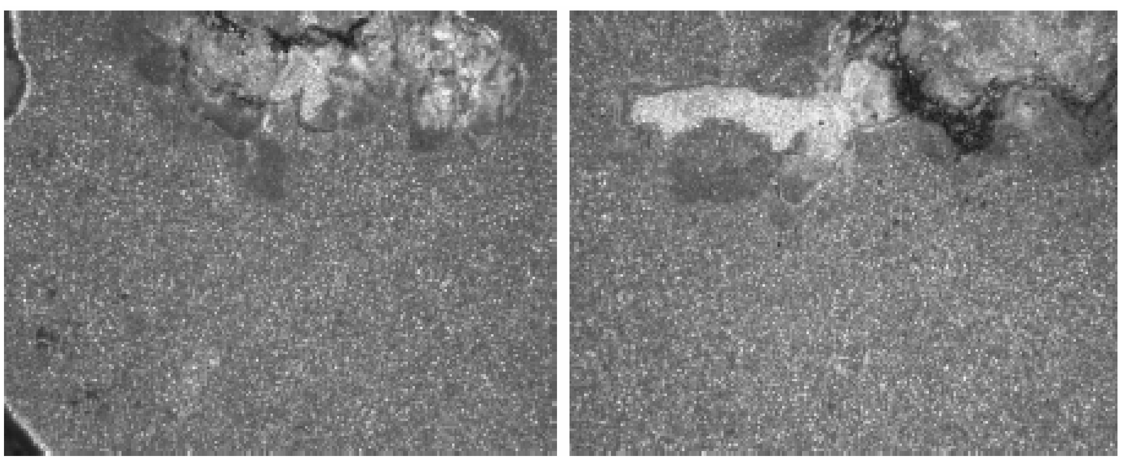


Figure 3-31 Fluid immersion specimens #46 (left) and #50 (right) with WC/CoCr coatings showing degradation after immersion in chlorine bleach.

The mass measurements indicate an anomaly for specimen number 6 in that it had a mass increase. Likewise, the surface roughness check of the WC/CoCr coatings provided no indication that the two specimens, 46 and 50, were deteriorated. Metals in general do not withstand attack by household bleach. Iron, and especially cobalt, are particularly susceptible to hypochlorite damage, rapidly corroding and degrading. Also, cobalt is used as a catalyst in the waste treatment of sodium hypochlorite; the metal accelerates the breakdown of the hypochlorite-ion to chloride-ion and oxygen. Since we observed the rapid evolution of gas at the surface of the specimens while immersed in the bleach solution, it seems evident that this reaction was occurring. Also, the reaction will hasten the general corrosion of the specimen, which is to say that it will self-accelerate until the hypochlorite ion concentration becomes sufficiently depleted by the ongoing reaction. Tribaloy-400 was attacked aggressively with almost immediate gas evolution and obvious degradation within a few minutes of immersion. WC/CoCr was also attacked, but at a substantially reduced rate. Figure 3-32 shows six bleach containing jars and the obvious attack on the specimens. The CrC/NiCr coatings were not attacked by the bleach solution.

Figure 3-32 Six specimens immersed in bleach solution at 20° C

All coatings appeared to resist the other 11 fluids. There was a trend with Tribaloy-400 to be slightly reduced in mass by exposure to the reactive chemicals, specifically, the high pH, heavy-duty cleaners and the ammonium persulfate etchant. The effect was limited in the mass data, and no effect was evident in the photographs or surface roughness measurements.

The surface roughness measurements showed no significant change due to the immersions, with the exception of chlorine bleach noted above.

Visual examination of specimens 6, 18, 46, and 50 immersed in bleach revealed the coating degradation, but visual examination of the remaining 68 specimens immersed in the respective fluids revealed little or no effect. These 68 specimens appeared visually to be the same before and after immersion in the test fluids.

3.6.6. Conclusions and Recommendations

Based on the results of the immersion tests, all coatings appear to be resistant to attack by the fluids, with the exception of bleach. Sodium hypochlorite attacks and degrades the cobalt-containing coatings. The HVOF Tribaloy-400 coating could be ill-suited to applications where it might be exposed to strong cleaning agents or other reactive chemicals. HVOF CrC/NiCr and WC/CoCr coatings can both be expected to resist common liquids during service and maintenance, but procedures should emphasize the danger of exposing WC/CoCr to sodium hypochlorite bleach, and measures should be implemented to guard against its use.

Given how aggressively chlorine bleach attacked the cobalt-containing coatings, it is recommended that an extensive investigation of sodium hypochlorite affects on HVOF coatings be conducted. A test procedure should be developed to investigate ramifications, and a test matrix should be developed for different concentrations of sodium hypochlorite and exposure times as well as different exposure conditions.

Since the active hypochlorite ion is apparently consumed in contact with cobalt, the test conditions are self-limiting, and reaction rates decrease with time. It is believed that a test with an excess quantity of bleach solution or a replenishment mechanism would be able to indicate whether or not other limiting factors exist.

These HVOF coatings resisted the organic liquids tested in this study, and an organic disinfectant might prove to be an acceptable alternative to chlorine bleach when circumstances require biological disinfection. This was a concern specifically regarding hoof-and-mouth disease. Another common recommended disinfectant for hoof-and-mouth disease is distilled white vinegar, which should be investigated as an alternative to bleach. Since most commercial aircraft are moving to the use of HVOF WC/CoCr in place of EHC, this finding is of concern for commercial as well as military aircraft. International cooperation and requirements from Boeing and other airframers will be required to validate and substitute an alternative disinfectant instead of bleach in wash-downs of landing gear and wheels to prevent the spread of livestock diseases.

Tribaloy-400 experienced mass loss after immersion in some of the test fluids. The weight loss was marginal, but consistent. It is recommended that additional investigations with an expanded test matrix be performed to definitively determine if the Tribaloy-400 is significantly affected by the suspected fluids.

Although the results of the immersion testing showed that the d-Limonene-based MIL-C-87937 cleaner did not affect the HVOF coatings, it is known that this cleaner can be corrosive and cause pitting on certain metals such as aluminum and magnesium. Therefore, if the HVOF coatings are to be used on these types of substrates, care should be taken to ensure use of this type of cleaner does not result in exposure of the base material.

3.7. Environmental Embrittlement (ASTM F519)

3.7.1. Background and Rationale

Hydrogen embrittlement is a serious problem for electroplated components, as is environmental embrittlement (re-embrittlement) due to corrosion. HVOF coatings avoid hydrogen embrittlement due to processing, but environmental embrittlement can still occur, most likely as a result of corrosion of the coating or substrate (including galvanic corrosion between the coating and adjacent metals such as the substrate or bushings).

Standard hydrogen embrittlement test results were reported in the Landing Gear Final Report [5]. The combinations were WC-Co and WC/CoCr coatings on 4340 steel. The test method used was ASTM F-519 using a notched 1a.2 specimen under constant load. This testing demonstrated that HVOF spraying does not cause embrittlement and that hydrogen can diffuse through HVOF coatings, although at a slower rate than through hard chrome. Environmental embrittlement was found to be much slower for HVOF than for EHC coatings, although neither reached the 200 hour life specified in the test.

It was determined that for this project there was no need to repeat the standard process hydrogen embrittlement testing since the landing gear data showed that HVOF does not cause embrittlement. The only important issue is whether, for the lower UTS materials used in actuators, use of an HVOF coating accelerates environmental embrittlement. Environmental embrittlement is governed by the production of hydrogen during corrosion enhanced by galvanic coupling between the coating and the substrate, by the trapping of hydrogen at stress concentrations in the material, and by the ability of that hydrogen to cause embrittlement. The different substrate and coating materials, as well as their different heat treatments mean that the data obtained for WC-Co and WC/CoCr on 4340 steel is relevant only to that substrate and those coatings. The 4340 steel used in the landing gear testing was heat treated to 260-280 ksi, which is the worst case scenario for embrittlement. This is the standard material available commercially for the F-519 test.

The F-519 test using the Type 1a.2 notched specimen proved to be a poor choice for HVOF coatings. Overspray coating powder accumulated in the notch to form a thick, porous coating completely different from the thin, compact coating over any normal component surface. If this coating had good mechanical properties it would reduce the Kt of the notch as well as carry some of the load. If it had poor mechanical and corrosion properties its behavior might not be at all characteristic of the normal coating material.

The only non-notched specimen recognized by ASTM F-519 is a Type 2a, which is a smooth ring 2.3” dia. The alternative is the Rising Step Load (RSL) test, which uses a plain cylindrical gauge section on which good quality HVOF coatings can be deposited.

However, the poor quality of the HVOF coating in the notch is not important for those embrittlement tests in which the notch is scribed, since scribing redefines the correct Kt, and cuts through the coating to expose the substrate, obviating both the coating porosity and the Kt problems (provided the scribe was completely circumferential). Therefore it was possible to use the standard Type 1a.2 specimen, but only for scribed testing, which represents corrosion through a damaged coating.

3.7.2. Specimen Fabrication and Coating

Special ASTM F519 Type 1a.2 hydrogen embrittlement bars were fabricated from the materials in the heat-treat condition as indicated in Section 3.2. Extra specimens were fabricated to measure the notch fracture load, with the following results:

4340: 13,056 lbs

PH15-5: 12,580 lbs

Ti-6Al-4V: 10,328 lbs

Subsequent to fabrication, the specimens were not shot-peened since this would reduce hydrogen penetration. Prior to application of the EHC and HVOF coatings, the specimens were grit blasted as indicated in Section 3.3, with the exception that the Ti-6Al-4V specimens were not grit blasted so as to avoid a possible situation of embedded grit creating stress risers. These specimens were only cleaned with acetone. The grit blasting on the other alloys required manipulating the specimens to ensure that the grit blast was reasonably uniform within the notch.

In previous HVOF spraying of these types of specimens, the overspray material, which would normally bounce back off the surface, tended to become trapped in the notch, producing a thicker and more porous coating. In order to minimize this entrapment for these specimens, a strong air stream was directed into the notch and the HVOF coatings were applied with the gun at an angle of 30° to the normal. During coating application the specimens were rotated while the gun was traversed, angling the gun at +30° from the normal when traveling in one direction and -30° from the normal when traveling in the other direction. During coating application, air cooling was used to ensure the surface of the specimen did not exceed 375ºF. Figure 3-33 shows the area on the specimens that was coated.

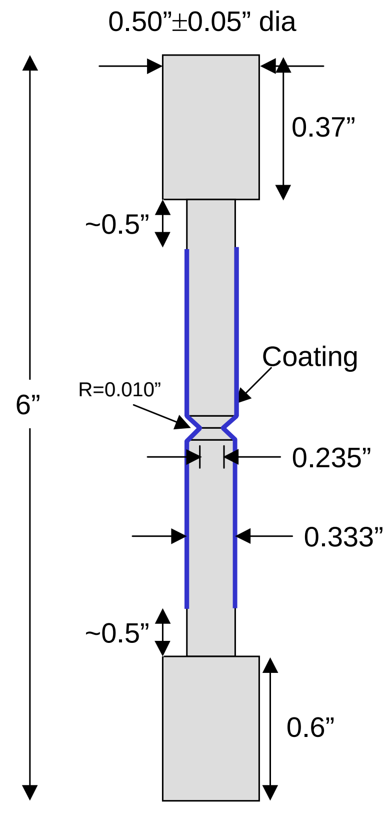


Figure 3-33 Type 1a.2 hydrogen embrittlement specimen showing the area on which the HVOF coating was applied.

On all bars, a cut was made through the coating in the notch with a shaped diamond-cutting wheel to just expose the substrate all around the circumference within the notch as indicated in Figure 3-34. The diamond cutting wheel had a blade with a 45° angle and a 0.010” radius OD. The blade was driven into the notch to cut just into the underlying material and then the blade was rotated around the specimen. Each specimen was visually examined at 10x to ensure complete coating removal in the scribed area before removing the sample from the machining holder.

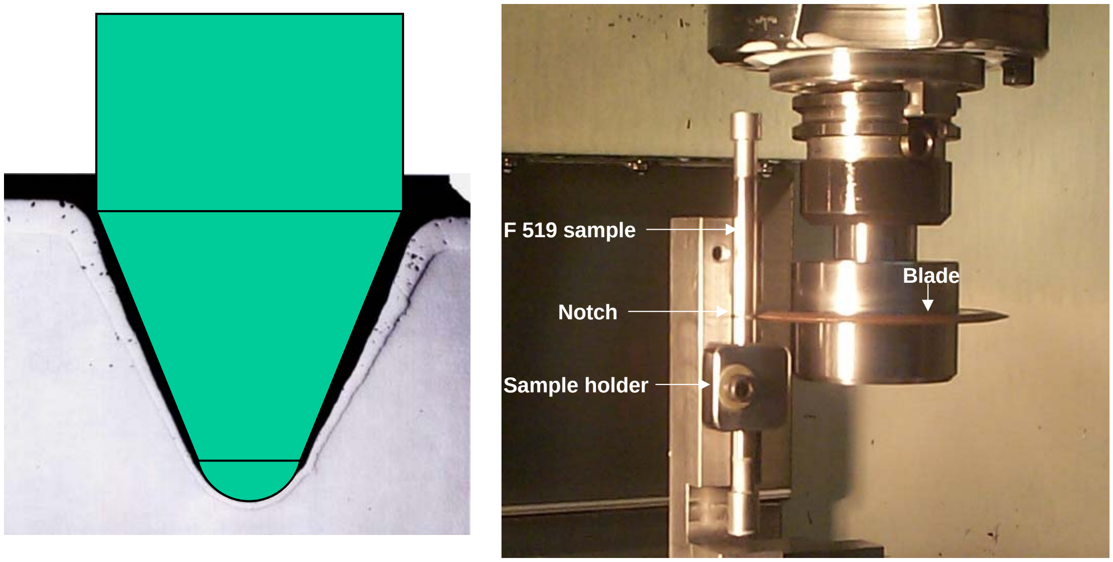


Figure 3-34 Illustration of the method used to cut through the HVOF or EHC coatings at the base of the notch.

3.7.3. Environmental Embrittlement Test Results

For each coating/substrate combination, three specimens were immersed in deionized (DI) water and three were immersed in a 5% NaCl solution and then subjected to a sustained tensile load of 45% of the notch fracture strength.

The test requirements were that the sustained tensile load was to be maintained for a period of 200 hours or specimen fracture, whichever occurred first, in accordance with ASTM F519. If a specimen fractured, then the time to failure was to be recorded and the fracture surface photographed.

Table 3-20 Environmental embrittlement test matrix – hours at 45% NFS.

	4340		Ti6Al4V		PH15-5	
Test environ.	DI H_2O	5% NaCl	DI H_2O	5% NaCl	DI H_2O	5% NaCl
Hard Chrome	>200	>200	>200	>200	>200	>200
WC/CoCr	>200	>200	>200	>200	>200	>200
T400	>200	>200	>200	>200	>200	>200
Cr_3C_2/NiCr	>200	>200	>200	>200	>200	>200
Total tests	**12**	**12**	**12**	**12**	**12**	**12**

The test matrix and results are shown in Table 3-20. The results of these tests were that none of the specimens fractured prior to the 200 hours.

3.7.4.Conclusions

Environmental hydrogen embrittlement is not an issue for either EHC or the HVOF coatings on these materials.

4. Functional Rod-Seal Testing

4.1.1.Data Summary

Table 4-1 Quick Reference to Primary Embrittlement Data.

Item	Item Number
Rod specifications – Phase I	Table 4-2
Seal configurations	Table 4-3
Rod specifications – Phase II	Table 4-4
Rod/seal leakeage for O-ring with Capstrip	Figure 4-15
Rod/seal leakeage for O-ring with + 2 backup rings	Figure 4-16
Rod/seal leakeage for Fluorosilicon O-ring + PTFE Capstrip	Figure 4-17
Rod/seal leakage for spring energized PTFE seals	Figure 4-18
Fluid leakage at each temperature for all rod/seal configurations	Figure 4-19
Summary of total leakage and leakage rate for all rod/seals	Figure 4-20

Click blue links to jump to data

4.2. Background and Objectives

A large percentage of hydraulic components on military aircraft hydraulic systems are removed due to external leakage. Most aircraft hydraulic system components are packed with Nitrile (MIL-P-25732) rubber seals that may become damaged at temperatures above 160° F. The amount of seal damage is cumulative with exposure time and increases rapidly with elevated temperatures. This has been a particular problem with components such as the F/A-18 C/D stabilator, which has required frequent overhaul to correct external leakage of hydraulic fluid.

To address these problems, the Naval Air Systems Command (NAVAIR) at Patuxent River, Maryland designed and constructed a test rig that would be capable of simultaneously evaluating multiple different seal configurations under rigorous conditions in order to determine those with the best possibility of performing satisfactorily in service. Multiple tests were performed using chrome-plated rods that showed that spring-energized PTFE seals demonstrated the best performance, with none of the elastomer-related degradation and virtually no leakage being observed.

The HCAT determined that the NAVAIR test rig would be ideal as a screening tool for evaluating the performance of various HVOF thermal spray coatings with different surface finishes against different types of seal materials. The performance of HVOF-coated rods would also be directly compared against the baseline performance of EHC-plated rods. Hard chrome plating is the industry standard practice for hydraulic and pneumatic actuator rods, although HVOF thermal spray coatings are seeing increasing use.

The intent of the testing performed in this project was to collect data on not only the performance of HVOF-coated rods compared to EHC-plated rods, but also to determine the optimum surface finishes on the HVOF-coated rods to minimize seal wear.

Two phases of functional rod/seal tests were performed. The objective of Phase I was to validate HVOF WC/CoCr as an acceptable replacement for EHC by conducting unloaded cycle testing of four different seal configurations. The objective of Phase II was to conduct unloaded cycle testing of one seal configuration against WC/CoCr with different surface finishes as well as one additional HVOF coating, WC/Cr_3C_2/Ni (73/20/7).

4.3. Description of Test Apparatus

The test apparatus is located at NAVAIR Patuxent River. It consists of a master hydraulic piston that drives the four test rods, each of which passes through two blocks. The portion of the apparatus consisting of the blocks and test rods is mounted inside an environmental chamber capable of maintaining a temperature between -65° and +300°F. The master piston passes through a sealed port on the environmental chamber. The hydraulic power supply is located outside the chamber for increased reliability of the test hardware. Hydraulic lines to the fixture are single-ended and thus would not heat or cool the test hardware.

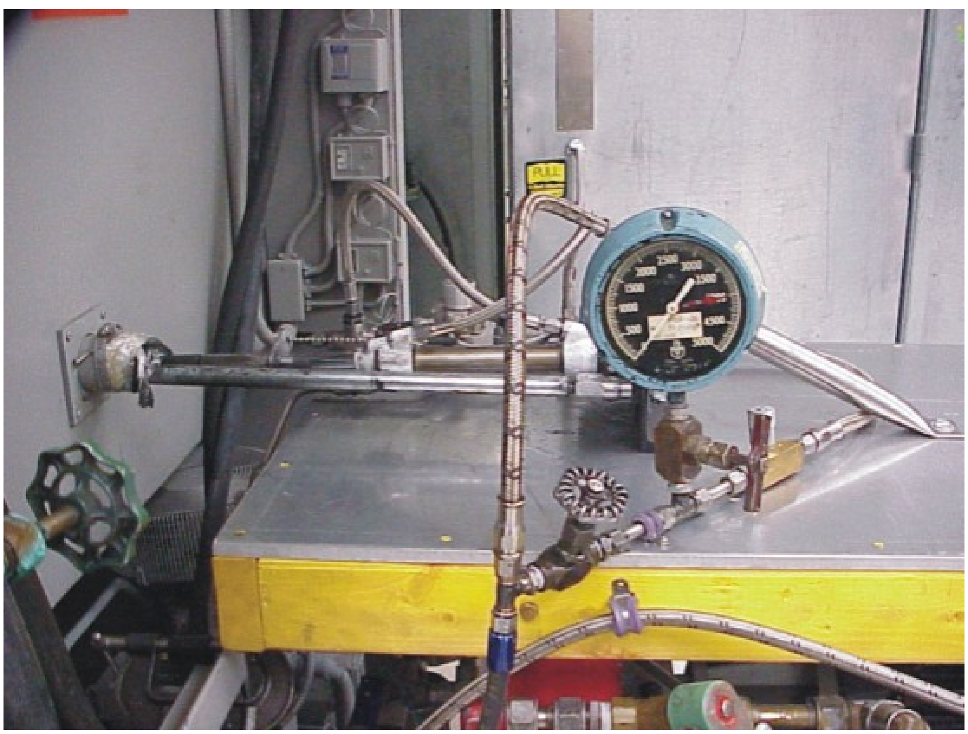


Figure 4-1 Photograph Showing Master Hydraulic Piston Passing Through Wall of Environmental Chamber at Left

Figure 4-1 is a photograph of the master hydraulic piston, showing it passing through the wall of the environmental chamber and also showing the pressure gage measuring the instantaneous fluid pressure. Figure 4-2 and Figure 4-3 show the apparatus consisting of

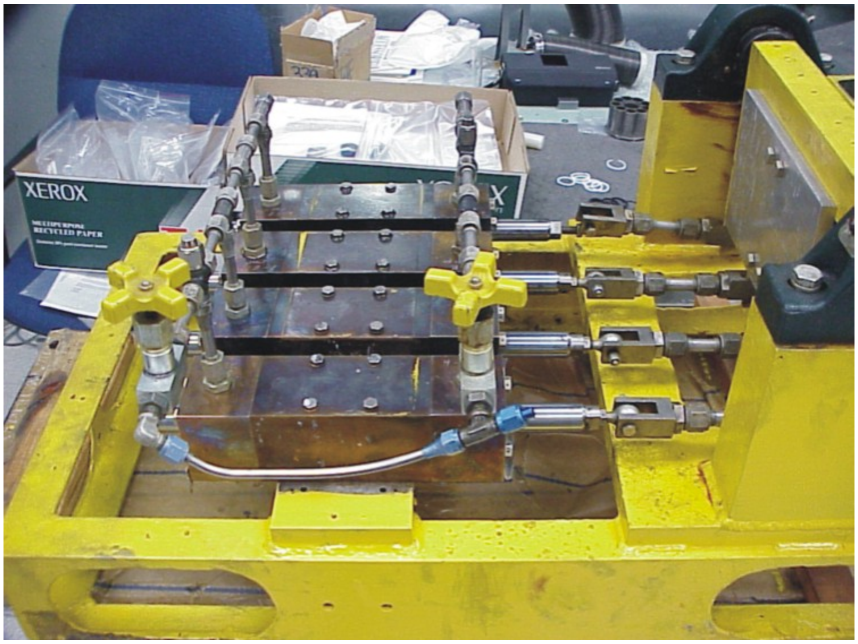


Figure 4-2 Test Apparatus Consisting of Four Rods Passing Through Blocks Containing Seals

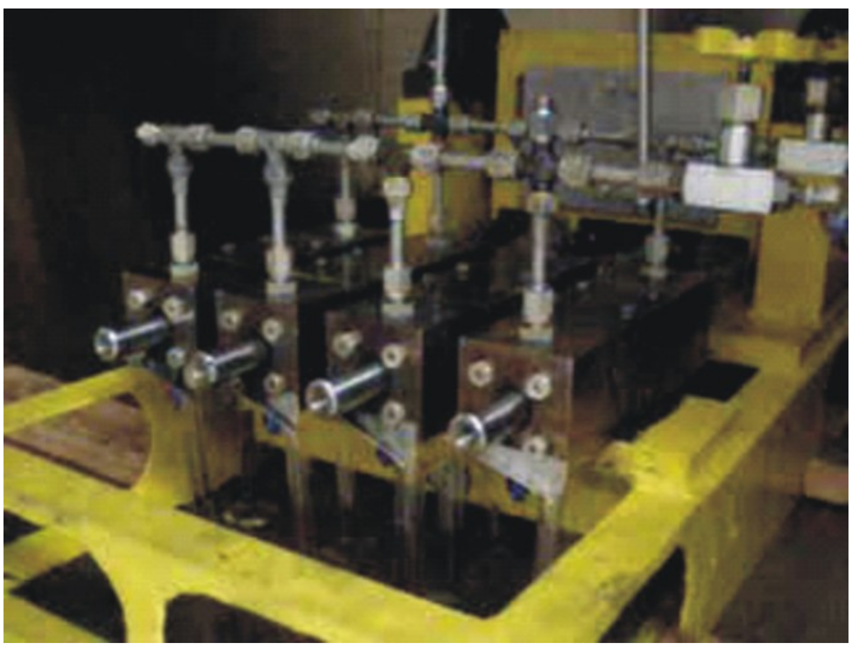


Figure 4-3 Photograph of Rod/seal Test Apparatus

the four test rods and the blocks that contain the seals. This entire apparatus fits inside the environmental chamber.

Figure 4-4 is a schematic of the test rod and block/seal configuration. There are two seal configurations per block and two blocks per rod. Thus, in any given test, there are 16 rod/seal configurations being evaluated. In the figure, the primary seals are indicated in blue and the secondary seals in magenta.

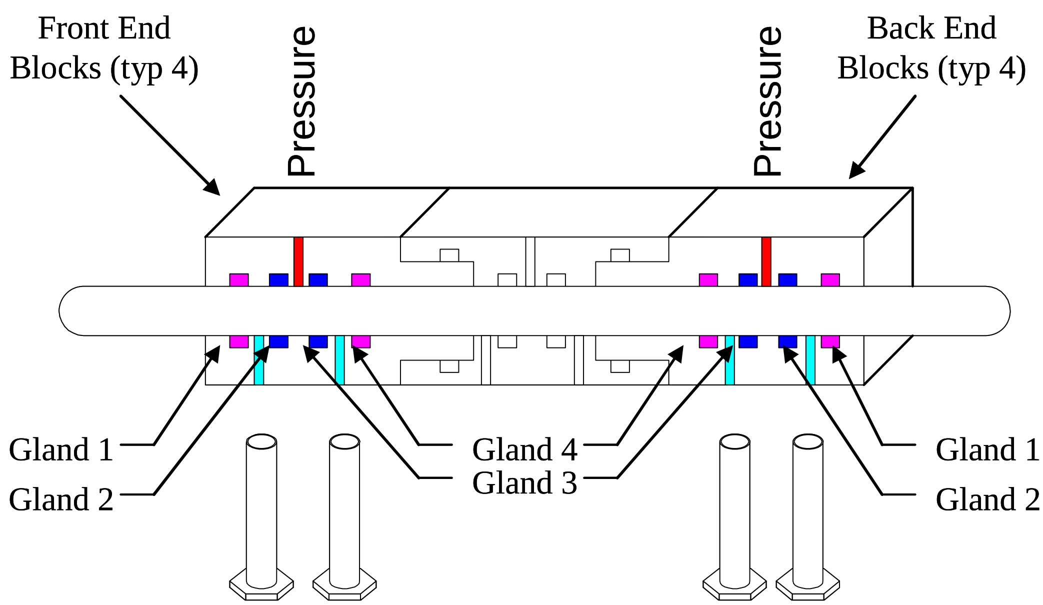


Figure 4-4. Schematic of Test Rod and Block/seal Configuration

Figure 4-5 is a schematic of the entire test system. It is simplified by only showing one rod and pair of seal blocks. As indicated above, the entire test apparatus consists of four sets of this hardware. The common stroking piston and common hydraulic tubing ensure that all seals under test are subject to the same rod motion and hydraulic system pressure. For this setup, the blue grooves contain seals under test. The magenta grooves contain scrapers to help gather leakage for collection in graduated cylinders.

MIL-PRF-83282 hydraulic fluid that was filtered with 5 micron elements and maintained to a Navy Class 4 or better contamination level was used for all tests. The drive piston operates at 3000 psi and static pressure acts on the seals in the block end cap that have ports on the top. A total of eight block end caps each have four seal grooves in accordance with MIL-G-5514 for a one O-ring and two backup groove width. Pressure was applied to each block from the top center and collection of leakage was measured in two locations per block. Leakage was collected in beakers set up between the test (primary position) and dummy (secondary position) seals such that only the test seal was evaluated and the dummy seal acted as a barrier to direct leakage to the collection beakers. There was no external loading provided by this test fixture.

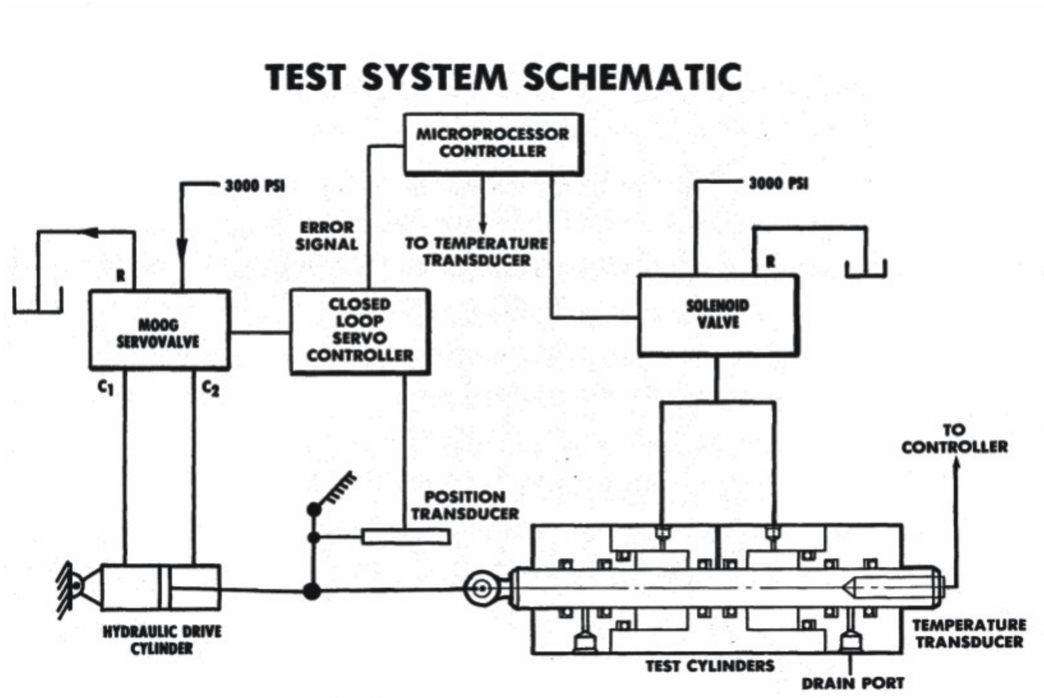


Figure 4-5 Schematic of Entire Test System, Showing Only One of the Four Rods

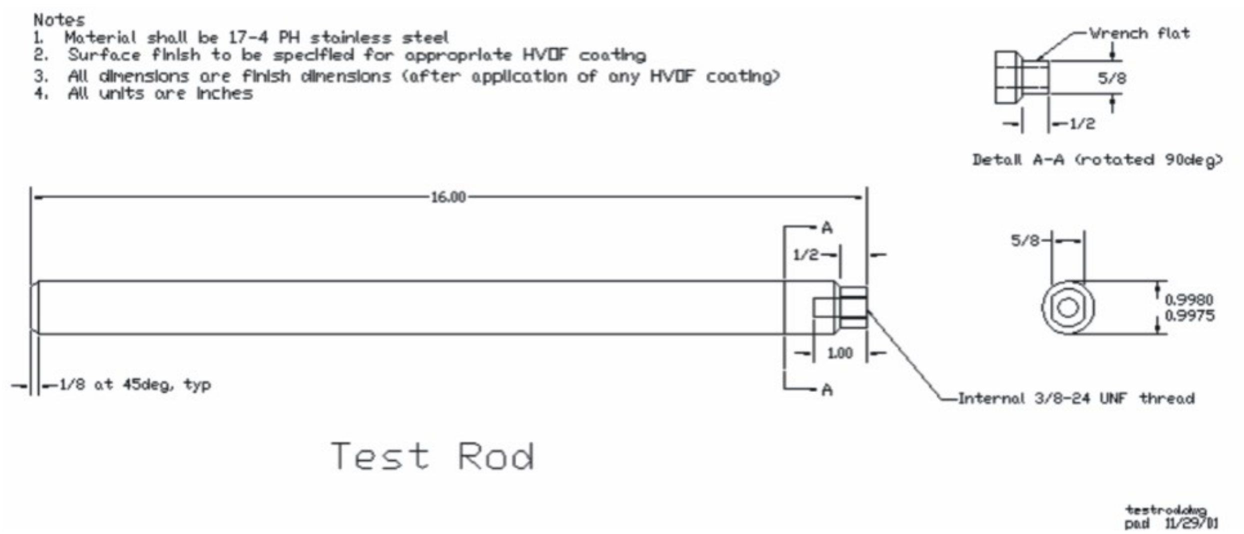
A position sensor was required for the control system to maintain position and stroke. The required ambient and fluid temperature was maintained by the environmental chamber set point. A control valve ported the fluid to the drive piston based on the cyclic profile computer software.

4.4. Preparation of Test Rods and Seal Configurations

Phase I

The test rods were fabricated from PH13-8Mo stainless steel and were 16 inches in length and nominally 1 inch in diameter. Figure 5-6 provides a schematic of the rods with exact dimensions. The rods were heat-treated following the H1000 process in accordance with AMS 5629 (220 ksi UTS and 43-45 HRc). Following fabrication and heat treatment, the rods were subjected to a nital etch in accordance with MIL-STD-867 to examine for grinding burns. After the nital etching, the rods were baked at 375° F for 23 hours to remove residual hydrogen.

The rods were then cleaned to remove moisture, oil, grease, and other foreign matter. Final cleaning was performed no more than four hours prior to coating. Cleaning procedures were followed such that they did not cause hydrogen embrittlement or other detrimental surface contamination.



Material: PH 13-8Mo (ignore Note 1 above)
Curved surface ground and polished to surface finish between 8-12 Ra
Finished Diameter (after HVOF coating) 0.9975-0.9980.
Internal thread on one end (3/8-24 UNF, one inch deep).
1/2 inch wide wrench flats for 5/8 inch wrench milled on threaded end.
Edges chamfered to 1/8 for ease of installation, other edges broken for safety.

Figure 4-6 Schematic and Requirements for Test Rods

The rods were grit blasted and HVOF WC/CoCr coatings were applied to rods numbered 1 through 3 as described in Section 4.3 and EHC was applied to rod number 4 as described in Section 4.3. The coating on Rod #1 was ground using a 320 grit diamond wheel, the coating on Rod #2 was ground using a 120 grit diamond wheel and then superfinished using the oscillating stone method, the coating on Rod #3 was ground using a 220 grit diamond wheel and then superfinished using the oscillating stone method, and Rod #4 was ground using a 60 grit alumina wheel. Table 4-2 summarizes the coating, grinding surface finish and superfinishing performed on each rod. It also provides the actual final Ra values as measured using a Taylor-Hobson Talysurf surface profilometer.

Table 4-2 Phase I Rod Specification (surface finishes are Ra values expressed in microinches)

Rod No.	Material Coating	Grinding Surface Finish	Super Finish
1	WC/CoCr 86/10/4	4-6 μ-in. Ra using 320 grit diamond wheel (actual 6.46)	As-Ground
2	WC/CoCr 86/10/4	20-22 μ-in. Ra using 120 grit diamond wheel	4 μ-in. or better (actual 2.31)
3	WC/CoCr 86/10/4	8-10 μ-in. Ra using 220 grit diamond wheel	2 μ-in. (actual 1.49)
4	Chrome	12-15 μ-in. Ra using 60 grit Al2O3 (actual 12.27)	As-Ground

Shamban, Green-Tweed and CoorsTek each provided four different seal configurations. From the received seals, the following seals in Table 4-3 were randomly selected for testing. The supplier of the spring energized PTFE configuration installed their seals in the blocks because the installation technique required specific skills to prevent the seals from becoming easily damaged. NAVAIR Patuxent River engineers installed the remaining seal configurations in the block cap glands and rods in the block fixture.

Table 4-3 Phase I Seal Configurations

Seal Configuration	Supplier	Part Number
#1 MIL-P-83461 O-ring and PTFE Cap strip	Busak+Shamban	O-ring (M83461/1-214) Double Delta (S32851-214-19N) Backup Ring (S11248-214-10)
#2 MIL-P-83461 O-ring and 2 backup rings	Greene Tweed Busak+Shamban	O-ring (A921499-00161) Backup Ring (2114-214-079) O-ring (M83461/1-214) Backup Ring (M8791/1-214)
#3 Fluorosilicon O-ring PTFE cap strip	CoorsTek	O-ring (TF2-214-813) Tetralon 902 Tetracap Seal (TF238M214-902N)
#4 Spring energized PTFE seal	CoorsTek	Metaplast Seal (TF888L214-902C) Backup Ring (TF91-214-901)

Phase II:

Six additional rods were fabricated as indicated in Figure 4-6, numbered 6 through 11. Of these, Rods 6, 8, 9, and 11 were selected for coating deposition and seal testing, with HVOF WC/CoCr applied to Rods 6, 8 and 9, and WC/Cr_3C_2/Ni applied to Rod 11. The deposition parameters for the latter coating were essentially the same as for the

WC/CoCr. The Phase II testing was intended to evaluate eight different processed rod halves on the four rods with only one seal configuration. The purpose was to evaluate the performance of ground versus superfinished coatings and whether there was a difference between the performance of coatings superfinished using the oscillating stone methods and those superfinished using the tape method.

Table 4-4 indicates the grinding and superfinishing procedures for each rod. Note that each half of each rod (identified as “a” or “b”) was processed differently. Rod half “a” was the portion of the rod closest to the master drive cylinder.

Table 4-4 Phase II Rod Specifications.

Rod No.	Material Coating	Grinding Surface Finish	Super Finish
6a	WC/CoCr	4-8 μ-in. Ra using 320 grit diamond	As-Ground
6b	WC/CoCr	2 $\pm$1 μ-in. Ra using 800 grit diamond	As-Ground
8a	WC/CoCr	8-16 μ-in. Ra using 220 grit diamond	4 μ-in. or better, tape method
8b	WC/CoCr	8-16 μ-in. Ra using 220 grit diamond	4 μ-in. or better, stone method
9a	WC/CoCr	16-32 μ-in. Ra using 120 grit diamond	4 μ-in. or better, tape method
9b	WC/CoCr	16-32 μ-in. Ra using 120 grit diamond	4 μ-in. or better, stone method
11a	WC-Cr_3C_2-Ni	8-16 μ-in. Ra using 220 grit diamond	4 μ-in. or better, tape method
11b	WC-Cr_3C_2-Ni	8-16 μ-in. Ra using 220 grit diamond	4 μ-in. or better, Stone method

One seal configuration, MIL-P-83461 O-ring and dual backup rings, provided by Greene-Tweed, was used in all blocks for the Phase II test. NAVAIR Patuxent River engineers installed the seals in the block cap glands and rods in the block fixtures.

4.5. Test Parameters

Phase I:

A specific temperature and cycling spectrum was established for the test which was run for 8 hours per day for 16 days to achieve a total of 1,040,000 cycles. The test specimens and fixture were maintained at 0 °F between each day of testing to evaluate static leakage at start-up. There was a static pressure of 3000 psi applied to both ends of each test block. Table 4-5 presents the cyclic test drive ram stroke conditions and Table 4-6 indicates the cyclic test cycle definitions. Table 4-7 gives the temperature cyclic profile. Figure 4-7, Figure 4-8 and Figure 4-9 show the profiles for full stroke, super-imposed dither stroke and dither stroke, respectively.

Table 4-5 Cyclic Test Drive Ram Stroke Conditions

Condition	Stroke Position (in.) (Measured from the main ram midstroke position) + = Extended from midstroke - = Retracted from midstroke
A	-1.75 ±0.25
B	-1.00 ±0.25
C	-0.25 ±0.10
D	0.00 ±0.25
E	+0.25 ±0.10
F	+1.00 ±0.25
G	+1.75 ±0.25

Table 4-6 Cyclic Test Cycle Definitions

Cycle	**Wave**	**Frequency**	**Duration**	**Definition**
Full Stroke	Sine	1.5 sec period	20 min per hr	Progress from Table 5 Condition D, to A, to G, to D
Super-imposed Dither	Cosine Sine	4 sec period 4 Hz	20 min per hr	Imposing Cosine wave progressing from Table 5 Condition D, to B, to F, to D and Sine wave progressing from table 2 Condition D, to C, to E, to D simultaneously.
Dither	Sine	4 Hz	20 min per hr	Progress from Table 5 Condition D, to C, to E, to D

Table 4-7 Temperature / Cyclic Profile

Fluid/Air Temp (°F)	**Total Hours**	**Full Stroke Cycles**	**Superimposed Dither Stroke**	**Dither Stroke**
160	59	38,400	230,400	230,400
200	10	6,400	38,400	38,400
225	10	6,400	38,400	38,400
250	20	12,800	76,800	76,800
275	20	12,800	76,800	76,800
- 40	5	3,200	19,200	19,200
TOTAL	124	80,000	480,000	480,000

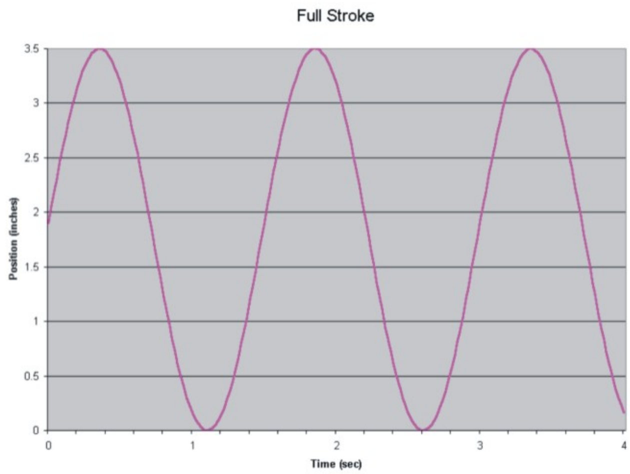


Figure 4-7 Full Stroke Profile

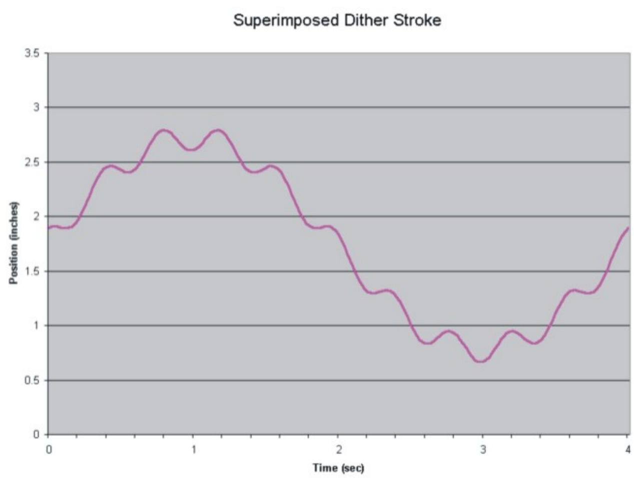


Figure 4-8   Superimposed Dither Stroke Profile

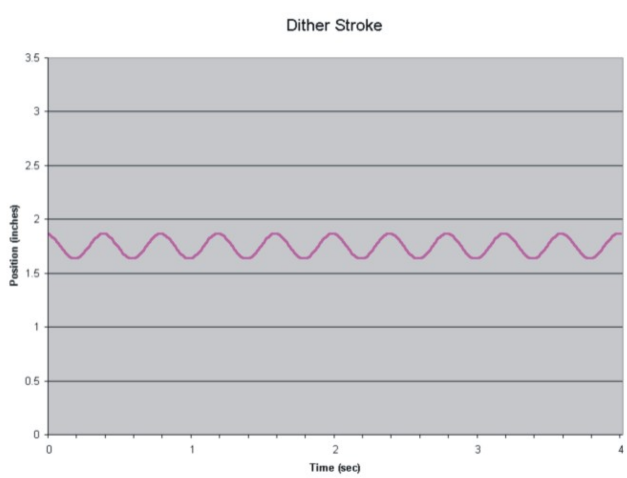


Figure 4-9   Dither Stroke Profile

Phase II:

The stroke profiles were the same for Phase II as for Phase I. This test was run for a total of 1,373,326 cycles with the temperature profile as indicated in Table 4-8.

Table 4-8 Time and Number of Cycles at Specified Temperatures for Phase II Testing

Temp (°F)	Hours	Cycles
160	70	645,187
200	14	129,037
225	14	129,037
250	23	211,990
275	23	211,990
- 40	5	46,085
totals	149	1,373,326

For tests in both Phase I and Phase II, the test block fixture was cold soaked prior to the beginning of each day of testing for a minimum of 4 hours after the surface temperature of the servocylinder had stabilized to 0 ± 5°F. Immediately after the cold soak and without allowing the test block fixture to warm up, the hydraulic pump was started and rods were immediately cycled in the block fixture at full-stroke while monitoring the cycling to evaluate low-temperature startup leakage for at least 100 cycles.

During the cyclic endurance tests, hourly measurements were made of the chamber fluid/air temperature, number of cycles completed and external fluid leakage. At the completion of the tests, the rods and seals were removed from the fixture and inspected. Photographs were taken of each rod and seal at different magnifications. The leakage and condition of all seals were documented.

4.6. Results

Phase I:

Figure 4-10 presents an overview of the Phase I test, including test article, the pre-test average surface roughness and the post-test average surface roughness measured in two locations. It can be seen that for both as-ground rods (HVOF #1 and EHC #4) the test resulted in a significant decrease in roughness. This indicates that the sliding action of the coatings against the seals wore down the peaks in the surface profile. Coarse linear scratches were observed on both as-ground rods as shown in Figure 4-11 and Figure 4-12.

Rod 1: "HVOF As-Ground"

Test Article	Supfina, Inc. Taylor-Hobson Cut Off – 0.030 In. WC/Co/Cr 86/10/4 Ground to 4 – 6 Ra 320 grit diamond As Ground
Pre-Test	Ra = 6.46 microinch
Post-Test	Location 1: Ra = 4.32 microinch Location 2: Ra = 2.95 microinch

Rod 2: "HVOF 20-22 Ground w/ SF"

Test Article	Supfina, Inc. Taylor-Hobson Cut Off – 0.030 In. WC/Co/Cr 86/10/4 Ground to 20 – 22 Ra 120 grit diamond Superfinished at NADEP JAX to 2 Ra
Pre-Test	Ra = 2.31 microinch
Post-Test	Location 1: Ra = 2.21 microinch Location 2: Ra = 2.21 microinch

Rod 3: "HVOF 8-10 Ground w/ SF"

Test Article	Supfina, Inc. Taylor-Hobson Cut Off – 0.030 In. WC/Co/Cr 86/10/4 Ground to 8 – 10 Ra 220 grit diamond Superfinished at NADEP JAX to 2 Ra
Pre-Test	Ra = 1.49 microinch
Post-Test	Location 1: Ra = 1.28 microinch Location 2: Ra = 1.68 microinch

Rod 4: "Chrome"

Test Article	Supfina, Inc. Taylor-Hobson Cut Off – 0.030 In. Chrome plated at NADEP JAX Ground to 12 – 15 Ra 60 grit Al2O3 As Ground
Pre-Test	Ra = 12.27 microinch
Post-Test	Location 1: Ra = 2.80 microinch Location 2: Ra = 4.82 microinch

Figure 4-10 Overview of Phase I Tests Providing Information on Test Article, Pre-Test Surface Roughness and Post-Test Surface Roughness Measured in Two Locations

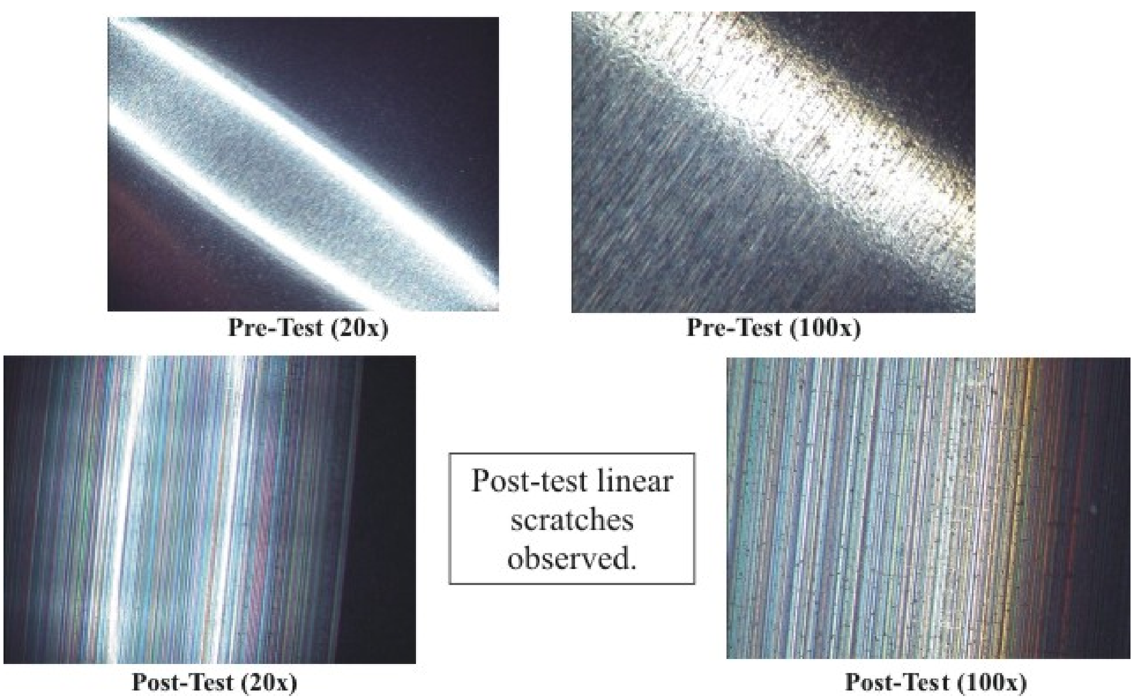


Figure 4-11 Surface of HVOF WC/CoCr-Coated Rod #1 (Ground, not Superfinished) Prior To and After Test

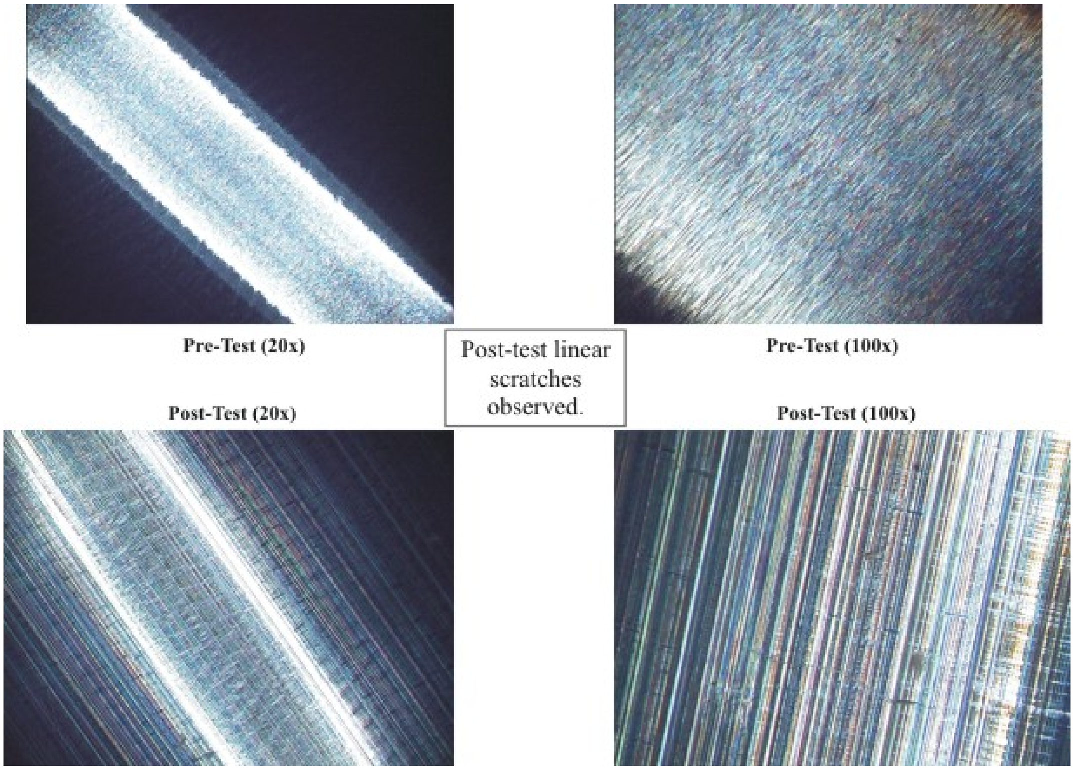


Figure 4-12 Surface of EHC-Coated Rod #4 Prior To and After Test

Seal configuration M83461 O-ring and two backup rings were damaged in all four glands while testing due to over extension of the drive piston into the block glands due to loss of the positioning sensor signal. As a result, the seals were replaced (as indicated in Table 4-3), and the same problem occurred again. Since this seal configuration was not exposed for the life of the test, this data should be considered less reliable. It should be noted that this was the seal configuration used for the Phase II tests.

As indicated in Figure 4-10, a comparison of surface finish before and after the test for Rods #2 and #3, both with WC/CoCr coatings, showed that there was essentially no change during the test (see Figure 4-13 and Figure 4-14). This indicated that superfinishing the rods protected the surface from wear.

Leakage of fluid was collected throughout the test period to determine each configuration's total leakage accumulated, leakage per temperature profile, and calculated trend rate of leakage. Figure 4-15, Figure 4-16, Figure 4-17 and Figure 4-18 show the rod/seal leakage for the O-ring with capstrip, O-ring with two backup rings, fluorosilicone O-ring with PTFE cap and spring energized PTFE seal, respectively. Figure 4-19 shows the fluid leakage at each temperature for all of the sixteen rod/seal configurations and Figure 4-20 shows the summary of the total leakage and leakage rates for the configurations.

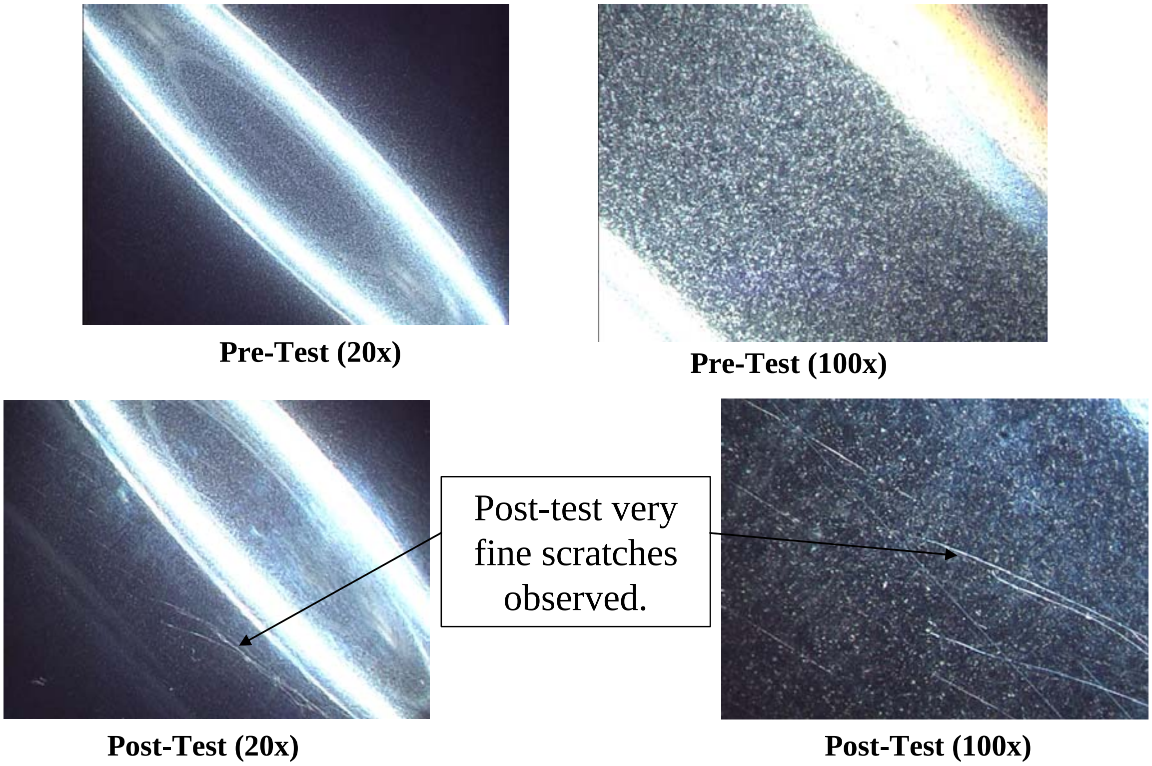


Figure 4-13 Surface of WC/CoCr-Coated Rod #2 Prior To and After Test

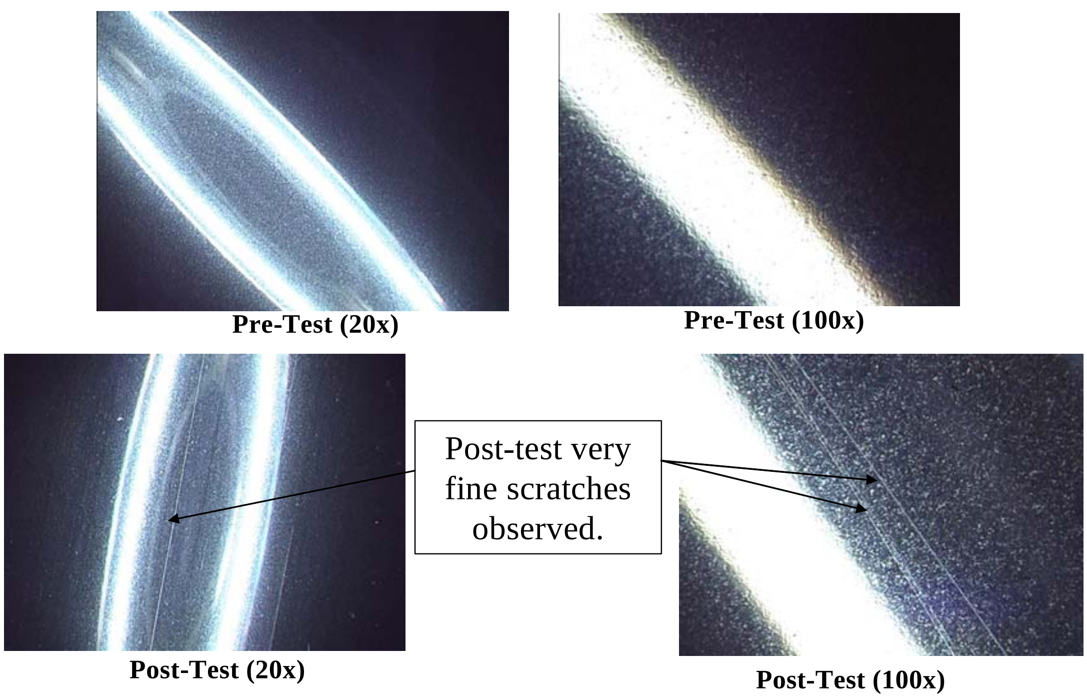


Figure 4-14 Surface of WC/CoCr-Coated Rod #3 Prior To and After Test

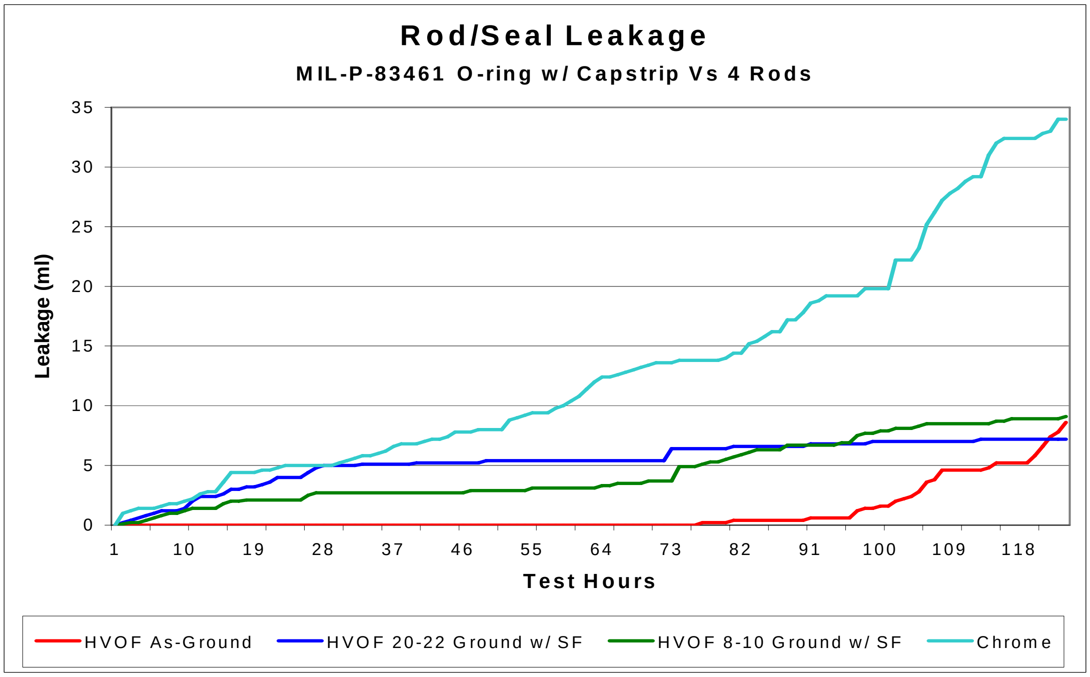


Figure 4-15 Rod/seal Leakage for O-ring With Capstrip Sliding Against Four Rods

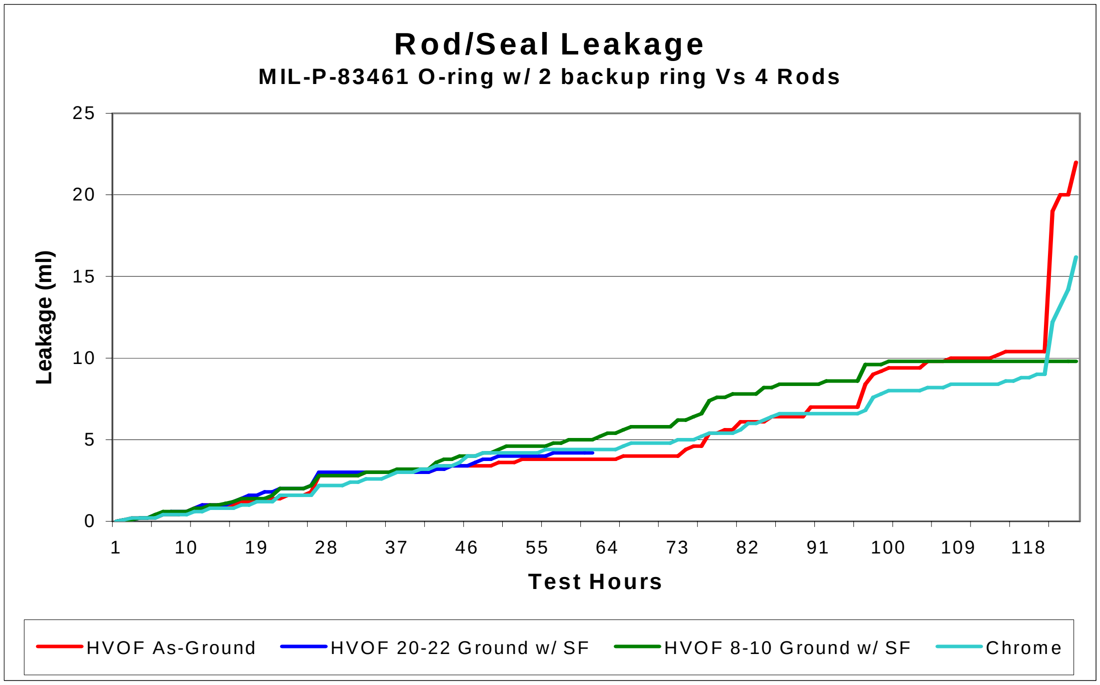


Figure 4-16 Rod/seal Leakage for O-ring With Two Backup Rings Sliding Against Four Rods

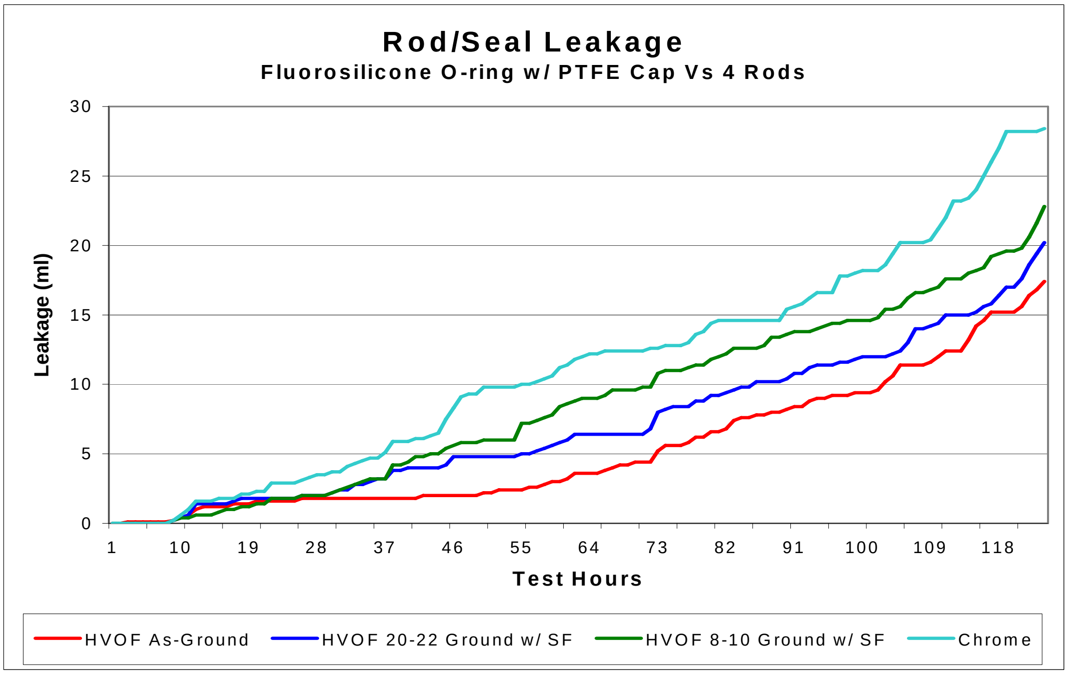


Figure 4-17 Rod/seal Leakage for Fluorosilicon O-ring and PTFE Cap Strip Sliding Against Four Rods

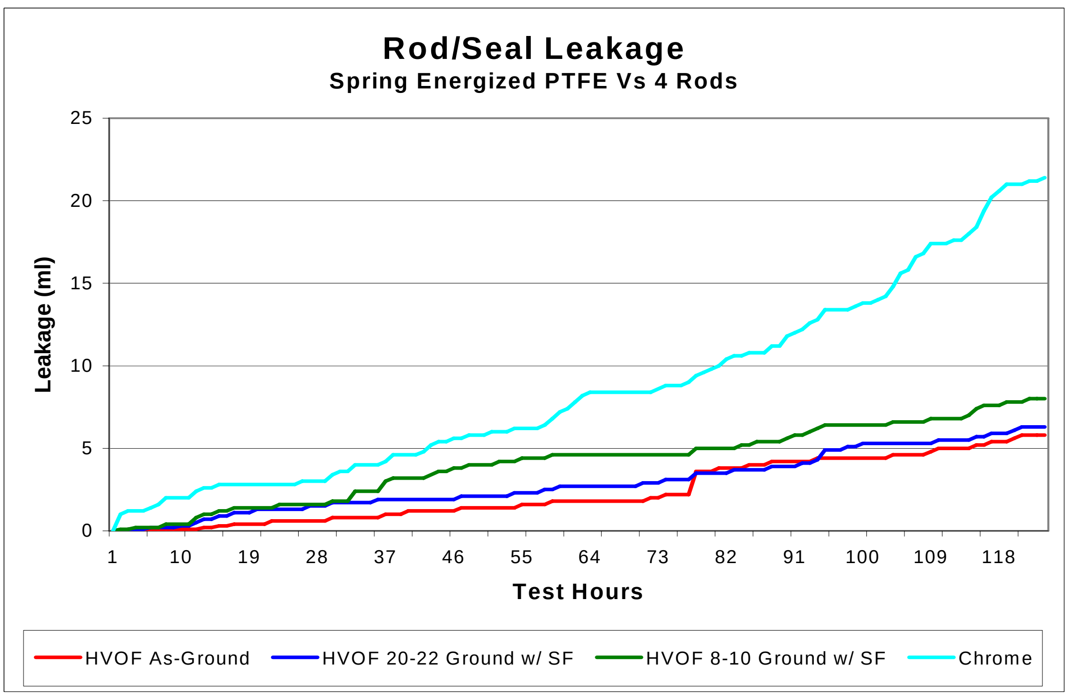


Figure 4-18 Rod/seal Leakage for Spring Energized PTFE Seals Sliding Against Four Rods

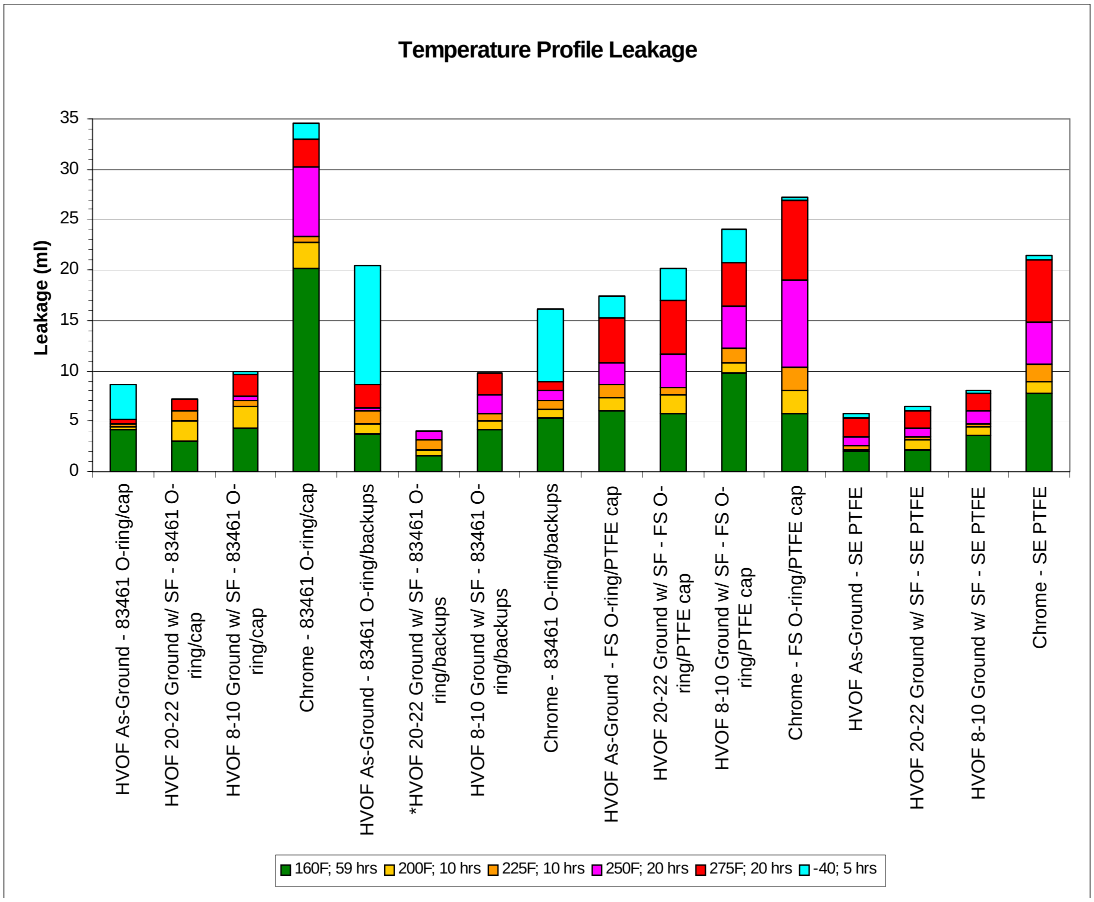


Figure 4-19 Fluid Leakage at Each Temperature For All of the Sixteen Rod/seal Configurations

All HVOF-coated rods had less leakage than the EHC-coated rod for their respective seal configurations. The M83461 O-ring and PTFE cap strip and spring energized PTFE seal configurations both had less than 10 ml cumulative leakage on all three HVOF-coated rods. The fluorosilicon O-ring and PTFE cap strip had more leakage than the other two seal configurations for the same HVOF-coated rods, but the leakage was still less than that of the EHC-coated rod. The leakage for the EHC-coated rod was over 3.5 times that of the HVOF-coated rods for M83461 O-ring with PTFE cap strip. The leakage for the EHC-coated rod was over 2.5 times that of the HVOF-coated rods for spring energized PTFE seals. The leakage for the EHC-coated rod was slightly greater than that of the HVOF-coated rods for the fluorosilicon O-ring with PTFE cap strip. From all of the collected fluid leakage data, the assessment was made that the highest performing configurations were all three HVOF rods having either the MIL-P-83461 O-ring with PTFE cap strip or spring energized PTFE seals with backup ring.

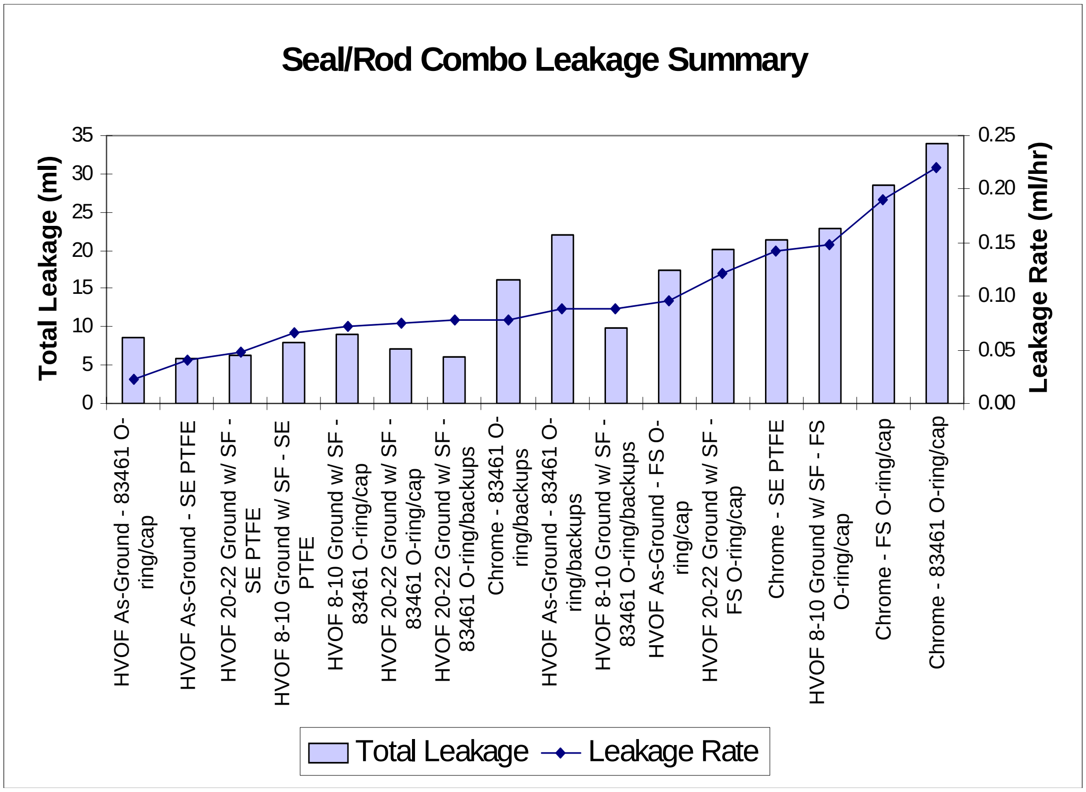


Figure 4-20 Summary of the Total Leakage and Leakage Rates for the Rod/seal Configurations

Inspection of the seals showed the most wear to be on the PTFE cap strip circumferential ribs on the ID sealing surface as shown in Figure 4-21. Scanning electron microscopic (SEM) analysis showed axial scratches on all cap strip seals as shown in Figure 4-22. Spring energized PTFE seals had very little wear. The following provides a general summary of the seal analyses.

- M83461 O-ring with PTFE cap strip assembly. The backup ring showed slight extrusion on the downstream side. The dimensions of these seals were within spec or within acceptable working limits. The O-ring showed no visible wear. The dimensions of these seals were within spec or within acceptable working limits. Visible axial scratches were found on the seal cap ID. The dimensions of these seals were within spec or within acceptable working limits.

- M83461 O-ring with two M8791 backup rings. O-rings had uneven wear on the ID, making it appear that the O-rings rolled during testing. The dimensions of these seals were within spec or within acceptable working limits. The backup rings in the downstream location showed slight extrusion on the ID, but upstream backup rings were in virgin condition. The dimensions of these seals were within spec or within acceptable working limits.

- Fluorosilicon O-ring with PTFE cap strip assembly. The Tetracap seal did not show any signs of wear. All dimensions were within spec except that there was an overall length expansion.
- Spring energized PTFE seal with backup ring. The PTFE seal contact area was in good condition but there were signs of damage. The backup ring showed a slight compression squeeze and material creep but no sign of extrusion. The backup ring was within spec.

Table 4-9 provides a relative comparison of the leakage for all rod/seal configurations, providing rankings of low, moderate, or high depending on the total leakage and leakage rate. Finally, Table 4-10 provides an overall ranking of the various rod/seal configurations based on fluid leakage and seal and coating wear. Based on these results, it is apparent that the performance of the HVOF coatings generally exceeded that of the

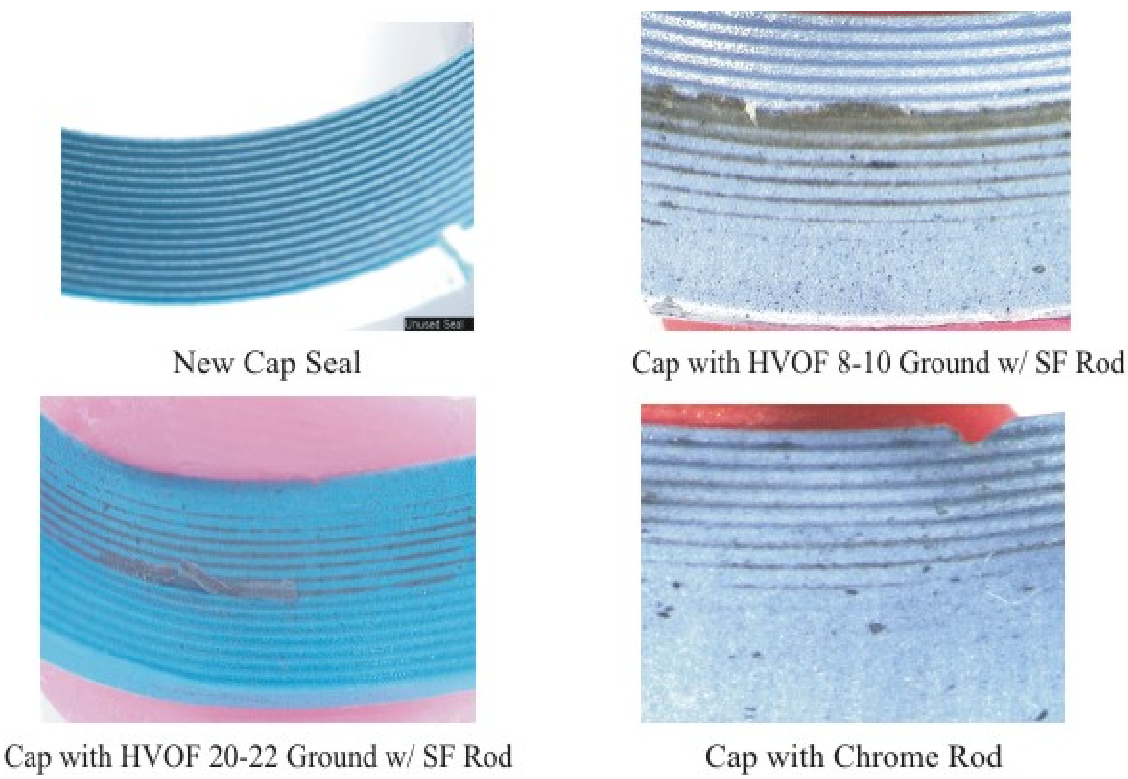


Figure 4-21 Photographs of PTFE Cap Seals Showing Wear on Three Seals Subsequent to Testing

EHC coatings.

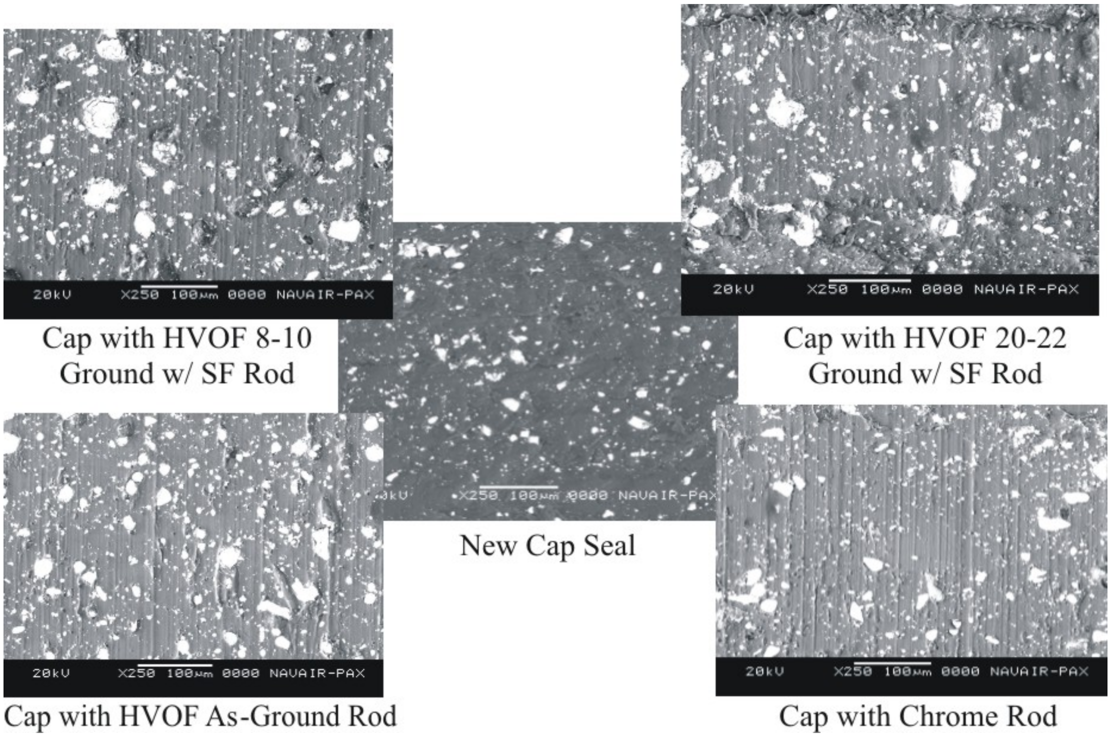


Figure 4-22 SEM Micrographs Showing the Surface of PTFE Cap Seals Before and After Testing

Table 4-9 Relative Comparison of the Leakage for All Rod/seal Configurations

SEAL/ROD CONFIGURATIONS	COLD TEMP (-40 F) LEAKAGE	HOT TEMP (250 and 275 F) LEAKAGE	TOTAL LEAKAGE	TREND LEAKAGE RATE
HVOF As-Ground - MIL-P-83461 O-Ring w/ Cap	Moderate	Low	Low	Low
HVOF 20-22 Ground w/ SF - MIL-P-83461 O-Ring w/ Cap	None	Low	Low	Low
HVOF 8-10 Ground w/ SF - MIL-P-83461 O-Ring w/ Cap	Low	Low	Moderate	Low
Chrome - MIL-P-83461 O-Ring w/ Cap	Low	High	High	High
HVOF As-Ground - MIL-P-83461 O-Ring w/ 2 Backup Rings	High	Low	High	Moderate
HVOF 20-22 Ground w/ SF - MIL-P-83461 O-Ring w/ 2 Backup Rings	N/A	N/A	N/A	Low
HVOF 8-10 Ground w/ SF - MIL-P-83461 O-Ring w/ 2 Backup Rings	None	Moderate	Moderate	Moderate
Chrome - MIL-P-83461 O-Ring w/ 2 Backup Rings	High	Low	Moderate	Low
HVOF As-Ground - Fluorosilicon O-ring w/ PTFE Cap	Low	Moderate	Moderate	Moderate
HVOF 20-22 Ground w/ SF - Fluorosilicon O-ring w/ PTFE Cap	Moderate	High	High	Moderate
HVOF 8-10 Ground w/ SF - Fluorosilicon O-ring w/ PTFE Cap	Moderate	High	High	High
Chrome - Fluorosilicon O-ring w/ PTFE Cap	Low	High	High	High
HVOF As-Ground - Spring Energized PTFE	Low	Low	Low	Low
HVOF 20-22 Ground w/ SF - Spring Energized PTFE	Low	Low	Low	Low
HVOF 8-10 Ground w/ SF - Spring Energized PTFE	Low	Moderate	Low	Low
Chrome - Spring Energized PTFE	Low	High	High	High
HOT/COLD TEMP LEAKAGE	TOTAL LEAKAGE		TREND LEAKAGE RATE	
Low – less than 3 ml	Low – less than 9 ml		Low – less than 0.08 ml/hr	
Moderate – 3 to 7 ml	Moderate – 9 to 20 ml		Moderate – 0.08 to 0.14 ml/hr	
High – greater than 7 ml	High – greater than 20 ml		High – greater than 0.14 ml/hr	

Table 4-10 Overall Ranking of the Various Rod/Seal Configurations

Ranking	Rod/Seal Configuration
Superior Performance	HVOF 20-22 Ground w/ SF with MIL-P-83461 O-ring/Cap HVOF As-Ground with Spring Energized PTFE HVOF 20-22 Ground w/ SF with Spring Energized PTFE HVOF 8-10 Ground w/ SF with Spring Energized PTFE HVOF As-Ground with MIL-P-83461 O-ring/Cap HVOF 8-10 Ground w/ SF with MIL-P-83461 O-ring/Cap
Fair Performance	* HVOF 8-10 Ground w/ SF with MIL-P-83461 O-ring/2 Backup Rings HVOF As-Ground with Fluorosilicon O-ring/PTFE Cap * Chrome with MIL-P-83461 O-ring/2 Backup Rings * HVOF As-Ground with MIL-P-83461 O-ring/2 Backup Rings HVOF 20-22 Ground w/ SF with Fluorosilicon O-ring/PTFE Cap
Worst Performance	Chrome with MIL-P-83461 O-ring/Cap Chrome with Fluorosilicon O-ring/PTFE Cap Chrome with Spring Energized PTFE HVOF 8-10 Ground w/ SF with Fluorosilicon O-ring/PTFE Cap

Phase II:

Table 4-11 provides various surface profile parameters for the rods both before and after testing, where Ra is the arithmetic average surface roughness, Rp is the maximum peak height, Rz is the 10-point average of the highest peaks plus lowest valleys, Rsk is the skewness and Tp is the bearing ratio at a depth of 8 microinches. It can be seen that there are no significant changes in surface roughness parameters resulting from the tests.

Table 4-11 Surface Profile Parameters for the Rods Before and After the Phase II Rod/seal Test

Rod Half	Material Coating	Pre-Test and Post-Test Surface Finish (Ra, Rp, Rz, Rsk, Tp)
6a	WC/CoCr (86/10/4) before	11.1, 42.7, 92.2, -1.1, 87%
	after	10.7, 38.5, 58.6, -0.4, 87%
6b	WC/CoCr (86/10/4) before	3.5, 10.6, 26.5, -.06, 88%
	after	3.0, 9.1, 16.7, -1.1, 59%
8a	WC/CoCr (86/10/4) before	2.4, 7.4, 37.2, -5.4, 85%
	after	2.1, 6.4, 13.9, -3.9, 85.2%
8b	WC/CoCr (86/10/4) before	1.8, 7.1, 17.8, -2.2, 86%
	after	2.0, 5.4, 9.8, -6.5, 89.6%
9a	WC/CoCr (86/10/4) before	1.4, 4.4, 24.3, -5.8, 87%
	after	1.4, 4.2, 9.3, -4.2, 94.6%
9b	WC/CoCr (86/10/4) before	2.1, 6.3, 24.8, -3.1, 84%
	after	1.8, 6.6, 9.0, -2.8, 91.5%
11a	WC-Cr_3C_2/NiCr (86/10/4) before	2.9, 8.3, 37.8, -3.7, 84%
	after	2.0, 6.5, 15.8, -5.6, 90.6%
11b	WC-Cr_3C_2/NiCr (86/10/4) before	2.8, 5.5, 54.2, -6.7, 81%
	after	2.4, 6.6, 19.0, -5.7, 86.3%

Table 4-12 provides the test gland identification, the type of coating, the final surface finish, the finish process, the cumulative fluid leakage from that gland and provides a relative ranking based on leakage. It is apparent that a superfinished surface provides significantly better performance compared to a ground surface. With respect to a comparison between tape (identified as "film" in the table) and stone superfinishing, on average it appears that the tape superfinished surfaces perform slightly better.

Table 4-12 Ranking of the Finished Surfaces Based on Cumulative Fluid Leakage

Rod Half	Test Gland	Material Coating	Final Surface Finish (Ra, Rp, Rz, Rsk, Tp)	Finish Process	Culmulative Leakage	Ranking
8b	BE2-C,	WC/CoCr (86/10/4)	1.8, 7.1, 17.8, -2.2, 86%	Stone, Superfinish	27.0	Best
11a	FE4-B	WC-Cr_3C_2-Ni (73/20/7)	2.9, 8.3, 37.8, -3.7, 84%	Film, Superfinish	29.4	Best
9a	FE3-B	WC/CoCr (86/10/4)	1.4, 4.4, 24.3, -5.8, 87%	Film, Superfinish	30.2	Best
8a	FE2-B	WC/CoCr (86/10/4)	2.4, 7.4, 37.2, -5.4, 85%	Film, Superfinish	32.8	Best
8b	BE2-D	WC/CoCr (86/10/4)	1.8, 7.1, 17.8, -2.2, 86%	Stone, Superfinish	35.6	Medium
9b	BE3-D	WC/CoCr (86/10/4)	2.1, 6.3, 24.8, -3.1, 85%	Stone, Superfinish	38.8	Medium
6b	BE1-D	WC/CoCr (86/10/4)	3.5, 10.6, 26.5, -0.6, 88%	Fine Stone, As-Ground	40.6	Medium
8a	FE2-A,	WC/CoCr (86/10/4)	2.4, 7.4, 37.2, -5.4, 85%	Film, Superfinish	43.0	Medium
11a	FE4-A,	WC-Cr_3C_2-Ni (73/20/7)	2.9, 8.3, 37.8, -3.7, 84%	Film, Superfinish	46.0	Medium
9b	BE3-C,	WC/CoCr (86/10/4)	2.1, 6.3, 24.8, -3.1, 85%	Stone, Superfinish	48.2	Medium
6b	BE1-C,	WC/CoCr (86/10/4)	3.5, 10.6, 26.5, -0.6, 88%	Fine Stone, As-Ground	51.6	Medium
9a	FE3-A,	WC/CoCr (86/10/4)	1.4, 4.4, 24.3, -5.8, 87%	Film, Superfinish	53.6	Medium
11b	BE4-D	WC-Cr_3C_2-Ni (73/20/7)	2.8, 5.5, 54.2, -6.7, 81%	Stone, Superfinish	65.0	Worst
11b	BE4-C,	WC-Cr_3C_2-Ni (73/20/7)	2.8, 5.5, 54.2, -6.7, 81%	Stone, Superfinish	67.4	Worst
6a	FE1-B	WC/CoCr (86/10/4)	11.1, 42.7, 92.2, -1.1, 87%	Coarse Stone, As-Ground	71.4	Worst
6a	FE1-A,	WC/CoCr (86/10/4)	11.1, 42.7, 92.2, -1.1, 87%	Coarse Stone, As-Ground	85.6	Worst

Figure 4-23 shows bar charts giving the temperature profile of the leakage for each of the glands. Figure 5-24 provides the cumulative leakage for each of the glands during phase 2 testing. Based on the relative amounts of time at each temperature, it is apparent that

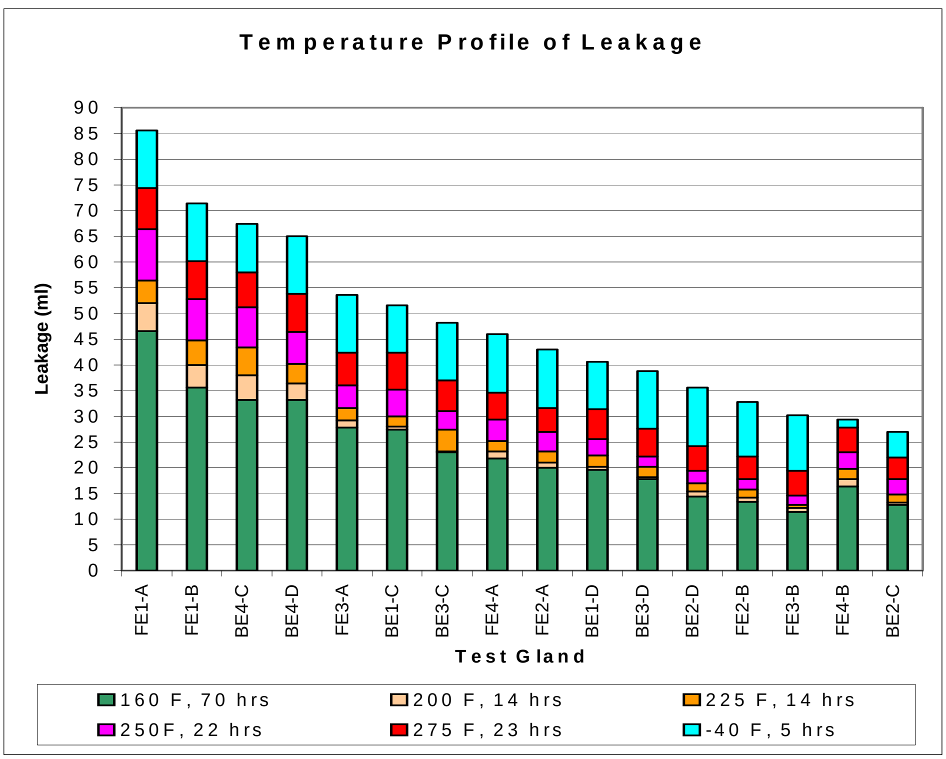


Figure 4-23 Temperature Profile of Total Fluid Leakage for Each Gland in Order of Greatest to Least

there was relatively more leakage at -40ºF than at the other temperatures for most of the glands. However, the leakage rate subsequent to the -40°F testing, as shown in Figure

4-24, returned to the same values as were obtained prior to the cold temperature testing.

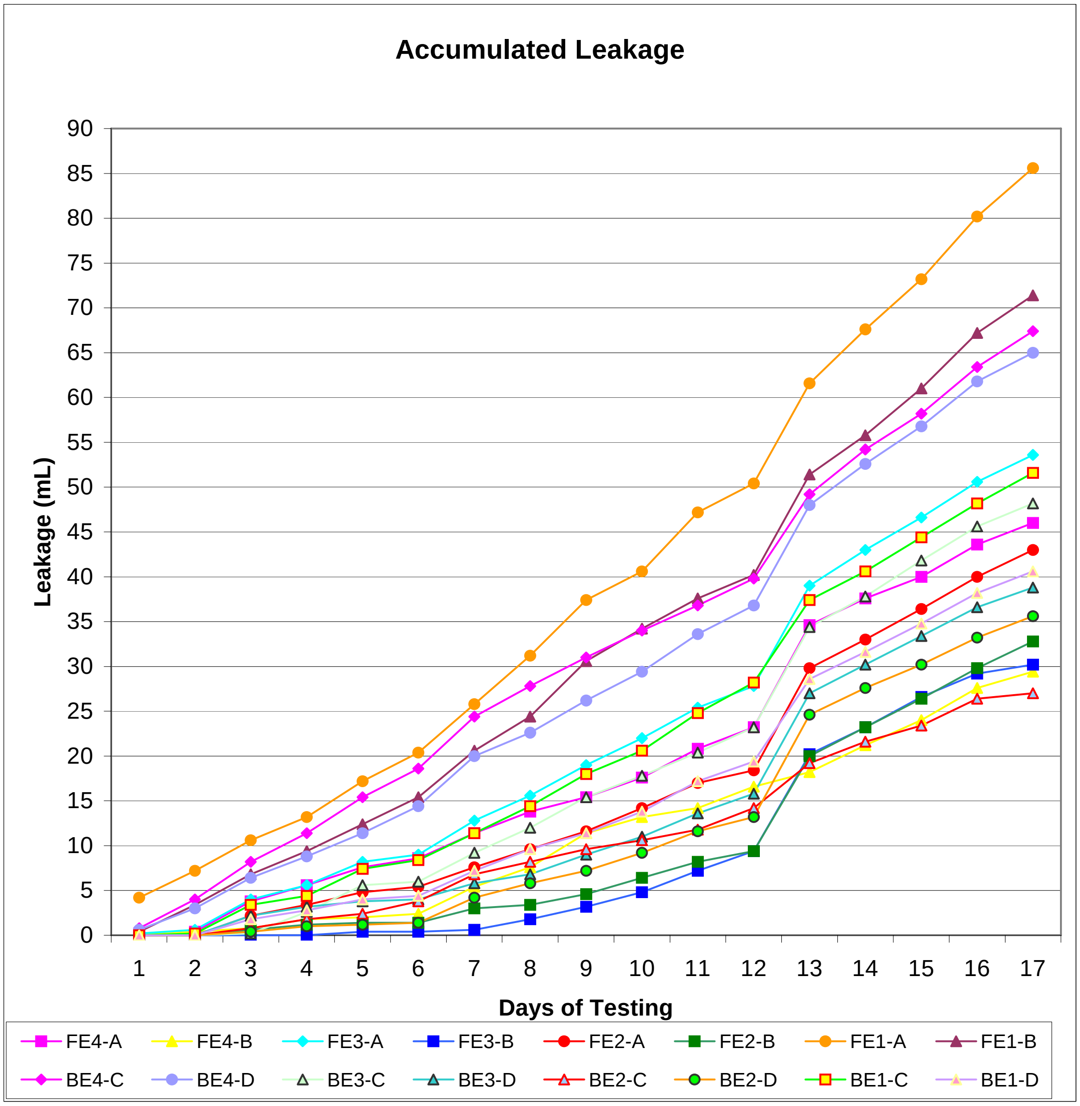


Figure 4-24 Cumulative Fluid Leakage for Each Gland as a Function of Time

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5. Component Testing and Qualification

5.1. Data Summary

Table 5-1 Quick Reference to Actuator Testing.

Item	Status
A-10 Aileron	Service test requirements under development
B-1 Horizontal Stabilizer	Passed testing. Service tests not needed. Dwgs updated, TOs being updated.
B-1 Pitch/Roll SCAS	Testing in progress
C/KC-135 Aileron Snubber Actuator	Passed rig test. In service testing.
C/KC-135 Main Landing Gear Actuator	Passed test with change to seal specs. In service testing.
C/KC-135 Main Landing Gear Door Actuator	Qualified for service testing.
C-130 Ramp Actuator	Passed test with change to seal specs. In service testing.
C130 Rudder Booster Actuator	Passed rig test. In service testing.
F-15 Pitch/Roll Channel Assembly	To be tested
F/A-18 C/D Stabilator	Same leakage as EHC, fewer scratches. ECP validated.
F/A-18 C/D Trailing Edge Flap	Same leakage as EHC, fewer scratches. ECP validated.
KC-135 Ruddevator Actuator	To be tested
T-38 Aileron Actuator	Passed rig test.

Click blue links to jump to data

5.2. Air Force Delta Qualification and Service Testing

The Oklahoma City Air Logistics Center Airborne Accessories Directorate Avionics and Accessories Division (OC-ALC/LGERC), in conjunction with the Air Force System Program Directors and the actuator/airframe OEMs, developed a plan for qualification and insertion of HVOF thermal spray coatings to replace EHC plating on most of the actuators used on Air Force aircraft.

Initially, they worked to identify and catalog chrome plated parts embedded in hydraulic actuators managed by OC-ALC/LGERC in order to determine the best approach to implementing alternatives to EHC plating during actuator manufacture and overhaul which is performed at Ogden ALC (OO-ALC). Those actuators managed by OC-ALC/LGERC and overhauled at OO-ALC were the principal focus so that the chrome plating requirement at the actuator depot facility could be reduced, if possible.

The effort was divided up by weapon system, based on the volume of actuators overhauled at OO-ALC and the anticipated future life of the weapon system. They examined in detail nine weapon systems (B-1, C-135, A-10, C-130, C-141, T-38, F-15, E-3, B-52). When this effort was initiated in 2001, there were approximately 125 Technical Orders (TOs) covering OC-ALC/LGERC-managed actuators overhauled at OO-ALC. Follow-on activities included similar reviews of TOs and drawings for field repaired actuators and for other hydraulic components managed by OC-ALC/LGERC. It was expected that their number would be as large or larger than those covering depot overhauled actuators.

OC-ALC/LGERC established a contract with ARINC to review TOs and drawings for flight control and utility actuators, and to construct and populate a searchable database with which one could view component identities, similarities and differences.

The intention was to select several actuators from these weapon systems and perform delta-qualification type testing on them as deemed necessary by the stakeholders. Actuator testing would be tailored for the specific actuator, would be based on original qualification requirements, and would address issues such as fatigue, endurance, and corrosion, as required. Completed material and component testing would be considered during determination of test requirements. The intent was to select actuators that impose the heaviest chrome plating load on OO-ALC, that represent a diversity of materials and seal designs, and that have sufficient commonality to other similar designs within and across weapon systems that could allow for qualification by similarity.

An overall four-phase program was established as follows:

- Phase 1: Tech Order and drawing review, database development and test requirement development
- Phase 2: Delta qualification and service testing
- Phase 3: Data evaluation
- Phase 4: Implementation

ARINC completed Phase 1 in late 2003. They reviewed 124 Air Force Technical Orders, 729 engineering drawings, and identified 276 EHC-plated components and 195 potentially EHC-plated components. For delta qualification and service testing, all actuators containing EHC-plated components were broken down into three categories:

- Flight control actuators (87 distinct part numbers)
- Utility actuators (73 distinct part number)
- Snubbers/Others (12 distinct part numbers)

The following flight control actuators were identified for delta qualification:

- C-130 Rudder Booster Actuator
- B-1 Horizontal Stabilizer
- B-1 Pitch/Roll SCAS

- A-10 Aileron
- F-15 Pitch/Roll Channel Assembly (PRCA)
- T-38 Aileron Actuator

The following utility actuators were identified for delta qualification:

- C-130 Ramp Actuator
- C/KC-135 Main Landing Gear Actuator
- C/KC-135 Main Landing Gear Door Actuator

The following snubbers and other actuators were identified for delta qualification:

- C-135 Aileron Control Surface Snubber
- KC-135 Ruddevator

A two-year service test period was planned for a number of actuators. These included:

- C/KC-135 Snubbers, Main Landing Gear Actuator, Main Landing Gear Door Actuator and Ruddevator
- C-130 Rudder, Elevator, Aileron, Ramp, and Aft Cargo Door Actuators
- A-10 Aileron, Rudder, and Elevator Actuators

It is the purpose of this section of the report to present an overview of the status of the Air Force delta qualification and service testing as of February 2006. Some of the delta testing has been completed whereas others are still in progress. Service test plans have been completed and actuators are being prepared for installation onto aircraft.

5.2.1. Delta Qualification Testing

C130 Rudder Booster Actuator (part number 5C5792-1):

Figure 5-1 is a schematic of this actuator. There are currently four EHC-plated surfaces. The first is the piston rod, fabricated from 4130 steel, which is divided into three sections with piston heads separating each section. The second are the two piston heads themselves. The third is the trunnion OD which mates with an aluminum-bronze bushing, and the fourth is the trunnion ID which is not a wear surface. The existing seals are elastomeric T-seals which contact the EHC-plated piston rod.

The piston OD is 0.9” and the piston head OD is 1.5”. The operating pressure is 3000 psi. The HVOF coatings applied were WC/CoCr to the piston rod and trunnion OD and ID, and T400 to the piston heads. The surface finish for the WC/CoCr coating on the piston rod was as follows:

- Ra – 4 microinches or less
- Rp – 8 microinches maximum (+4 tolerance)
- Rz – 40 microinches maximum (+5 tolerance)
- Tp – 60-90% at a depth of 25% Rz (± 5% tolerance)

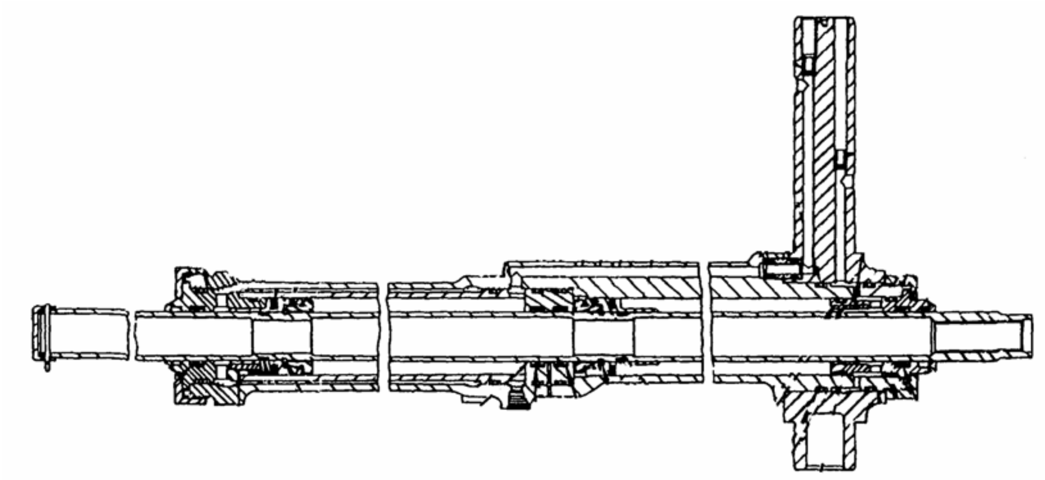

Figure 5-1 Schematic of the C130 Rudder Booster Actuator

Figure 5-2 is a photograph of the piston rods subsequent to application and grinding of the HVOF WC/CoCr coatings (three for testing and one spare). Coating application was performed by Southwest Aeroservice in May 2004, the assembly of the actuators was performed by OO-ALC in May 2004 and the testing was performed by Smiths Aerospace in Duarte, California in July 2004. They performed an endurance test for 1,000,000 cycles in a temperature range of -65ºF to +160°F. Figure 5-3 shows an assembled rudder boost pack.

Figure 5-2 C130 Rudder Booster Actuator Piston Rods Coated with HVOF WC/CoCr

Figure 5-3   C130 Rudder Booster

Three WC/CoCr-coated piston rods completed the 1,000,000 cycles and three sets of seals passed the endurance testing, an elastomeric T-seal, an Enercap II from Greene-Tweed and a Plus Seal II from Shamban. A piston rod with standard EHC plating failed after 415,145 cycles. Figure 5-4 is a photograph of a portion of the failed rod. No data was provided on the cause of this failure.

Figure 5-4   Portion of EHC-plated Piston Rod from C130 Rudder Booster Actuator that Failed Endurance Test.

All four actuators (three with HVOF coatings and one with EHC) failed low-temperature testing due to excessive fluid leakage. Follow-on testing was awarded to Smiths Aerospace and they determined that the leakage was due to the gland OD seals. These were replaced which solved the problem.

It was concluded from these tests that the HVOF coatings provided at least equivalent and potentially superior performance to EHC and therefore service testing could be initiated.

B-1 Horizontal Stabilizer (part number L5873400-061/062):

Figure 5-5 is a photograph of the B-1 horizontal stabilizer actuator which drives the horizontal stabilizer surfaces for pitch and roll control. Its location on the aircraft is indicated in Figure 5-6. The forward piston required redesign to eliminate fatigue failures (a problem not associated with the EHC plating on the piston rod). The qualification of the new design required fatigue and endurance tests, which provided an opportunity to qualify HVOF WC/CoCr as an alternative coating on both the forward and aft piston rods.

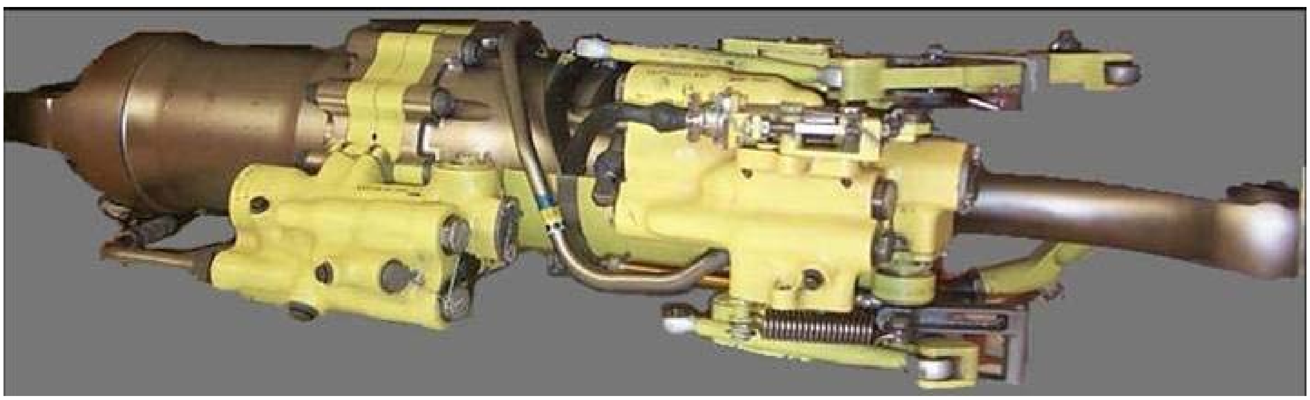

Figure 5-5 Photograph of the B-1 Horizontal Stabilizer Actuator.

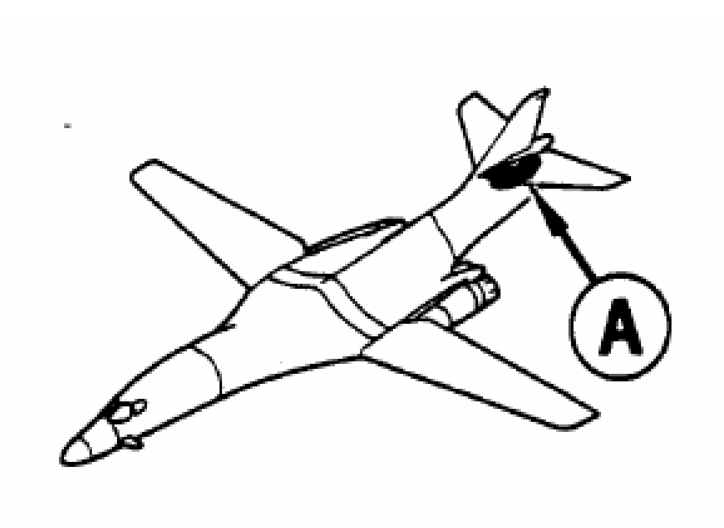

Figure 5-6 Illustration Showing the Location on the B-1 of the Horizontal Stabilizer Actuator

For this actuator the operating pressure is 4000 psi and the stroke is 6.843 inches. The forward piston OD is 2.4 inches, the forward head OD is 4.8 inches, the aft piston OD is 3.1 inches and the aft head OD is 5.2 inches. The piston rod material is HP9-4-30.

For the delta qualification test, the forward piston was coated with WC/CoCr by Southwest United Industries and the aft piston was coated with WC/CoCr by Plasma Technologies Inc. Figure 5-7 is a photograph of the two pistons subsequent to coating application and grinding.

Figure 5-7 Photograph of Forward and Aft Pistons from the B-1 Horizontal Stabilizer Actuator Following Application of HVOF WC/CoCr Coating

Qualification testing was performed by Boeing and including an endurance test of 750,000 cycles, representing approximately 50% of the aircraft life. Seals used were Enercap II HP manufactured by Greene-Tweed. The test was successfully completed with no unallowable fluid leakage and no wear on the coatings.

No service tests are planned for this actuator. Drawing updates have been completed to provide for use of the HVOF WC/CoCr coatings and Tech Order and stocklist updates are in progress. This actuator, using HVOF WC/CoCr, is ready for implementation. It is expected that other B-1 flight control actuators will be qualified by similarity.

B-1 Pitch/Roll SCAS (part number L5877400-071):

This component, shown in Figure 5-8, provides pitch and roll input to mixers and on to horizontal stabilizer surfaces for added stability and for autoflight. The stroke is 3.5 inches and the operating pressure is 4000 psi. The primary piston OD is 0.7 inches, the secondary piston OD is 0.5 inches, the head OD is 1.2 inches and the groove OD is 0.9 inches. The piston rod material is HP9-4-30.

For the delta qualification test, HVOF WC/CoCr coatings were applied to the piston rods and head. Boeing was placed under contract to coordinate the application of the coatings and the performance of the qualification testing, which is currently in progress.

Figure 5-8 B-1 Pitch/roll SCAS

A-10 Aileron (part number 2730500-5):

This component provides actuation of the ailerons on the A-10. The stroke is 5.81 inches and the operating pressure is 3000 psi. The primary piston OD is 1.2475 inches, the primary head OD is 2.2415 inches, the secondary piston OD is 1.248 inches and the secondary head OD is 2.241 inches. The piston rod material is 4340 steel.

HVOF WC/CoCr coatings were applied to the piston rods and heads by Plasma Technology Incorporated. The qualification testing was performed by Parker Hannifin which consisted of a 1,875,200 cycle endurance test and a temperature cycling test in a range of -40ºF to 275°F. Seals used during the test were Coorstek Metaplast. Salt fog tests were also performed on WC/CoCr-coated rods in accordance with MIL-STD-810B, Method 509, Procedure 1.

During testing there were two fixture failures unrelated to the coatings which delayed completion of the tests. Testing was successfully completed in late 2004 with no unallowable fluid leakage and no wear on the coatings. The actuator also successfully passed the temperature cycling test and the salt fog corrosion test.

With the successful completion of the delta qualification tests, it is expected that actuators containing HVOF-coated components will begin service testing sometime in 2006. It is expected that the A-10 rudder and elevator actuators will be able to be qualified by similarity.

F-15 Pitch/Roll Channel Assembly (PRCA):

Figure 5-9 is a photograph of this component which serves as the mechanical link between the pilots' stick and the flight control actuators, summing pilot input with additional inputs such as altitude, attitude, and airspeed. It provides hydraulic boost and variable ratio output scheduling based on speed and acceleration.

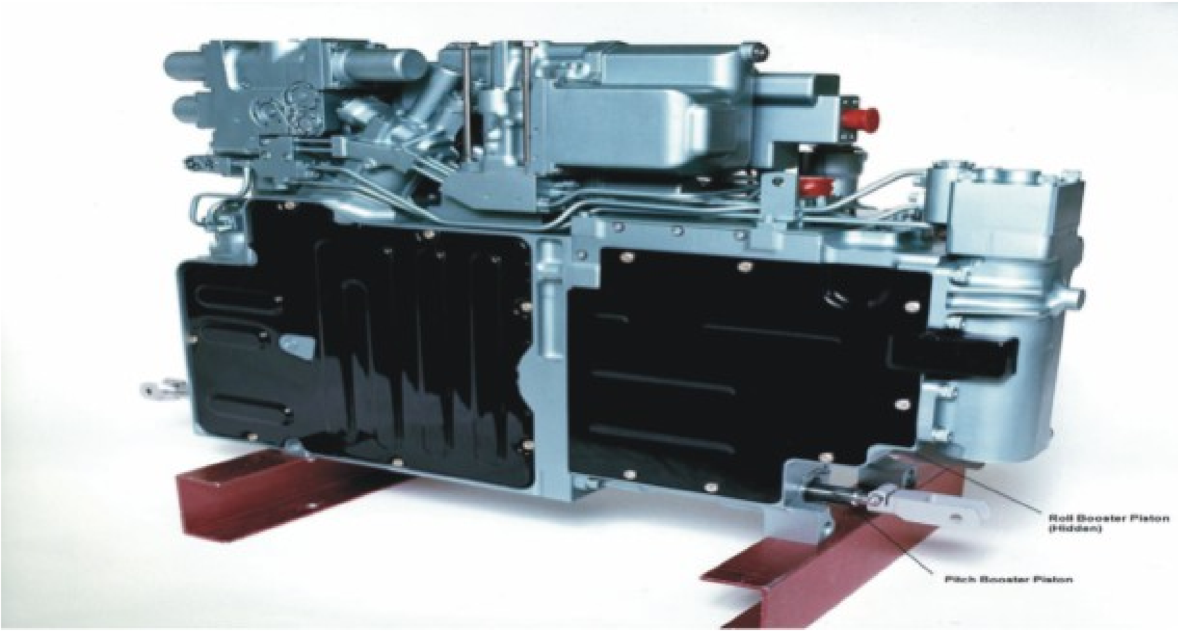

Figure 5-9 F-15 Pitch/Roll Channel Assembly

A contract has been issued to Moog, the OEM for this component, for rig testing which will commence in early 2006. It is anticipated that HVOF WC/CoCr will be applied to the piston for this test.

<u>T-38 Aileron Actuator (part number 2-431610-505/506/508:</u>

This component has a stroke of 2.02-2.10 inches, a retracted/extended length of 8.62 to 10.80 inches and an operating pressure of 3000 psi. The piston OD is 0.9 inches and the head OD is 2.1 inches. The piston rod material is 4130 steel.

A contract was issued to Smiths Aerospace to perform the qualification testing. Pistons were coated with HVOF WC/CoCr by Plasma Coating Corporation and were assembled into a complete actuator by Smiths. The seals are as follows:

- Primary: Shamban Variseal W2 and Coorstek Metaplast Assembly
- Secondary: Shamban Turcon Plus Seal II and Coorstek Unilock
- Scraper: Shamban Excluder DC and Coorstek Metaplast

This test was successfully completed in January 2006 and the report is currently being written. There were some failures of piston seals (seals which do not contact the coated surfaces and were likely due to the fixture configuration) which may warrant additional testing.

<u>C-130 Ramp Actuator (part number 370750-1):</u>

This component, shown installed on the aircraft in Figure 5-10 and removed for disassembly in Figure 5-11, is used to operate the C-130 ramp door. It has a stroke of 64.998 inches, a retracted/extended length of 74.6/139.6 inches and an operating pressure of 3000 psi. The piston OD is 1.8 inches and the head OD is 2.3 inches. The piston rod

Figure 5-10 C-130 Ramp Actuator Installed on Aircraft

material is 4340 steel.

Two piston rods were coated with HVOF WC/CoCr by Southwest United Industries. Figure 5-12 is a photograph of one piston rod subsequent to application of the coating and grinding. Testing was performed by ARINC and OC-ALC/ENFLL in the OC-ALC Engineering Laboratory. It consisted of a 20,000 cycle endurance test and a temperature test in which each actuator was subjected to a cold soak at -65ºF and then cycled 5 times while still at that temperature. Figure 5-13 is a photograph of the test fixture at OC-ALC.

Figure 5-11 C-130 Ramp Actuator Prior to Disassembly

Figure 5-12 C-130 Ramp Actuator Piston After Application of HVOF WC/CoCr Coating

Figure 5-13 C-130 Ramp Actuator Text Fixture Showing Actuator in Extended Position

For the endurance testing, Actuator A included ACGTL Rod Seals manufactured by Greene-Tweed and a Coorstek Scraper. Fluid leakage was excessive so Greene-Tweed developed a modification to the seal which then passed the 20,000 cycle test with minimal leakage. Actuator B included a Coorstek Scraper and the rod seals included an AGT Seal manufactured by Greene-Tweed, a VL Seal manufactured by Shamban, an RSA Seal manufactured by Greene-Tweed, and a Metaplast seal manufactured by Coorstek. There was excessive leakage for the AGT and VL Seals; the RSA Seal completed the 20,000 cycle test with almost zero leakage and the Metaplast seal also completed the 20,000 cycles with acceptable leakage. Finally, a modified Greene-Tweed AGT seal was cycled sufficiently to demonstrate acceptability as well. Some leakage occurred during the temperature testing, but due to ice, it was not possible to determine the exact quantity.

Overall, it was concluded by OC-ALC that the HVOF WC/CoCr coatings passed the qualification test if the correct seals were used. This actuator was designated for service testing. It was expected that the WC/CoCr coatings would be qualified on the C-130 Aft Cargo Door Actuator by similarity.

C/KC-135 Main Landing Gear Actuator (part number 5-84046-6):

This component, shown in Figure 5-14, is used to extend and retract the C/KC-135 main landing gear. It has a stroke of 13.78 inches, a retract/extended length of 30.84/44.62 inches, and an operating pressure of 3000 psi. The piston OD is 2.995 inches and the head OD is 4.8 inches. The piston rod material is 4340 steel. Two piston rods were coated with HVOF WC/CoCr by Southwest United Industries. The testing was performed by ARINC and OC-ALC/ENFLL in the OC-ALC Engineering Laboratory. For endurance testing, each actuator was subjected to 20,000 cycles and for temperature testing each actuator was subjected to a cold soak at -65°F, then cycled 5 times while still at that temperature.

Figure 5-14 C/KC-135 Main Landing Gear Actuator

Actuator A contained an elastomeric O-ring with backups and Actuator B contained a spring-energized Coorstek Rod Seal with a Coorstek Scraper. The O-ring configuration failed the endurance test due to excessive leakage. The spring-energized seal passed the endurance test with very little leakage. The O-ring configuration failed the temperature test due to excessive leakage whereas the spring-energized seal successfully passed the test with no leakage.

Overall, it was concluded by OC-ALC that the HVOF WC/CoCr coatings passed the qualification test if the correct seals were used. This actuator was designated for service testing. It was expected that the WC/CoCr coatings would be qualified on the E-3 main landing gear actuator by similarity.

C/KC-135 Main Landing Gear Door Actuator (part number 5-84045-9):

This component, shown in Figure 5-15, is used to open and close the main landing gear door on the C/KC-135. It has a stroke of 20.66 inches, a retracted/extended length of 31.00/51.66 inches, and an operating pressure of 3000 psi. The piston OD is 1.3 inches and the head OD is 2.1 inches. The piston rod material is 4140 or 4340 steel.

Figure 5-15 C/KC-135 Main Landing Gear Door Actuator

It was decided by OC-ALC that the HVOF WC/CoCr coatings would be considered qualified on this component due to the successful results of the testing on the main landing gear actuator. This actuator was designated for service testing.

C/KC-135 Aileron Snubber Actuator (part number 5-88763-7/10:

This component, shown in Figure 5-16, is used to dampen the oscillations of the C/KC-135 aileron. It has a stroke of 1.81 inches, a retracted/extended length of 15.595/17.455 inches and an operating pressure of 3000 psi. It has a piston OD of 0.6 inches and the piston rod material is 4340 steel.

Figure 5-16 C/KC-135 Aileron Snubber Actuator

HVOF WC/CoCr coatings were applied to two pistons by Southwest United Industries and they were assembled into two actuators. Testing was performed by ARINC. For endurance testing, each actuator was subjected to 21,200 cycles and for temperature testing each actuator was subjected to a cold soak at -65ºF, then cycled 5 times while still at the same temperature.

Actuator A, with O-ring and backup rings, completed 21,200 cycles with zero leakage. Actuator B, with VLS Seal manufactured by Shamban, completed 21,200 cycles with 8 total drops of fluid which was considered acceptable. It was noted that the piston rod from this actuator had a small circumferential scratch. For the temperature testing, both actuators completed the test with zero leakage.

The HVOF WC/CoCr coatings passed the qualification test and this actuator was designated for service testing. It was anticipated that the C/KC-135 rudder and elevator snubber actuators could be qualified by similarity.

KC-135 Ruddevator Actuator (part number 65-6750-1):

Delta qualification testing on this actuator has not yet been initiated.

5.2.2. Air Force Service Testing

As indicated at the beginning of this section, the Air Force was planning on conducting a two-year service test for actuators from the C/KC-135, C-130 and A-10 aircraft. Detailed test plans were developed and these are provided in Appendix A, B, and C, respectively. The test plans for the C/KC-135 and C-130 have been approved by the Air Mobility Command Configuration Control Board and by the System Program Office for each aircraft. Negotiations are still in progress for approval of the A-10 service test plan.

The C/KC-135 service test will include the evaluation of two snubbers, two main landing gear actuators, two main landing gear door actuators and two ruddevator actuators, all containing piston rods coated with HVOF WC/CoCr. Figure 5-17 shows the actuators prepared and ready for installation which is planned to be conducted on aircraft at Grand Forks AFB and MacDill AFB in March 2006.

Figure 5-17 C/KC-135 Actuators Prepared for Service Testing

The C-130 service test will include one rudder actuator, one aileron actuator, two elevator actuators, two ramp actuators and two aft cargo door actuators. The piston rods and other components of these actuators are currently being coated. Actuator assembly is planned for March 2006, with installation into operational aircraft at Little Rock AFB and Delaware Air National Guard in April 2006.

5.3. Navy Actuator Qualification Testing

F/A-18 C/D Stabilator Actuator:

There had been a history of significant reliability problems with this actuator, shown in Figure 5-18 and schematically in Figure 5-19, due to external fluid leakage, requiring rework every six months. Based on laboratory testing, the elastomeric seals were replaced with fluorocarbon static seals and PTFE spring-energized dynamic seals. Rebuild kits were developed by seal vendors and endurance testing of the seal kits from three vendors showed excellent performance, with post-test leakage within acceptable limits. All of these tests were performed using standard EHC plating on the piston rods.

Figure 5-18 F/A-18 C/D Stabilator Actuator

Follow-on testing was conducted in which the EHC-plated rod was replaced with HVOF

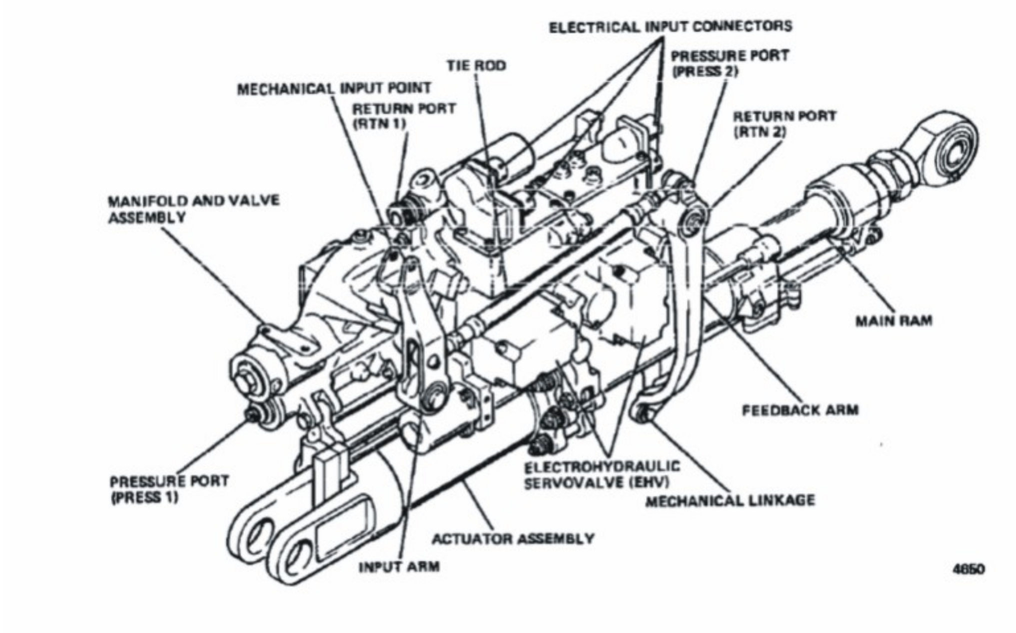

Figure 5-19 Schematic of F/A-18 C/D Stabilator Actuator

coatings using the new seal kits. The shorter external end of the rod was coated with WC/10Co4Cr and the longer internal end was coated with WC/17Co. Both coatings were ground to an 8-16 microinch Ra finish and then superfinished to less than 2 microinch Ra. Testing was performed on the same rig as was used for the functional rod/seal testing described in Section 5. It consisted of 10 layers of testing, with each hour consisting of 3 minutes full stroke, 9 minutes of half-strokes and 48 minutes of dither strokes. One layer was conducted at 275°F, two layers at 250ºF, three layers at 225°F and four layers at 185ºF. The actuator was chilled to -40ºF each night to evaluate static leakage.

The results of these tests were that the fluid leakage was the same for the HVOF-coated rod as for the EHC-coated rod, with fewer scratches observed on the HVOF-coated rods at the end of the testing. An Engineering Change Proposal was validated for replacement of EHC with HVOF WC/Co or WC/CoCr. As of the date of this report, it is not clear if the HVOF coatings will actually be implemented into repair operations.

F/A-18 C/D Trailing Edge Flap:

This component uses the same static and dynamic seal materials as were developed for the stabilator. The side-by-side design on this actuator allowed for simultaneous testing of an EHC-plated rod and an HVOF WC/CoCr-coated rod. For the component test, the same rig was used as for the functional rod/seal testing with the same protocol as for the stabilator. One rod was coated with EHC and ground to the standard 12-16 Ra finish. The other rod was coated with HVOF WC/CoCr, ground to an 8-16 microinch Ra finish and then superfinished to less than 2 microinches.

Endurance testing was completed with equivalent results for the EHC-plated and WC/CoCr-coated rods. An Engineering Change Proposal is being developed so that the HVOF coatings can be applied in repair operations.

6. Cost Benefit Analysis

6.1. Approach

The CBA, which was performed using the guidelines described in the *Cost Benefit Analysis (CBA) Methodology Handbook* [9], reports the estimated financial impact of replacing hard chrome plating with HVOF thermal spray coatings at a facility that currently conducts repair and overhaul of aircraft components, primarily landing gear and hydraulic actuators.

This CBA methodology uses the Environmental Cost Analysis Methodology (ECAM^{SM}). The ECAM was developed to provide users with a consistent and accurate tool for conducting economic analyses, especially where new environmental technologies are being considered. The ECAM integrates activity-based costing concepts and provides standard economic indicators, including net present value (NPV), payback period, and internal rate of return (IRR). The labor rate used in this analysis is $65 per hour; this is considered a fully burdened rate and is often used as a default rate for Department of Defense (DoD) cost benefit analyses. This analysis does not include the project costs associated with qualification testing of the process.

Three scenarios were developed and analyzed for this CBA. The first scenario (Base Scenario) considers both landing gear and actuator components. Scenario 2 evaluates just actuator components only. It should be noted that actuator components only account for 5% of total chrome electroplating at the facility that was analyzed. In an attempt to isolate these costs, 5% of the total electroplating costs were used. Since these costs cannot be easily separated, this method provides only a rough estimate of actual actuator plating costs. Scenario 3, which includes both landing gear and actuators, also includes expected capital expenditures for the plating department. This scenario assumes that these expected costs could be avoided if the alternative process was implemented. Scenario 1 and Scenario 2 do not include these capital expenditures in the analysis as they are considered sunk costs due to expenditures already being scheduled. In addition, alternative cases were analyzed for the Base Scenario. Case 1 analyzes the impact of expected increased service life of the landing gear and actuators with HVOF coating. Case 2 analyzes the potential impact of proposed Occupational Safety and Health Administration (OSHA) regulations for chromium exposure.

6.2. Baseline Process

6.2.1. Process Description

Hard chrome is applied to landing gear and actuator components to restore dimensions on worn or repaired parts. For most components, a 0.015”-thick coating is deposited, which is then machined down to a dimensional thickness of approximately 0.010”. The hard chrome plating process utilizes hexavalent chromium, a human carcinogen. Due to its toxicity, hexavalent chromium is a regulated hazardous material (HazMat) under the Clean Air Act (CAA), Clean Water Act (CWA), and Resource Conservation and Recovery Act (RCRA). The current chrome plating process at the facility includes sixteen chrome-plating tanks and four stripping tanks. To prepare parts for plating, several activities are performed, including inspection, stripping, blasting, and masking. Masking typically consists of the use of tape and plating wax. Post-processing steps include demasking, cleaning, baking, grinding, and inspection. Specific activities, their frequency and sequence, vary depending on part geometry, condition, and other parameters.

The baseline process flow diagram for the current hard chrome electroplating process at the facility is provided in Figure 6-1.

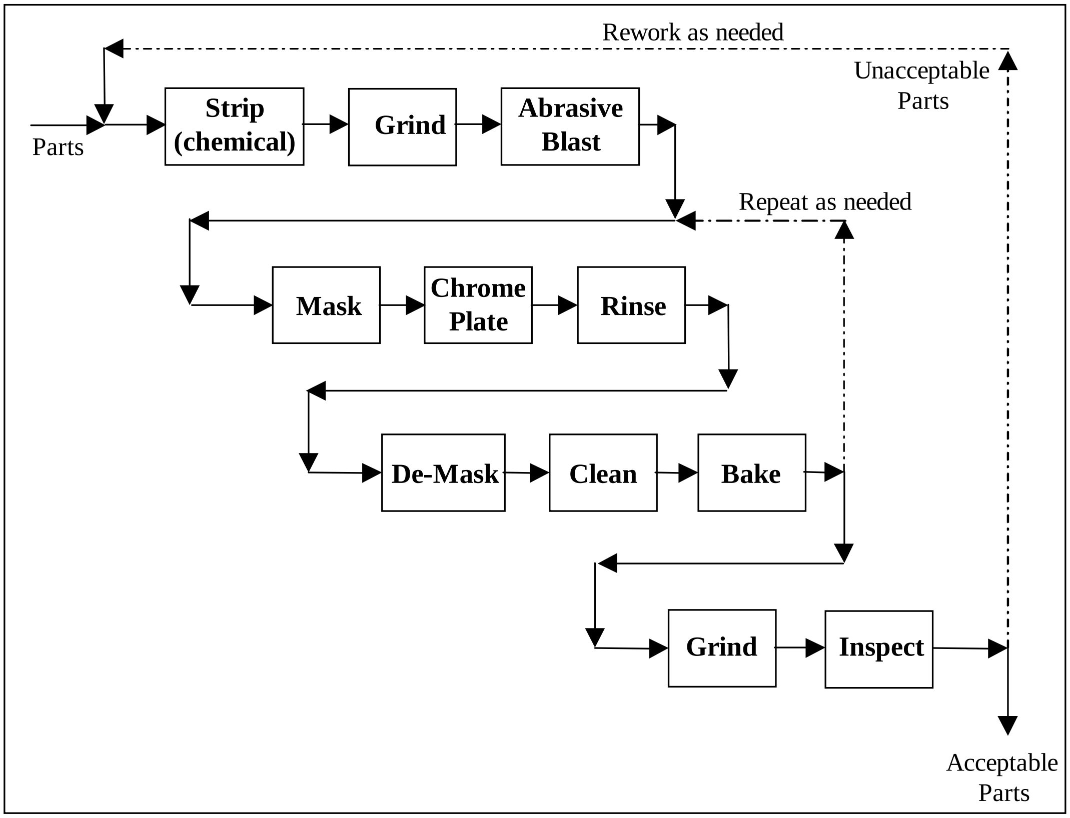

Figure 6-1 Process Flow of Hard Chrome Electroplating at the repair facility

6.2.2. Data Collection

A site visit was conducted on December 17-19, 2002 to collect baseline data on the hard chrome plating process at the repair facility. During the site visit, interviews were held with process engineers, plating operators, plating supervisors, turbine engine program managers, environmental staff, and other employees throughout the facility. The information gathered during the site visit was supplemented with additional correspondence following the visit.

6.2.2.1. Data Provided by Repair Facility

OO-ALC provided information on the following items, either during the site visit or during follow-up correspondence.

A. Annual current usage in chrome plated department
B. Annual quantities and/or costs for electroplating and stripping chemicals, maskant and tape
C. Annual costs for fixturing and anodes
D. Annual labor required for plating, fixturing design and lab analysis
E. Cost of water purchase and treatment
F. Cost of plating filters
G. Annual costs for scrubber mesh pads
H. Total plating tank electricity usage and cost
I. Annual quantities and/or cost of Personal Protective Equipment (PPE)
J. Labor required for Industrial Hygiene reporting, assisting with the Inspector General's (IG) audit and addressing safety problems in the plating area
K. Air Sampling and Analysis costs
L. Expected costs for anode testing and upgrade project.

6.2.2.2. Assumptions

The following engineering assumptions were used in evaluating the baseline hard chrome plating process.

A. The chrome plating shop is operated 50 weeks per year with overtime as required.
B. Total annual surface area chrome plated for landing gear and actuators was calculated using plating records and an estimated average current density of 2 amps per square inch.
C. It is assumed, based on input from the repair facility, that 90% of chrome production and costs are for landing gears and 5% are for actuators.
D. Water usage was estimated based on facility utility records; 20% of total water usage was estimated to be for chrome electroplating.
E. Cost to produce di-ionized water was estimated at $0.02 per gallon.
F. Fifty percent of plating rinse water is recycled.
G. Scrubber costs used in this analysis were limited to air ventilation costs, facility replacement air-cooling and heating costs, and air sampling and analysis costs. These cost were estimated based on facility input for a previous project. Scrubber maintenance and scrubbing solution costs (ion exchange) were not available and therefore were not included in this analysis.
H. Cost for plating waste disposal was estimated based on data supplied by the repair facility for a previous project.
I. Cost for anode disposal is minimal as lead is recycled.

J. Cost for fixturing disposal is minimal as it falls under the RCRA scrap metal exclusion.

K. Rework is estimated at 4%, however these costs were not calculated independently, but captured in the total annual operating costs.

L. Costs for medical exams were estimated at $200 per exam and 1.5 hours of lost work.

M. Labor to maintain/inspect hazardous accumulation sites was estimated at 4 hours per week.

N. Bi-annual Hazardous Materials Reporting to Commander was estimated at 120 hours preparation for each report.

6.2.3. Capital Costs

All capital costs for the baseline process are considered sunk costs; therefore the Base Scenario and Scenario 2 do not include any capital expenditures. Two large capital expenditures are budgeted for the plating shop in the near future. This includes an anode upgrade and testing project in year one, which includes $350,000 for materials and labor consisting of 0.5 full time equivalents (FTE) for that year. Also included is a plating shop upgrade expected to cost $1,500,000 in the year two and year three. Scenario 3 considers these costs to be avoidable if the HVOF systems are implemented, and therefore they are included as baseline costs.

6.2.4. Operating Costs

Table 6-1 provides a summary of annual labor, material, utility, and waste disposal costs for the baseline hard chrome plating process (for landing gear and actuators). In addition to these annual costs, periodic costs were captured: material costs of $4,750 every five years for scrubber mesh pads, $35,000 every five years for air sampling and analysis costs, and $1,560 every three years for labor to oversee the IG audit. Table 6-2 provides a summary of these costs for actuators only. In addition to these annual costs, periodic costs were captured: material costs of $240 every five years for scrubber mesh pads, $1,750 every five years for air sampling and analysis costs, and $80 every three years for labor to oversee the IG audit.

Table 6-1 Annual Operating Costs for Hard Chrome Plating Process for Landing Gear and Actuators

Resource	Annual Cost [a] ($/yr)
Labor	
Process operations	$3,965,000
Fixturing Design	$154,370
Laboratory Analysis	$35,040
Materials	
Anodes and Fixturing	$123,500
Process Chemicals	$45,280
Maskants and Tapes	$94,660
Utilities	
Electricity	$820,940
Water	$37,060
Waste for Disposal	
Hazardous Waste	$8,700
Solid Waste	$4,750
Wastewater	$10,680
Environmental Management Costs	
Personal Protective Equipment	$8,030
Medical Exams	$7,740
Environmental Health and Safety	$51,550
Total Annual Operating Cost	**$5,367,300**

[a] Values are rounded to the nearest tenth

Table 6-2 Annual Operating Costs for Hard Chrome Plating Process for Actuators only

Resource	Annual Cost [a] ($/yr)
Labor	
Process operations	$679,250
Fixturing Design	$7,720
Laboratory Analysis	$1,750
Materials	
Anodes and Fixturing	$6,180
Process Chemicals	$2,260
Maskants and Tapes	$4,730
Utilities	
Electricity	$41,050
Water	$1,850
Waste for Disposal	
Hazardous Waste	$440
Solid Waste	$240
Wastewater	$530
Environmental Management Costs	
Personal Protective Equipment	$1,540
Medical Exams	$1,490
Environmental Health and Safety	$2,580
Total Annual Operating Cost	**$751,610**

[a] Values are rounded to the nearest tenth

6.3. HVOF Process

6.3.1. Process Description

HVOF is a line-of-site coating process in which a metal or alloy in powder form is heated to a semi-molten state, and then deposited upon a substrate in an automated process. Semi-molten powder particles are propelled toward the substrate by a stream of inert gas and compressed oxygen that have been accelerated to supersonic velocities. The HVOF process deposits coatings with a predictable chemistry, fine granular structure, and low porosity.

A process flow diagram of the application of WC/Co and WC/CoCr by HVOF thermal spraying was developed to aid in the collection of data for the HVOF process alternative. An expected proposed process flow diagram for HVOF is shown in Figure 6-2. Note that five process steps, other than the plating (coating application) step, are expected to be eliminated when transitioning from hard chrome electroplating to HVOF thermal spraying: (Rinse, Clean, Hot Rinse, Dry, and Bake). In addition, the masking required for HVOF consists of tape and hard fixturing, as opposed to the tape and wax dip process

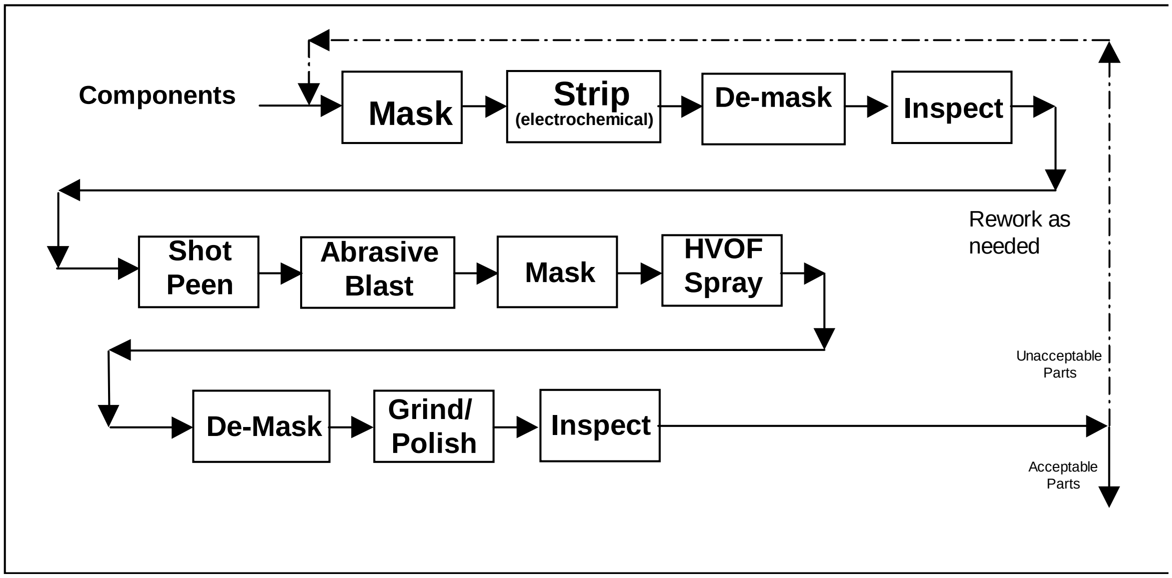

Figure 6-2 Projected Process Flow of HVOF Thermal Spraying

used for hard chrome plating.

6.3.2. Data Collection

6.3.2.1. Data provided by repair facility and/or the equipment vendor

A. Cost of WC/Co material is $32.5 per pound
B. Cost of WC/CoCr material is $29.33 per pound
C. WC/Co spray rate is 10.61 pounds per hour
D. WC/CoCr spray rate is 5 pounds per hour
E. WC/Co spray weight is 0.057 lb/ft2/mil
F. WC/CoCr spray weight is 0.071 lb/ft2/mil
G. Transfer efficiency of WC/Co is 33% and WC/CoCr is 42% based on equipment vendor and trials conducted by the repair facility; this includes a 10% stand off time
H. Gun barrels costs $108
I. Gun barrel life is 10 hours of spray time
J. Labor for laboratory analysis
K. Equipment utility requirements
L. Equipment needs and costs
M. Facility expansion costs for HVOF implementation
N. WC/Co and WC/CoCr are deposited to a thickness of 0.010”
O. All operating parameters are based on PraxAir specifications for a JP-8000 system.

6.3.2.2. Assumptions

The following engineering assumptions were used in evaluating the HVOF thermal spray coating process.

A. Approximately 80% of the landing gear parts that are currently chrome plated will be transitioned to HVOF; the remainder of the parts have inner diameter plating that cannot be transitioned to HVOF; so it is assumed that 20% of the landing gear surface area will still be plated.
B. Electroplating labor requirements will decrease by 80% after HVOF implementation.
C. HVOF labor requirements were estimated at one FTE per booth for spraying and two FTE total for assisting with the process.
D. HVOF equipment will operate two shifts per day, 50 weeks per year.
E. 100% of actuators will be transitioned to HVOF.
F. Ten of 15 plating tanks will be decommissioned after HVOF implementation.
G. The following plating costs were estimated by taking the current annual cost times a ratio of the number of tanks expected to be needed after implementation to the existing plating tanks (i.e., 10/15 or 2/3):
   - Plating chemicals
   - Liquid maskant
   - Plating filters
   - Labor for laboratory analysis
   - Anode materials
   - Water
   - Electricity
   - Wastewater
   - Waste disposal
   - Fixturing labor
H. Electroplating costs for fixturing materials were estimated at 20% of the original costs. New HVOF material costs were estimated at 2/3 of the electroplating costs and fixturing labor costs was estimated at 1/3 since some fixturing will have a longer recycle life.
I. Electroplating tape costs were estimated at 20% of the original costs. New HVOF tape costs were estimated at 2/3 of the electroplating costs since reusable shields will replace some disposable tape.
J. Two out of the three sodium hydroxide stripping tanks will be decommissioned after HVOF implementation.
K. Chemicals and electricity costs for stripping tanks were estimated by taking the current annual usage times a ratio of the number of tanks expected to be needed after implementation to the existing stripping tanks (i.e., 2/3).
L. Annual costs for maskants, tape and their disposal will be 25% of plating costs, as reusable shielding will replace some of the maskant materials.

M. Rework is estimated at 1%.

N. High Efficiency Particulate Arresting (HEPA) filters in the dust collection system are reversed air pulsed to clean, however eventually replacement will be required. An estimate of five years replacement at a cost of $20,000, plus $250 for disposal of spent filters was used for this analysis.

O. The cost of goggles, respirators and hearing protection per employee is not expected to change with implementation

P. Reporting costs for spill/emergency release, Toxic Release Inventory (TRI) and Emergency Planning and Community Right-to-know Act (EPCRA) are not expected to change with implementation of HVOF.

Q. Baking ovens will not be shut down with HVOF implementation as some baking is still needed for the electroplated parts and the ovens are used as a facility heat source.

R. Implementation of HVOF would allow for one of the three plating tank scrubbers to be shut down; consequently operating costs and air sampling and analysis costs after implementations were estimated at 2/3 of the original costs.

S. The increased cost of diamond grinding wheels for HVOF will be off set by reduced time of grinding; therefore these costs were not included in this analysis.

T. The general air CAA permit is for entire plating building; therefore it will not be affected by implementation.

U. One base-wide CWA permit (one industrial Waste Water (WW) treatment plus on-site WW facility); therefore there will be not change with implementation.

V. The plating operation is not a production bottleneck; therefore implementation of HVOF and the resulting reduced through put would not result in any cost savings other than the elimination of overtime costs.

W. Since reduced through put would not result in a cost savings, inventory costs were not calculated.

X. The net cost for disposing of HVOF waste is zero, because the material can be sold to a third party for reprocessing, with the proceeds offsetting any internal handling costs.

Y. Medical exams will not be required for HVOF operators since they are not working with a hazardous waste.

Z. All hazardous waste accumulation costs were based on two accumulation points; it is estimated that only one point will be needed after implementation; consequently associated costs would be cut in half.

AA. Labor for report preparation to the Commander is estimated to decrease from 120 hours to 80 hours per report after implementation.

BB. Labor costs associated with the Industrial Hygiene (IH) reporting and safety after implementation were estimated by taking the current annual cost times a ratio of the number of tanks expected to be needed after implementation to the existing plating tanks.

CC. Labor to oversee the IG audit will decrease by 80% after implementation.

DD. A cooling tower will be installed to recycle 90% of cooling water.

EE. CAA permit will need modified.

FF. Maintenance to clean spray booths are performed quarterly; eight hours per booth.

GG. Maintenance to clean hard masking fixtures is performed monthly; six hours per booth.

HH. Annual equipment maintenance is estimated at one hour per week per booth.

6.3.3. Capital Costs

The cost for deconstruction of the ten process tanks is expected to be roughly equal to the salvage value of the equipment; therefore, this cost was not captured in this analysis.

For the Base Scenario the following capital equipment costs were considered: $1,857,580 in HVOF equipment costs, $100,000 in installation costs, $740,000 in facility expansion costs, $10,000 in stripping rectifier costs and $920,930 in grinding equipment costs; all costs are expensed in year zero. An additional $740,000 in facility expansion costs is expensed in year one. Additional costs include training costs of $114,400 and a $5,000 cost for modification of the Clean Air Act permit expensed in year 0. For Scenario 2 the following capital equipment costs are considered: $535,000 in HVOF equipment costs, $75,000 in installation costs, $740,000 in facility expansion costs, $10,000 in stripping rectifier costs and $265,200 in grinding equipment costs; all costs are expensed in year zero. Additional costs include training costs of $33,800 and a $5,000 cost for modification of the CAA permit expensed in year zero.

All equipment costs were expensed using straight-line depreciation over ten years. All facility construction costs were expensed using straight-line depreciation over 20 years. Useful life and salvage values were estimated using Air Force Instruction 38-203 as guidance.

6.3.4. Operating Costs

Table 6-3 provides a summary of annual labor, material, utility, and waste disposal costs for the HVOF thermal spray process for landing gear and actuators. In addition to these annual costs, periodic plating and HVOF equipment maintenance costs were included: material costs include $3,560 every five years for scrubber mesh pads, $23,330 every five years for air sampling and analysis costs, $20,000 every five years for HVOF dust collection filters, $250 every five years for disposal of dust collection filters, and $300 every three years for labor to oversee the IG audit. Table 6-4 provides a summary of annual labor, material, utility, and waste disposal these for actuators only. In addition to these annual costs, periodic HVOF equipment maintenance costs were included: $20,000 every five years for dust collection filters, $250 every five years for disposal of dust collection filters.

Table 6-3 Annual Operating Costs for HVOF Thermal Spray Process for Landing Gear and Actuators (includes continued Electroplating of 20% of parts) a

Resource	Annual Cost [b] ($/yr)	
	Plating	**HVOF**
Labor		
Process operations	$780,000	$1,560,000
Fixturing Design	$51,460	$51,460
Laboratory Analysis	$11,680	$6,500
Booth and Equipment Maintenance	$0	$40,040
Materials		
Anodes and/or Fixturing	$34,830	$31,670
Process Chemicals	$15,690	$2,400
Maskants and Tapes	$24,000	$14,170
Powder	$0	$359,070
Gun Barrels	$0	$11,970
Utilities		
Electricity	$630,410	$3,590
Water	$12,350	$2,100
Equipment Fuel	$0	$29,630
Waste for Disposal		
Hazardous Waste	$2,010	$0
Solid Waste	$1,580	$140
Wastewater	$3,560	$2,040
Environmental Management Costs		
Personal Protective Equipment	$1,850	$90
Medical Exams	$1,790	$0
Environmental Health and Safety	$25,210	$0
Total Annual Operating Cost	**$3,711,290**	

[a] Periodic costs given in Section 4.4 are not summarized in this table
[b] Values are rounded to the nearest tenth

Table 6-4 Annual Operating Costs for HVOF Thermal Spray Process for Actuators (assumes 100% transition to HVOF) a

Resource	**Annual Cost [b]($/yr)**
Labor	
Process operations	$520,000
Fixturing Design	$2,580
Laboratory Analysis	$3,250
Booth and Equipment Maintenance	$4,600
Materials	
Anodes and/or Fixturing	$1,580
Process Chemicals	$120
Maskants and Tapes	$710
Powder	$17,100
Gun Barrels	$1,260
Utilities	
Electricity	$140
Water	$220
Equipment Fuel	$3,050
Waste for Disposal	
Hazardous Waste	$0
Solid Waste	$10
Wastewater	$170
Environmental Management Costs	
Personal Protective Equipment	$30
Medical Exams	$0
Environmental Health and Safety	$0
Total Annual Operating Cost	**$554,820**

[a] Periodic costs given in Section 4.4 are not summarized in this table
[b] Values are rounded to the nearest tenth

6.4. Alternative Cases

In addition to the scenarios above, the impact of other variables on the coating process has been considered. Case 1 analyzes the impact of increased service life of the landing gear and actuators expected to be realized with implementation of the HVOF coating. Case 2 analyzes the potential impact of proposed OSHA regulations for worker exposure to chromium. It should be noted, however that it is not known whether these impacts will in fact occur and additionally that limited information is known about these potential impacts. Therefore the analyses of these cases are based on more assumptions than the scenarios above. However, it is considered beneficial to try to quantify these potential cases since, if they do occur, their impact on the process is expected to be substantial. Both of these cases have been applied to the Base Scenario only, (e.g., landing gear and actuators) with no expected elimination of pending electroplating upgrade costs.

6.4.1. Case 1: Increased Service Life of HVOF Coating (Declining Throughput)

It is estimated that a constant throughput of chrome-plated parts will come in for repair and will be recoated using HVOF for a minimum of five years. However, based on the anticipated extension in service life that HVOF is expected to provide, components previously coated with HVOF that return to the depot may not necessarily be processed. If it is agreed that HVOF thermal sprayed components do not have to be stripped for inspection upon return to the depot (unless required for repair purposes), the number of landing gear and actuator parts processed annually will decrease over time. The following assumptions were used to analyze the cost benefit of this scenario.

A. Years 1-5: All landing gear and actuators components coming into the depot have chrome plating that is stripped for inspection and repair purposes. Applicable components are recoated using HVOF thermal spray at the current throughput rate of 9,755 parts per year.

B. Years 6-10: 50% of the components processed are chrome-plated parts, which are stripped, inspected, repaired, and recoated using HVOF thermal spray. It is assumed that the remaining 50% of the parts were previously coated using HVOF. It is estimated that 25% of these components (12.5% of the total throughput) will be stripped, inspected/repaired, and recoated using HVOF. The remaining components (37.5% of the total throughput) will require no processing. Thus, the total number of parts processed annually will be 6,097 components.

C. Years 11-15: All components coming into the depot were previously coated using HVOF. Of these, 25% will be stripped, inspected/repaired, and recoated using HVOF thermal spray. The total number of parts processed annually will be 1,524 components.

6.4.1.1. Capital Costs

As this case is applied to the Base Scenario, the capital costs are the same as those identified for that scenario (Section 3.3 and Section 4.3).

6.4.1.2. Operating Costs

Table 6-5 provides a summary of annual labor, material, utility, and waste disposal costs for the declining throughput rate scenario (Case 1) for the landing gear and actuator components. Costs for each time period were scaled based on the production rate; except for the cost items of laboratory testing, electricity for ventilation and PPE; these costs are not expected to be correlated directly with the production rate.

Table 6-5 Annual Operating Costs for HVOF Thermal Spray Process

	Annual Cost [a] ($/yr)		
Resource	**Years 1-5**	**Years 6-10**	**Years 11-15**
Labor			
Process operations	$1,560,000	$967,200	$390,000
Fixturing Design	$51,460	$31,910	$12,870
Laboratory Analysis	$6,500	$3,250	$3,250
Booth and Equipment Maintenance	$40,040	$24,830	$10,010
Materials			
Anodes and/or Fixturing	$31,670	$19,640	$7,920
Process Chemicals	$2,400	$1,490	$600
Maskant and Tapes	$14,170	$8,790	$3,540
Powder	$359,070	$222,620	$89,770
Gun Barrels	$11,970	$7,420	$2,990
Utilities			
Electricity	$3,590	$2,440	$1,320
Water	$2,100	$1,300	$530
Equipment Fuel	$29,630	$18,370	$7,410
Waste for Disposal			
Hazardous Waste	$0	$0	$0
Solid waste	$140	$90	$40
Wastewater	$2,040	$1,270	$510
Environmental Management Costs			
Personal Protective Gear	$90	$90	$90
Medical Exam	$0	$0	$0
Environmental Health and Safety	$0	$0	$0
Total Annual Operating Cost	**2,114,870**	**$1,310,710**	**$530,850**

[a] Values are rounded to the nearest tenth

6.4.2. Case 2: Effect of Proposed OSHA Regulations

The OSHA has established stringent permissible exposure limits (PELs) for hexavalent chromium. In the near future, OSHA is expected to issue new regulations lowering the PELs for chromium even further. OSHA has proposed to reduce the current PEL of 100 $\mu g/m^3$ (as chromates) to an 8-hour time-weighted average between 0.5 and 5.0 $\mu g/m^3$, with an action level at one-half the PEL. In most cases, this will require a significant investment in appropriate environmental control equipment to meet the revised PELs.

Chromium electroplating produces vapor and mist of hexavalent chromium compounds above the plating tank. OSHA 29 CRF 1910.1000 defines PELs for contaminants found in plating shops and requires that engineering controls (local ventilation) be implemented whenever feasible. The ventilation control velocities currently recommended by industrial hygienists and required by 29CFR 1910.94 may not reduce employee exposure below the anticipated OSHA PEL of 0.5 $\mu g/m^3$. It is likely that additional respiratory protection would be required in addition to local exhaust ventilation at a PEL of 0.5 $\mu g/m^3$. It is possible that additional respiratory protection would be required at a PEL of 5 $\mu g/m^3$ to meet the action level of 2.5 $\mu g/m^3$.

Case 2A evaluates the impact of an OSHA PEL of 5 $\mu g/m^3$. Case 2B evaluates the impact of an OSHA PEL of 0.5 $\mu g/m^3$.

6.4.2.1. Capital Costs

For the analyses factoring in the potential impact of reduced OSHA PELs for chromium, Monte Carlo simulation was used to allow input of a range of capital equipment costs. Case 2A: Figure 6-3 shows the distribution profile for the cost of an engineering control upgrade to meet a PEL of 5 $\mu g/m^3$, which is estimated to range from $0 to $50K, with a most likely value of $32.8K. Figure 6-4 shows the distribution profile for the expected salvage value of the equipment, which is expected to range from $0 to $3,000 with a most likely value of $1,571. Case 2B: Figure 6-5 shows the distribution profile for the cost of an engineering control upgrade to meet a PEL of 0.5 $\mu g/m^3$, which is estimated to range from $0 to $500K, with a most likely value of $233.2K. Figure 6-6 shows the distribution profile for the expected salvage value of the equipment, which is expected to range from $0 to $22,000 with a most likely value of $11,170. Most likely values for salvage values were set using Air Force Instruction 38-203 as guidance. Note that the capital investment requirements for a PEL of 0.5 $\mu g/m^3$ is significantly greater than what would be required for a PEL of 5 $\mu g/m^3$.

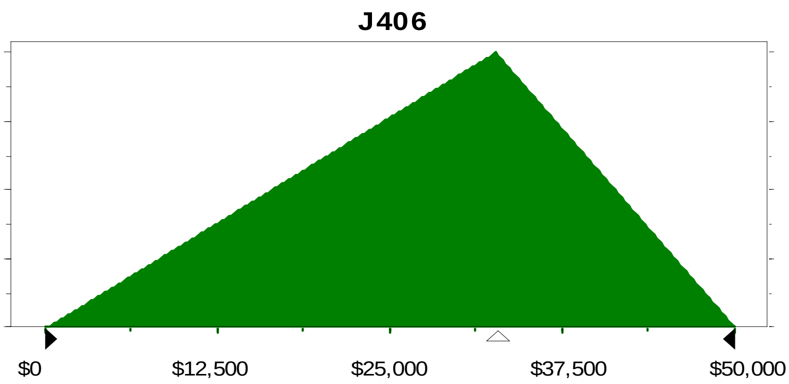

Figure 6-3 Capital Investment Cost Assumption for PEL of 5 µg/m^3

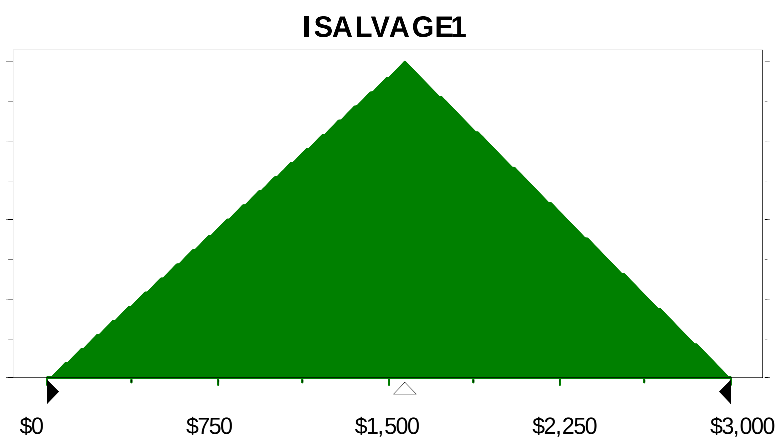

Figure 6-4 Salvage Value Assumption for PEL of 5 µg/m^3

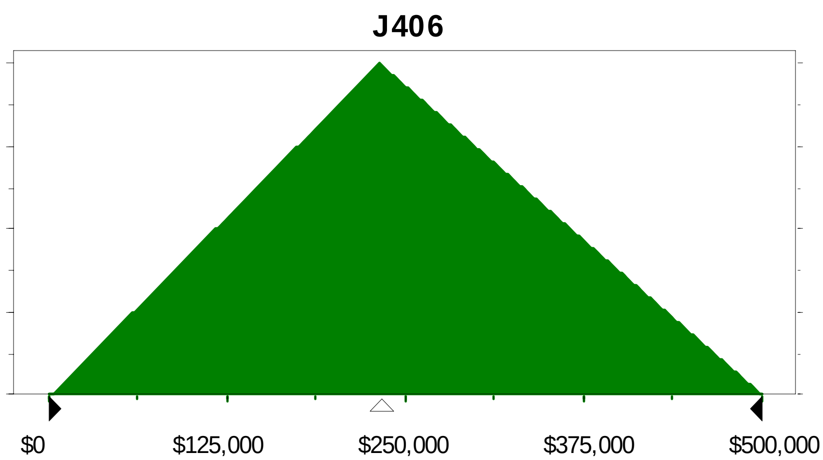

Figure 6-5 Capital Investment Cost Assumption for PEL of 0.5 µg/m^3

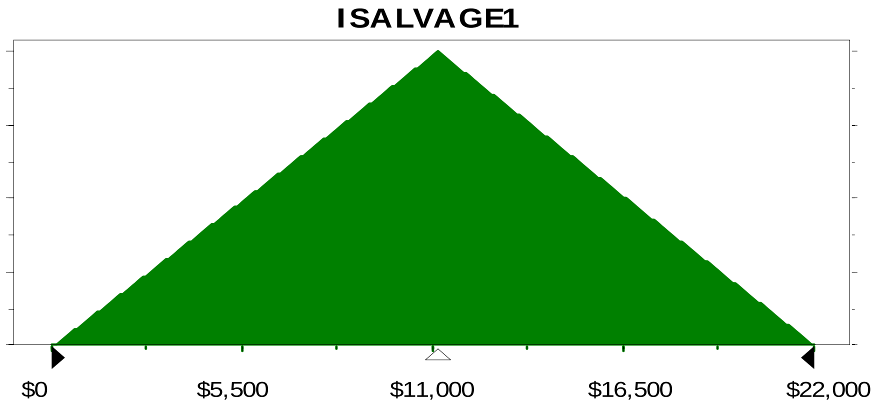

Figure 6-6 Salvage Value Assumption for PEL of 0.5 µg/m^3

6.4.2.2. Operating Costs

For Case 2, factoring in the potential impact of reduced OSHA PELs for chromium, Monte Carlo simulation was used to allow input of a range of additional operating costs for upgraded environmental controls. Figure 6-7 shows the distribution profile for the operating cost of additional engineering controls required to meet a PEL of 5 µg/m^3, which is estimated to range from $0 to $20K, with a most likely value of $10.8K. Figure 6-8 shows the distribution profile for the operating cost of additional engineering controls required to meet a PEL of 0.5 µg/m^3, which is estimated to range from $0 to $500K, with a most likely value of $258.4K. These values are correlated to the capital cost assumptions, so that a high capital investment cost corresponds to a high additional operating cost.

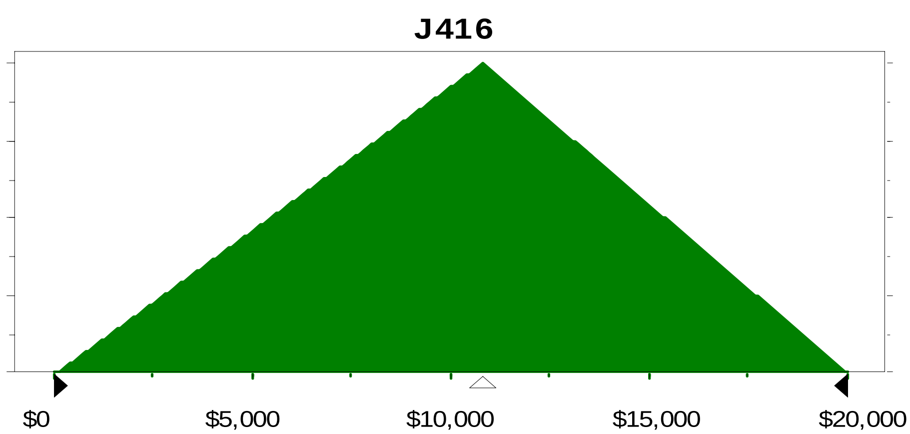

Figure 6-7 Annual Additional Operating Cost Assumption for PEL of 5 µg/m^3

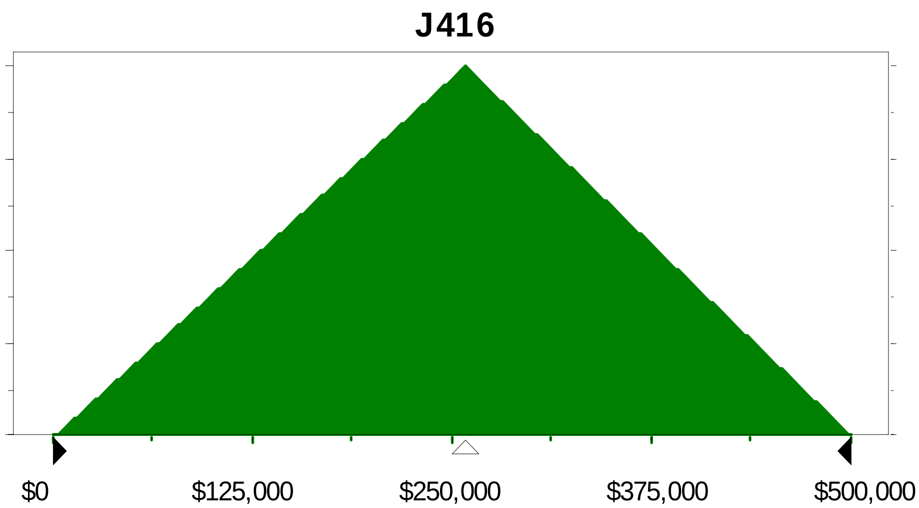

Figure 6-8 Annual Additional Operating Cost Assumption for PEL of 0.5 µg/m^3

In addition to the operating costs for additional engineering controls, a reduced OSHA PEL would also result in additional environmental, safety, and occupational health (ESOH) costs and reduced worker productivity. ESOH costs include training, PPE, monitoring, and medical surveillance. The reduced productivity is a result of workers having to spend additional time donning PPE and potentially having to change clothes and shower after working in the process area. ESOH and lost productivity costs are estimated at $11,600 per exposed worker. It is assumed that all twenty-six workers would be potentially affected by a PEL of 0.5 µg/m^3, which equates to an annual ESOH/ productivity cost of $116,000 (Case 2B). It is assumed that 20% (i.e., 5) of the workers potentially exposed over 0.5 µg/m^3 would be exposed over 5 µg/m^3, at an annual cost of $23,200 (Case 2A).

6.5. Cost Benefit Analysis

The ECAM includes a financial analysis that was performed using the Pollution Prevention Financial Analysis and Cost Evaluation System (P2/FINANCE) software. The P2/FINANCE software generates financial indicators that describe the expected performance of a capital investment. A brief explanation on interpreting these financial indicators is provided, as are the results of the financial analyses for the implementation of HVOF thermal spray for landing gear and actuators at the repair facility.

To measure the financial viability of this project, three performance measures for investment opportunities were used: net present value (NPV), internal rate of return (IRR), and payback period. The NPV is the difference between capital investments and the present value of future annual cost benefits associated with the alternatives. The IRR is the discount rate at which NPV is equal to zero. NPV and IRR account for the time value of money, and discount the future capital investments or annual cost benefits to the current year. For NPV and IRR, a 2.7% discount rate was used for this financial evaluation, which is consistent with the (Office of Management and Budget) OMB

Circular Number A-94 and the ECAM. The payback period is the time period required to recover all of the capital investment with future cost savings. Guidelines for these performance measures are listed in Table 6-6.

Table 6-6 Summary of Investment Criteria

Criteria	Recommendations/Conclusions
NPV > 0	Investment return acceptable
NPV < 0	Investment return not acceptable
Highest NPV	Maximum value to the facility
IRR > discount rate	Project return acceptable
IRR < discount rate	Project return not acceptable
Shortest payback period	Fastest investment recovery and lowest risk

Adapted from *ECAM Handbook*.

A summary of the financial evaluation for implementing HVOF to replace hard chrome electroplating of landing gear and actuators is listed in Table 6-7, Table 6-8, and Table 6-9 for Base Scenario and Scenario 2 and Scenario 3, respectively.

Table 6-7 Base Scenario: Results of Financial Evaluation (Landing Gear and Actuators without expected plating capital expenditures)

Financial Indicator	5-yr	10-yr	15-yr
NPV	$3,084,200	$9,694,900	$15,780,900
IRR	25.7%	36.4%	37.9%
Discounted Payback		2.88 years	

The Base Scenario was used as the basis of two additional analyses. Case 1 takes into account the potential increased service life of HVOF coating and consequently a declining through put of components needing coated. Table 6-10 is a summary of the financial evaluation for implementing HVOF to replace hard chrome electroplating of landing gear and actuators for a declining through put.

Table 6-8 Scenario 2: Results of Financial Evaluation (Actuators only without expected plating capital expenditures)

Financial Indicator	5-yr	10-yr	15-yr
NPV	($797,900)	($39,800)	$710,500
IRR	(16.3%)	2.2%	7.8%
Discounted Payback		10.31 years	

Table 6-9 Scenario 3: Results of Financial Evaluation (Landing Gear and Actuators with expected plating capital expenditures)

Financial Indicator	5-yr	10-yr	15-yr
NPV	$4,887,500	$11,497,100	$17,582,300
IRR	40.0%	47.2%	48.0%
Discounted Payback		2.10 years	

Table 6-10 Case 1: Results of Financial Evaluation for Increased Service Life of HVOF Coating (Declining Throughput)

Financial Indicator	5-yr	10-yr	15-yr
NPV	$3,082,300	$12,973,700	$24,717,800
IRR	25.5%	39.7%	41.8%
Discounted Payback	2.88 years		

Case 2 accounts for the additional cost avoidance that may be realized if OSHA reduces the PELs for hexavalent chromium in the near future. Due to the difficulties associated with predicting the economic impact of a proposed regulation, Monte Carlo simulation was used to forecast the potential impact using the variable capital and operating costs provided in Figure 6-3 through Figure 6-8. Using Monte Carlo simulation, key variables are defined within a given range and distribution profile instead of a single (uncertain) value. The output shows the range of possible results and degree of certainty that any desired outcome can be achieved. During the Monte Carlo simulation, 5,000 trials (possible combinations of variable assumptions) were run for each case study.

Figure 6-9 shows the results of the Monte Carlo simulation for the 15-year NPV for a PEL of 5 µg/m^3 (Case 2A). The 15-year NPV ranges from $16.4 Million to $16.7M, with a mean value of $16.5M.

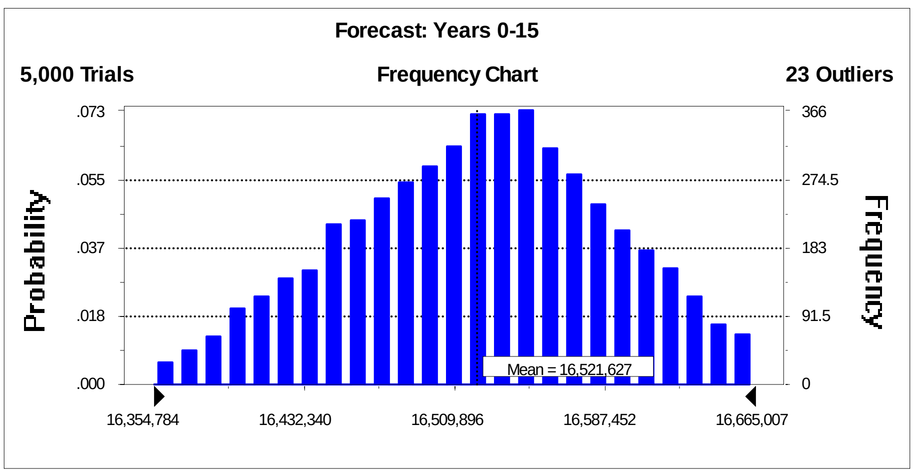

Figure 6-9 15-Yr NPV for PEL of 5 µg/m^3

A summary of the cost benefit indicators for Case 2A is presented in Table 6-11. All data are mean values.

Table 6-11 Base 2B: Results of Financial Evaluation for PEL of 5 µg/m^3

Financial Indicator	Cost Benefit
15-Year NPV	$16,522,000
IRR	39.6%
Discounted Payback	2.76 years

Figure 6-10 shows the results of the Monte Carlo simulation for the 15-year NPV for a PEL of 0.5 µg/m^3 (Case 2B). The 15-year NPV ranges from $18.6M to $25.6M, with a mean value of $22.1M.

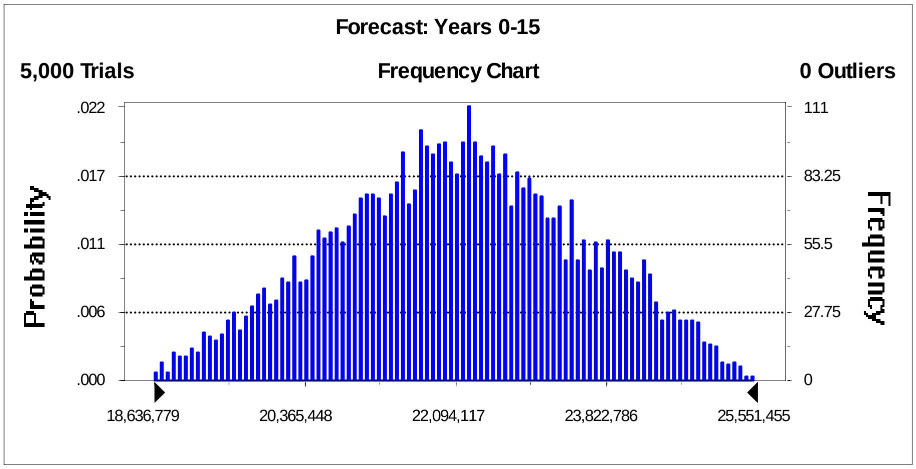

Figure 6-10 15-Yr NPV for PEL of 0.5 µg/m^3

A summary of the cost benefit indicators for Case 2B is presented in Table 12. All data are mean values.

Table 6-12 Case 2B: Results of Financial Evaluation for PEL of 0.5 µg/m^3

Financial Indicator	Cost Benefit
15-Year NPV	$22,128,400
IRR	53.3%
Discounted Payback	2.09 years

6.6. Summary and Conclusions

The results indicate that HVOF is an economically feasible alternative for chromium electroplating for landing gear and actuators at the repair facility that was analyzed.

A base scenario, two additional scenarios and three cases applied to the base scenario all showed an economic benefit with implementation of HVOF for landing gear and actuators. Analysis of the Base Scenario (landing gear and actuators) indicated an expected payback of under 3 years. The 15-year net present value is $15.8 Million and the 15-year IRR is 38%. The analysis of scenario 2 (actuators only), which accounts for just 5% of the chrome plating, indicated an expected payback of 10 years. This scenario did not show a positive NPV until year 11; the 15-year NPV was $727,000 and the corresponding IRR is 8.2%. Scenario 3 (landing gear and actuators) also includes expected capital expenditures for the plating department. This scenario assumes that these expected costs could be avoided if the alternative process was implemented. Scenario 3 had a 15-year NPV of $17.6 Million, a corresponding IRR of 48.2% and a payback of 2 years. The primary cost driver for these scenarios is the reduced labor costs associated with HVOF; a secondary cost driver is the expected reduction in environmental management costs associated with HVOF coating.

The above scenarios represent the expected cost impact of implementation HVOF using the same repair schedule and under present environmental regulatory conditions. However, for a thorough analysis, two additional cases were considered. Case 1 considered the expected impact on service life of the components after HVOF implementation. Since HVOF has reportedly shown wear resistance of up to four times as great as that of electroplated chrome, it is expected that the repair schedule could be reduced after HVOF implementation. Therefore Case 1 analyzes a declining through put of components; this scenario is expected to have a 15-year NPV of $24.8 Million with a corresponding IRR of 41.9%. The payback period is expected to be 2.87 years. The primary cost driver for Case 1 is the reduction in overall operating costs due to the increased service life of the components with HVOF coating.

Case 2 analyzes the potential impact of proposed OSHA regulations for worker exposure to chromium. OSHA has proposed to reduce the current PEL of 100 $\mu g/m^3$ (as chromates) to an 8- hour time-weighted average between 0.5 and 5.0 $\mu g/m^3$. Case 2A evaluates the impact of an OSHA PEL of 5 $\mu g/m^3$. Case 2B evaluates the impact of an OSHA PEL of 0.5 $\mu g/m^3$. For the analyses factoring in the potential impact of reduced OSHA PELs for chromium, Monte Carlo simulation was used to allow input of a range of capital equipment costs. The 15-year NPV for Case 2A ranges from $16.3Million to $16.7M, with a mean value of $16.5M. Mean values for IRR and payback are 39.6% and under 3 years respectively. The 15-year NPV for Case 2B ranges from $18.6M to $25.5M, with a mean value of $22.1M. Mean values for IRR and payback are 53.3% and 2 years respectively. The primary cost drivers for Case 2A is still labor as in the Base Scenario. The primary cost driver for Case 2B is the regulatory burden costs that are expected to be realized with the proposed OSHA PEL of 0.5 $\mu g/m^3$.

Economic studies of HVOF implementation at other facilities have shown a range of results, indicating that the economic feasibility of HVOF implementation is highly dependent on site-specific details. The actual economic effects at the repair facility that was analyzed or other facilities will vary depending on the actual throughput converted, future workloads, and other factors specific to each facility.

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7. Implementation

This validation project was designed to obtain all the data needed for implementation, with the knowledge that additional rig testing and service testing will still be necessary to obtain flight qualification on individual actuators for OEM use or for repair. Thus the project covered the following:

1. Coating performance (coupon tests)
2. Actuator performance (rod/seal tests, functional tests of actuators and service evaluations)
3. Cost/benefit analysis

The results of these tests and how they impact implementation are discussed below.

7.1. Coating Performance (Coupon testing)

Substrates evaluated:

- 4340 high strength steel, 180-200ksi
- PH15-5 stainless steel, 155ksi
- Ti-6Al4V, 130ksi.

HVOF coatings evaluated (compared with EHC):

- WC/10Co4Cr
- Cr_3C_2/20(80Ni-20Cr)
- Tribaloy 400 (T400, nominal composition 57Co-28.5Mo-8.5Cr-3.0Ni-3.0Si).

The results of coupon testing were as follows :

1. **Axial Fatigue** (pass, Ti-6Al4V not verifiable)

   4340 and PH15-5 **–** All HVOF coatings on 4340 and PH15-5 steel were equal to or better than EHC, with T400 having significantly better fatigue. This is in accord with results of prior programs. As has been seen on landing gear in testing and in service, there was some circumferential cracking of the HVOF coatings at the highest loads as well as at the highest cycles. Spalling of the HVOF coatings occurred on 4340 at the highest load (160ksi) and also at the highest cycles (9.5 million cycles). There was cracking, but no spalling, on the PH15-5 specimens.

   Ti-6Al4V – The data on Ti-6Al4V were unreliable because of poor adhesion of both the EHC and the HVOF coatings. The EHC adhered poorly presumably due to inadequate activation, since titanium alloys are known to be very difficult to activate because they rapidly form strong oxides. The HVOF failed to adhere properly because the surface was not grit blasted. The team specified that grit blasting not be used so as to avoid embedding grit particles. As a result all the EHC coatings on Ti-6Al4V spalled, while the HVOF coatings also spalled over some of their range. This means that the baseline EHC performance could not be established.

2. **Salt Fog Corrosion**, ASTM 1,000 hour B117 (fail, but performance similar to other HVOF coatings, which have proved superior to EHC in beach exposure and service environments)

   Both rods and flat panels were evaluated, most as-ground but some with superfinished surfaces. As in previous tests, the EHC coatings in general provided somewhat better appearance rankings than HVOF coatings. Thicker EHC or HVOF coatings did not in general provide any better protection and there was no consistent performance differences between flats and rods.

   It was found in previous work that there is very poor correlation (in fact a negative correlation) between the standard B117 cabinet testing of HVOF and EHC coatings and their actual performance in beach exposure and in service. (This is probably because the B117 test was designed for testing chromated primers, not coatings of this type.) Although HVOF coatings have always been inferior to EHC in B117 testing, they have always proved superior in beach exposure and service evaluations. The B117 corrosion behavior on the substrates in this testing was similar to what has been seen in our other evaluations. It is therefore expected that the service performance of HVOF coatings on these substrates will be superior to that of EHC, just as it is on 300M and fully hardened 4340.

3. **Fluid Immersion** (pass for all OEM and MRO fluids tested, but Co-containing coatings are attacked by bleach, which although not an approved disinfectant, has been used on aircraft wheels to inhibit the spread of livestock diseases)

   The coatings were tested for weight loss and roughening in a wide variety of commonly-used cleaners, etchants, hydraulic fluids, fuels and other chemicals likely to be encountered during service or overhaul. WC/CoCr and Cr_3C_2/NiCr were not affected by any of these chemicals, while T400 showed slight attack by strong cleaners and reactive chemicals.

   The one exception was that WC/CoCr and T400 were both strongly attacked by bleach (sodium hypochlorite), which appeared to attack the Co in the coatings. Bleach is not an approved MRO chemical, but is sometimes used as a disinfectant on commercial aircraft during disease outbreaks. Cr_3C_2/NiCr was unaffected, presumably because bleach attacks Co.

4. **Environmental Embrittlement**, 200 hour ASTM F519 (pass)

   None of the coatings, including EHC, caused environmental embrittlement (re-embrittlement) in DI water or 5% NaCl solution.

Wear testing was not done under this program since it is known that the wear rate for HVOF carbides is much less than for EHC.

From the coupon testing it was concluded that HVOF WC/CoCr and Cr_3C_2/NiCr will both provide good performance on 4340 and PH15-5 actuator rods. Tribaloy 400 was also shown to perform well in fatigue, but is attacked to a limited extent by strong MRO chemicals. In addition, since it is a softer coating its wear resistance is not as good as the carbides. Another limitation of T400 is that it cannot be deposited with the same extremely low porosity and fine surface finish of the carbides, but this is balanced by its higher lubricity and its somewhat better fatigue performance and resistance to spalling. Thus the carbides are in general the best options for maximum service life, but T400 may be the better choice for applications involving high strain or high fatigue.

The fluid immersion data confirm that it is most important that landing gear and the actuators on them (steering, brakes, etc.) not be washed down with bleach. Further testing is needed to identify a coating-safe disinfectant that can be used for landing gear, and international cooperation will be required to ensure that only the approved disinfectant is used. An option is to use Cr_3C_2/NiCr rather than WC/CoCr on brake, steering and other actuators in the lower areas of landing gear.

7.2. Actuator Performance

7.2.1.Functional rod/seal testing

Rod/seal testing was done at NAVAIR Patuxent River. HVOF WC/CoCr was applied to test rods and finished to two different surface conditions:

- 4-6μ-in Ra ground with 320 grit diamond wheel
- 4μ-in Ra ground with 120 grit diamond wheel
- 2 μ-in Ra stone superfinished
- 4 μ-in Ra or less stone superfinished and 4 μ-in tape superfinished, using different initial grind surfaces

Several seals from different manufacturers (Busak+Shamban, Greene, Tweed, CorrsTek) were tested:

- O-ring with cap strip
- O-ring with two backup rings
- Fluorosilicone O-ring with PTFE cap
- Spring energized PTFE

In almost all tests HVOF-coated rods gave lower leakage than EHC-coated rods, with less rod wear and seal wear for superfinished surfaces. Surprisingly, the ground finish gave the least leakage of all, but ground surfaces did polish over time, whereas superfinished surfaces showed no change but light scratches (as against the heavily-scratched EHC). Tape superfinished coatings performed slightly better than stone superfinished. Overall the best performance was for a superfinished rod with either a MIL-P-83461 O-ring with PTFE cap strip or spring energized PTFE seals with backup ring. This is in accord with common industry findings that energized PTFE seals work best with HVOF surfaces.

The recommendation from the rod/seal testing is that rods should be coated with WC/CoCr, superfinished to 2-4 μ-in Ra with a Tp of 85-90% at a depth of 8 μ-in. Seals should be energized PTFE or O-ring cap.

7.2.2.Actuator testing

Actuators with HVOF-coated rods were tested by the Oklahoma City Air Logistics Center Airborne Accessories Directorate Avionics and Accessories Division (OC-ALC/LGERC). The three primary types of actuators were tested, with test components chosen to permit qualification of additional components by similarity:

1. Flight control actuators
2. Utility actuators
3. Snubbers

Actuators tested were:

1. C130 Rudder Booster Actuator (passed testing, to be service tested)
2. A-10 Aileron Actuator (passed testing, to be service tested)
3. C/KC-135 Aileron Snubber (passed testing, to be service tested)
4. B-1 Horizontal Stabilizer (endurance testing successful, no service tests needed, drawings updated, Tech Order and stocklist updates in progress)
5. B-1 Pitch/Roll SCAS (testing in progress)
6. F-15 Pitch/Roll Channel Assembly (to be tested)
7. T-38 Aileron (testing successful)
8. C-130 Ramp (passed testing with change to seal specification, to be service tested)
9. C-KC-135 Main Landing Gear Actuators (passed testing with change to seal specification, to be service tested)
10. C/KC-135 Main Landing Gear Door (qualified for service testing)
11. Navy F/A-18 C/D Stabilator (same leakage as EHC, but fewer scratches, Engineering Change Proposal validated)
12. Navy F/A-18 C/D Trailing Edge Flap (same leakage as EHC, but fewer scratches, Engineering Change Proposal validated).

Overall, actuators with HVOF-coated rods were found to perform as well as or better than those with EHC-coated rods, although in some cases different seals were required. A number of actuators have passed rig tests and are going into service testing. One, the B-1 Horizontal Stabilizer, is now qualified and TOs are being updated to permit production coating at OO-ALC.

Once service evaluations are completed it is expected that a large number of other actuators will be able to be qualified by similarity.

7.3. Cost/Benefit Analysis

A CBA was conducted for HVOF coating of actuators and landing gear at a facility that conducts repair and overhaul of aircraft components, principally landing gear and actuators, where actuators are about 5% of the workload. Various scenarios were considered in which all landing gear and actuators were stripped of EHC and recoated

Table 7-1. Cost Benefit Analysis Summary (numbers rounded).

Scenario	15 yr NPV	15 yr IRR	Payback period (Yr)
Same service life of HVOF and EHC-coated components, no additional expenditures on chrome plating baseline. Landing gear + actuators	$16 million	38%	2.9
Same service life of HVOF and EHC-coated components, no additional expenditures on chrome plating baseline. Actuators only	$710,500	8%	10.3
Same service life of HVOF and EHC-coated components, includes additional expenditures on chrome plating line. Landing gear + actuators	$18 million	48%	2.1
Improved service life (reduced strip and recoat) for HVOF	$25 million	42%	2.9
No increase in service life, but OSHA Cr^{6+} PEL of 5 $\mu g\ m^{-3}$	$17 million	40%	2.8

with HVOF at overhaul (see Table 7-1).

Clearly, there are strong economic reasons to replace EHC with HVOF on actuators and landing gear. The analysis does not combine the effects of the new OSHA PEL and the improved service life, both of which will improve the financial payback. Note, however, that the reduced PEL is not expected to greatly increase chrome plating costs at the repair facility analyzed, and so has a rather small effect on the economics.

A major contributor to the economic payback is the improved performance afforded by HVOF, which leads to less frequent strip and recoat operations.

7.4. Implementation at Repair Depots

Once service testing is complete, it will be possible to modify TOs to permit the use of HVOF coatings in depot overhaul of actuators. While it is expected that most actuators will be able to be qualified by similarity, there are likely to be special cases, such as actuators whose rods are subjected to severe side loading or excessive fatigue. These will need to be qualified individually. In most systems seals should also be changed to modern PTFE energized or cap types to obtain the best overall performance and minimal leakage.

In coating the test articles for OC-ALC/LGERC, there was some difficulty in spraying very long actuator rods, which tended to warp due to the heat of the flame. With this type of part care must be taken to remove stresses prior to coating, and to ensure that the coated part is straight prior to grinding and assembly.

When changing from EHC to HVOF it is also necessary to redefine the runout at the edge of the coatings. A set of HVOF Guidelines is under development that covers all of these issues for both actuators and landing gear.

7.5. Implementation at OEMs

HVOF WC/CoCr and Cr_3C_2/NiCr are already replacing EHC on hydraulic designs in new systems such as the F-35. There are a number of aerospace-qualified vendors capable of applying these HVOF coatings. The coatings are usually superfinished to 4 μ-in Ra, often with Tp also defined by the designer, and are used in conjunction with various types of energized PTFE seals.

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APPENDIX A

Service Test Plan

For

C/KC-135 Hydraulic Actuators

135 Test Plan-Rev A1.pdf

APPENDIX B

Service Test Plan

For

C-130 Hydraulic Actuators

130 Test
Plan-Revision A-Final.

APPENDIX C

Service Test Plan

For

A-10 Hydraulic Actuators

A-10 Test
Plan-Final1.pdf