

**U.S. DEPARTMENT OF DEFENSE  
Environmental Security Technology Certification Program (ESTCP)  
Joint Group on Pollution Prevention (JG-PP)  
And  
CANADA DEPARTMENT OF NATIONAL DEFENCE  
INDUSTRY CANADA**

## **JOINT TEST PROTOCOL**

**Validation of WC/Co and WC/CoCr HVOF  
Thermal Spray Coatings as a  
Replacement for Hard Chrome Plating  
On Aircraft Landing Gear**

### **PART I: MATERIALS TESTING**

**Date: June 11, 1999**

**Revision A issued September 10, 1999  
(incorporating non-technical corrections)**

**Prepared By:  
U.S. Hard Chrome Alternatives Team (HCAT)  
Canadian Hard Chrome Alternatives Team (CHCAT)**



## Table of Contents

<b>Amendments</b>	4
<b>1.0 Introduction</b>	5
<i>Applicable Test Standards</i>	10
<b>2.0 Fatigue</b>	11
<b>2.1 U.S. HCAT Testing</b>	11
<i>Material Preparation Table 2.1.1</i>	11
<i>Acceptance Criteria</i>	13
<i>Fatigue Test Matrix Table 2.1.2</i>	14
<b>2.2 Canadian HCAT Testing</b>	15
<i>Fatigue Test Matrix Table 2.2.1</i>	17
<i>Acceptance Criteria</i>	17
<b>3.0 Corrosion</b>	18
<b>3.1 U.S. HCAT Testing</b>	18
<i>Corrosion test specimen Figure 3.1.1</i>	18
<i>Illustration of scratched corrosion test specimen Figure 3.1.2</i>	20
<i>General Motors Test Protocol Table 3.1.1</i>	21
<i>Acceptance Criteria</i>	22
<i>Corrosion Test Matrix Table 3.1.2</i>	23
<b>3.2 Canadian HCAT Testing</b>	25
<i>Corrosion Test Matrix Table 3.2.1</i>	26
<i>Acceptance Criteria</i>	27
<b>4.0 Wear</b>	28
<b>4.1 U.S. HCAT Testing</b>	28
<i>Cross sectional schematic of piston and bushing wear test Figure 4.1.1</i>	28
<i>Cross sectional schematic of fretting wear test Figure 4.1.2</i>	28
<i>Wear test material matrix Table 4.1.1</i>	29
<i>Specifications for Fretting Block and Shoe Figure 4.1.3</i>	30
<i>Specifications for Oscillating Wear Rods Figure 4.1.4</i>	31
<i>Acceptance Criteria</i>	33
<i>Wear test Variables (DoE Design Factors) Table 4.1.2</i>	33
<i>Pre-DoE Trial Wear Tests Table 4.1.3</i>	34
<i>L12 DoE for Measuring Sensitivity to Wear Test Variables Table 4.1.4</i>	35
<i>L8 DoEs for Measuring Sensitivity to Wear Test Variables Table 4.1.5</i>	36

<b>4.2 Canadian HCAT Testing</b>	37
<i>Material Preparation</i> <i>Table 4.2.1</i>	37
<i>Acceptance Criteria</i>	39
<i>Wear Test Protocol</i> <i>Table 4.2.2</i>	40
<b>5.0 Impact Testing</b>	43
<b>5.1 U.S. HCAT Testing</b>	43
<i>Impact Test Matrix</i> <i>Table 5.1</i>	45
<b>5.1.7.1 ASTM D3170</b>	45
<b>5.1.7.2 Dropped Ball</b>	46
<i>Acceptance Criteria</i>	46
<b>6.0 Hydrogen Embrittlement (ASTM F 519-97)</b>	47
<i>Hydrogen Embrittlement Specimens</i> <i>Figure 6.1</i>	47
<i>Acceptance Criteria</i>	49
<i>Hydrogen Embrittlement Test Matrix</i> <i>Table 6.1</i>	50

## AMENDMENTS

The following are amendments to the Joint Test Protocol issued by the Joint Group on Pollution Prevention for endorsement. They consist of minor corrections, clarifications, or deletions of extraneous information. All of the amendments were reviewed by the stakeholders at the meeting held on 1 September 1999 in Halifax, Nova Scotia, with mutual agreement that none of the amendments constitute a technical change to the JTP.

The page numbers referred to in the following list are those from the original document. The page numbers for this revised document have been changed to accommodate this page of amendments.

1. Page 14, Section 2.2.2: Add period after the word “lot.”
2. Page 14, Section 2.2.4: Delete the phrase, “as indicated in figure 1.” This figure does not exist.
3. Page 15, Section 2.2.7: Delete the phrase, “(see test specification).” There is no separate test specification.
4. Page 15, Section 2.2.7: Change low-temperature ambient test temperature tolerances to: “ $-40\pm 4$  °F ( $-40\pm 2$  °C).” These tolerances are more realistic.
5. Page 25, at end of Section 3.2.5: Add the following statement: “Note: Specimens will not be scratched for the Canadian corrosion tests.”
6. Page 25, Table 3.2.1: Change the fifth column heading to: “Thickness, mils.”
7. Page 36, Section 4.2.1: Insert the phrase, “and bushing material” in front of “Al-Ni-Bronze.” This clearly identifies the Al-Ni-Bronze as the bushing material.
8. Page 36, Section 4.2.1: Change “6460” to “4640” to correct typographical error.
9. Page 36, Section 4.2.3: Change “table 2.3.1” to “Table 4.2.1” to correct typographical error.
10. Page 36, Section 4.2.3: Replace the word “blocks” with “bushings” and the word “block” with “bushing.” This clarifies the terminology
11. Page 36, Section 4.2.3: Add “(+0.001/-0)” after “1.00.” This provides the tolerances at the first mention of this dimension.
12. Page 36, Section 4.2.4: For the quantities of wear rods, replace “18” with “36,” and replace “105” with “96” in both instances. This corrects typographical errors.
13. Page 36, Section 4.2.4: Replace the sentence “All wear blocks will be EDM to 1.75” x 1.75” x 1.75”” with “The length of the wear rods will be 4.62”. All bushings will be machined to a 1.475” O.D. at a length of 1.75”.” This clarifies specimen geometry.
14. Page 36, Section 4.2.5: Change “Table 2.3.1” to “Table 4.2.1” to correct typographical error.
15. Page 39, Table 4.2.2: Delete “2.3.8.1” in front of the word “BASELINE.”
16. Page 46, Section 6.1.4: Change “Type 1b” to “Type 1a.2” to correct typographical error.
17. Page 46, Figure 6.1: Change “3/4”-1”” to “4”-5”” to correct typographical error
18. Page 46, Section 6.1.5: Delete the phrase “(see figure 3.1.1)” as this is not relevant.
19. Page 46, Section 6.1.6: Change “3/8”-1/2”” to “2 3/8” – 2 1/2”” to correct typographical error

## 1.0 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 and the Canadian Department of National Defence. 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 landing gear components such as axles, hydraulic cylinders, pins and races. 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-chrome 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). Recent studies have clearly shown that there are a significant number of excess deaths at the current PEL of 100 micrograms-per-cubic-meter ( $\mu\text{g}/\text{m}^3$ ), which is causing OSHA to release in late 1999 new draft standards that could reduce the PEL for airborne hex-Cr by as much as two orders of magnitude. A Navy/Industry task group under the coordination of the Naval Sea Systems Command has conducted an assessment of the technical and economic impact of such a drastic change. It concluded that the cost of compliance for all Navy operations that utilize hex-Cr (i.e., not just plating) would be as much as \$46 million per year in collection, treatment, and disposal costs, plus one time facilities costs of \$22 million to upgrade exhaust and ventilation equipment, personal protective gear, and industrial waste treatment facilities. 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.

Previous research and development efforts [1,2] had established that high-velocity oxygen-fuel (HVOF) thermal spray coatings are the leading candidates for replacement of hard chrome. HVOF thermal spraying can be used to deposit both metal alloy and ceramic/metal (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 what is currently being used for chrome plating. Currently, there are HVOF thermal spray systems commercially available. Although there are a wide number of applications for these coatings, their qualification as an acceptable replacement for hard chrome plating has not been adequately demonstrated, particularly for fatigue-sensitive aircraft components.

The Environmental Security Technology Certification Program (ESTCP) was established as a program of the U. S. Department of Defense (DOD) in December, 1993. The ESTCP, which is managed by the Deputy Under Secretary of Defense for Environmental Security (DUSD-ES), demonstrates and validates lab-proven technologies that target the most urgent DOD environmental needs. These technologies provide a return on investment through reduced environmental, safety, and occupational health (ESOH) risks; cost savings; and improved efficiency. The new technologies typically have broad application both to the DOD sustainment community and industry.

In order to conduct the advanced development work required for qualification of the HVOF coatings, a project entitled, "Tri-Service Dem/Val of Chromium Electroplating Replacements," principally sponsored by ESTCP, was established in March 1996. A project team, designated the Hard Chrome Alternatives Team (HCAT) was established to execute the project. The following are the principal organizations that constitute the HCAT:

- Naval Research Laboratory (NRL) (Project Lead)
- Air Force Research Laboratory (AFRL)
- Naval Aviation Depot- Jacksonville (NADEP-JAX)
- Naval Aviation Depot- Cherry Point (NADEP-CP)
- Ogden Air Logistics Center (OO-ALC)
- Sacramento Air Logistics Center (SA-ALC)
- Corpus Christi Army Depot (CCAD)
- Naval Air Warfare Center, Aircraft Division, Patuxent River
- Rowan Technology Group
- GE Aircraft Engines (GEAE)
- Metcut Research, Inc.
- National Technical Systems (NTS)
- Boeing Defense Group

Under this project, HVOF systems were acquired and installed at NADEP-CP and CCAD, and extensive training has been conducted for personnel at those depots. NADEP-JAX and OO-ALC already had HVOF systems, and it was determined that because of the anticipated base closure, SA-ALC would not acquire a system, although they would continue to participate in the project in specific areas of testing. The HCAT also conducted extensive "generic" testing of HVOF WC/Co and Tribaloy 400 coatings in comparison with hard chrome, which included axial fatigue, salt-fog and cyclic corrosion, and abrasive wear testing. Base materials included 4340 steel, 7075 aluminum alloy, and PH13-8Mo stainless steel. In general, the HVOF coatings performed as well as or better than the hard chrome.

To enhance the technology implementation and transfer of the "Tri-Service Dem/Val of Chromium Electroplating Replacements" project, ESTCP tasked the HCAT to adapt and apply portions of the Joint Group on Pollution Prevention (JG-PP) Methodology. JG-PP is chartered by the Joint Logistics Commanders (JLC) to coordinate joint service pollution prevention activities during the acquisition and sustainment of weapon systems. JG-PP has partnered with the HCAT to execute several projects to qualify HVOF thermal spray coatings as replacements for hard chrome plating. Table 1.1 summarizes the target hazardous material, current process, application, current specifications, and affected defense system programs (delineated according to the U.S. DOD aviation depot at which the overhaul of the landing gear from that aircraft takes place).

**Table 1.1 HVOF Thermal Spraying Summary: Landing Gear Aircraft Applications**

<b>Target HazMat</b>	<b>Current Process</b>	<b>Application</b>	<b>Current Specifications</b>	<b>Candidate Parts/Substrates</b>
Hexavalent Chromium	Hard Chromium Electroplating	Rebuilding Worn Components  Wear-resistant Coating  Corrosion-resistant Coating	DOD-STD-2182 MIL-C-14538C MIL-C-20218F MIL-H-83282 MIL-STD-1501C QQ-C-320B	Landing Gear

<b>Potentially Affected Defense System Programs</b>				
<b>CCAD:</b>	<b>NADEP Cherry Point:</b>	<b>NADEP JAX:</b>	<b>Ogden ALC:</b>	
SH-60 (Navy) UH-60	AV-8B C-130 E-2/C-2 H-1 H-46 H-53 H-60  P-3	E-6 EA-6B F-14 F-18 P-3 S-3 T-45	A-7 A-10 B-1B B-2 B-52 C-5 C-17  C-130 C-141 F-5 F-15	F-16 F-22 F-104 F-106 F-111 H-3 H-53 (USAF/Navy) KC-135 T-37 T-38

In order to successfully execute this project, it was essential to define the technical and performance requirements necessary to qualify HVOF thermal spray coatings as a replacement for hard chrome plating for aircraft landing gear components. Following the JG-PP Methodology, the U.S. portion of the Joint Test Protocol was developed by the members of the HCAT plus the following organizations:

- Naval Air Systems Command
- Air Force Landing Gear Single Item Manager OO-ALC/LIL
- Boeing St. Louis
- Lockheed-Martin

The Canadian Government, through the Department of National Defence (DND) and Industry Canada (IC), facing environmental restrictions on chrome plating similar to the U.S., also became

interested in qualifying HVOF thermal spray coatings on aircraft landing gear both for manufacturing and maintenance operations. The Canadian Government formed their own project team, designated the Canadian Hard Chrome Alternatives Team (CHCAT), and a partnership was formed between both projects. A formal Project Arrangement, conducted under the auspices of the U.S.-Canadian Research and Technology Projects Memorandum of Understanding (MOU), was negotiated and executed in March 1999. In order to achieve maximum impact, the joint project will concentrate on landing gear systems common to both U.S. and Canadian aircraft and on landing gear components that are supplied by Canadian companies for use in U.S. aircraft.

The following are the principal organizations that constitute the CHCAT and which participated in the development of the Canadian portion of the JTP:

- Department of National Defence
- Industry Canada
- Technology Partnerships Canada
- Messier-Dowty
- Menasco Aerospace
- Heroux, Inc.
- Orenda Aerospace Corporation
- National Research Council of Canada

Overall, the JTP includes: (1) material testing on coupons designed for the particular type of test, and (2) operational testing which involves the coating of actual components and their evaluation in test rigs or in actual flight operations. This part of the JTP involves only the material testing which includes fatigue, corrosion, wear, impact, and hydrogen embrittlement testing on defined specimens fabricated from the base materials currently used for the manufacture of landing gear components.

In general, the U.S. HCAT will be evaluating WC/Co (83%/17%) HVOF coatings whereas the CHCAT will be evaluating WC/CoCr (86%/10%4%) HVOF coatings, although there will be some cross-evaluation of the coatings. Orenda Aerospace was principally responsible for developing the Canadian portion of the material testing.

This Material Testing JTP is organized in sections, with each section devoted to the type of test being conducted (e.g., fatigue, and corrosion). Each section is divided into two subsections, the first for the U.S. portion of the testing and the second for the Canadian portion of the testing. The testing by the two teams on the two different HVOF coatings was meant to be very similar, but there are some differences. For that reason, the complete test plans are presented here even though there is some redundancy, especially in the area of fabrication of test coupons and coating deposition.

## References

1. "High Velocity Oxy Fuel Final Results Report," Final Report issued by Science Applications International Corporation under Government Contract F09603-90-D2215, Oklahoma City Air Logistics Center, Tinker Air Force Base, May 25, 1994
2. "Hard Chrome Coatings: Advanced Technology for Waste Elimination," Final Report issued by Northwestern University, Evanston, IL, under DARPA Contract MDA972-93-1-0006, 1996

**Notice: This document is intended to contain sufficient detail such that all stakeholders can assess the adequacy of the proposed testing. However, to avoid excessive length of the document, several standards and specifications are referenced without providing details. The military standards and AMS standards that are referenced are considered to be readily available and no further information needs to be provided. There are several Boeing specifications referenced that are not readily available. These include:**

- 1. P.S. 15169: Heat treatment specifications for Aermet 100 steel**
- 2. BAC 5851: Deposition of HVOF thermal spray coatings**
- 3. BAC 5855: Low-stress grinding of coatings**
- 4. P.S. 11501: Application of polystyrene resin impregnation sealer on EHC coatings**

**Boeing will make these standards available to appropriate stakeholders on a "need-to-know" basis. Requests should be forwarded through Bruce Sartwell at the Naval Research Laboratory.**

## **Applicable test standards**

### **ASTM Standards:**

- ASTM E466: Standard Practice for Fatigue testing
- ASTM B117: Standard Practice for Salt Spray (fog) Apparatus, Operating
- ASTM G85: Standard Practice for Modified Salt Spray (FOG)
- ASTM B537: Standard Practice for Ranking Electroplated Panels Subject to Atmospheric Exposure
- ASTM D3170: Standard Practice for Coatings, Chipping Resistance
- ASTM F519: Mechanical Hydrogen Embrittlement Testing of Plating Processes and Aircraft Maintenance Chemicals, Method for

### **Boeing Aircraft Corporation (BAC) Standards:**

- P.S. 15169: Heat treatment specifications for Aermet 100 steel
- P.S. 11501: Application of polystyrene resin impregnation sealer on EHC coatings
- BAC 5851: Deposition of HVOF thermal spray coatings
- BAC 5855: Low-stress grinding of coatings

### **Military Specifications:**

- DOD-STD-2182: Engineering Chromium Plating (Electrodeposit for Repair of Shafting)
- MIL-C-14538: Chromium Plating, Black (Electrodeposited)
- MIL-C-20218: Chromium Plating, Electrodeposited, Porous
- MIL-H-83282: Hydraulic Fluid, Fire Resistant, Synthetic Hydrocarbon Base
- MIL-STD-1501: 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-867: Temper Etch Inspection
- MIL-STD-1504: Abrasive Blasting
- QQ-C-320: Chromium Plating (Electrodeposited)
- QQ-N-290: Nickel Plating (Electrodeposited)
- MIL-A-8625: Anodic Coatings for Aluminum and Aluminum Alloys

### **SAE Standards:**

- AMS-81934: Bearings, Sleeves, Plain and Flanged, Self-lubricating, General Spec for
- AMS-4640: Aluminum Bronze, Bars, Rods, Shapes, Tubes, and Forgings 81.5Cu-10.0 Al-4.8 Ni-3.0 Fe, Drawn and Stress Relieve (HR50) or Temper Anneals
- AMS-2432: Shot Peening, Computer Controlled
- AMS-6875: Heat treating of high strength Steels
- SAE J400: Gravelometer Testing

### **Other specifications:**

- GM9540P/B: GM corrosion test

## 2.0 FATIGUE

### 2.1 U.S. HCAT Testing

#### 2.1.1 Substrate Materials:

4340, 300M, Aermet 100

#### 2.1.2 Material acquisition:

Round bar. All bars for each material to come from same lot.

#### 2.1.3 Specimen Fabrication:

Rough machining, followed by vacuum heat treat to tensile strengths as indicated in Table 2.1.1, followed by low-stress grinding to final dimension. The heat treat for the 4340 and 300M will be in accordance with MIL-H-6875 and the heat treat for the Aermet 100 will be in accordance with P.S. 15169. If possible, heat treat all specimens at same time; if not, then uniformity in heat treating runs will be essential. Grinding to be performed IAW MIL-STD-866. Nital etching IAW MIL-STD-867 will be conducted on all specimens to examine for grinding burns. All specimens to be baked subsequent to nital etching to remove residual hydrogen.

#### 2.1.4 Specimen Geometry:

- A. Hourglass: 0.25-inch gage diameter for specimens receiving 3-mil-thick coatings  
0.50-inch gage diameter for specimens receiving 10-mil-thick coatings
- B. Smooth bar: 0.25-inch gage diameter over a gage length of 0.75 inches

The specimens will not be threaded on the ends. Because most specimens will be tested with  $R = -1$ , a straight shank configuration is indicated (i.e., the ends of the specimens are placed in hydraulic clamps as opposed to screwed into a holder for testing).

---

**Table 2.1.1 Material Preparation**

<u>Material</u>	<u>Heat Treat (tens. strength)</u>	<u>Shot Peen</u>
4340	260-280 ksi	8-10A, S230, wrought steel
300M	280-300 ksi	8-10A, S230, wrought steel
Aermet 100	280-290 ksi	8-10A, S230, wrought steel

---

#### 2.1.5 Specimen Preparation:

A. Shot peening: Where specified in the test matrix, shot peening is to be conducted IAW AMS-2432 under computer control using the conditions specified in Table 1. Shot peening is to be conducted over the entire surface of the specimens with a 100% surface coverage.

B. Grit blasting: For specimens that will receive the HVOF coatings, subsequent to shot peening, grit blasting will be conducted with 54 grit aluminum oxide at 60 psi at 90 degree angle of impingement in accordance with MIL-STD-1504. A uniform standoff distance will be used. For specimens that will receive hard chrome coatings, subsequent to shot peening, grit blasting will be conducted with 180-200 grit aluminum oxide or glass beads in accordance with standard procedure for hard chrome plating. A uniform standoff distance will be used.

#### 2.1.6 Coating Deposition and Grinding:

A. Electrolytic hard chrome (EHC) deposited in accordance with MIL-STD-1501, supported by QQ-C-320. There will be no interfacial layer between the specimen and EHC coating. No sealer will be applied to the EHC. The thicknesses will be 0.003” and 0.010” +/- 0.0005” subsequent to grinding (i.e., coatings will be deposited approximately 0.002” to 0.003” thicker than specified and then ground to final dimension). Subsequent to deposition, each coating will be ground to a surface finish of 16 microinches (+0/-4 microinches) using low-stress grinding techniques in accordance with specification MIL-STD-866.

B. 83/17 WC/Co deposited by the high-velocity oxygen-fuel (HVOF) technique (designated WC/Co). The coatings will be deposited in accordance with Boeing specification BAC 5851, Class 2, Type I with the following additions/clarifications. The coatings will be deposited using a Sulzer Metco Diamondjet hybrid gun with hydrogen as the fuel gas. The WC/Co powder material shall be Sulzer-Metco Diamalloy 2005. Uniform deposition conditions will be utilized for all specimens. Air cooling will be utilized to ensure the specimen surface temperature does not exceed 350° F. The WC/Co will be deposited directly onto the substrate material with no interfacial layer. No sealer will be applied to the HVOF coatings. The thicknesses will be 0.003” and 0.010” +/- 0.0005” subsequent to grinding (i.e., coatings will be deposited approximately 0.002” to 0.003” thicker than specified and then ground to final dimension). All HVOF coatings will be deposited to an Almen number of 3-12N. Subsequent to deposition, each coating will be ground to a surface finish of 8 microinches (+0/-2 microinches) 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 infeeds 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 workpiece should have a speed of 50 to 100 surface feet per minute.

### 2.1.7 Fatigue Testing:

All fatigue tests will be load-controlled constant amplitude axial fatigue in accordance with ASTM E466-96, and standard S-N curves will be generated.

Number of stress levels: 4

Number of specimens at each stress level: 5

Environment: (1) Laboratory air at ambient temperature (2) 3.5% NaCl solution at ambient temperature. The procedure for conducting the corrosion fatigue tests will be to immerse the entire fatigue specimen in a 3.5% NaCl solution for 24 hours. Then the specimen will be removed, dried, stored in a desiccator for approximately 24-48 hours and then placed into the fatigue-testing machine in a cell containing a 3.5% NaCl solution. The entire gage section of the fatigue specimen will remain immersed in the NaCl solution during the entire fatigue test. This cell will be replenished with a constant flow of 3.5% NaCl solution during the test. The excess solution will not be returned to the system.

The matrix for fatigue testing is indicated in Table 2.1.2.

### 2.1.8 Acceptance Criteria

After data (i.e., cycles to failure) has been obtained for all specimens tested under identical parameters (e.g., same coating thickness, same environment) for the coatings, the data will be plotted with stress on the vertical axis and cycles-to-failure on the horizontal axis. Smooth curves shall be least-squares fit to the data. If the curves for the HVOF coatings fall on or above the curves for the EHC, then the HVOF coatings will be considered to have met the acceptance criteria.

A failure to meet the acceptance criteria for either of the above will be considered an overall failure.

### 2.1.9 Rationale

The rationale for conducting the coupon fatigue tests is that the landing gear components that contain chrome plating are fatigue sensitive and the application of the hard chrome results in a reduction in fatigue life. Establishing the impact of application of the HVOF coatings on fatigue life is critical and the best method for assessing that is to conduct well-controlled coupon tests. The exact specifications for the coupon fatigue tests were developed by the HCAT and CHCAT, including Navy and Air Force stakeholders.

**Table 2.1.2 Fatigue test matrix for U.S. HCAT testing**

Material	Geometry	Peen	Coating	Thickness (mil)	R	Environment	# of specimens
4340	Hourglass	No	WC/Co	3	-1	Air	20
4340	Hourglass	No	WC/Co	3	0.1	Air	20
4340	Hourglass	No	EHC	3	-1	Air	20
4340	Hourglass	No	EHC	3	0.1	Air	20
4340	Hourglass	Yes	EHC	3	-1	Air	20
4340	Hourglass	Yes	EHC	3	0.1	Air	20
4340	Hourglass	Yes	WC/Co	3	-1	Air	20
4340	Hourglass	Yes	WC/Co	3	0.1	Air	20
4340	Hourglass	Yes	WC/Co	10	-1	Air	20
4340	Hourglass	Yes	EHC	10	-1	Air	20
4340	Hourglass	Yes	EHC	3	-1	NaCl	20
4340	Hourglass	Yes	WC/Co	3	-1	NaCl	20
4340	Smooth bar	Yes	EHC	3	-1	Air	20
4340	Smooth bar	Yes	WC/Co	3	-1	Air	20
						Total	280

300M	Hourglass	No	Uncoated	3	-1	Air	20
300M	Hourglass	No	EHC	3	-1	Air	20
300M	Hourglass	No	WC/Co	3	-1	Air	20
300M	Hourglass	Yes	EHC	3	-1	Air	20
300M	Hourglass	Yes	WC/Co	3	-1	Air	20
300M	Hourglass	Yes	EHC	3	-1	NaCl	20
300M	Hourglass	Yes	WC/Co	3	-1	NaCl	20
300M	Hourglass	Yes	EHC	10	-1	NaCl	20
300M	Hourglass	Yes	WC/Co	10	-1	NaCl	20
300M	Smooth bar	Yes	EHC	3	-1	Air	20
300M	Smooth bar	Yes	WC/Co	3	-1	Air	20
						Total	220

Aermet 100	Hourglass	No	Uncoated	3	-1	Air	20
Aermet 100	Hourglass	No	EHC	3	-1	Air	20
Aermet 100	Hourglass	No	WC/Co	3	-1	Air	20
Aermet 100	Hourglass	Yes	EHC	3	-1	Air	20
Aermet 100	Hourglass	Yes	WC/Co	3	-1	Air	20
Aermet 100	Hourglass	Yes	EHC	3	-1	NaCl	20
Aermet 100	Hourglass	Yes	WC/Co	3	-1	NaCl	20
Aermet 100	Hourglass	Yes	EHC	10	-1	NaCl	20
Aermet 100	Hourglass	Yes	WC/Co	10	-1	NaCl	20
Aermet 100	Smooth bar	Yes	EHC	3	-1	Air	20
Aermet 100	Smooth bar	Yes	WC/Co	3	-1	Air	20
						Total	220
						Grand Total	720

## **2.2 Canadian HCAT Testing**

### 2.2.1 Substrate Materials:

300 M (AMS6419 C), Aermet 100 (MMS-217 or PS 15169)

### 2.2.2 Material acquisition:

Round bar, 0.76" diameter (Aermet 100), 1.00" diameter (300M). Note: all specimens for each material to come from same lot.

### 2.2.3 Specimen Fabrication:

Material is received in final heat treated state for tensile strengths as indicated in Table 2.1.1. Material will be machined at slow rate to prevent induced residual stresses including final passes of 0.0002" per pass for the last 0.005". Final grinding will be performed IAW MIL-STD-866. Sample specimens will be x-rayed to determine any if any residual stresses were induced. If so, a stress relief heat treatment at 375 °F for 4 hours will be conducted.

### 2.2.4 Specimen Geometry:

All specimens will have an hourglass geometry with a test area cross section of 0.25". The specimens will have a button head on the ends. Because most specimens will be tested with  $R = -1$ , the button heads will be pre-stressed prior to test commencing.

### 2.2.5 Specimen Preparation:

**Shot peening:** Where specified in the test matrix, shot peening is to be conducted IAW AMS-2432 under computer control using the parameters specified in Table 2.1.1. Shot peening will be conducted over the entire surface of the specimens with a 100% surface coverage.

**Grit blasting:** For specimens that will receive the HVOF and chrome coatings, grit blasting will be conducted subsequent to shot peening. Grit blast with 54 grit aluminum oxide at 60 psi at 90 degree angle of impingement in accordance with MIL-STD-1504. A uniform standoff distance will be used.

### 2.2.6 Coatings Deposition and Grinding:

**Electrolytic hard chrome (EHC):** Will be deposited in accordance with MIL-STD-1501, supported by QQ-C-320. There will be no interfacial layer between the specimen and EHC coating. No sealer will be applied to the EHC. The thicknesses will be 0.003" and 0.010" +/- 0.0005" subsequent to grinding (i.e., coatings will be deposited approximately 0.001" to 0.002" thicker than specified and then ground to final dimension). Subsequent to deposition, the EHC will be ground to a surface finish of 16 microinches (+0/-4 microinches) using low-stress grinding techniques in accordance with specification MIL-STD-866.

**WC-10% Co-4% Cr:** Will be deposited by the high-velocity oxygen-fuel (HVOF) technique (designated WC/Co/Cr). The parameters for spraying will be defined prior to coating commencement by NRC-IMI through the deliverables outlined in Task 1 of contract W2207-8-EH02/001/SV. The WC/Co/Cr will be deposited directly onto the substrate

material with no interfacial layer. No sealer will be applied to the HVOF coatings. The thicknesses will be 0.003” and 0.010” +/- 0.0005” subsequent to grinding (i.e., coatings will be deposited approximately 0.001” to 0.002” thicker than specified and then ground to final dimension). All HVOF coatings will be deposited to an Almen number of 3-12N. Subsequent to deposition, each coating will be ground to a surface finish of 8 microinches (+0/-2 microinches) in accordance with specification BAC 5855 with the following exceptions:

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 infeeds 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.

### 2.2.7 Fatigue Testing:

All fatigue tests will be conducted in load-control with constant amplitude using MTS hydraulic test frames. All axial fatigue tests will be conducted in accordance with ASTM E466-96 and standard S-N curves will be generated. Tests will be conducted at 5Hz using a generated sine wave.

Number of stress levels: 4

Number of specimens at each stress level: 5

Environments: (1) Laboratory air: Tests will be conducted without environmental control assuming a temperature of 70 °F (21 °C); (2) 3.5% NaCl solution: The procedure for conducting the corrosion fatigue tests will be to immerse the entire fatigue specimen in a 3.5% NaCl solution for 24 hours. Then the specimen will be removed, dried and stored in a desiccator for approximately 24-48 hours before testing. During the entire fatigue test, the gage section of the fatigue specimen will remain immersed in a cell containing a 3.5% NaCl solution. This cell will be replenished with a constant flow of 3.5% NaCl solution during the test. The excess solution will not be returned to the system; (3) Low Temperature, Laboratory air: Tests will be conducted in an environmental chamber, which will reduce the ambient temperature to  $-40 \pm 4$  °F ( $-40 \pm 2$  °C). It will still use laboratory air. Specimens will be mounted into the fatigue rig and then reduced to required temperature that it will remain for the duration of the test.

The matrix for fatigue testing is indicated in Table 2.2.1

**Table 2.2.1 Fatigue test matrix for Canadian HCAT testing**

Test #	Peen	Coating	Thickness (mil)	R	Environment	Temp °F	# of specimens
1	No	uncoated		-1	Air	70	20
2	No	uncoated		-1	Air	-40	20
3	No	uncoated		-1	NaCl	70	20
4	Yes	CHROME	3	-1	Air	70	20
5	Yes	CHROME	3	-1	Air	-40	20
6	Yes	CHROME	3	-1	NaCl	70	20
7	Yes	CHROME	10	-1	Air	70	20
8	Yes	CHROME	10	-1	Air	-40	20
9	Yes	CHROME	10	-1	NaCl	70	20
10	Yes	WC-10Co-4Cr	3	-1	Air	70	20
11	Yes	WC-10Co-4Cr	3	-1	Air	-40	20
12	Yes	WC-10Co-4Cr	3	-1	NaCl	70	20
13	Yes	WC-10Co-4Cr	10	-1	Air	70	20
14	Yes	WC-10Co-4Cr	10	-1	Air	-40	20
15	Yes	WC-10Co-4Cr	10	-1	NaCl	70	20
<b>TOTAL:</b>							<b>300</b>

**Note:** This test matrix will be repeated twice, once for 300 M, once for Aermet 100 for a total of 600 tests.

2.2.8 Acceptance Criteria:

After all data (i.e., cycles to failure) has been obtained for all specimens tested under identical parameters (e.g., same coating thickness, same environment) for the coatings, the data will be plotted with stress on the vertical axis and cycles-to-failure on the horizontal axis. Smooth curves shall be least-squares fit to the data. If the curves for the HVOF coatings fall on or above the curves for the EHC, then the HVOF coatings will be considered to have met the acceptance criteria.

A failure to meet the acceptance criteria for of the above will be considered an overall failure.

### 3.0 CORROSION

#### 3.1 U.S. HCAT Testing

##### 3.1.1 Substrate Materials:

4340, 300M, Aermet 100

##### 3.1.2 Material acquisition:

1-inch diameter round bar. All bar stock for each material is to come from the same lot.

##### 3.1.3 Specimen fabrication:

Bars to be cut into six-inch-long rods.

##### 3.1.4 Specimen preparation

Vacuum heat treat specimens to the tensile strengths specified in Table 2.1.1.

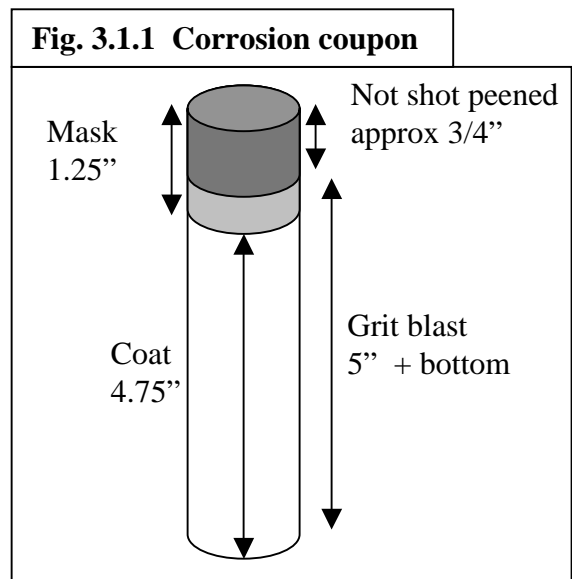
Circumference grind to a surface finish of 32-64 microinches.

Shot Peen: The circumference will be shot peened in accordance with AMS-2432 under computer control using wrought steel, S230, Almen 8-10A. All curved surfaces are to be shot peened with the exception of a ¾-inch length at the end of each rod. There should be 100% surface coverage for the area that is shot peened.

Grit Blasting: For the specimens that will receive the hard chrome plating, prior to application of the coating, each rod shall be gripped by the non-shot-peened area and a 5-inch length on the rod shall be grit blasted with 180-220 grit aluminum oxide or glass beads in accordance with standard procedure for hard chrome plating described in Section 2.1.5B (see figure 3.1.1). For specimens that will receive the HVOF coatings, grit blasting will be conducted with 54 grit aluminum oxide at 60 psi at 90 degree angle of impingement in accordance with MIL-STD-1504.

##### 3.1.5 Coating Deposition and Grinding:

A. Electrolytic hard chrome (EHC) will be deposited in accordance with MIL-STD-1501, supported by QQ-C-320. The thicknesses will be 0.003" and 0.010" +/- 0.0005" subsequent to grinding (i.e., coatings will be deposited approximately 0.002 to 0.003" thicker than specified and then ground to final dimension). The coatings will be applied to the curved surfaces of the rods over a length of 4.75" (see Fig. 3.1.1). It is not necessary to apply the coatings to the ends. A sulfamate Ni underlayer will be applied to a minimum thickness of 0.0015" in accordance with specification QQ-N-290 on some of the rods to receive the EHC coating (see test matrix, Table



3.1.2). Subsequent to deposition, each EHC coating will be ground to a surface finish of 16 microinches (+0/-4 microinches) using low-stress grinding techniques in accordance with specification MIL-STD-866. Subsequent to grinding, on some of the EHC coatings (see test matrix, Table 3.1.2), a polystyrene resin impregnation sealer will be applied in accordance with P.S. 11501.

B. 83/17 WC/Co HVOF coatings will be deposited in accordance with Boeing specification BAC 5851, Class 2, Type I and 86/10-4 WC/Co-Cr HVOF coatings will be deposited in accordance with Boeing specification BAC 5851, Class 2, Type XVII with the following additions or clarifications. The HVOF coatings will be deposited using a Sulzer Metco Diamondjet hybrid gun with hydrogen as the fuel gas. The WC/Co powder material shall be Sulzer-Metco Diamalloy 2005 and the WC/Co-Cr powder materials shall be Sulzer-Metco 5847. Uniform deposition conditions will be utilized for all specimens. Air cooling will be utilized to ensure the specimen surface temperature does not exceed 350° F. The thicknesses will be 0.003” and 0.010” (+/- 0.0005”) subsequent to grinding (i.e., coatings will be deposited approximately 0.002” to 0.003” thicker than specified and then ground to final dimension). All HVOF coatings will be deposited to an Almen number of 3-12N. Subsequent to deposition, each coating will be ground to a surface finish of 8 microinches (+0/-2 microinches) 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.

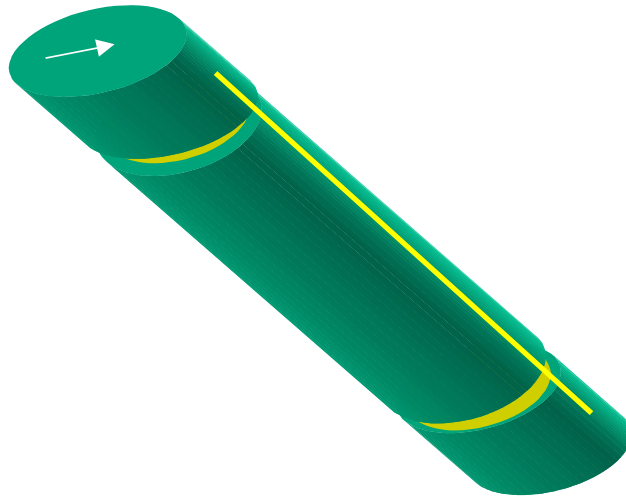
Paragraph 8.3.c.(4): Hardness – L, M, N, P, or R

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

Subsequent to grinding, on some of the HVOF coatings a Metco URS sealer will be applied (see test matrix, Table 3.1.2).

Subsequent to coating and grinding, an inert epoxy will be placed on the ends of the specimens to ensure no galvanic couple exists between the coated and uncoated sections. An arrow will be scribed on the upper end of each specimen indicating the “up” direction during the corrosion tests. For those specimens with the scratches, the “up” position will correspond to the linear scratch being uppermost during the corrosion test.

One specimen in each group of five will have multiple scratches made in the coating. These scratches will be made using a diamond indenter (such as a Rockwell C indenter) and the scratches will be such that they penetrate through the coating into the substrate. Two scratches will be made around the circumference of the specimen 3-inches apart and a linear scratch will be made 3-1/2 inches in length, crossing both circumferential scratches as shown in figure 3.1.2



**Figure 3.1.2 Illustration of scratched corrosion test specimen**

**3.1.6 Corrosion Testing:**

Three types of corrosion tests will be conducted. They all will be conducted in a salt spray chamber, Q-Fog Model CCT600 or equivalent. All corrosion tests will be conducted at ambient temperature. Specimen holders (made from an inert material such as teflon) will be devised in which the rods can be placed, with at least 4 inches of the specimen extending out from the holder. The holders will be constructed such that the rods will sit at an angle of 45 degrees to the vertical. In mounting the specimens in the holders, the scribed arrows on the end will always point vertically.

A. Salt Fog Corrosion Test. This test will be conducted in accordance with ASTM B117-94. Visually inspect the specimens for surface corrosion after 125 hours, and every 125 hours thereafter. Remove the samples at 500 and 1000 hours for photographing.

B. GM Cyclic Corrosion Test. This test will be conducted in accordance with GM9540P/B protocol, which is indicated in Table 3.1.1.

At each 500 hour interval, the specimens will be removed from the test chamber, inspected, and photographed.

**Table 3.1.1 GM Test Protocol**

<b>Solution:</b>	0.9% NaCl, 0.1% CaCl <sub>2</sub> and 0.25% NaHCO <sub>3</sub>			
<b>pH:</b>	6.0 - 8.0			
<b>Test protocol:</b>				
Step 1	Sub-cycle step 2-3 repeat 4 times			
Step 2	Salt mist	25	C	15 min
Step 3	Dry-off	25	C	75 min
Step 4	Dry-off	25	C	120 min
Step 5	RH 95-100%	49	C	8 hours
Step 6	Dry-off	60	C	7 hours
Step 7	Dry-off	25	C	1 hour
Step 8	Final step, go to step 1			
Note: RH = relative humidity				
Test duration:	2000	Hrs		
Examined every	125	Hrs		

C. SO<sub>2</sub> Salt Fog Test. This test will be conducted in accordance with ASTM G85-85. Visually inspect the samples at 48 hours, 96 hours, and every 100 hours between 200 and 1000 hours. After 500 and 1000 hours exposure, the specimens will be removed and photographed.

Based on visual inspection, a ranking will be applied to each specimen at each interval of inspection and these rankings will be tabulated and displayed graphically. The rankings will be assigned in accordance with ASTM B537-70 as follows:

<b>Defect area (%)</b>	<b>Rank #</b>
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

In general, when the ranking of a specimen reaches a value of 1, it will be considered to have failed the corrosion test and it will be removed from the test cabinet.

In addition to the rankings assigned by visual inspection, at 500 and 1000 hours of exposure, or at failure as defined above, whichever comes first, the coated surface on two out of the four non-scratched specimens in each group will be lightly abraded using Scotchbrite to remove any loose corrosion product. Following removal of any corrosion product, a new, separate, ranking number will be assigned and the specimens will be placed back into the test cabinet, unless the assigned ranking is less than or equal to 1.

The corrosion test matrix for the U.S. HCAT corrosion testing is indicated in Table 3.1.2.

### 3.1.7 Acceptance Criteria:

The average appearance rankings (as determined by averaging the four non-scratched specimens) will be plotted as a function of time for the EHC, WC/Co, and WC/Co-Cr coatings testing using the same parameters (type of test, thickness, and sealer). If the average curves for the HVOF coatings in all cases are above the average curves for the EHC coatings, then the HVOF coatings will be considered to have met the acceptance criteria. In addition, if the average rankings for the scratched HVOF coatings are higher than the average rankings for the scratched EHC coatings, then the HVOF coatings will be considered to have met the acceptance criteria.

There are different scenarios for the corrosion test results that would require judgement calls which are difficult to codify in this test plan. For example, if the average rankings for the non-sealed HVOF coatings are lower than for the non-sealed EHC coatings, but the exact opposite is obtained for the sealed coatings, then it is possible that the HVOF coatings would be qualified as an alternative to EHC only if the sealer is used. As another example, if the average rankings for the HVOF coatings are higher than EHC for the B117 and GM tests, but are lower than EHC for the SO<sub>2</sub> tests, then a determination would have to be made as to the types of environments in which the HVOF coatings could be used.

### 3.1.8 Rationale:

The rationale for conducting the coupon corrosion tests is that the landing gear components that contain chrome plating are exposed to corrosive environments and the application of the hard chrome results in a modest increase in corrosion resistance compared to the uncoated steels. Establishing the impact of application of the HVOF coatings on corrosion behavior is critical and the best method for assessing that is to conduct well-controlled coupon tests. The HCAT and CHCAT, including Navy and Air Force stakeholders, developed the exact specifications for the coupon corrosion tests.

**Table 3.1.2 Corrosion Test Matrix**

<b>Test</b>	<b>Material</b>	<b>Coating</b>	<b>Thickness</b>	<b>Ni sublayer</b>	<b>Sealed</b>	<b># of specimens</b>
B117	4340	Uncoated	N/A	N/A	N/A	5
B117	4340	EHC	3	No	No	5
B117	4340	EHC	3	Yes	No	5
B117	4340	EHC	3	No	Yes	5
B117	4340	EHC	10	No	No	5
B117	4340	EHC	10	No	Yes	5
B117	4340	EHC	10	Yes	No	5
B117	4340	WC/Co	3	no	No	5
B117	4340	WC/Co	3	no	Yes	5
B117	4340	WC/Co	10	no	No	5
B117	4340	WC/Co	10	no	Yes	5
B117	4340	WC/Co-Cr	3	no	No	5
B117	4340	WC/Co-Cr	10	no	No	5
B117	300M	EHC	3	no	No	5
B117	300M	EHC	3	no	Yes	5
B117	300M	EHC	3	yes	No	5
B117	300M	EHC	10	no	no	5
B117	300M	WC/Co	3	no	no	5
B117	300M	WC/Co	3	no	yes	5
B117	300M	WC/Co	10	no	no	5
B117	Aermet 100	EHC	3	no	no	5
B117	Aermet 100	EHC	3	no	yes	5
B117	Aermet 100	EHC	3	yes	no	5
B117	Aermet 100	EHC	10	no	no	5
B117	Aermet 100	WC/Co	3	no	no	5
B117	Aermet 100	WC/Co	3	no	yes	5
B117	Aermet 100	WC/Co	10	no	no	5

Test	Material	Coating	Thickness	Ni Sublayer	Sealed	# of specimens
GM	300M	EHC	3	no	no	5
GM	300M	EHC	3	no	yes	5
GM	300M	WC/Co	3	no	no	5
GM	300M	WC/Co	3	no	yes	5
GM	Aermet 100	EHC	3	no	no	5
GM	Aermet 100	EHC	3	no	yes	5
GM	Aermet 100	WC/Co	3	no	no	5
GM	Aermet 100	WC/Co	3	no	yes	5
SO2	4340	Uncoated	N/A	N/A	N/A	5
SO2	4340	EHC	3	no	no	5
SO2	4340	EHC	3	no	yes	5
SO2	4340	EHC	3	yes	no	5
SO2	4340	EHC	10	no	no	5
SO2	4340	WC/Co	3	no	no	5
SO2	4340	WC/Co	3	no	yes	5
SO2	4340	WC/Co	10	no	no	5
SO2	4340	WC/Co-Cr	3	no	no	5
SO2	4340	WC/Co-Cr	10	no	no	5
SO2	300M	EHC	3	no	no	5
SO2	300M	EHC	3	no	yes	5
SO2	300M	EHC	3	yes	no	5
SO2	300M	WC/Co	3	no	no	5
SO2	300M	WC/Co	3	no	yes	5
SO2	Aermet 100	EHC	3	no	no	5
SO2	Aermet 100	EHC	3	no	yes	5
SO2	Aermet 100	EHC	3	yes	no	5
SO2	Aermet 100	WC/Co	3	no	no	5
SO2	Aermet 100	WC/Co	3	no	yes	5
					Total	275

## 3.2 Canadian HCAT Testing

### 3.2.1 Substrate Materials:

300 M (AMS 6419 C), Aermet 100 (MMS-217 or PS 15169)

### 3.2.2 Material acquisition:

Round bar, 5.25" diameter (Aermet 100), 5.25" diameter (300M). Note: all specimens for each material to come from same lot.

### 3.2.3 Specimen Fabrication:

Material is received in final heat treated state for tensile strengths as indicated in Table 2.1.1. Material will be rough machined by EDM (electric discharge machining) to its rectangular shape. Final machining will be conducted at a slow rate to prevent induced residual stresses. Final grinding will be performed IAW MIL-STD-866. All specimens will be 3" x 4" x 3/16" (76mm x 102mm x 4.8mm) and will be parallel to within 0.005".

Specimens will have a surface finish of  $\leq 16$  microinches.

### 3.2.4 Specimen Preparation:

Shot peening: Where specified in the test matrix, shot peening is to be conducted in accordance with AMS-2432 under computer control using the parameters specified in Table 2.1.1. Shot peening will be conducted over the entire surface of the specimens with a 100% surface coverage.

Grit blasting: For specimens that will receive the HVOF and chrome coatings, grit blasting will be conducted subsequent to shot peening. Grit blast with 54 grit aluminum oxide at 60 psi at 90 degree angle of impingement MIL-STD-1504. A uniform standoff distance will be used.

### 3.2.5 Coating Deposition:

A. Electrolytic hard chrome (EHC) will be deposited in accordance with MIL-STD-1501, supported by QQ-C-320. There will be no interfacial layer between the specimen and EHC coating. No sealer will be applied to the EHC. The thicknesses will be 0.003" and 0.010"  $\pm 0.0005$ " subsequent to grinding (i.e., coatings will be deposited approximately 0.001" to 0.002" thicker than specified and then ground to final dimension). Subsequent to deposition, the EHC will be ground in accordance with BAC 5855 (low-stress grinding), with modifications indicated in Section 3.1.5. The surface finish of the EHC coatings shall be less than or equal to 16 microinches.

B. WC-10%Co-4%Cr will be deposited by the high-velocity oxygen-fuel (HVOF) technique (designated WC/Co-Cr). The parameters for spraying will be defined prior to coating commencement by NRC-IMI through the deliverables outlined in Task 1 of contract W2207-8-EH02/001/SV. The WC/Co/Cr will be deposited directly onto the substrate material with no interfacial layer. No sealer will be applied to the HVOF coatings. The thicknesses will be 0.003" and 0.010"  $\pm 0.0005$ " subsequent to grinding (i.e., coatings will be deposited approximately 0.001" to 0.002" thicker than specified and then ground to final dimension). All HVOF coatings will be deposited to an Almen number of 3-12N.

Subsequent to deposition, the WC/Co/Cr will be ground to a surface finish of 8 microinches (+0/-2 microinches) in accordance with BAC 5855 (low-stress grinding), using modifications as specified in Section 3.1.5.

Note: Specimens will not be scratched for the Canadian corrosion tests.

### 3.2.6 Corrosion Testing:

All corrosion tests will be conducted at ambient temperature. Specimen holders (made from an inert material such as teflon) will be devised in which the plates can be placed, with at least 85% of the specimen extending from the holder.

These tests will be conducted in accordance with ASTM B117-94. Specimens will be visually inspected for surface corrosion after 125 hours, and every 125 hours thereafter. The samples will be removed at 500 and 1000 hours for photographing.

The procedure for conducting the salt fog corrosion tests will be to place the entire specimen in a 5% NaCl solution fog. This environment will have a ph balance of 6.5-7.2 and will be held at 95±2 °F (35±1 °C).

The test matrix for salt fog corrosion tests is indicated in Table 3.2.1

**Table 3.2.1 Corrosion Test Matrix**

Test #	# Spec	Material	Coating	Thickness, mils
1	5	Aermet 100	BARE	N/A
2	5	Aermet 100	SP+CHROME	3
3	5	Aermet 100	SP+CHROME	10
4	5	Aermet 100	SP+WC-10Co-4Cr	3
5	5	Aermet 100	SP+WC-10Co-4Cr	10
1	5	300 M	BARE	N/A
2	5	300 M	SP+CHROME	3
3	5	300 M	SP+CHROME	10
4	5	300 M	SP+WC-10Co-4Cr	3
5	5	300 M	SP+WC-10Co-4Cr	10

At the completion of the corrosion testing, an abrasive pad will be used to clean and remove corrosion product and blisters. Each specimen will be visually examined and ranked in accordance with ASTM B537-70 as follows:

Defect area (%)	Rank #
0	10
>0 – 0.1	9
>0.1 – 0.25	8
>0.25 – 0.5	7
>0.5 – 1.0	6
>1.0 – 2.5	5
>2.5 – 5.0	4
>5.0 – 10.0	3
>10 – 25	2
>25 – 50	1
>50	0

### 3.2.7 Acceptance Criteria:

The average appearance rankings (as determined by averaging the five non-scratched specimens) will be plotted as a function of time for the EHC and WC/Co-Cr coatings. If the average curves for the HVOF coatings in all cases are above the average curves for the EHC coatings, then the HVOF coatings will be considered to have met the acceptance criteria.

## 4.0 WEAR

### 4.1 U.S. HCAT Testing

Tests shall be conducted using a Design of Experiment (DoE) configuration to provide information on manufacturing variables and wear conditions including coating material, surface finish, lubrication, side loads, velocities, type of wear, and other wear environment factors with a minimum number of tests. Two test methods shall be employed:

1. A low-frequency, long stroke oscillating piston test that simulates piston actuation.
2. A high-frequency, short stroke fretting test that simulates piston dithering or vibration at a given position.

The piston and bushing oscillating wear test shall be used to reflect typical conditions of use under a side load. This type of equipment is shown schematically in Figure 4.1.1. Standard ASTM tests shall not be used since they do not reflect conditions of use in hydraulic systems related to landing gear.

The fretting wear test shall be used to reflect typical actuator piston dithering or vibration movement. This equipment is shown schematically in Figure 4.1.2. Standard ASTM tests shall not be used since they do not reflect conditions of use in hydraulic system related to landing gear.

The shoe and block materials shall correspond to the piston and the bushing/seal materials, respectively. The material combinations, finishes, and wear test conditions are provided in the following sections.

#### 4.1.1 Substrate Materials:

Test materials shall be as shown in Table 4.1.1.

#### 4.1.2 Materials Acquisition:

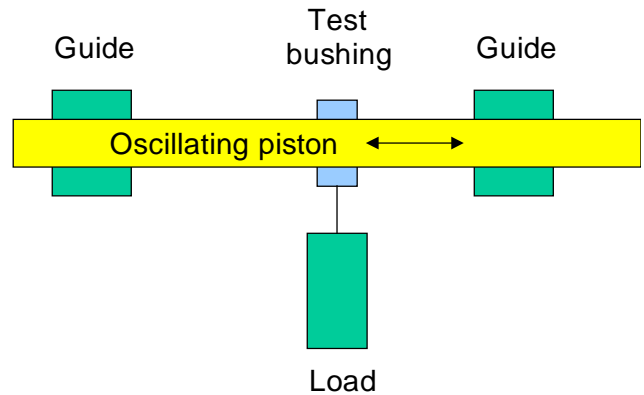
Rods:

4340 steel will be obtained as 1" barstock and heat treated to 260-280 ksi.

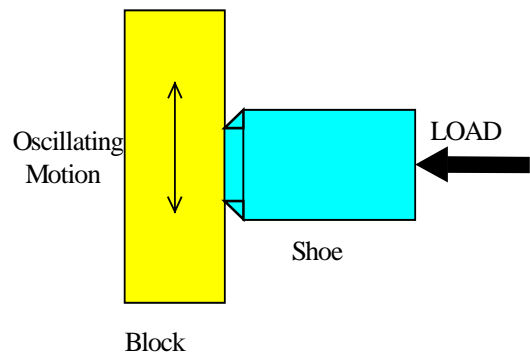
Bushings:

4340 steel will be obtained as 1.5" barstock and heat treated to 160-180 ksi.

AMS 4640 Al-Ni-bronze rod will be obtained in the TQ50 or equivalent HR50 condition (hardness HB 201-248) as round rod or hexagonal rod under 2" dimension.



**Figure 4.1.1 Cross sectional schematic of piston and bushing oscillating wear test.**



**Figure 4.1.2 Cross sectional schematic of the fretting wear test.**

Fretting shoes and blocks:

4340 steel will be obtained as plate stock greater than 1/4" thick to allow for clean-up.

Seals:

Nitrile rubber T-seals (Shore hardness 75) with standard PTFE backer rings (Green Tweed 7-214-FT-160-T).

Sprayed and cured Caron B polyester with PTFE filler, SAE AMS-81934, nominally 0.015 inches thick.

#### 4.1.3 Specimen Fabrication:

Fretting blocks and shoes will be machined per the specifications of Figure 4.1.3.

Oscillating wear rods of 4340 steel will be centerless ground to final dimension and centers added, as specified in Figure 4.1.4.

Bushings are to be fabricated by turning the OD and boring the ID to print dimensions as specified in Figure 4.1.4. Aluminum bushings will be hard anodized to MIL-A-8625, Type III, Class 1, nominally 0.001-0.002 inches thick.

<b>Table 4.1.1 Wear Test Material Matrix</b>	
<b>Piston/coating material (Fretting Shoe/Coating)</b>	<b>Bushing material (Fretting Block)</b>
4340/Hard Chrome Plate	4340 steel
4340/HVOF WC-CO	AMS 4640 (Al-Ni-bronze)
4340/HVOF WC-10Co-4Cr	Anodized aluminum
	Caron B on Al bronze
	Nitrile/PTFE T-seals in 4340

#### 4.1.4 Specimen Geometry:

Specimen geometry is shown in Figure 4.1.3 and 4.1.4.

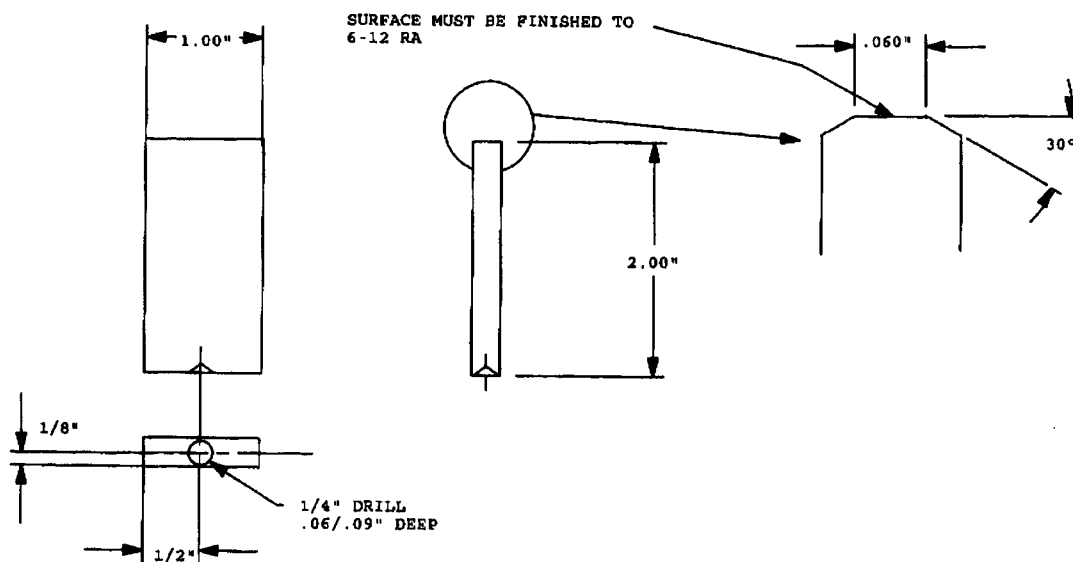
Bushings will be fabricated in three forms

1. straight through bore,
2. grooves for seal
3. Al bronze bushings will be bored out to about 0.030" larger ID and coated with Caron B liner material by Kamatics, Inc.(MIL-B-81934).

#### 4.1.5 Specimen Preparation:

Since shot peening has no effect on wear, wear rods will not be shot peened prior to coating. Grit blasting will be done manually or automatically with 54 grit aluminum oxide at approximately 45 psi and 5-6" blast distance at a nominal 45 degree angle.

a)



b)

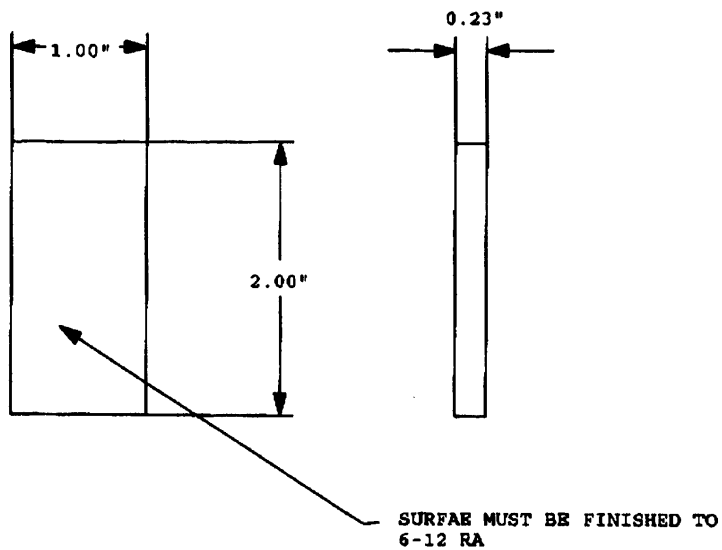


Figure 4.1.3 a) Fretting shoe, b) fretting block.

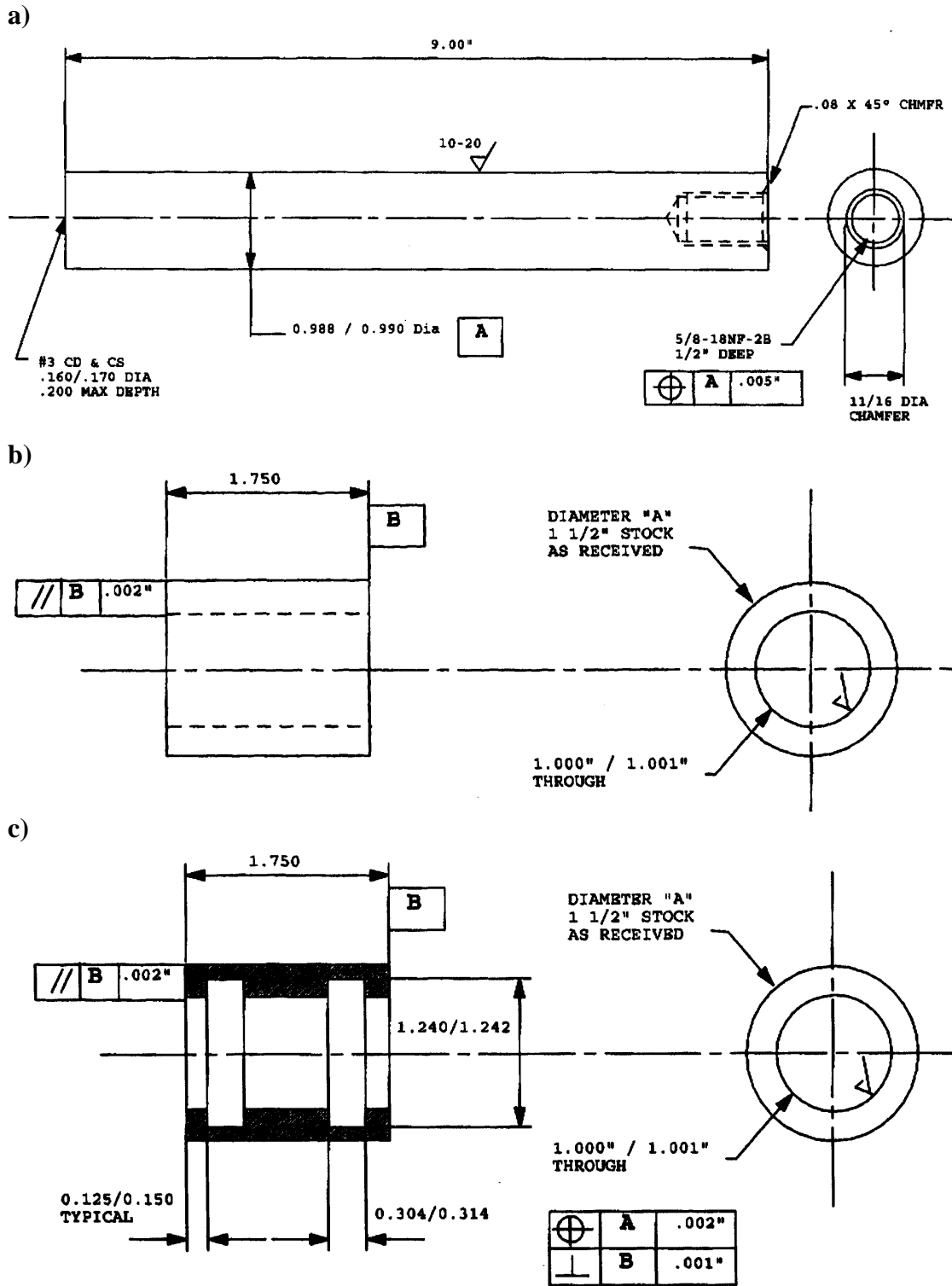


Figure 4.1.4 Wear test rods and bushings - a) rod, b) straight bushing, c) seal groove bushing.

#### 4.1.6 Coating Deposition and Grinding:

The electrolytic hard chrome and HVOF WC/Co and WC/CoCr coatings shall be deposited and ground in accordance with the same procedures as for the fatigue specimens as delineated in Section 2.1.6. In each case, coatings will be deposited with additional thickness to allow for finish grinding and clean-up. Final ground surface finishes on the HVOF coatings will be a variable in the testing and these are specified in the following section.

#### 4.1.7 Wear Testing:

The matrix of wear test materials is given in Table 4.1.1. Wear test variables are indicated in Table 4.1.2. A total of 116 oscillating wear tests shall be conducted as described in the following paragraphs. Tests shall consist of 92 bushing wear tests and 24 fretting wear tests. The tests shall consist of 24 pre-DoE trials, a set of 24 DoE trials to measure sensitivity of a broad range of wear test variables, and a second set of 68 DoE experiments to measure sensitivity to interactions for a limited number of wear test variables. Bushing seal tests shall be pressurized to 3000 psi and seals pre-soaked 24 hours in hydraulic fluid. Seal weights shall be determined before soak, after soak prior to testing, and after wear testing.

The initial pre-DoE tests shall be as specified in Table 4.1.3, Pre-DoE Test Matrix Trials, subject to specific changes as indicated by on-going test results. The purpose of the pretrial test matrix is to determine the range of test conditions that are necessary to provide reasonable, measurable ranges of wear rates for the material combinations in tests typically averaging no more than 48 hours. This information will then be used to confirm or reassign specific values to the conditions for the design factors in the first DoE test matrix as specified in Table 4.1.4, L12 DoE for Measuring Sensitivity to Wear Test Variables.

The wear sensitivity data analysis for Table 4.1.4 and 4.1.5 tests (L12 and L8 DOEs) shall quantify the relative contributions of each design factor to the wear process and the preferred conditions for minimizing wear. The second set of DoE experiments shall be as specified in Table 4.1.5, L8 DOEs for Measuring Sensitivity & Interactions of Wear Test Variables. These tests shall consist of a L8 two level DoE, five half replicates, and one 3/4 replicate for additional rod coatings and opposing bushing and seal materials. The test matrix design allows for analyses of main effects and investigates possible 2-way interactions between the design factors. The L8 and partial replicates shall include three coatings, three bushing materials, two types seal materials, and two additional design factors selected by HCAT personnel after analyses of the L12 DOE. A total of 116 sets of bushing test specimens and 36 sets of fretting wear specimens will be manufactured to assure materials will be available for any additional testing which may be required. The 96 rod specimens, the 36 fretting shoes, and the 36 fretting blocks shall all be 4340 steel. Twelve (12) of the fretting blocks shall be designed to hold a segment of the nitrile T-seal (PTFE) seal material. The bushings shall be divided amongst 5 materials as follows:

1. Forty-two (42) 4340 steel bushings
2. Twenty-six (26) 4340 steel grooved bushings to hold Nitrile/PTFE seals
3. Eighteen (18) aluminum bronze bushings for the Caron B liner seals
4. Eighteen (18) Al-Ni-bronze bushings for direct wear against the coated rods
5. Twelve (12) 2024 aluminum bushings to be hard anodized

All bushing, rod, block, and shoe materials shall be provided in accordance with current actuator and landing gear piston material specifications.

**4.1.8 Acceptance Criteria:**

Based on the analysis of all data generated in these tests, the average weight loss and average wear volume for the HVOF coated system must be equal to or less than that for the hard chrome coated system.

**Table 4.1.2 Wear Test Variables (DoE Design Factors)**

Variable	Default value	Alternatives or Ranges		
Test Type	Bushing wear	Fretting wear		
Rod, Shoe Materials	4340 + Hard Chrome	4340 + HVOF WC-17% Co	4340 + HVOF WC-10Co-4Cr	
Bushing, Block Matls	4340	AMS 4640	Anodized Al	4340 with nitrile or PTFE seals; 24 hydraulic fluid pre-soak
Finish, Ra microinches	8-12, (target 8)	2-6, (target 4)		
Lubrication	none	MIL-H-83282 hydraulic fluid	Pressurized to 3000 psi for seal tests	
Load, lbs.	72 lbs.	30 lbs. minimum	240 lbs. Maximum	capable of up to 1000 lbs
Stroke, inches	0.010 Fretting 0.5 Bushing	0.005 to 0.1 inch range for fretting	0 to 3" range for Bushing test	
Frequency (Speed)	10 Hz, Fretting 90 cpm, Bushing	1 - 70 Hz Fretting test	1 - 90 cpm Bushing test	
Duration, hrs (cycles)	20 hrs, (cycles = 720,000 fretting & 108,000 bushing)	0 - 48 hrs	Note: Longer times can be run if required to get sufficient amounts of wear to distinguish between tests.	
Temperature	Room temp.	200°F seals 350 °F all other	No active cooling	(Capable of higher temps)
Operating Environment	Ambient air			

**Table 4.1.3 Pre-DoE Trial Wear Tests**

Test No.	DoE Expt. No.	Wear Test	Block or Bushing	Coating	Load, lbs	Coating	
						Finish	Lube
1	Pre-trial	Fretting	4340	WC-10Co-4Cr	72	8	no
2	Pre-trial	Fretting	4340	Chrome	72	8	no
3	Pre-trial	Fretting	4340	WC-17Co	72	8	no
4	Pre-trial	Fretting	4340	Chrome	144	8	no
5	Pre-trial	Fretting	4340	Chrome	36 or 288	8	no
6	Pre-trial	Fretting	4340	Chrome	72	4	no
7	Pre-trial	Fretting	4340	Chrome	288 or 144	8	yes
8	Pre-trial	Fretting	4340	WC-17Co	288 or 144	8	yes
9	Pre-trial	Fretting	Nitrile/PTFE	Chrome	288 or 144	8	no
10	Pre-trial	Fretting	Nitrile/PTFE	Chrome	288 or 144	8	yes
11	Pre-trial	Fretting	Nitrile/PTFE	WC-17Co	288 or 144	8	yes
12	Pre-trial	Fretting	Nitrile/PTFE	WC-17Co	288 or 144	8	no
13	Pre-trial	Bushing	4340	WC-10Co-4Cr	72	8	no
14	Pre-trial	Bushing	4340	Chrome	72	8	no
15	Pre-trial	Bushing	4340	WC-17Co	72	8	no
16	Pre-trial	Bushing	4340	Chrome	144	8	no
17	Pre-trial	Bushing	4340	Chrome	36 or 288	8	no
18	Pre-trial	Bushing	4340	Chrome	72	4	no
19	Pre-trial	Bushing	4340	Chrome	288 or 144	8	yes
20	Pre-trial	Bushing	4340	WC-17Co	288 or 144	8	yes
21	Pre-trial	Bushing	Nitrile/PTFE	Chrome	288 or 144	8	no
22	Pre-trial	Bushing	Nitrile/PTFE	Chrome	288 or 144	8	yes
23	Pre-trial	Bushing	Nitrile/PTFE	WC-17Co	288 or 144	8	yes
24	Pre-trial	Bushing	Nitrile/PTFE	WC-17Co	288 or 144	8	no

<i>Table 4.1.4. L12 DoE for Measuring Sensitivity to Wear Test Variables</i>													<b>Resultant Factors</b>		1 rep	test stands	
Design F	1	2	3	4	5	6	7	8	9	10	11	Sliding	Avg.	test	1 rep	2 reps	
DoE Std.	Wear	Block or	Rod/Shoe	Coating			Hydraulic	Stroke	Frequency	Cycles	Temp	Salt	Distance	Velocity	hours	test	test days
Order	Test	Bushing	Coating	Load, lbs	Finish	Lube	(inches)	(cycles/min)	n	(Deg F)	Expos	(inches)	(in/min)		days		
1	Fretting	4340	Chrome	72	4	no	0.01	600	720000	70	no	14400	12.0	20	1		
2	Fretting	4340	Chrome	72	4	yes	0.05	240	360000	200	yes	36000	24.0	25	1		
3	Fretting	4340	WC-17Co	288	8	no	0.01	600	360000	200	yes	7200	12.0	10	1		
4	Fretting	Nitrile	Chrome	288	8	no	0.05	240	720000	70	yes	72000	24.0	50	2		
5	Fretting	Nitrile	WC-17Co	72	8	yes	0.05	240	720000	200	no	72000	24.0	50	2		
6	Fretting	Nitrile	WC-17Co	288	4	yes	0.01	600	360000	70	no	7200	12.0	10	1	16	
7	Bushing	4340	WC-17Co	288	4	no	1.0	30	108000	200	no	216000	60.0	60	3		
8	Bushing	4340	WC-17Co	72	8	yes	1.0	90	108000	70	yes	216000	180.0	20	1		
9	Bushing	4340	Chrome	288	8	yes	0.1	30	54000	70	no	10800	6.0	30	1.5		
10	Bushing	Nitrile	WC-17Co	72	4	no	0.1	30	54000	70	yes	10800	6.0	30	1.5		
11	Bushing	Nitrile	Chrome	288	4	yes	0.1	90	108000	200	yes	21600	18.0	20	1		
12	Bushing	Nitrile	Chrome	72	8	no	1.0	90	54000	200	no	108000	180.0	10	1	18	
														335	17		
						no = 1hr slow drip and shut off											
						Yes = cont. slow drip								3 weeks to execute L12			

Table 4.1.5. L8 DoEs for Measuring Sensitivity and Interactions of Wear Test Variables

		Design Factors								
<b>Bushing Test</b>		<b>A</b>	<b>B</b>	<b>C</b>	<b>D</b>					
<b>Test No.</b>	<b>DOE Expt. No.</b>	4340 RodCtg	<b>Bushing</b>	<b>TBD</b>	<b>TBD</b>					
49	L8-01, 1st Rep	Chrome	4340	1	1					
50	L8-02, 1st Rep	Chrome	4340	2	2					
51	L8-03, 1st Rep	Chrome	AMS 4640*	1	2	* Al-Ni-bronze				
52	L8-04, 1st Rep	Chrome	AMS 4640	2	1					
53	L8-05, 1st Rep	WC-17Co	4340	1	2					
54	L8-06, 1st Rep	WC-17Co	4340	2	1					
55	L8-07, 1st Rep	WC-17Co	AMS 4640	1	1					
56	L8-08, 1st Rep	WC-17Co	AMS 4640	2	2					
<b>1st L8 Half Replicate (a)</b>										
57	L8-5a, 1st rep	WC-Co-Cr	4340	1	2					
58	L8-6a, 1st rep	WC-Co-Cr	4340	2	1					
59	L8-7a, 1st rep	WC-Co-Cr	AMS 4640	1	1					
60	L8-8a, 1st rep	WC-Co-Cr	AMS 4640	2	2					
<b>2nd L8 Half Replicate (b)</b>										
61	L8-3b, 1st Rep	Chrome	Anodiz Al	1	2					
62	L8-4b, 1st Rep	Chrome	Anodiz Al	2	1					
63	L8-7b, 1st Rep	WC-17Co	Anodiz Al	1	1					
64	L8-8b, 1st Rep	WC-17Co	Anodiz Al	2	2					
<b>3rd L8 Half Replicate (c)</b>										
65	L8-3c, 1st Rep	Chrome	Nitrile seal	1	2					
66	L8-4c, 1st Rep	Chrome	Nitrile seal	2	1					
67	L8-7c, 1st Rep	WC-17Co	Nitrile seal	1	1					
68	L8-8c, 1st Rep	WC-17Co	Nitrile seal	2	2					
<b>4th L8 Half Replicate (d)</b>										
69	L8-3d, 1st Rep	Chrome	CAron B seal	1	2					
70	L8-4d, 1st Rep	Chrome	CAron B seal	2	1					
71	L8-7d, 1st Rep	WC-17Co	CAron B seal	1	1	need 16 CAron bushings				
72	L8-8d, 1st Rep	WC-17Co	CAron B seal	2	2	need 12 WC-Co-Cr rods				
<b>1st L8 3/4 Replicate (f)</b>										
73	L8-01f, 1st Rep	Chrome	CAron B seal	1	1	need 16 AMS 4640 bushings				
74	L8-02f, 1st Rep	Chrome	CAron B seal	2	2	need 12 chrome rods				
75	L8-05f, 1st Rep	WC-Co-Cr	CAron B seal	1	2	do 28 addn'l wear tests				
76	L8-06f, 1st Rep	WC-Co-Cr	CAron B seal	2	1					
77	L8-07f, 1st Rep	WC-Co-Cr	AMS 4640	1	1					
78	L8-08f, 1st Rep	WC-Co-Cr	AMS 4640	2	2					
<b>5th L8 Half Replicate (g)</b>										
79	L8-01f, 1st Rep	Chrome	Nitrile seal	1	1					
80	L8-02f, 1st Rep	Chrome	Nitrile seal	2	2					
81	L8-05f, 1st Rep	WC-Co-Cr	Nitrile seal	1	2					
82	L8-06f, 1st Rep	WC-Co-Cr	Nitrile seal	2	1					

## 4.2 Canadian HCAT Testing

### 4.2.1 Substrate Materials:

300 M (AMS 6419 C), Aermet 100 (MMS-217 or PS 15169) and bushing material Al-Ni-Bronze (AMS 4640)

### 4.2.2 Material Acquisition:

Round bar, Wear rods, 1.01" diameter (Aermet 100), 1.00" diameter (300 M), Wear blocks, 2.5" diameter (Al-Ni-Bronze(CuSn)). Note: all specimens for each material to come from same lot.

### 4.2.3 Specimen Fabrication:

Material is received in final heat-treated state for tensile strengths as indicated in Table 4.2.1. Wear rods will be machined at a slow rate to prevent induced residual stresses including final passes of 0.0002" per pass for the last 0.005". Final grinding will be conducted to MIL-STD-866. Wear bushings will be EDM from round bar. A 1.00" (+0.001"/-0) hole will be machined through the centre. The bushing will be split in half using EDM.

### 4.2.4 Specimen geometry:

36 wear rods will be 0.999" (+0/-0.001), 96 wear rods will be 0.996" (+0/-0.001), 96 wear rods will be 0.989" (+0/-0.001) for a total of 228 specimens per material. The length of the wear rods will be 4.62". All bushings will be machined to a 1.475" O.D. at a length of 1.75". A 1.00" (+0.001/-0) hole will be machined in the centre of the block. The block is then split through the centre of the circle to give two halves. One of these blocks is used in a single test.

---

**Table 4.2.1 Material Preparation**

<u>Material</u>	<u>Heat Treat (tens. strength)</u>	<u>Shot Peen</u>
Al-Ni-CuSn	105 ksi	none
300 M	280-300 ksi	8-10A, S230, wrought steel
Aermet 100	280-300 ksi	8-10A, S230, wrought steel

---

### 4.2.5 Specimen Preparation:

Shot peening: Where specified in the test matrix, shot peening is to be conducted AMS-2432 under computer control using the parameters specified in Table 4.2.1. Shot peening will be conducted over the entire surface of the specimens with a 100% surface coverage.

Grit blasting: For specimens that will receive the HVOF and chrome coatings, grit blasting will be conducted subsequent to shot peening. Grit blast with 54 grit aluminum

oxide at 60 psi at 90 degree angle of impingement MIL-STD-1504. A uniform standoff distance will be used.

#### 4.2.6 Coatings Deposition and Grinding:

Electrolytic hard chrome (EHC): Will be deposited in accordance with MIL-STD-1501, supported by QQ-C-320. There will be no interfacial layer between the specimen and EHC coating. No sealer will be applied to the EHC. The thicknesses will be 0.003” and 0.010” +/- 0.0005” subsequent to grinding (i.e., coatings will be deposited approximately 0.001” to 0.002” thicker than specified and then ground to final dimension). Subsequent to deposition, the EHC will be ground in accordance with BAC 5855 (low-stress grinding), using changes in speeds and feeds specified herein. Prior to determining the effect of surface finish, 12 will be ground to 4 microinches and 12 will be ground to 8 microinches for both coating thicknesses. After determining the superior coating finish, 24 specimens will be ground to that surface finish for each coating thickness.

WC-10% Co-4% Cr: Will be deposited by the high-velocity oxygen-fuel (HVOF) technique (designated WC/Co/Cr). The parameters for spraying will be defined prior to coating commencement by NRC-IMI through the deliverables outlined in Task 1 of contract W2207-8-EH02/001/SV. The WC/Co/Cr will be deposited directly onto the substrate material with no interfacial layer. No sealer will be applied to the HVOF coatings. The thicknesses will be 0.003” and 0.010” +/- 0.0005” subsequent to grinding (i.e., coatings will be deposited approximately 0.001” to 0.002” thicker than specified and then ground to final dimension). All HVOF coatings will be deposited to an Almen number of 3-12N. Subsequent to deposition, the WC/Co/Cr will be ground in accordance with BAC 5855 (low-stress grinding), using changes in speeds and feeds specified herein. Prior to determining the effect of surface finish, 12 will be ground to 4 microinches and 12 will be ground to 8 microinches for both coating thicknesses. After determining the superior coating finish, 24 specimens will be ground to that surface finish for each coating thickness.

#### 4.2.7 Wear Testing:

Tests shall be conducted using a Design of Experiment (DoE) configuration to provide information on manufacturing variables and wear conditions including coating material, surface finish, side loads, velocities, type of wear, and other wear environment factors with a minimum number of tests.

The piston and bushing oscillating wear test shall be used to reflect typical conditions of use under a side load. ASTM standards shall be used where applicable.

The wear test protocol as indicated in Table 4.2.2 outlines the test conditions of each test. The protocol will be repeated twice, once for Aermet 100 and once for 300 M. In both cases the wear blocks will be manufactured from Al-Ni-Bronze. For each test condition, 3 tests will be conducted for a total of 228 oscillating wear tests per material.

The following information will be generated from these tests:

- 1) Coating hardness and surface finish.
- 2) Frictional force and total wear (movement of the bushing) as a function of time.
- 3) Measurements of weight loss and wear scar volume at the end of each test for the coated rod and the bushing.
- 4) Analysis of material transfer direction (if any).
- 5) Surface micrographs of typical wear scars and subsequent same-area metallographic cross-section micrographs.
- 6) A multivariate regression analysis for the wear rates and wear coefficients of each coating type.

#### 4.2.8 Acceptance Criteria:

Based on the analysis of all data generated in these tests, the average weight loss and average wear volume for the HVOF coated system must be equal to or less than that for the hard chrome coated system.

**Table 4.2.2 Wear Test Protocol (repeated for each material):**

Design factors	1	2	3	4	5	6	7	8	9	Resultant	
Test #	Rod Coating	Load (lbs)	Coat Finish (microinch)	Coat Thick (0.00x")	Stroke (inch)	Freq (cpm)	Cycles	Temp (°F)	Enviro **	Sliding Dist. (inch)	Avg. Vel (in/min)
<b>BASELINE</b>											
1	NONE	144	N/A	N/A	1.0	30	7,200	70	AIR	14,400	60
2	NONE	144	N/A	N/A	1.0	90	7,200	70	AIR	14,400	180
3	NONE	144	N/A	N/A	1.0	30	36,000	70	AIR	72,000	60
4	NONE	144	N/A	N/A	1.0	90	36,000	70	AIR	72,000	180
5	NONE	144	N/A	N/A	1.0	30	7,200	70	NaCl	14,400	60
6	NONE	144	N/A	N/A	1.0	90	7,200	70	NaCl	14,400	180
7	NONE	144	N/A	N/A	1.0	30	36,000	70	NaCl	72,000	60
8	NONE	144	N/A	N/A	1.0	90	36,000	70	NaCl	72,000	180
9	NONE	144	N/A	N/A	1.0	30	7,200	-40	AIR	14,400	60
10	NONE	144	N/A	N/A	1.0	90	7,200	-40	AIR	14,400	180
11	NONE	144	N/A	N/A	1.0	30	36,000	-40	AIR	72,000	60
12	NONE	144	N/A	N/A	1.0	90	36,000	-40	AIR	72,000	180

\*\* : Air (Lab Air), NaCl (pre-corroded salt specimen)

WP1: Winner Phase 1, best resulting surface finish of phase 1

**Table 4.2.2 Wear Test Protocol (repeated for each material) cont.:**

Design factors	1	2	3	4	5	6	7	8	9	Resultant	
Test #	Rod Coating	Load (lbs)	Coat Finish (microinch)	Coat Thick (0.00x")	Stroke (inch)	Freq (cpm)	Cycles	Temp (°F)	Enviro* *	Sliding Dist. (inch)	Avg. Vel (in/min)
<b>PHASE 1 (Determination of Surface Finish)</b>											
13	SP+CHROME	144	4	3	1.0	30	7,200	70	AIR	14,400	60
14	SP+CHROME	144	4	3	1.0	90	7,200	70	AIR	14,400	180
15	SP+CHROME	144	4	3	1.0	30	36,000	70	AIR	72,000	60
16	SP+CHROME	144	4	3	1.0	90	36,000	70	AIR	72,000	180
17	SP+CHROME	144	4	10	1.0	30	7,200	70	AIR	14,400	60
18	SP+CHROME	144	4	10	1.0	90	7,200	70	AIR	14,400	180
19	SP+CHROME	144	4	10	1.0	30	36,000	70	AIR	72,000	60
20	SP+CHROME	144	4	10	1.0	90	36,000	70	AIR	72,000	180
21	SP+CHROME	144	8	3	1.0	30	7,200	70	AIR	14,400	60
22	SP+CHROME	144	8	3	1.0	90	7,200	70	AIR	14,400	180
23	SP+CHROME	144	8	3	1.0	30	36,000	70	AIR	72,000	60
24	SP+CHROME	144	8	3	1.0	90	36,000	70	AIR	72,000	180
25	SP+CHROME	144	8	10	1.0	30	7,200	70	AIR	14,400	60
26	SP+CHROME	144	8	10	1.0	90	7,200	70	AIR	14,400	180
27	SP+CHROME	144	8	10	1.0	30	36,000	70	AIR	72,000	60
28	SP+CHROME	144	8	10	1.0	90	36,000	70	AIR	72,000	180
29	SP+WC-10Co-4Cr	144	4	3	1.0	30	7,200	70	AIR	14,400	60
30	SP+WC-10Co-4Cr	144	4	3	1.0	90	7,200	70	AIR	14,400	180
31	SP+WC-10Co-4Cr	144	4	3	1.0	30	36,000	70	AIR	72,000	60
32	SP+WC-10Co-4Cr	144	4	3	1.0	90	36,000	70	AIR	72,000	180
33	SP+WC-10Co-4Cr	144	4	10	1.0	30	7,200	70	AIR	14,400	60
34	SP+WC-10Co-4Cr	144	4	10	1.0	90	7,200	70	AIR	14,400	180
35	SP+WC-10Co-4Cr	144	4	10	1.0	30	36,000	70	AIR	72,000	60
36	SP+WC-10Co-4Cr	144	4	10	1.0	90	36,000	70	AIR	72,000	180
37	SP+WC-10Co-4Cr	144	8	3	1.0	30	7,200	70	AIR	14,400	60
38	SP+WC-10Co-4Cr	144	8	3	1.0	90	7,200	70	AIR	14,400	180
39	SP+WC-10Co-4Cr	144	8	3	1.0	30	36,000	70	AIR	72,000	60
40	SP+WC-10Co-4Cr	144	8	3	1.0	90	36,000	70	AIR	72,000	180
41	SP+WC-10Co-4Cr	144	8	10	1.0	30	7,200	70	AIR	14,400	60
42	SP+WC-10Co-4Cr	144	8	10	1.0	90	7,200	70	AIR	14,400	180
43	SP+WC-10Co-4Cr	144	8	10	1.0	30	36,000	70	AIR	72,000	60
44	SP+WC-10Co-4Cr	144	8	10	1.0	90	36,000	70	AIR	72,000	180

**Table 4.2.2 Wear Test Protocol (repeated for each material) cont.:**

Factors	1	2	3	4	5	6	7	8	9	Resultant	
Test #	Rod Coating	Load (lbs)	Coat Finish (microinch)	Coat Thick (0.00x")	Stroke (inch)	Freq (cpm)	Cycles	Temp (°F)	Enviro* *	Sliding Dist. (inch)	Avg. Vel (in/min)
PHASE II											
45	SP+CHROME	144	WP1	3	1.0	30	7,200	70	NaCl	14,400	60
46	SP+CHROME	144	WP1	3	1.0	90	7,200	70	NaCl	14,400	180
47	SP+CHROME	144	WP1	3	1.0	30	36,000	70	NaCl	72,000	60
48	SP+CHROME	144	WP1	3	1.0	90	36,000	70	NaCl	72,000	180
49	SP+CHROME	144	WP1	10	1.0	30	7,200	70	NaCl	14,400	60
50	SP+CHROME	144	WP1	10	1.0	90	7,200	70	NaCl	14,400	180
51	SP+CHROME	144	WP1	10	1.0	30	36,000	70	NaCl	72,000	60
52	SP+CHROME	144	WP1	10	1.0	90	36,000	70	NaCl	72,000	180
53	SP+CHROME	144	WP1	3	1.0	30	7,200	-40	AIR	14,400	60
54	SP+CHROME	144	WP1	3	1.0	90	7,200	-40	AIR	14,400	180
55	SP+CHROME	144	WP1	3	1.0	30	36,000	-40	AIR	72,000	60
56	SP+CHROME	144	WP1	3	1.0	90	36,000	-40	AIR	72,000	180
57	SP+CHROME	144	WP1	10	1.0	30	7,200	-40	AIR	14,400	60
58	SP+CHROME	144	WP1	10	1.0	90	7,200	-40	AIR	14,400	180
59	SP+CHROME	144	WP1	10	1.0	30	36,000	-40	AIR	72,000	60
60	SP+CHROME	144	WP1	10	1.0	90	36,000	-40	AIR	72,000	180
61	SP+WC-10Co-4Cr	144	WP1	3	1.0	30	7,200	70	NaCl	14,400	60
62	SP+WC-10Co-4Cr	144	WP1	3	1.0	90	7,200	70	NaCl	14,400	180
63	SP+WC-10Co-4Cr	144	WP1	3	1.0	30	36,000	70	NaCl	72,000	60
64	SP+WC-10Co-4Cr	144	WP1	3	1.0	90	36,000	70	NaCl	72,000	180
65	SP+WC-10Co-4Cr	144	WP1	10	1.0	30	7,200	70	NaCl	14,400	60
66	SP+WC-10Co-4Cr	144	WP1	10	1.0	90	7,200	70	NaCl	14,400	180
67	SP+WC-10Co-4Cr	144	WP1	10	1.0	30	36,000	70	NaCl	72,000	60
68	SP+WC-10Co-4Cr	144	WP1	10	1.0	90	36,000	70	NaCl	72,000	180
69	SP+WC-10Co-4Cr	144	WP1	3	1.0	30	7,200	-40	AIR	14,400	60
70	SP+WC-10Co-4Cr	144	WP1	3	1.0	90	7,200	-40	AIR	14,400	180
71	SP+WC-10Co-4Cr	144	WP1	3	1.0	30	36,000	-40	AIR	72,000	60
72	SP+WC-10Co-4Cr	144	WP1	3	1.0	90	36,000	-40	AIR	72,000	180
73	SP+WC-10Co-4Cr	144	WP1	10	1.0	30	7,200	-40	AIR	14,400	60
74	SP+WC-10Co-4Cr	144	WP1	10	1.0	90	7,200	-40	AIR	14,400	180
75	SP+WC-10Co-4Cr	144	WP1	10	1.0	30	36,000	-40	AIR	72,000	60
76	SP+WC-10Co-4Cr	144	WP1	10	1.0	90	36,000	-40	AIR	72,000	180

WP1: Winner Phase 1, best resulting surface finish of phase 1

## 5.0 IMPACT TESTING – ASTM D 3170-87 AND DROPPED BALL

### 5.1 U.S. HCAT Testing

#### 5.1.1 Substrate Materials:

4340 only

The similarity of materials makes it unnecessary to carry out this test on all three landing gear steels.

#### 5.1.2 Material acquisition:

1-inch diameter round bar. All bar stock for each material is to come from the same lot.

Alternative material for ball drop test - 1/4" flat plate.

#### 5.1.3 Specimen fabrication:

Bars to be cut into six-inch-long rods.

Plate to be cut into 2.5"x2.5" squares.

#### 5.1.4 Specimen Geometry

The gravelometer test will utilize specimens of the same dimensions as those used for corrosion testing, i.e. 1" diameter by 6" long, instead of the conventional flat plate. This will permit performance to be evaluated as a function of angle of incidence.

If possible, the ball drop test will use the same circular geometry. However, because of the difficulty of accurately striking the centerline of a circular rod, it may be necessary to revert to the square plate conventionally used for this test.

#### 5.1.5 Specimen preparation

Vacuum heat treat specimens to the tensile strengths specified in Table 2.1.1.

Circumference grind rod to a surface finish of 32-64 microinches. Surface grind plate to a surface finish of 32-64 microinches.

Shot Peen: The rod circumference will be shot peened in accordance with AMS-2432 under computer control using wrought steel, S230, Almen 8-10A. All curved surfaces are to be shot peened with the exception of a 3/4-inch length at the end of each rod. There should be 100% surface coverage for the area that is shot peened. The plate will be shot peened in the same manner on both square surfaces.

Grit Blasting: For the specimens that will receive the hard chrome plating, prior to application of the coating, each rod shall be gripped by the non-shot-peened area and a 5-inch length on the rod shall be grit blasted with 180-220 grit aluminum oxide or glass beads in accordance with standard procedure for hard chrome plating described in Section 2.1.5B (see figure 3.1.1). For specimens that will receive the HVOF coatings, grit blasting will be conducted with 54 grit aluminum oxide at 60 psi at 90 degree angle of impingement in accordance with MIL-STD-1504. The plate will be grit blasted in the same manner on both square surfaces.

#### 5.1.6 Coating Deposition and Grinding:

A. Electrolytic hard chrome (EHC) will be deposited in accordance with MIL-STD-1501, supported by QQ-C-320. The thickness will be 0.003" and 0.010" +/- 0.0005" subsequent to grinding (i.e., coatings will be deposited approximately 0.002 to 0.003" thicker than specified and then ground to final dimension). The coatings will be applied to the curved surfaces of the rods over a length of approximately 4.75". It is not necessary to apply the coatings to the ends. Subsequent to deposition, each EHC coating will be ground to a surface finish of 16 microinches (+0/-4 microinches) using low-stress grinding techniques in accordance with specification MIL-STD-866.

The square specimens will be electroplated and surface ground in the same manner. However, to avoid edge build-up the periphery of the square may be masked over the outside 1/4" approximately. No coating is required on the rectangular sides of the specimens. Fixturing that prevents plating in the corners is acceptable.

B. 83/17 WC/Co HVOF coatings will be deposited in accordance with Boeing specification BAC 5851, Class 2, Type I and 86/10-4 WC/Co-Cr HVOF coatings will be deposited in accordance with Boeing specification BAC 5851, Class 2, Type XVII with the following additions or clarifications. The HVOF coatings will be deposited using a Sulzer Metco Diamondjet hybrid gun with hydrogen as the fuel gas. The WC/Co powder material shall be Sulzer-Metco Diamalloy 2005 and the WC/Co-Cr powder materials shall be Sulzer-Metco 5847. Uniform deposition conditions will be utilized for all specimens. Air cooling will be utilized to ensure the specimen surface temperature does not exceed 350° F. The thickness will be 0.003" and 0.010" (+/- 0.0005") subsequent to grinding (i.e., coatings will be deposited approximately 0.002" to 0.003" thicker than specified and then ground to final dimension). All HVOF coatings will be deposited to an Almen number of 3-12N. Subsequent to deposition, each coating will be ground to a surface finish of 8 microinches (+0/-2 microinches) 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 infeeds 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.

#### 5.1.7 Impact Testing:

Two types of tests will be used to assess different damage mechanisms that are expected for landing gear:

1. Gravelometer testing (ASTM D 3170-87) - which impinges gravel in a high-velocity air stream onto the surface (high hardness projectiles, high speed, low mass, small impact area). The gravelometer test is most commonly used to assess the chip resistance of paints, although it is also used to assess the brittleness and chip resistance of hard materials such as glass. The air velocity is approximately 100 m/s (200 mph), but the gravel velocity is considerably less, depending on its size and shape.
2. Ball impact testing - in which a 1lb hardened steel ball is dropped from varying heights (up to about 6 ft) onto the surface (relatively soft projectile, low speed, low mass, large impact area). After a 6 ft drop the ball velocity is about 13 mph.

The test matrix for both the gravelometer and ball drop tests is indicated in Table 5.1

<b>Table 5.1 Impact test matrix</b>		
	<b>Coating thickness</b>	
<b>Coating</b>	<b>3 μm</b>	<b>10 μm</b>
EHC	3	3
WC-17Co	3	3
WC-10Co4Cr	3	3

Total 18 specimens

#### 5.1.7.1 Gravelometer Test (ASTM D3170-87, SAE J400)

ASTM D 3170 specifies flat samples, but in common with our wear and corrosion tests, we will use rod samples, held stationary, for a variable angle of impingement in the gravelometer test.

The test standard is a 5 - 10 second feed of 550ml of road gravel (size 9.5 - 16 mm) into an air stream passing at a rate of 100 cfm (47 l/s) and a pressure of 70 or 80 psi (480 or 550 kPa). The surface is then examined for chips. Since HVOF WC-Co will be more difficult to chip than paints, or even glass, the test may be increased in severity by increasing the air pressure or the exposure time. The severity of the test will be increased until significant numbers of chips are seen in either the HVOF or chrome coatings. Both materials will be tested at this level on one end each specimen. The severity of the test will be again increased until the second material (chrome or either HVOF coating) shows significant chipping, and both materials will again be tested at that level on the other end. After each test the surface will be examined visually and with a binocular microscope for evidence of chips or cracking of the coating. The number (chips per unit area) and size of chips and cracks will be recorded by position around the rod (i.e. angle of incidence). Damage will be recorded photographically.

#### 5.1.7.2 Dropped Ball Test

A 1lb ball of hardened steel will be dropped down a tube onto the surface of the coated flat or rod (ensuring that it strikes the rod radially - i.e. squarely in the center), striking once before bouncing off the surface. The extent of coating damage (cracked area and delaminated area) will be recorded as a function of drop height. Damage will be recorded photographically. Prior to each drop the ball will be checked to ensure that it is not deformed or damaged.

#### 5.1.8 Acceptance Criteria:

There is no specific pass/fail criterion for either of these tests. A pass for the HVOF coating will be performance equal to that of hard chrome.

#### 5.1.9 Rationale:

The rationale for conducting the coupon impact tests is that landing gear components are subject to impact by gravel and debris thrown up from the runway on takeoff and landing, and also may be subject to damage from dropped tools and other items during servicing. The coatings should be able to withstand normal impacts.

## 6.0 HYDROGEN EMBRITTLEMENT – ASTM F 519-97

### 6.1 U.S. HCAT Testing

#### 6.1.1 Substrate Materials:

4340 only.

The similarity of materials makes it unnecessary to carry out this test on all three landing gear steels.

#### 6.1.2 Material acquisition:

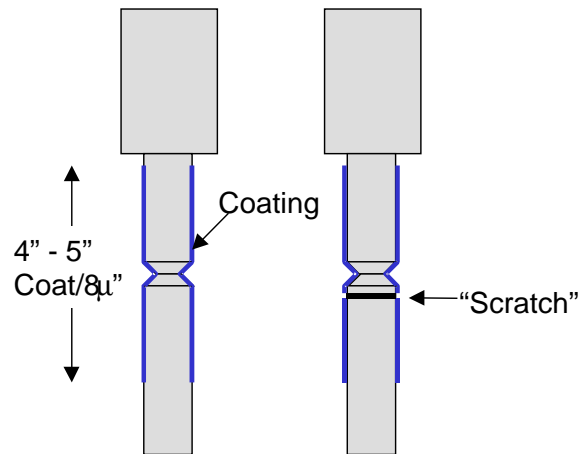
1-inch diameter round bar. All bar stock for each material is to come from the same lot.

#### 6.1.3 Specimen fabrication:

Bars to be cut into six-inch-long rods.

#### 6.1.4 Specimen geometry

The specimen type will be a notched round bar of 4340 high strength steel, Type 1a.2 as defined in ASTM F519-97. Since these will be standard commercial hydrogen embrittlement test samples they will not be heat treated or ground prior to coating.



**Figure 6.1 Hydrogen embrittlement specimens - unscratched and scratched.**

#### 6.1.5 Specimen preparation

**Shot Peen:** Samples will **not** be shot peened, since this reduces hydrogen penetration.

**Grit Blasting:** For the specimens that will receive the hard chrome plating, prior to application of the coating, each rod shall be grit blasted on the area to be coated. For chrome plating, 180-220 grit aluminum oxide or glass beads in accordance with the standard procedure for hard chrome plating described in Section 2.1.5B. For specimens that will receive the HVOF coatings, grit blasting will be conducted with 54 grit aluminum oxide at 60 psi at 90 degree angle of impingement in accordance with MIL-STD-1504. The specimen surfaced will be examined by binocular microscope to ensure that there is adequate grit blasting within the notch to ensure surface cleanliness and coating adhesion.

#### 6.1.6 Coating Deposition and Grinding:

The coatings will be applied to the notched areas of the specimens up to approximately 2 3/8" – 2 1/2" each side of the notches. It is not necessary to apply the coatings to other areas or to the ends of most samples (although this may be done if desired). However, 3 samples of each coating are to be applied over the entire surface to eliminate hydrogen

evolution paths. Subsequent to deposition, each specimen is to be rough-ground (63 microinches maximum) to the dimensions specified for the test equipment. The coating within 3/8" - 1/2" each side of the notch is to be ground to a surface finish of 8 microinches (+0/-4 microinches) using low-stress grinding techniques in accordance with specification MIL-STD-866. Coated ends do not need to be ground.

The notched area will be lightly dressed with the corner of the fine grinding wheel to redefine the notch only, but not to achieve a specific surface finish.

Those specimens defined as being scratched in Table 6.1.1 will be cut through the coating with a SiC or diamond cutting wheel (or similar tool) to just expose the substrate around the entire circumference approximately 0.020" from one notch edge (see Figure 6.1.1).

A. Electrolytic hard chrome (EHC) will be deposited in accordance with MIL-STD-1501, supported by QQ-C-320. The thickness will be 0.003" and 0.010" +/- 0.0005" subsequent to grinding (i.e., coatings will be deposited approximately 0.002 to 0.003" thicker than specified and then ground to final dimension).

B. 83/17 WC/Co HVOF coatings will be deposited in accordance with Boeing specification BAC 5851, Class 2, Type I and 86/10-4 WC/Co-Cr HVOF coatings will be deposited in accordance with Boeing specification BAC 5851, Class 2, Type XVII with the following additions or clarifications. The HVOF coatings will be deposited using a Sulzer Metco Diamondjet hybrid gun with hydrogen as the fuel gas. The WC/Co powder material shall be Sulzer-Metco Diamalloy 2005 and the WC/Co-Cr powder materials shall be Sulzer-Metco 5847. Uniform deposition conditions will be utilized for all specimens. Air cooling will be utilized to ensure the specimen surface temperature does not exceed 350° F. The thickness will be 0.003" and 0.010" (+/- 0.0005") subsequent to grinding (i.e., coatings will be deposited approximately 0.002" to 0.003" thicker than specified and then ground to final dimension). All HVOF coatings will be deposited to an Almen number of 3-12N. Subsequent to deposition, each coating will be ground to a surface finish of 8 microinches (+0/-4 microinches) 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 infeeds 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.

#### 6.1.7 Embrittlement Testing:

The test matrix of Table 6.1.1 will be used. Tests will be made as defined in ASTM F 519 at 75% and 45% of Notch Strength as indicated in Table 6.1.

Sequence 1. As-coated - to ensure that there is no contribution to embrittlement due to HVOF coating alone.

Sequence 2. Specimens will be allowed to absorb hydrogen during an aqueous processing prior to HVOF coating. This will be done by either chrome or zinc plating and stripping the plate without a hydrogen bakeout treatment prior to HVOF coating. One set of specimens will be tested without heat treating to determine whether the heat supplied by the HVOF process itself removes the hydrogen. A second set will be heat treated by Boeing's standard hydrogen bakeout treatment prior to testing to establish whether hydrogen can evolve through the HVOF coating. A control set will not be HVOF coated.

Note that the 3 specimens of each coating that are coated over their entire surface will be used for the tests in this sequence that include heat treating.

Sequence 3. The specimens will not be loaded with hydrogen prior to HVOF coating. The HVOF coated specimens will be immersed in standard corrosive environments (DI water and 5% NaCl) during the 45% load test. Tests will be made with and without scratching, to simulate damaged and undamaged surfaces subject to corrosion.

1. The standard test duration will be 200 hours for specimens 75% loaded in air.
2. The test duration will be 150 hours for specimens 45% loaded in the environment.

#### 6.1.8 Acceptance Criteria:

Sequence 1 - The HVOF coating process may not cause embrittlement.

Sequence 2 - No specific acceptance criteria - the test determines sequencing of plating and heat treating only.

Sequence 3 - Performance equal to hard chrome.

#### 6.1.9 Rationale:

Hydrogen embrittlement is a serious problem for electroplated components, as is re-embrittlement due to corrosion. In manufacturing and maintenance the same component may be coated with both electroplates (e.g. Cd) and HVOF coatings. Whether or not hydrogen introduced during plating can diffuse through the HVOF coating is important in properly sequencing coating operations. Corrosion through a damaged coating may cause re-embrittlement if the hydrogen is unable to escape.

The purpose of the hydrogen embrittlement test matrix is the following:

1. Demonstrate that the HVOF coating process does not contribute to hydrogen embrittlement (Sequence 1, Table 6.1.1).

2. Evaluate whether, after hydrogen-charging from a plating process, hydrogen can pass through an HVOF layer during either HVOF coating or subsequent heat treating.
3. Evaluate whether re-embrittlement can occur due to galvanic corrosion between the HVOF coating and the steel substrate.

**Table 6.1 Hydrogen embrittlement test matrix.**

	Sequence 1	Sequence 2			Sequence 3			
	Baseline	Hydrogen pre-test loading			Hydrogen loading in standard solutions			
Pretest H load	No	Yes	Yes	Yes	No	No	No	No
Test environ.	Air	Air	Air	Air	DI H2O	DI H2O	5% NaCl	5% NaCl
Coat/grind notch area	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes
Coat entire surface	No	No	No	Yes	No	No	No	No
Heat treat	No	No	No	Yes	No	No	No	No
Scratch	No	No	No	No	No	Yes	No	Yes
Load (%)	75%	45%	45%	75%	45%	45%	45%	45%
Hard chrome	2	2	3	3	3	3	3	3
WC-Co	2	2	3	3	3	3	3	3
WC-Co-Cr	2	2	3	3	3	3	3	3

Total 66 specimens