

FINAL REPORT

IMPROVED MAGNESIUM PROTECTION FOR DOD AVIATION AND WEAPON COMPONENT TECHNOLOGY

ESTCP Project WP-201319

Kyu Cho
CCDC Army Research Laboratory

Bill Gorman
Technology Applications Group

Version 3

May 2019

Approved for public release; distribution is unlimited.

Table of Contents

List of Figures……..…….iv

List of Tables…….…..…viii

List of Acronyms and Symbols…… ……...…xi

Acknowledgements……..……..…..…....xii

Abstract ……..xiii

Executive Summary……xiv

1.0 Introduction…….1

1.1 Background……..1

1.2 Objective of the Demonstration……..2

1.3 Regulatory Drivers……..4

2.0 Technology……..….8

2.1 Technology Description……..8

2.2 Technology Development…….…….11

2.3 Advantages and Limitations of the Technology…….12

3.0 Performance Objectives……14

4.0 Sites/Platforms Descriptions……...…….23

4.1 Test Platforms/Facilities……23

4.2 Present Operations…….23

4.3 Site-Related Permits and Regulations……..32

5.0 Test Design…….33

5.1 JTP…….....33

5.2. Demonstration Plan - Experimental Design……..60

6.0 Performance Assessment…….70

6.1 JTP Testing and Results……...70

6.2 Demonstration and Validation……..175

6.3 Performance Assessment Plan……..182

7.0 Cost Assessment……..190

8.0 Implementation Issues……191

9.0 References……194

Appendix A: Points of Contact

Appendix B: Joint Test Protocol

Appendix C: Equipment Release Statement

Appendix D: University of Dayton Research Institute (UDRI) Paint Adhesion Report #1

Appendix E: University of Dayton Research Institute (UDRI) Paint Adhesion Report #2

Appendix F: North Dakota State University (NDSU) Galvanic Corrosion Report for Repair Compatibility Study

Appendix G: AZ91C Statistical Dimensional and Weight Change Summary

Appendix H: EV31A Statistical Dimensional and Weight Change Summary

Appendix I: ZE41A Statistical Dimensional and Weight Change Summary

Appendix J: AMSAM-ENVI-TI Memo on Hydrogen Embrittlement Test Requirements

Appendix K: Brush Tagnite Compatibility Testing – Panel ID and Pretreatment

Appendix L: North Dakota State University (NDSU) Galvanic Corrosion Report for Brush Tagnite Qualification Study

Appendix M: ZE41A Neutral Salt Fog: Photos at Different Time Intervals

Appendix N: QE22A Neutral Salt Fog: Photos at Different Time Intervals

Appendix O: AZ91C Neutral Salt Fog: Photos at Different Time Intervals

Appendix P: EV31A Neutral Salt Fog: Photos at Different Time Intervals

Appendix Q: NAVAIR SO2 Raw Data

Appendix R: AZ91C Acidified SO_2 Salt Fog: Photos at Different Time Intervals

Appendix S: EV31A Acidified SO_2 Salt Fog: Photos at Different Time Intervals

Appendix T: QE22A Acidified SO_2 Salt Fog: Photos at Different Time Intervals

Appendix U: ZE41A Acidified SO_2 Salt Fog: Photos at Different Time Intervals

Appendix V: Fatigue Specimen ID

Appendix W: UDRI Report: ZE41A Axial Fatigue Results

Appendix X: Revised UDRI Report: ZE41A Axial Fatigue Results

Appendix Y: Westmoreland Testing Report: AZ91C, EV31A and QE22A Axial Fatigue Results

Appendix Z: NASA Outdoor Exposure Statement of Work

Appendix AA: AZ91C Outdoor Exposure: Photos at Different Time Intervals

Appendix AB: EV31A Outdoor Exposure: Photos at Different Time Intervals

Appendix AC: QE22A Outdoor Exposure: Photos at Different Time Intervals

Appendix AD: ZE41A Outdoor Exposure: Photos at Different Time Intervals

List of Figures

Figure 1: ZE41 Magnesium Panels after ASTM B117 Salt Fog……....2

Figure 2: Process Flow Diagram of Immersion Tagnite Line……...8

Figure 3: Magnesium Panel during Tagnite Anodic Spark Deposition……....9

Figure 4: Examples of Threaded Stud Masking……..…..10

Figure 5: Masking of H-64 Tail Rotor Gearbox……....10

Figure 6: Close-up of Brush Tagnite Application Process……....11

Figure 7: CCAD Current Processes for Magnesium Components……..24

Figure 8: CCAD Plating Shop D-Line in Prior to Tagnite Conversion……..25

Figure 9: CCAD D-Line Original Layout…….……26

Figure 10: D-Line Conversion to Tagnite Layout……...27

Figure 11: Tagnite Anodization Line Schematic Diagram……28

Figure 12: Tagnite Capital Equipment – New Tagnite Tank…….29

Figure 13: Tagnite Capital Equipment – New Rectifier…….....30

Figure 14: Tagnite Capital Equipment – New Chilling System…….……31

Figure 15: Machining of Defect into Panel for DEVCON Al Liquid and Ti Putty Repair ……..…..35

Figure 16: Machining of Defect into Panel for Cold Spray/HVOF Repair…….36

Figure 17: Machining of Defect into Panel for TIG Weld Repair…..……..37

Figure 18: Process Flow Diagram of Immersion Tagnite Line……..38

Figure 19: AZ91D Magnesium Panel during the Tagnite Anodic Spark Deposition…...38

Figure 20: Close-up of Brush Tagnite Application to a bare area on a used magnesium aerospace component……..39

Figure 21: Location of Micrometer Measuring Locations on Dimensional Loss Panels.47

Figure 22: Machining Diagram for Axial Fatigue Specimen…….58

Figure 23: Gantt Chart – Testing Schedule for Dem/Val at CCAD Plating Shop……...61

Figure 24: Basement at CCAD Plating Shop……...63

Figure 25: Tank D-4……...……63

Figure 26: Tank D-7……...…64

Figure 27: Paint Adhesion Panels after testing wrong side……70

Figure 28: Visual Summary of Tagnite Stripping Process…….82

Figure 29: Effect of Tagnite Chemical Stripping Process on Legacy Coatings……...84

Figure 30: Revised Location of Micrometer Measuring Locations on Dimensional Loss Panels……..…….…88

Figure 31: Dimensional Change Summary for AZ91C…….…….93

Figure 32: Dimensional Change Summary for EV31A……..94

Figure 33: Dimensional Change Summary for ZE41A……..95

Figure 34: Weight Change Summary for AZ91C…….…..98

Figure 35: Weight Change Summary for EV31A…….……..99

Figure 36: Weight Change Summary for ZE41A……..100

Figure 37: Paint Chemical Stripping Results for Legacy Coatings…….102

Figure 38: ZE41A Neutral Salt Fog Photos after 123 hours of Exposure……...119

Figure 39: ZE41A Neutral Salt Fog Photos after 192 hours of Exposure……..120

Figure 40: QE22A Neutral Salt Fog Photos after 123 hours of Exposure……..123

Figure 41: QE22A Neutral Salt Fog Photos after 171 hours of Exposure……..124

Figure 42: AZ91C Neutral Salt Fog Photos after 500 hours of Exposure……...126

Figure 43: AZ91C Neutral Salt Fog Photos after 1150 hours of Exposure ……127

Figure 44: EV31A Neutral Salt Fog Photos after 500 hours of Exposure……..…130

Figure 45: EV31A Neutral Salt Fog Photos after 1394 hours of Exposure……...131

Figure 46: AZ91C Acidified SO_2 Salt Fog Photos after 648 hours of Exposure…..…..135

Figure 47: AZ91C Acidified SO_2 Salt Fog Photos after 1200 hours of Exposure ……136

Figure 48: EV31A Acidified SO_2 Salt Fog Photos after 648 hours of Exposure……139

Figure 49: EV31A Acidified SO_2 Salt Fog Photos after 1536 hours of Exposure……..140

Figure 50: QE22A Acidified SO_2 Salt Fog Photos after 144 hours of Exposure……142

Figure 51: QE22A Acidified SO_2 Salt Fog Photos after 312 hours of Exposure……143

Figure 52: QE22A Acidified SO_2 Salt Fog Photos after 1536 hours of Exposure……..144

Figure 53: ZE41A Acidified SO_2 Salt Fog Photos after 144 hours of Exposure…….147

Figure 54: ZE41A Acidified SO_2 Salt Fog Photos after 1536 hours of Exposure……...148

Figure 55: Picture of Magnesium Round Bar Stock…….150

Figure 56: ZE41A Fatigue Curve……152

Figure 57: AZ91C Fatigue Curve……155

Figure 58: EV31A Fatigue Curve……156

Figure 59: QE22A Figure Curve…….158

Figure 60: AZ91C Outdoor Exposure Photos after 14 months of Exposure……..161

Figure 61: AZ91C Outdoor Exposure Photos after 24 months of Exposure……..162

Figure 62: EV31A Outdoor Exposure Photos after 15 months of Exposure……..164

Figure 63: EV31A Outdoor Exposure Photos after 24 months of Exposure……..165

Figure 64: QE22A Outdoor Exposure Photos after 10 months of Exposure ……167

Figure 65: **QE22A Outdoor Exposure Photos after 24 months of Exposure…….….168**

Figure 66: **ZE41A Outdoor Exposure Photos after 16 months of Exposure……..170**

Figure 67: **ZE41A Outdoor Exposure Photos after 24 months of Exposure……..171**

Figure 68: **Immersion Tagnite Rectifier and Chilling System…….176**

Figure 69: **Tank D-4 (Fluoride Activator) after Tank Modifications……..176**

Figure 70: **Tagnite Anodization Tank (D-7) after Tagnite Modifications……...177**

Figure 71: **Taber Abraser……....183**

Figure 72: **Demonstration Parts after Removal of Legacy Coatings by SodaBlast……186**

Figure 73: **Demonstration Parts after Immersion Tagnite and High Temperature Rockhard……189**

List of Tables

Table 1: Target HazMat Compounds…….....3

Table 2: List of Priority Parts for Dem/Val at CCAD Plating Shop……..…4

Table 3: Tagnite Advantages and Limitations…….13

Table 4: Performance Objectives for JTP and Demonstration Phases……...…....15

Table 5: Tagnite Process Stream in the CCAD D-Line……..25

Table 6: Pull-off Adhesion for Repair Compatibility Testing……...……41

Table 7: Galvanic Corrosion Test Description for Repair Compatibility Testing……..43

Table 8: Dimensional Change Test Description for Chemical Stripping of Legacy Coatings ……48

Table 9: Paint Scheme to Test Effective of MIL-DTL-83936 Paint Stripper……..50

Table 10: Sampling Plan and Test Conditions for Hydrogen Embrittlement Study…..….52

Table 11: Pull-off Adhesion Test Matrix for Brush Tagnite Qualification Testing……....53

Table 12: Galvanic Corrosion Test Matrix for Brush Tagnite Qualification Testing…….54

Table 13: Neutral Salt Fog Corrosion Test Matrix for Brush Tagnite Qualification Testing ……..55

Table 14: Acidified (SO_2) Salt Fog Corrosion Test Matrix for Brush Tagnite Qualification Testing……56

Table 15: Outdoor Exposure Test Matrix for Brush Tagnite Qualification Testing…..…57

Table 16: Axial Fatigue Strength Test Matrix for Brush Tagnite Qualification Testing...58

Table 17: QC Testing during Tagnite Training and Demonstration…….…..67

Table 18: UDRI Paint Adhesion Testing Raw Data for DEVCON Aluminum Liquid Repair…….……..71

Table 19: UDRI Paint Adhesion Testing Raw Data for DEVCON Titanium Paste Repair ……..…72

Table 20: UDRI Paint Adhesion Testing Raw Data for TIG Weld Repair……..…..73

Table 21: UDRI Paint Adhesion Testing Raw Data for Cold Spray Repair……..……74

Table 22: UDRI Paint Adhesion Testing Raw Data for HVOF Repair…….…….75

Table 23: Summary of Paint Adhesion Statistical Analysis…….77

Table 24: Paint Adhesion Performance Summary……78

Table 25: Summary of Galvanic Corrosion Performance Ratings……..…….80

Table 26: Original Dimensional Change Test Description of Chemical Stripping of Legacy Coatings ……..…….89

Table 27: Modified Dimensional Change Test Description of Chemical Stripping of Legacy Coatings……..……..90

Table 28: AMSAM-ENVI-TI Hydrogen Embrittlement Test Matrix…….....103

Table 29: Normal Tagnite Stripping Parameters vs. Notched C Ring Stripping Parameters…….……104

Table 30: UDRI Paint Adhesion Testing Raw Data for AZ91C……..106

Table 31: UDRI Paint Adhesion Testing Raw Data for EV31A……..107

Table 32: UDRI Paint Adhesion Testing Raw Data for QE22A……..108

Table 33: UDRI Paint Adhesion Testing Raw Data for ZE41A……..109

Table 34: Paint Adhesion Summary for Brush Tagnite vs. DOW 19…….111

Table 35: Paint Adhesion Summary for Brush Tagnite vs. TCP……....112

Table 36: TAG Paint Adhesion Testing Raw Data for ZE41A……114

Table 37: Summary of Average Galvanic Corrosion Current Readings……117

Table 38: ZE41A Neutral Salt Fog Ranking Summary……...121

Table 39: QE22A Neutral Salt Fog Ranking Summary……...122

Table 40: AZ91C Neutral Salt Fog Ranking Summary……...128

Table 41: EV31A Neutral Salt Fog Ranking Summary…….…..129

Table 42: AZ91C Acidified SO_2 Salt Fog Ranking Summary…….…134

Table 43: EV31A Acidified SO_2 Salt Fog Ranking Summary…….138

Table 44: QE22A Acidified SO_2 Salt Fog Ranking Summary……..141

Table 45: ZE41A Acidified SO_2 Salt Fog Ranking Summary…….……..146

Table 46: AZ91C Outdoor Exposure Ranking Summary…….160

Table 47: EV31A Outdoor Exposure Ranking Summary…….163

Table 48: QE22A Outdoor Exposure Ranking Summary…….166

Table 49: ZE41A Outdoor Exposure Ranking Summary……..169

Table 50: QC Testing during Tagnite Training and Demonstrations…….181

List of Acronyms and Symbols

AvMC:	**Aviation and Missile Command**
AMA-F:	**Structures and Materials Division**
AMA-M:	**Maintenance Engineering Division**
AED:	**Aviation Engineering Directorate**
AEM:	**Aviation Engineering and Maintenance**
AMRDEC:	**Aviation and Missile Research Development and Engineering Center**
ANOVA:	**Analysis of Variance**
ASTM:	**American Society for Testing and Materials**
BER:	**Beyond Economic Repair**
Cad:	**Cadium**
CCAD:	**Corpus Christi Army Depot**
CCDC:	**Combat Capabilities Development Command**
CMM:	**Coordinate Measuring Machine**
JTP:	**Joint Test Protocol**
HVOF:	**High Velocity Oxy Fuel**
MEC:	**Maintenance Engineering Call**
MED:	**Maintenance Engineering Division**
MEO:	**Maintenance Engineering Order**
NAVAIR:	**U.S. Navy Naval Air Systems Command**
NFS:	**Notch Fatigue Strength**
PATTI:	**Pull-off Strength of Coatings Using Portable Adhesion Testers**
PEL:	**Permissible Exposure Limits**
PEO:	**Plasma Electrolytic Oxidation (PEO)**
POTS:	**Pull-off Strength**
PPE:	**Personnel Protective Equipment**
QC:	**Quality Control**
TAG:	**Technology Applications Group**
TCP:	**Trivalent Chromate Conversion Coating**
TIG:	**Tungsten Inert Gas**
TLV:	**Threshold Limit Value**
TWA:	**Time Weighted Average**
UDRI:	**University of Dayton Research Institute**

Acknowledgments

Name	Organization	Phone	e-mail
Mr. Kyu Cho	U.S. Army Research Laboratory	(410) 306-0820	kyu.c.cho2.civ@mail.mil
Dr. Bill Gorman	Technology Applications Group	(701) 746-1818	bgorman@tagnite.com
Mr. Ricky McNalley	U.S. Army Aviation Engineering Directorate (AED)	(256) 955-6854	ricky.o.mcnalley.civ@mail.mil
Mr. Scott Howison	U.S. Army AMCOM G-4	(256) 876-6129	stephen.s.howison.civ@mail.mil
Mr. Antonio Cereceres	U.S. Army CCDC AvMC AMA-M	(361) 961-2663	antonio.cereceres.civ@mail.mil
Mr. Humberto Hernandez	U.S. Army CCDC AvMC AMA-M	(361) 961-2771	humberto.hernandez52.civ@mail.mil
Dr. Elizabeth Berman	U.S. Air Force Research Laboratory	(937) 656-5700	elizabeth.berman@wpafb.af.mil
Dr. Michael John Kane	Chief, Materials Division Aviation Engineering Directorate AMRDEC	(256) 313-8727	michael.john.kane@us.army.mil
Mr. Luke Kingsbury	Engineer, Huntington Ingalls Industries MDIS, CCDC AvMC AMA-M	(361) 961-4063	luke.e.kingsbury.ctr@mail.mil
Ms. Anne Crago	Engineer, Torch Technologies FCDD AvMC AMA-M	(361) 961-5967	anne.e.crago.ctr@mail.mil
Mr. Charles Benson	Chemist USARMY USAMC		charles.e.benson26.civ@mail.mil

Abstract

Introduction and Objectives: All military aviation platforms have magnesium castings, however, magnesium is a very electrochemically "active" metal which leads to moisture induced corrosion and galvanic corrosion due to mating with dissimilar metals. During the overhaul phase of the aviation magnesium components the protective coating, primer and topcoat paint are stripped off to allow visual and penetrant inspection of the casting. After passing the inspection, the magnesium castings are dipped in a chemical conversion coating such as DOW 7 or DOW 19 before being placed back into service. Both of these DOW coatings contain hexavalent chromium (Cr^{6+}). The objective of the Tagnite demonstration at the CCAD plating shop is to eliminate the use of hexavalent chromium DOW 7 and DOW 19 tanks that are currently being used. This will be accomplished by masking off the dissimilar metals and applying the anodized coating Tagnite to these legacy magnesium components. The advantages of the Tagnite anodize coating are twofold: 1) The Tagnite electrolyte and anodic coating contain no hazardous materials and 2) The Tagnite coating has better corrosion resistance than the currently used hexavalent chromium coatings.

Technology Description: Historically, anodic coatings could not be used to coat fully assembled magnesium housings because the anodic process is an oxidation process and would rapidly convert the steel components to rust. TAG has developed the technology to mask off dissimilar metals such as steel in completed magnesium components in order to apply the Tagnite coating to legacy components without harm to the dissimilar metals.

Performance and Cost Assessment: The Immersion Tagnite coating was found to be compatible with five repair techniques; DEVCON Al liquid, DEVCON Ti Paste, TIG Welding, HVOF and Al Cold Spray. The MIL-PRF-23377 primer adhesion and galvanic corrosion response was equal to or better than the performance of the DOW 19 coating. The Brush Tagnite coating performed as well or better than DOW 19 under neutral and SO_2 acidified salt fog testing, coastal outdoor exposure, MIL-PRF-23377 primer adhesion and galvanic corrosion testing. Fatigue testing was performed but was inconclusive due to a very limited sample size. The demonstration of the masking technology/Immersion Tagnite on three (3) H-60 magnesium components at the CCAD Plating Shop was successful with no damage to any dissimilar metals.

There was no information available on the cost to run the DOW 7/DOW 19 tanks at CCAD so the cost assessment was based on the replacement cost of the H-60 components. The cost to apply the Immersion Tagnite was between 5 – 11 % of the replacement cost for the H-60 demonstration parts. Therefore, if the parts lasted at least one additional overhaul cycle there would be a significant cost savings.

Implementation Issues: The demonstration was very successful and CCAD is moving forward to approve this process for production parts. The primary implementation concern is the 9 – 12 month lag time between the training/demonstration phase and actual production. TAG proposed a chemical stripping method to remove the legacy coatings, however, this effort was not successful. An alternate media blast technology was studied during the demonstration phase and found to be effective in removing legacy coatings.

Publications: None at this time

EXECUTIVE SUMMARY

INTRODUCTION: All military aviation platforms have magnesium castings which are incorporated into various functions of the aircraft such as drive train components, auxiliary gearboxes and generator housings. Magnesium has the advantage of being a lightweight material which allows for greater payload or longer fuel ranges; however, magnesium is a very electrochemically "active" metal which leads to moisture induced corrosion and galvanic corrosion due to mating with dissimilar metals. As a consequence, magnesium components on aviation platforms must be inspected and replaced quite frequently.

During the overhaul phase of the magnesium component, the protective coating, primer and topcoat paint are stripped off to allow visual and penetrant inspection of the casting. After passing the inspection, the magnesium castings are dipped in a chemical conversion coating such as DOW 7 or DOW 19 before being placed back into service. The purpose of the DOW coatings is to act as a base for paint application. There are multiple problems with this approach:

1. These DOW chemical coatings leave a toxic hexavalent chromium film on the magnesium components. Exposure to hexavalent chromium during the application of the DOW chemical coatings is hazardous to operation personnel.
2. The cost of disposal of used chromate solution, contaminated containers, rinse water, contaminated auxiliary supply, etc. is expensive.
3. The DOW chemical overhauled magnesium components have dramatically short service life due to lack of corrosion protection seen with the chromate conversion coatings. Figure 1 shows ZE41 magnesium test coupons that have been treated with DOW 7 or DOW 19 and exposed to testing in a salt fog chamber for 9 hours along with a bare ZE41 panel. The picture clearly shows that the DOW coatings provide little, if any corrosion protection when compared to bare ZE41.

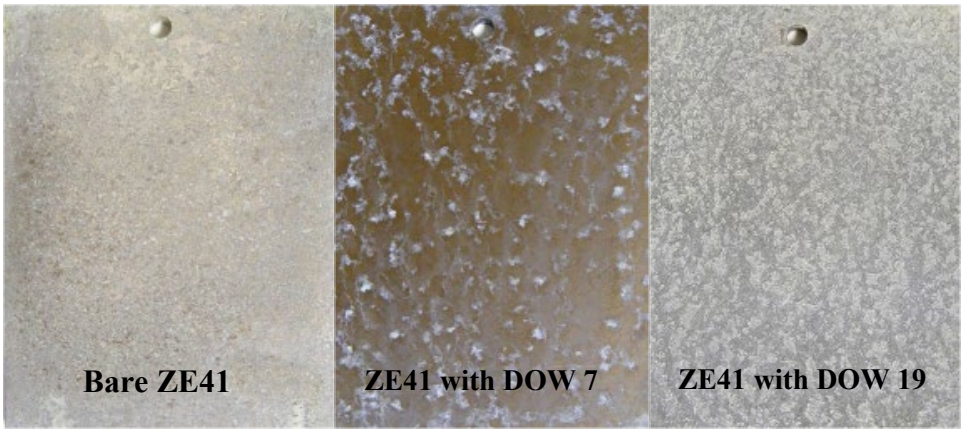


Figure 1: ZE41 Magnesium Panels after 9 hours of ASTM B 117 Salt Fog

Tagnite was developed as an anodized coating for magnesium that provides superior corrosion resistance, wear resistance and “green chemistry” formulation (no chromates or heavy metals) and it is approved for use on all the new magnesium components for the UH-60, AH-64, CH-47, AH-6, F-22 and F-35. In the past, refurbishment of legacy components with the Tagnite coating system was problematic due to the presence of dissimilar metals (e.g. steel studs, liners, etc.) and incomplete compatibility studies with current and potential repair techniques such as corrosion pit fillers, weld repair and additive repair. Masking technology has been developed by TAG to

overcome the dissimilar metal issue and this masking technology has been used at the TAG facility in North Dakota for over seven years. However, this masking technology requires demonstration at the military depot before the use of chromated coatings on magnesium components can be eliminated or phased out. The DoD demonstration site was the Corpus Christi Army Depot (CCAD) Plating Shop. One of the plating lines at CCAD was converted into an Immersion Tagnite line and CCAD plating shop personnel trained in the operation of the Immersion Tagnite line and masking protocols. Implementation of the masking technology along with the Tagnite coating will allow DoD depots to eliminate the need for chromate solutions in their magnesium finishing processes, thereby eliminating chromate exposure to depot personnel, reduce the waste disposal costs, meet current DoD environmental directives while applying a more robust coating system to the overhauled parts leading to lower life cycle costs.

OBJECTIVES: The objective of the Tagnite demonstration at the CCAD plating shop is to eliminate the use of hexavalent chromium DOW 7 and DOW 19 tanks that are currently being used to pretreat DoD magnesium aviation assets after these components have been stripped down to bare metal for inspection. This will be accomplished by masking off the dissimilar metals and applying the anodized coating Tagnite to these legacy magnesium components. The advantages of the Tagnite coating are twofold:

1. The Tagnite electrolyte and anodic coating contain no hazardous material.
2. The Tagnite coating provides better corrosion resistance than the currently used hexavalent chromium coatings.

TECHNOLOGY DESCRIPTION: The Tagnite coating process has been approved for DoD magnesium aviation components starting in 1997 and is the standard practice for magnesium protection on new magnesium components prior to the installation of studs, bearing liners and other steel inserts. Historically, anodic coatings could not be used to coat fully assembled magnesium housings because the anodic process is an oxidation process and would rapidly convert the steel components to rust. Steel, iron, stainless steel, brass, cadmium plating and other metals cannot be anodized. If any of these dissimilar metals is in contact with the Tagnite electrolyte during the anodization process, these metals will react vigorously with the charged electrolyte bath which leads to the rapid oxidation (i.e. rust formation) of the ferrous material. The highly conductive nature of these dissimilar metals and the high voltage/high current density conditions of the Tagnite anodization process will cause all of the power for the process to concentrate on the dissimilar metals. The result is the dissimilar metals will literally burn away as well as heavily damage the surrounding magnesium. Therefore, all ferrous material must be "masked off" or sealed off from electrolyte contact to prevent the selective oxidation of ferrous material. TAG has developed the technology to mask off dissimilar metals such as steel in completed magnesium components in order to apply the Tagnite coating to legacy components without harm to the dissimilar metals. The materials used for "masking" of dissimilar metal must meet the following criteria:

- Must be chemically compatible with the entire Tagnite process
- Must be able to handle large temperature extremes (36^{o}F to 180^{o}F)
- Must be easily removed after the Tagnite process and leave a residue-free surface

The primary technical challenge of applying Tagnite to used magnesium casting is the vast majority of these housings contain steel liners, inserts or bearing races. These types of steel inserts have non-threaded surfaces with overhangs or lips on the magnesium casing. The profile

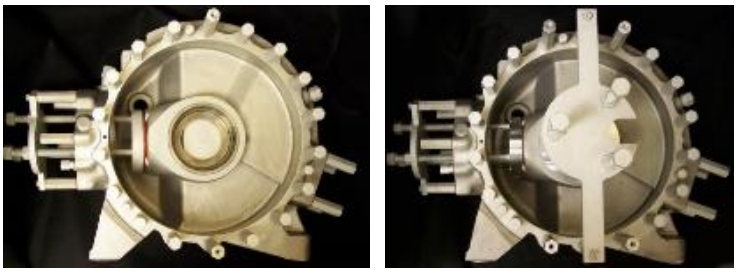


Figure 2: H-64 Tail Rotor Gearbox:
Left: Bearing liner exposed **Right:** Bridge in place to hold down liner cover

of these types of inserts have proven to be technically difficult to mask off or isolate in the past. However, TAG has developed a series of aluminum covers with O-rings to mask off these areas using variety of techniques including direct attachment to mating covers or use of aluminum "bridges" to hold covers in place (Figure 2). In addition, silicone molding material has been used to create custom molds that fit inside the liners to seal internal core passages and/or drain holes. Regardless of the care taken in designing and installing masking tools, the masking process will leave small, uncoated areas around the ferrous inserts that must be treated. These uncoated areas are treated with a process known as Brush Tagnite.

Brush Tagnite is a handheld, selective anodization of magnesium castings using a brush or wand to deposit the Tagnite coating on areas that have been re-machined, scratched or left bare after Immersion Tagnite. The operator is able to selectively anodize the areas of exposed magnesium without harming the exposed ferrous components as seen in Figure 3. The Brush Tagnite electrolyte and rectifier waveforms were specifically developed to not harm ferrous components in case of contact while depositing a coating. In addition, the Brush Tagnite coating has superior corrosion protection compared to the chromate conversion coatings.



Figure 3: Close-up of Brush Tagnite application to a bare area on a used magnesium aerospace casting

PERFORMANCE ASSESSMENT: The initial phase of this project was to conduct a Joint Test Protocol (JTP) to answer some questions about the compatibility of Immersion Tagnite and Brush Tagnite with several current and proposed repair techniques and also qualify the Brush Tagnite process on the four most widely used aerospace alloys. In addition, TAG had developed a chemical stripping process for the Tagnite coating using the Immersion Tagnite pretreatment process. This process needed to be evaluated for dimensional change, hydrogen embrittlement and ability to strip the legacy anodize coatings HAE and DOW 17.

Immersion Tagnite/Brush Tagnite Repair Compatibility Testing: Magnesium components that have come in for overhaul might have some corrosion damage that needs to be repaired before being placed back into service. There was a need to verify that the Immersion Tagnite process did not affect the repairs and to evaluate the performance of Brush Tagnite when applied over these repairs. The repair techniques evaluated consisted of three currently used corrosion repair techniques;

- DEVCON Al Liquid F2

- DEVCON Ti Paste
- TIG Welding using ZE41A magnesium welding rod

and two proposed repair or additive techniques:

- HVOF Thermal Spray using Al-12Si Feedstock
- 6061 Aluminum Cold Spray

The testing involved pull-off adhesion strength per ASTM D 4541 after applying MIL-PRF-23377 primer and galvanic corrosion response (without primer) per ASTM G71. For the repair testing, only ZE41A test coupons were used. Both pull-off adhesion and galvanic corrosion testing were done over the repair area. The acceptance criteria was the performance of the Immersion Tagnite/Brush Tagnite must be equal to or better than the performance of the DOW 19 coating which is the currently used for coating treatment after repair at CCAD.

1. Immersion Tagnite/Brush Tagnite Repair Compatibility - Paint Adhesion Testing: For the paint adhesion testing, there were five (5) panels tested for each treatment (Immersion Tagnite, Brush Tagnite and DOW 19) after painting with MIL-PRF-23377 primer. Each panel was tested in two locations over the repair areas. The average pull-off strength (POTS) was calculated and statistical means testing was used to determine if the average POTS values between each treatment were equivalent. The paint adhesion summary for Immersion Tagnite/Brush Tagnite vs. DOW 19 is seen in Table 1. In all cases, both Immersion Tagnite and Brush Tagnite met the performance criteria of performing as well or better than the DOW 19.

Table 1: Paint Adhesion Performance Summary

	Devcon Al F2 Liquid		**Devcon Ti Paste**		**TIG Welding**	
	Immersion Tagnite	DOW 19	Immersion Tagnite	DOW 19	Immersion Tagnite	DOW 19
POTS Mean (psi)	2685	1735	3184	1618	1712	1180
Performance Results	Imm. Tagnite > DOW 19		Imm. Tagnite > DOW 19		Imm. Tagnite > DOW 19	
	Brush Tagnite	DOW 19	Brush Tagnite	DOW 19	Brush Tagnite	DOW 19
POTS Mean (psi)	2989	1735	3038	1618	1628	1180
Performance Results	Brush Tagnite > DOW 19		Brush Tagnite > DOW 19		Equivalent Performance	

	Cold Spray		**HVOF**	
	Immersion Tagnite	DOW 19	Immersion Tagnite	DOW 19
POTS Mean (psi)	1778	1644	1283	1279
Performance Results	Equivalent Performance		Equivalent Performance	
	Brush Tagnite	DOW 19	Brush Tagnite	DOW 19
POTS Mean (psi)	1717	1644	1462	1279
Performance Results	Equivalent Performance		Equivalent Performance	

2. Immersion Tagnite/Brush Tagnite Repair Compatibility - Galvanic Corrosion Testing: The galvanic corrosion test panels were analyzed at the North Dakota State University (NDSU) Department of Coatings and Polymeric Materials (CPM) in multiple batches. Each panel was tested in the two separate areas where the specified repair took place and the galvanic current was measured for 24 hours. The values used for the data analysis were the average of the galvanic current values measured during stable periods which in this case was between the 15th hour and the 24th hour (10 hour period) of the experiment. There were two trials performed for each repair/coating scheme. TAG analyzed the galvanic corrosion current response of Immersion Tagnite, Brush Tagnite and DOW 19 for each of the five different repair techniques. TAG looked at the average galvanic currents for Immersion Tagnite, Brush Tagnite and DOW 19 and rated the performance of the pretreatments relative to the magnitude of the DOW 19 galvanic current. The rating system is as follows:

"**Best**": Magnitude of Tagnite/Brush Tagnite Galvanic Current is 3 – 5x less than DOW 19
"**Better**": Magnitude of Tagnite/Brush Tagnite Galvanic Current is 1 – 2x less than DOW 19
"**Equal**": Magnitude of Tagnite/Brush Tagnite Galvanic Current is same magnitude as DOW 19

Galvanic Corrosion Conclusion: Based on this rating system and the galvanic current readings, Immersion Tagnite and Brush Tagnite had a galvanic corrosion response that was better or equal to the DOW 19 conversion coating in all five repair schemes and therefore passed the performance criteria specified in the JTP.

3. Brush Tagnite Qualification Studies: In order to qualify Brush Tagnite, test coupons of the magnesium alloys AZ91C, EV31A, QE22A and ZE41A were treated with Brush Tagnite, DOW 19 and TCP (Trivalent Chromium Preservative). The following tests (Table 2) were performed and the results are summarized in Table 3.

Table 2: Brush Tagnite Qualification Testing

Treatment Scheme	Testing	Testing Requirements	Performance Criteria
Brush Tagnite **or** DOW 19 **with** MIL-PRF-23377 Primer	Pull-off Paint Adhesion	ASTM D 4541	Brush Tagnite must perform as well or better than DOW 19
	Neutral Salt Fog	ASTM B 117 ASTM D 1654	
	SO2 Salt Fog	ASTM G-85, Annex A4 ASTM D 1654	
	NASA Outdoor Exposure	24 month exposure in Florida Coast environment	
Brush Tagnite **or** DOW19	Galvanic Corrosion	ASTM G71	Brush Tagnite must perform as well or better than DOW 19
	Axial Fatigue	ASTM E 466	

Table 3: Brush Tagnite Qualification Results (where Ranking of 1 = Best, Ranking of 15/9 = Worse)

AZ91C Magnesium Test Panels								
Treatment	**Paint Adhesion**		**Neutral Salt Fog**		**SO2 Salt Fog**		**Outdoor Exposure**	
	POTS Mean (psi)	**Performance**	**Hours of Exposure**	**Ranking**	**Hours of Exposure**	**Ranking**	**Months of Exposure**	**Ranking**
BT	1886	BT = DOW19	1150	1,2,4,6,7	1536	1-5	24	1-3
DOW 19	1706		1150	3,5,8,9,11	1200	6-10	24	6,7,9
TCP	1650	BT > TCP	760 (avg)	10,12-15	648	11-15	24	4,5,8
EV31A Magnesium Test Panels								
Treatment	**Paint Adhesion**		**Neutral Salt Fog**		**SO2 Salt Fog**		**Outdoor Exposure**	
	POTS Mean (psi)	**Performance**	**Hours of Exposure**	**Ranking**	**Hours of Exposure**	**Ranking**	**Months of Exposure**	**Ranking**
BT	1594	BT > DOW19	1394	1-5	1536	1-3,5,6	24	1,2,4
DOW 19	1130		1394	8, 11,13,14T	648	11-15	24	7-9
TCP	1762	TCP > BT	1394	6,7,9,10,12	1536	4,7-10	24	3,5,6
QE22A Magnesium Test Panels								
Treatment	**Paint Adhesion**		**Neutral Salt Fog**		**SO2 Salt Fog**		**Outdoor Exposure**	
	POTS Mean (psi)	**Performance**	**Hours of Exposure**	**Ranking**	**Hours of Exposure**	**Ranking**	**Months of Exposure**	**Ranking**
BT	1648	BT = DOW19	192	1-5	1536	1-5	10	1-3
DOW 19	1719		110 (avg)	11-15	144	11-15	10	6-8
TCP	1677	BT = TCP	156	6-10	312	6-10	10	4,5,9
ZE41A Magnesium Test Panels								
Treatment	**Paint Adhesion**		**Neutral Salt Fog**		**SO2 Salt Fog**		**Outdoor Exposure**	
	POTS Mean (psi)	**Performance**	**Hours of Exposure**	**Ranking**	**Hours of Exposure**	**Ranking**	**Months of Exposure**	**Ranking**
BT	**2858**	BT = DOW19	192	1-5	1536	1-5	24	1-3
DOW 19	**2792**		119 (avg)	6-10	144	11-15	24	4,7,8
TCP	**2806**	BT = TCP	66 (avg)	11-15	144	6-10	24	5,6,9

There were five (5) panels per treatment of the paint adhesion, neutral salt fog and SO_2 salt fog. The panels were rating from 1 (Best) to 15 (Worse). There were only three (3) panels per treatment tested for outdoor exposure. These panels were rated from 1 (Best) to 9 (Worse)

Brush Tagnite Qualification Conclusions: The Brush Tagnite coating performed as well or better than DOW 19 under neutral and SO_2 acidified salt fog testing, coastal outdoor exposure, MIL-PRF-23377 primer adhesion and galvanic corrosion testing. Fatigue testing was performed but was inconclusive due to a very limited sample size of ten (10) specimens per treatment.

4. Chemical Stripping of Legacy Coatings: Through the years, scientists at Technology Applications Group have developed a procedure for removing the Tagnite coating using the Tagnite pretreatment process to loosen and/or dissolve the Tagnite coating. This process also allows TAG operators to remove the Tagnite coating that was damaged or improperly applied without any adverse effect on the surface finish or dimensional tolerances of the original casting. Once this process has been completed, the parts can be placed in the Tagnite anodize bath and a new Tagnite coating applied. It was originally thought that this process would be useful in stripping the legacy coatings from used magnesium components during overhaul.

There was some success in stripping the legacy anodize coatings, DOW 17 and HAE, however the stripping process would not work at all if primers or paint were placed over the legacy anodized coatings. Even after using DoD approved paint strippers, there was still primer/paint embedded in the porosity of the legacy anodize coatings as well in the pores of the Immersion Tagnite. The embedded paint would inhibit the Tagnite stripping process and the legacy coatings could not be chemically removed. For the demonstration/validation (dem/val) phase, a baking soda media blast was used to strip the legacy coatings and leave a surface finish that was acceptable for the Tagnite process.

Hydrogen Embrittlement: The Tagnite chemical stripping process will still be needed at CCAD to strip Tagnite so the impact on hydrogen embrittlement was evaluated using Type 1d notched C rings per ASTM F519-13, reference 1c and a test matrix (Table 4) developed by materials engineers at CCDC AvMC AMA-M.

Table 4: AMSAM-ENVI-TI Hydrogen Embrittlement Test Matrix

Specimen Condition	No Preload	Preload to 75% NFS	Strip @ Max Temp - Max Concentration and 2X Time	Post Exposure Stress 200 hrs @ 75% NFS
Bare	4		All	All
Bare		4	All	All
Cad Plated	4		All	All
Cad Plated		4	All	All

The two Tagnite pretreatment baths needed for stripping (mild alkaline etch and fluoride activator solution) were adjusted to the maximum allowable concentration and the Type 1d notched C rings were placed in these solutions for twice (2x) the maximum allowable time.

C Ring Hydrogen Embrittlement Testing Results:

1. There were no notch fractures seen on any of the specimens after 200 hours @ 75 % NFS during the specimen batch (lot) validation testing. Therefore, the specimen batch (lot) was validated.
2. After 30 minutes in the mild alkaline etch under the conditions listed above, there were no notch fractures noted.
3. After 3 hours in the fluoride activator under the conditions listed above, there were no notch fractures noted. ***However***, both the bare and Cad plated C rings had softened significantly and were rotating back and forth on the notch. The notch was acting like a hinge for the two C rings sections to flop up and down. This is considered an adverse event and therefore a failure.

Hydrogen Embrittlement Conclusions:

1. The fluoride activator step of the stripping process had an adverse effect on the Type 1d notched C rings. Therefore, any steel on a magnesium housing should be properly masked off before using the Tagnite chemical stripping process.
2. The fluoride activator is also used during as the final pretreatment step prior to Tagnite anodize. Therefore, all steel on a magnesium housing should be properly masked off before pretreating/anodizing using the Tagnite process.

PERFORMANCE ASSESSMENT PLAN

The demonstration was carried out on three (3) H-60 components in the CCAD plating shop. The performance of the demonstration phase of this project focused on four different areas:

1. Quality of the Tagnite Coating
2. Stability/Maintainability of the Tagnite Process Solutions
3. Effectiveness of the stripping process to remove legacy coatings
4. Effectiveness of the masking process at protecting the steel components

1. Quality of the Tagnite Coatings

The primary objective of this phase is to show that the quality of the Tagnite coating applied at the CCAD plating shop is "as good or better" than the characteristics of the coatings currently used in the CCAD plating shop. In addition, the quality of the Tagnite coating applied at the CCAD plating shop needs to be compared to the Tagnite coating applied at TAG's facility. The quality of the Tagnite coating was to be determined by determining the wear resistance, salt fog corrosion resistance and paint adhesion of CCAD coated Tagnite panels vs. TAG's historical data for these tests. This testing was originally designed to:

1. Check the interlaboratory taber endpoint determination between CCAD and TAG using taber panels coated at CCAD.
2. Compare the taber values obtained from CCAD Tagnited panels vs. TAG historical taber data.
3. Compare the salt fog and paint adhesion results from CCAD Tagnited panels vs. TAG historical salt fog and paint adhesion data.

Testing Results: At the time of the demonstration/validation, the CCAD laboratory did not have a functioning taber abraser. In addition, CCAD do not have a supply of test coupons to coat,

therefore none of this testing was done. The demonstration parts were thoroughly inspected by CCAD engineers and TAG personnel. TAG personnel stated that the look and feel of the Tagnite was equivalent to the "normal" Tagnite and CCAD engineers agreed with this observation and stated that the parts passed their demonstration/validation criteria.

2. Stability/Maintainability of the Tagnite Process Solutions

Testing Rationale: In order to apply a quality Tagnite coating, the Tagnite process baths must be maintained per TAG's specifications. TAG specifications state the need for daily and periodic testing of all process tanks and timely chemical additions when tank parameters exceed the process and/or specifications limits. In addition, there are set criteria when a process bath should be dumped and replaced. In order to proceed with production parts, control charts of all process data will be graphed and reviewed as evidence that the Tagnite process baths at CCAD can be monitored and maintained so that a consistent quality Tagnite coating is produced. The daily/periodic testing, control charts and chemical addition records will be reviewed by TAG personnel on a weekly basis. TAG will work with CCAD chemists to maintain the process baths in order to meet all specification limits.
Results: During the dem/val phase, the CCAD lab was able to do the necessary daily analyses and the results were within TAG's specifications. The chemicals needed to do the periodic testing had not been purchased at the time of the demonstration/validation. In addition, the Tagnite process baths were only operated for one week and very little square footage was run through the tanks so very little chemical consumption occurred. TAG personnel spent several hours with the CCAD plating shop chemists during the dem/val phase reviewing the periodic testing procedures and testing schedules. TAG personnel were more than satisfied that CCAD understood the procedures and the testing frequency would be met. Once productions starts, CCAD chemists must monitor the Tagnite Process solutions as dictated in the testing schedules supplied to the CCAD plating shop laboratory.

3. Effectiveness of the Legacy Coating Stripping Process

The Tagnite chemical stripping process was unable to adequately remove legacy coatings due to the Rockhard sealant that was embedded in the pores of the anodize coatings. As a result of this finding, engineers at CCAD decided that the best alternative way to remove legacy coatings was through baking soda media blast (aka. Sodablast). Prior to the Tagnite dem/val, the demonstration parts were stripped using the Sodablast process. TAG personnel were present during this process and gave the CCAD artisans feedback on the appearance of the parts and when an acceptable level of cleanliness was reached. The effectiveness of the legacy coating stripping process was based entirely on visual inspection. The criteria when determining if the part had been stripped effectively enough for the Tagnite process to deposit a high quality coating was:

- There can be no residual inorganic or organic coatings present on the magnesium component after stripping
- The magnesium surface must have a bright, metallic, bare metal appearance

Results: With guidance from TAG personnel, the Sodablast media was able to remove the legacy coatings to a level of cleanliness that was acceptable for the Tagnite process.

4. Effectiveness of the Masking Process at Protecting Steel Components

During the initial masking training, CCAD personnel were given detailed masking procedures and the masking kits. They underwent individualized masking training from TAG personnel while using scrap BER parts. During the demonstration/validation process, the CCAD artisans installed the masking tools under the supervision of TAG personnel. The parts were then run through the Immersion Tagnite process.

After the Tagnite process, the masking tools were removed. The steel liner covers were closely inspected for damage such as signs of arcing, metal loss and/or gaps in the sealing surface. Bolts and treaded inserts were inspected after removal for damage to the threads or chemical buildup in the threads that would interfere with installation on subsequent parts. There was no evidence of damage to the masking tools.

Once the masking tools were removed, the parts were visually inspected with and without the use of hand held magnifiers. The performance of the masking tool installation was graded based on the following performance criteria:

- No arcing
- No material loss
- Coating shall be continuous, smooth and uniform in appearance
- Color shall be white to gray
- No rust on steel liners
- No loss of cad plating on studs and inserts

All three (3) demonstration parts passed the masking performance criteria as no failures were seen.

Transitioning from Demonstration to Production Parts: The three (3) demonstration parts were thoroughly examined by AMA-M engineers after the Tagnite process and after the Rockhard sealant process. They were very happy with the quality of the parts after both processes. They recommended that the Tagnite masking and anodizing process transition to actual production parts. In order to process production parts, maintenance engineering orders (MEO) must be generated by AMA-M engineers and circulated through the appropriate departments at CCAD for sign-off approval. This approval cycle could take 9 – 12 months until all the documentation and approvals are collected.

COST ASSESSMENT: There was no information available on the cost to run the DOW 7/DOW 19 tanks at CCAD so the cost assessment was based on the replacement cost of the H-60 components. The cost to apply the Immersion Tagnite was between 5 – 11 % of the replacement cost for the H-60 demonstration parts. Therefore, if the parts lasted at least one additional overhaul cycle there would be a significant cost savings.

IMPLEMENTATION ISSUES: The demonstration was very successful and CCAD is moving forward to approve this process for production parts. The primary implementation concern is the 9 – 12 month lag time between the training/demonstration phase and actual production. TAG proposed a chemical stripping method to remove the legacy coatings, however, this effort was not successful. An alternate media blast technology was studied during the demonstration phase and found to be effective in removing legacy coatings which allowed a Tagnite coating to be applied.

1.0 INTRODUCTION

All military aviation platforms have magnesium castings which are incorporated into various functions of the aircraft such as drive train components, auxiliary gearboxes and generator housings. Magnesium has the advantage of being a lightweight material which allows for greater payload or longer fuel ranges; however, magnesium is a very electrochemically "active" metal which leads to moisture induced corrosion and galvanic corrosion due to mating with dissimilar metals. As a consequence, magnesium components on aviation platforms must be inspected and replaced quite frequently.

1.1 BACKGROUND

During the overhaul phase of the magnesium component, the anodic protective coatings (HAE, DOW 17 or Tagnite), primer and topcoat paint are stripped off to allow visual and penetrant inspection of the casting. After passing the inspection, the magnesium castings are dipped in a chemical conversion coating such as DOW 7 or DOW 19 before being placed back into service. The purpose of the DOW coatings is to act as a base for paint application. There are multiple problems with this approach:

1. These DOW chemical coatings leave a toxic hexavalent chromium film on the magnesium components. Exposure to hexavalent chromium during the application of the DOW chemical coatings is hazardous to operation personnel. For example, the magnesium component is placed in a vat of boiling hexavalent chromium DOW 7 solution for 30 minutes. Hexavalent chrome has been proven to cause lung cancer. The OSHA PEL for chromic acid is 0.005 mg (8-hour TWA) and the TLV is 0.05 mg/m^3. These PEL values are considered very low and the low PEL values require substantial ventilation engineering.
2. The cost of disposal of used chromate solution, contaminated containers, rinse water, contaminated auxiliary supply, etc. is expensive.
3. The DOW chemical overhauled magnesium components have dramatically short service life due to lack of corrosion protection seen with the chromate conversion coatings. Figure 1 shows ZE41 magnesium test coupons that have been treated with DOW 7 or DOW 19 and exposed to testing in a salt fog chamber for 9 hours along with a bare ZE41 panel. The picture clearly shows that the DOW coatings provide little, if any corrosion protection when compared to bare ZE41.
4. DOW 7 is not recommended for use on the following highly used magnesium alloys EK30A (UNS M12300), EK41A (UNS M12410), HK31A (UNS M13310), HM21A (UNS 13210), HM31A (UNS M13312), ZK60A (UNS 16600), LA141A (UNS M14141), and M1A (UNS M15100).
5. There are evidences that DOW 7 and DOW 19 do not produce adequate coatings on the newest aerospace magnesium alloy, EV31 (AMS 4429), an alloy is being heavily used in the Apache Block III Drivetrain Upgrade.

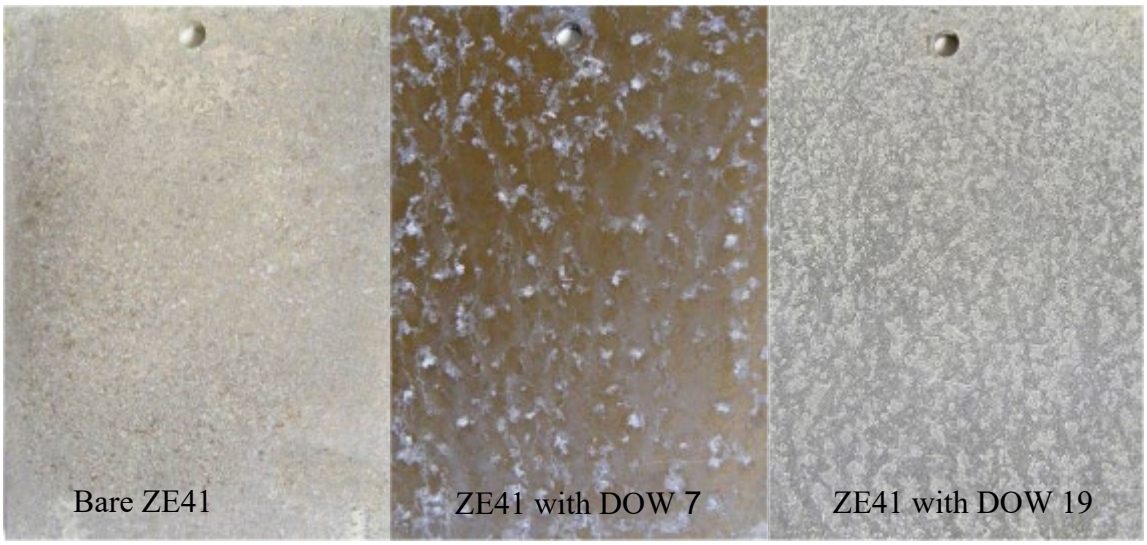


Figure 1: ZE41 Magnesium Panels after 9 hours of ASTM B 117 Salt Fog

Tagnite is approved for use on all the new magnesium components for the UH-60, AH-64, CH-47, AH-6, F-22 and F-35 due to the superior corrosion resistance, wear resistance and "green chemistry" formulation (no chromates or heavy metals). In the past, refurbishment of legacy components with the Tagnite coating system was problematic due to the presence of dissimilar metals (e.g. steel studs, liners, etc.) and incomplete compatibility studies with current and potential repair techniques such as corrosion pit fillers, weld repair and cold spray repair. Masking technology has been developed by Technology Applications Group (TAG) to overcome the dissimilar metal issue and this masking technology has been used at the TAG facility in North Dakota for over five years. However, this masking technology requires demonstration at the depot before the use of chromated coatings on magnesium components can be eliminated or phased out. The DoD demonstration site will be the Corpus Christi Army Depot (CCAD) Plating Shop. One of the plating lines at CCAD will be converted into an Immersion Tagnite line and CCAD plating shop personnel trained in the operation of the Immersion Tagnite line and masking protocols. Implementation of the masking technology along with the Tagnite coating will allow DoD depots to eliminate the need for chromate solutions in their magnesium finishing processes, thereby eliminating chromate exposure to depot personnel, reduce the waste disposal costs, meet current DoD environmental directives while applying a more robust coating system to the overhauled parts leading to lower life cycle costs.

1.2 OBJECTIVE OF THE DEMONSTRATION

The objective of the Tagnite demonstration at the CCAD plating shop is to eliminate the use of hexavalent chromium DOW 7 and DOW 19 tanks that are currently being used to pretreat DoD magnesium aviation assets after these components have been stripped down to bare metal for inspection. This will be accomplished by masking off the dissimilar metals and applying the anodized coating Tagnite to these legacy magnesium components. The advantages of the Tagnite coating are twofold:

1. The Tagnite electrolyte and anodic coating contain no hazardous materials

2. The Tagnite coating has better corrosion resistance than the currently used hexavalent chromium coatings.

The Tagnite coating process has been approved for DoD magnesium aviation components starting in 1997 and is the standard practice for magnesium protection on new magnesium components prior to the installation of studs, bearing liners and other steel inserts. Historically, anodic coatings could not be used to coat fully assembled housings because the anodic process is an oxidation process and would rapidly convert the steel components to rust. TAG has recently developed the technology to mask off dissimilar metals such as steel in completed magnesium components in order to apply the Tagnite coating to legacy components without harm to the dissimilar metals. This masking process has only been used at the Tagnite facility and another objective of this demonstration is to show that this technology can be transferred to DoD overhaul facilities.

The targeted hazardous material is hexavalent chromium (Cr^{6+}) which is used at the military depots in various formulations (Table 1). The most typically used formulations are called DOW 7 and DOW 19.

Table 1: Target HazMat Compounds

Target HazMat	Current Process	Applications	Current Specifications	Affected Programs	Priority Parts and Substrates
Hexavalent Chromium	DOW 7	Used as paint adhesion coating on magnesium aviation components	AMS-M-3171 Type III	UH-60 AH-64 CH-47 T-38/F-5	**See Table 2**
Hexavalent Chromium	DOW 19	Used as paint adhesion coating on magnesium aviation components	AMS-M-3171 Type VI	UH-60 AH-64 CH-47 T-38/F-5	**See Table 2**

The environmental, safety and occupational health benefits of applying the Tagnite coating in the CCAD plating shop are:

1. The use of the Tagnite coating will lead to the elimination of the DOW 7 and DOW 19 processes which will result in eliminating several hexavalent chromium sources at the depot.
2. The Tagnite formulation contains only hydroxide, silicate and fluoride. These are commonly used compounds that are not targeted by the DoD for reduction or removal which will lead to greater margin of safety when personnel are exposed to the Tagnite electrolyte or vapors.
3. The Tagnite coating consists of magnesium oxide (MgO) and magnesium silicate ($MgO{\cdot}SiO_2$) which are non-hazardous compounds. Using the Tagnite coating would

eliminate any hexavalent chromium exposure to depot, field maintenance or aviation personnel.

Table 2 lists the magnesium priority parts as determined by the ESTCP working group that are currently being pretreated with the DOW or DOW 19 hexavalent chromium solutions at the CCAD facility.

Table 2: List of Priority Parts for Dem/Val at CCAD

Platform	Assembly	Assembly P/N	Description	Substrate
UH60A-L	Intermediate Gearbox	70357-06305-043/-042	Center Housing Assembly	Magnesium
UH60A-L	Tail Gearbox	70358-06607-041/-042	Center Housing Assembly	
UH60A-L	Input Module	70351-08018-042	Output Housing Assembly	

1.3 REGULATORY DRIVERS

Specific regulatory drivers that impact surface treatment operations are as follows:

- Under the Clean Air Act (CAA), EPA (Environmental Protection Agency) regulates Hazardous Air Pollutant (HAP) and Volatile Organic Compound (VOC) emissions. The 188 HAPs identified by EPA are regulated through the establishment of Maximum Achievable Control Technologies (MACT) via National Emission Standards for Hazardous Air Pollutants (NESHAPs). Three NESHAPs impact metal finishing processes. They are as follows:
    - 40 CFR 63, Subpart N, National Emission Standards for Chromium Emissions From Hard and Decorative Chromium Electroplating and Chromium Anodizing Tanks, establishes emission limits and control techniques. Emission limits are established for large and new tanks as well as existing small tanks. Standard work practices are also established to minimize impact to workers in the vicinity of the plating operation. Applies to Major and area sources.
    - 40 CFR 63, Subpart GG, National Emission Standards for Aerospace Manufacturing and Rework Facilities. Mitigation of regulatory requirements imposed by this NESHAP are addressed in a separate program and are therefore, not relevant to the discussion here.
    - 40 CFR Part 63, Subpart WWWWWW National Emission Standards for Hazardous Air Pollutants: Area Source Standards for Plating and Polishing Operations must also be complied with for applicable installations. This NESHAP addresses the following processes:
    - Cadmium electroplating
    - Nickel electroplating
    - Electroless nickel plating
    - Chromate conversion coating
    - Sodium dichromate sealing
    - Thermal metal spraying

Although this ruling does not establish emission limits, it does require compliance with generally available control technology (GACT) standards. To meet this regulation, affected facilities have several choices including use of wetting agents/fume suppressants (WAFS), air pollution control devices or tank covers. This rule does not apply to sources that must comply with 40 CFR part 63, subpart N (National Emission Standards for Chromium Emissions from Hard and Decorative Chromium Electroplating and Chromium Anodizing Tanks). Air permitting is generally required for metal finishing operations.

- The Clean Water Act (CWA) sets effluent limits on pollutants. Water treatment systems must be utilized to permit discharge of effluents. Direct discharges require a permit (National Pollution Discharge Elimination System (NPDES)). Effluent Guidelines and Standards for Metal Finishing (40 CFR Part 433) and the Effluent Guidelines and Standards for Electroplating (40 CFR Part 413) have been established. Electroplating Categorical Standards are applicable to wastewater from these six specific operations:
- Electroplating
- Electroless Plating
- Anodizing
- Coatings
- Chemical Etching and Milling
- Printed Circuit Board Manufacturing

40 CFR 433 (metal finishing) establishes categorical standards for an additional 40 operations. Lastly, the General Pretreatment Regulations affect all metal finishing and electroplating manufacturing facilities that discharge process wastewater to a Public owned Treatment Works (POTW). All facilities must comply with the Prohibited Discharge rules (40 CFR 403.5).

- The Emergency Planning and Community Right-to-Know Act regulates environmental releases of specified toxic chemicals that must be reported.
- The Resource Conservation and Recovery Act directly regulates several metal finishing wastes as hazardous wastes. It requires all hazardous waste generators, including metal finishers, to certify that they have a program in place to reduce the volume or quantity and toxicity of the waste they generate. Specific hazardous waste codes exist for halogenated solvents, plating, anodizing and conversion coating wastewater sludges and wastes from cyanide processes. The level of compliance is dependent on whether the facility is a large or small quantity generator. Common listed hazardous wastes generated by metal finishing facilities include:
    - F001 through F005 – Specific spent solvents and still bottoms.
    - F006 – Wastewater treatment sludge from plating operations.
    - F007 through F009 – Spent cyanide based plating, cleaning and stripping solutions and associated tank sludges.
    - F019 – Wastewater treatment sludges from aluminum finishing.

- The Toxic Release Inventory under the Comprehensive Environmental Response, Compensation, and Liability Act, requires facilities track releases of air emissions,

wastewater discharges, landfill disposal and transfers of waste with respect to acids, metals, solvents and cyanide.

- The DOD has established 48 CFR Parts 223 and 252 Defense Federal Acquisition Regulation Supplement, "Minimizing the Use of Materials Containing Hexavalent Chromium" (DFARS Case 2009–D004), which prohibits use of hexavalent chromium unless specifically approved by the Government. The regulation states that new procurements will not contain hexavalent chromium in a concentration greater than 0.1 percent by weight in any homogeneous material. A waiver is required to deviate from this requirement and must be approved by the respective Program Executive Office (PEO) and Army Corrosion Control Executive. DOD has proposed to amend the regulation to include Commercial off the Shelf (COTS) items.
- In accordance with DOD Instruction 5000.02, "The PM shall ensure that appropriate HSI and ESOH efforts are integrated across disciplines and into systems engineering to determine system design characteristics that can minimize the risks of acute or chronic illness, disability, or death or injury to operators and maintainers; and enhance job performance and productivity of the personnel who operate, maintain, or support the system."
- Registration, Evaluation, Authorization and Restriction of Chemicals (REACH) imposes requirements on EU (European Union) manufacturers and importers of "substances" greater or equal than one ton per year. REACH is the European Community Regulation on chemicals and their safe use. These "substances" must be registered and a dossier (a more extensive version of a Material Safety Data Sheet, MSDS) created. "Substances" also include any chemicals within "preparations" (e.g. cleaners, topcoats, primers, paint strippers etc.) and "articles" (components such as a part, wheeled vehicle or aircraft/missile). Vendors must register their "substances" with the European Chemicals Agency (ECHA) in Helsinki. The US Army cannot register substances. REACH will also designate some "substances" as "Substances of Very High Concern (SVHC)." Use of these "SVHCs" will have to be justified and can only be used if no other alternative exists or if banning the "SVHC" causes significant socioeconomic impacts within the EU. In the case of plating operations, certain chemicals (e.g. chromic acid) will not be able to be imported or manufactured without authorization.
- Restriction of Use of Certain Hazardous Substances in Electrical and Electronic Equipment" (RoHS), imposed by European regulations, places limits on the use of certain inorganic and organic chemicals, such as cadmium, hexavalent chromium, lead, and mercury.

Other requirements that impact surface finishing operations are policy letters issue by the DOD and Army. They are as follows:

- Memorandum from John Young, USD(ALT), to Secretaries of Military Departments, "Minimizing the Use of Hexavalent Chromium." This memorandum directs DOD military departments to invest in appropriate R&D, approve alternatives, update technical documents/specifications and implement alternatives to hexavalent chromium on DOD weapon systems. This memo also requires the appropriate PEO and Military Department's Corrosion Control and Prevention Executive to certify there are no acceptable alternatives to use of hexavalent chromium on new systems and procurements. Lastly, it required the

Defense Acquisition Regulation Council to prepare a clause for defense contracts prohibiting the use of hexavalent chromium in future procurements.

In summary, surface treatment operations are significantly regulated and pose risk to the sustainability of maintenance operations and warrant mitigation via alternative technologies.

2.0 TECHNOLOGY

2.1 TECHNOLOGY DESCRIPTION

Immersion Tagnite: The need for a superior chromate-free surface finish on magnesium led Technology Applications Group, Inc. (TAG) to develop silicon oxide-containing coatings which have markedly improved corrosion protection and abrasion characteristics relative to the more popular anodize and chromate chemical conversion coatings for magnesium. This silicon oxide coating has been given the trademark TAGNITE™.

The application of the TAGNITE coating as well as the performance characteristics are summarized in MIL-DTL-32459.

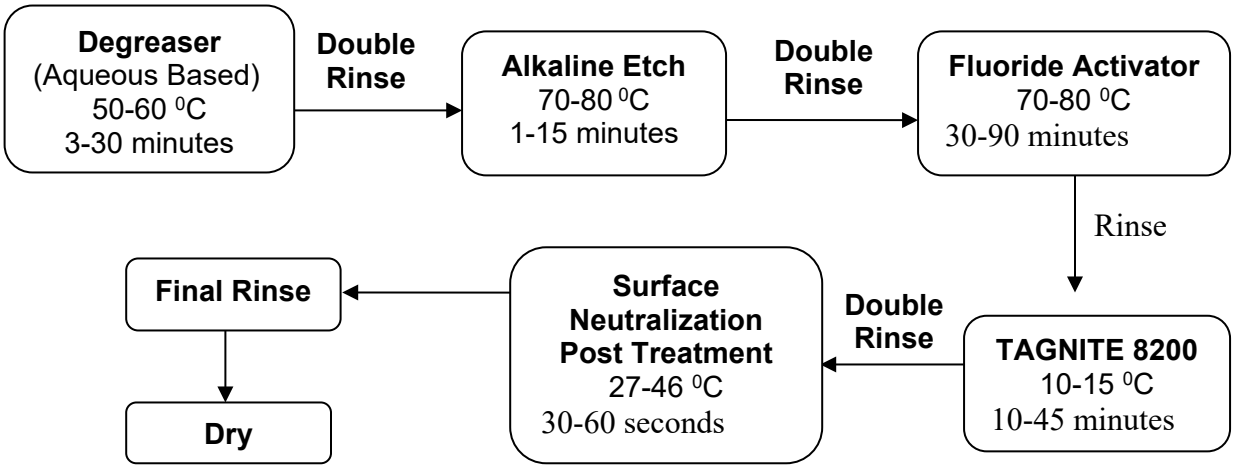


Figure 2: Process Flow Diagram of Immersion Tagnite Line

Typically, the degreaser and alkaline etch cleaning procedures shown in the process flow diagram (Figure 2) are sufficient to degrease and clean the surface. The coating process itself consists of two steps: (1) a chemical step which produces a barrier film coating which acts as an interface with the metal alloy and prepares the surface for the second step and (2) an electrodeposition step in which the magnesium alloy component is the anode in an electrolytic cell.

The first step in the Tagnite anodization process (Fluoride Activator) is a simple chemical process in which the magnesium alloy is immersed into a heated solution containing the fluoride ion. This solution chemically reacts with the magnesium surface to leave a layer containing a mixture of magnesium fluoride/oxofluorides and magnesium oxide which serves as a base for the second step. An added benefit of this chemical step is the removal of minor corrosion products.

The second step (Tagnite 8200) is an electrochemical process in which the magnesium component is made the anode in an electrolytic cell. The electrolytic process is accomplished

using a specially designed high voltage rectifier that supplies a combination AC/DC signal to the electrochemical cell. As in other anodization processes, the magnesium alloy is the anode while the stainless steel coating tank serves as the cathode. The electrolytic process involves the concurrent anodization or oxidation of the metal substrate and deposition of inorganic species from the silicate-containing electrolyte. As a result of the relatively high voltages, greater than 150V, a spark process develops during the deposition as seen in Figure 3.

Most finished magnesium castings have ferrous materials such as studs, liners and threaded inserts. Anodization involves the formation of an oxide layer on the surface of the magnesium component, in this case magnesium oxide (MgO) is formed. Steel, iron, stainless steel, brass, cadmium plating and other metals cannot be anodized. If any of these dissimilar metals is in contact with the Tagnite electrolyte during the anodization process, these metals will react vigorously with the charged electrolyte bath which leads to the rapid oxidation (i.e. rust formation) of the ferrous material. The highly conductive nature of these dissimilar metals and the high voltage/high current density conditions of the Tagnite anodization process will cause all of the power for the process to concentrate on the dissimilar metals. The result is the dissimilar metals will literally burn away as well as heavily damage the surrounding magnesium. Therefore, all ferrous material must be "masked off" or sealed off from electrolyte contact to prevent the selective oxidation of ferrous material.

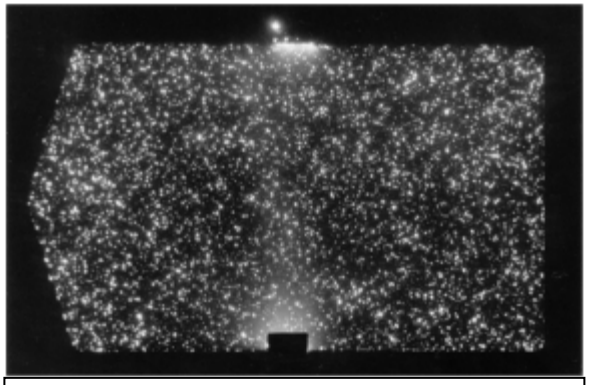


Figure 3: AZ91D magnesium panel during the Tagnite anodic spark deposition

The materials used for "masking" of dissimilar metal must meet the following criteria:

- Must be chemically compatible with the entire Tagnite process
- Must be able to handle large temperature extremes (36ºF to 180ºF)
- Must be easily removed after the Tagnite process and leave a residue-free surface

Following this criteria, the materials listed below have been evaluated and proven compatible with the Tagnite process:

- 6061 Aluminum
    - Used as racking (fixturing) material for Tagnite process
    - Used to make caps for threaded studs
    - Used to make covers for steel liners
- Silicone Rubber
    - O-rings for sealing aluminum covers
    - Gasket material for large surface masking (coupled with aluminum backer plates)
- UV curable maskant
    - For difficult to reach areas or difficult to seal by conventional means
- Siliconee Molding Material

- For specialized sealing of internal cores or drain holes



Figure 4: Typical masking of threaded studs

The easiest items to mask are studs and helicoils. The masking approach for studs was to manufacture threaded caps made from 6061 aluminum to be installed over the studs. An O-ring was installed at the bottom of the stud to prevent leakage on Tagnite electrolyte around the stud as seen in Figure 4. Non-threaded studs were masked using press-in aluminum plugs with O-rings. The press-in plugs were held in place using a "bridge" between two threaded studs. Helicoils were masked using threaded aluminum plugs and O-rings.

However, the primary technical challenge of applying Tagnite to used magnesium casting is the vast majority of these housings contain steel liners, inserts or bearing races. These types of steel inserts have non-threaded surfaces with overhangs or lips on the magnesium casing. The profile of these types of inserts have proven to be technically difficult to mask off or isolate in the past. However, TAG has developed a series of aluminum covers with O-rings to mask off these areas using variety of techniques including direct attachment to mating



Figure 5: H-64 Tail Rotor Gearbox:

Left: Bearing liner exposed

Middle: Aluminum cover in place

Right: Bridge in place to hold down liner cover

covers or use of aluminum “bridges” to hold covers in place (Figure 5). In addition, silicone molding material has been used to create custom molds that fit inside the liners to seal internal core passages and/or drain holes.

Regardless of the care taken in designing and installing masking tools, the masking process will leave small, uncoated areas around the ferrous inserts that must be treated. These uncoated areas are treated with a process known as Brush Tagnite.

Brush Tagnite is a handheld, selective anodization of magnesium castings using a brush or wand to deposit the Tagnite coating on areas that have been re-machined, scratched or left bare after Immersion Tagnite. The operator is able to selectively anodize the areas of exposed

magnesium without harming the exposed ferrous components. The Brush Tagnite electrolyte and rectifier waveforms were specifically developed to not harm ferrous components in case of contact while depositing a coating. In addition, the Brush Tagnite coating has superior corrosion protection compared to the chromate conversion coatings. Figure 6 is a close-up view of the application of the Brush Tagnite coating to a bare area on a magnesium aerospace casting.



Figure 6: Close-up of Brush Tagnite application to a bare area on a used magnesium aerospace casting

2.2 TECHNOLOGY DEVELOPMENT

The first military application of Immersion Tagnite was on the main transmission housing and tail rotor gearbox on the AH-64 Apache in 1993 [1]. In 1997, Tagnite was approved for use on the H-53 oil sump by Sikorsky. Immersion Tagnite has been in use on the new build Apache Helicopters since 2003 and has been implemented on the newest fixed wing platforms; F-22 Raptor and F-35 Lightning II. In August 2006, NAVAIR issued a memo of authorization allowing the use of Immersion Tagnite as a substitute for HAE or DOW 17 magnesium anodized coatings [2]. Brush Tagnite units have been at the Corpus Christi Army Depot (CCAD) since 2008. CCAD plating shop and gearbox artisans have been trained by TAG personnel on multiple occasions. Funding for Brush Tagnite development was obtained through Army Phase I and Phase II Small Business Innovation Research (SBIR) programs. The Phase 1 and Phase 2 results are summarized in two separate final reports [3,4].

The processing of legacy B-52 and KC-135 parts has been on-going at TAG for 8 years. Currently, TAG coats 22 parts for the B-52 and 17 parts for the KC-135. These parts do not have any dissimilar metal inserts or the inserts have been removed prior to arrival at TAG. The most difficult issue when dealing with these legacy parts is the removal of the old coatings. Great care must be taken to ensure that all paints and coatings are removed prior to the Immersion Tagnite process. TAG circulated a list of appearance criteria of the legacy components after removal of the legacy coatings to the overhaul shops doing this work. The removal method of the old coatings from the legacy coatings was determined by the shop(s) overhauling the legacy components so long as the surface finish of the legacy components met TAG's appearance criteria. It is TAG's understanding that the old coatings were removed by several different types of media blast.

The masking of new magnesium components with installed steel liners is currently done on a routine basis for three components on the F-35 Fighter and 18 components for a new commercial helicopter being made by Bell Helicopter. At the time of this proposal, TAG has masked and coated 80 sets of F-35 housings (3 components per housing) without a significant failure. In

addition, TAG has masked and coated three ship sets (a total of 54 individual components) for the Bell Relentless Commercial Helicopter with success.

Masking protocols and the successful coating on used magnesium components containing ferrous compounds have been completed on various gearbox components from the H-60 Blackhawk, H-64 Apache and H-47 Chinook. Development of masking protocols for Army helicopters was funded by Industrial Base Innovation Fund (IBIF III). Masking tools for magnesium components are developed specifically for each individual magnesium component and the masking tools must be developed and tested at TAG prior to demonstration. The results of the IBIF effort were summarized in a final report to ARL in 2013 [5].

2.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

The Immersion Tagnite coating process will be used in this dem/val phase as an alternate to the DOW 7 conversion coating currently used at the CCAD plating shop. Table 3 below lists the advantages and limitations of the Tagnite process.

The only prominent alternative technology to Tagnite is an anodize coating called Keronite. The technology has been approved as an alternate anodize coating to Tagnite by multiple OEMs as well as the DoD. At this point in time, the Keronite process has not had much acceptance with OEMs and the DoD due to processing inconsistencies and lack of any masking technology. There are numerous other Plasma Electrolytic Oxidation (PEO) processes for magnesium but none of these other processes have been approved by the military for magnesium aerospace parts.

Table 3: Tagnite Advantages and Limitations

Criteria	Immersion Tagnite with Masking		DOW 7	
	Advantages	**Limitations**	**Advantages**	**Limitations**
Cost		Higher manpower cost to install masking, applying Tagnite and unmasking	Lower manpower costs because no masking necessary and fewer processing steps to apply coating	
Military Performance	Superior corrosion protection which leads to longer component life cycle			Minimal corrosion protection leads to shorter component life cycle
Environment Issues	a. Tagnite baths contain no toxic or hazardous chemicals b. Tagnite coatings contain no toxic or hazardous chemicals c. Disposal costs are lower			DOW 7 bath and coatings contain hexavalent chromium (Cr^{6+}) which is targeted for removal from DoD facilities. Disposal costs are high due to toxic nature

3.0 PERFORMANCE OBJECTIVES

The performance objectives will be evaluated during two phases of this ESTCP project:

- JTP (detailed description in Appendix B)
- Demonstration phase at CCAD plating shop (detailed explanation is this section)

JTP Quantitative Performance Objectives: See Table 4

JTP Qualitative Performance Objectives: See Table 4

Table 4: Performance Objectives for JTP and Demonstration Phases

Performance Objective	Data Requirements	Success Criteria	Results
JTP Quantitative Performance Objectives			
Product Testing: Compatibility with Repair Techniques • Paint Adhesion Pull-off Testing • Galvanic Corrosion	• Paint Adhesion Testing per ASTM D 4541 • Galvanic Corrosion per ASTM G71	As described in JTP (Appendix B)	Testing was a success, Tagnite met or exceeded the benchmark
Product Testing: Stripping of Legacy Coatings • Dimensional change due to chemical stripping • Effect of chemical stripping process on Hydrogen Embrittlement of Steel	• Dimensional change measured by weight loss and micrometer measurement • Hydrogen embrittlement per ASTM F519-13, Reference 1c	As described in JTP (Appendix B)	• Dimensional change testing was successful • Hydrogen Embrittlement testing was a failure but no impact on processing parts
Product Testing: Brush Tagnite Qualification Testing • Paint Adhesion Pull-off Testing • Neutral Salt Fog • SO_2 Salt Fog • Outdoor Exposure • Galvanic Corrosion • Axial Fatigue	• Paint Adhesion Testing per ASTM D 4541 • Neutral Salt Fog Testing per ASTM B117 and ASTM D 1654 • SO_2 Salt Fog Testing per ASTM G-85, Annex A4 and ASTM D 1654 • Outdoor Exposure per written Statement of Work • Galvanic Corrosion per ASTM G71 • Axial Fatigue per ASTM E 466	As described in JTP (Appendix B)	Testing was a success, Tagnite met or exceeded the benchmark
JTP Qualitative Performance Objectives			
Product Testing: Stripping of Legacy Coatings	Visual inspection of condition of panel and/or magnesium aerospace component	As described in JTP (Appendix B)	• Chemical Stripping Testing

• Define chemical stripping process • Eliminate residual fluid leakage • Effectiveness of MIL-DTL-83936 Paint Stripper • Effect of chemical stripping process on Cad Plate Fasteners	by TAG scientists and technicians after treatments.		was a failure, alternate stripping methods were used • Residual Fluid, testing was successful • Paint Stripper was partially successful • Chemical Stripping Testing was a failure, process will remove Cad plating
Field Testing Quantitative Performance Objectives			
Solution Testing: Monitoring of Tagnite Baths to ensure stability and maintainability of Tagnite baths	• Chemical monitoring of Tagnite pretreatment and coating baths • Maintain Tagnite solutions to specification and process limits per chemical additions and/or bath replacement	• Analyses and/or chemical additions per TAG Lab Procedures Manual • Analysis Frequency and Operating limits per TAG Standard 7TS-020	• Both objectives were successful, written procedures and schedules were delivered and reviewed with CCAD Plating Shop chemists
Product Testing: Quality of Tagnite generated at CCAD plating shop • Neutral Salt Fog • Wear Resistance • Coating Adhesion Pull-off Testing • Paint Adhesion Pull-off Testing • Stability/Maintainability of Tagnite	• Neutral Salt Fog Testing per ASTM B117 and ASTM D 1654 • Wear Resistance Testing per ASTM D4060 • Coating Adhesion Testing per ASTM D 3359	Performance must meet or exceed the currently used processes at CCAD plating shop	

	• Paint Adhesion Testing per ASTM D 870 and ASTM D 3359		
Product Testing: Repeatability of Process • Show no dimensional loss or material loss (weight loss) after multiple overhaul stripping and recoating	• CMM at designated locations on magnesium component after each Tagnite/chemical stripping cycle • Weight loss measurement after each Tagnite/chemical stripping cycle		Chemical stripping was eliminated, therefore testing was not done
Product Testing: • No detriment to AH-64 ballistic liners	• Visual and optical inspection • Mechanical Testing on Test Coupons and/or scrap parts • Hardness per ASTM E18 • Elongation per ASTM D5278	Mechanical Testing must meet Boeing-Mesa specifications	No results, H-60 parts were used during Dem/Val and there were no ballistic liners involved.
Transition from SAFR (BER) parts to actual production components	Meet Airworthiness Qualification Criteria set by CCDC AvMC AMA-M	Meeting Product Testing Quantitative and Qualitative Criteria listed this table	Successful, CCAD engineers are writing MEOs to allow production to begin
Reduction of hazardous waste generated	• Raw materials usage, review of MSDS • Analysis of hazardous materials by EPA standard test number during demonstration	> 90 % reduction from current process	Unknown at this time, not enough parts processed to make determination
Field Testing Qualitative Performance Objectives			
Masking Evaluation: • No arcing on magnesium component • No material loss • Repeatability of process • Estimate Lifetime of Masking Tools	• Observation of arcing or material loss by visual and optical inspection • Repetitive use of masking tools without failure • Visual inspection of masking tools for signs of arcing/ metal loss/ gaps in sealing surfaces. Visual inspection of bolt threads for stripping or debris buildup on threads. Tracking of damaged masking		Successful, no arcing or metal loss observed after processing. Masking tools were used over 20 times without failure. Based on this, initial lifetime estimates of masking tools were made.

	tools in order to estimate masking tools lifetimes.		
Ease of Use • Masking Procedures • Masking Installation and Testing	Feedback from CCAD plating artisans on clarity of procedures, usability of technology and time required for masking installation and removal during demonstration		Successful, feedback was all positive. CCAD personnel were pleased with the written procedures and the training. There was no feedback on the time commitment to install and remove masking.

Field Testing Quantitative Performance Objectives:

1. Solution Testing (needed to operate Tagnite line with operating specifications and generate a high quality Tagnite coating):

Performance Objective – Teach CCAD plating shop chemists:

- The chemical overview of the Tagnite process,
- Provide and discuss the laboratory procedures necessary to maintain the Tagnite line solutions within specifications,
- Provide and explain the analysis frequency schedule(s)
- How to calculate the necessary chemical addition amounts
- When to replace a bath

Resources Provided:

- Manual explaining the chemistry for each pretreatment, anodize and post-treatment bath on the Tagnite line
- Detailed testing schedules (chemical analysis and product testing)
- Detailed laboratory procedures manual

Demonstration Success Criteria:

- CCAD chemists had to perform each individual laboratory procedure in the presence of TAG personnel
- CCAD chemists had to be able to show if the chemical components were within specification by calculating the chemical bath concentrations from the procedures and referencing the appropriate TAG standard to determine if the bath(s) was within operating parameters
- CCAD chemists had to show TAG personnel where to find the testing schedules and determine the analysis frequency.

Demonstration Success Score: 75 %

At the time of the demonstration/validation, the CCAD plating lab did not have all the chemicals and equipment to perform all of the chemical analyses. They were able to perform all of the daily analysis but several of the weekly/biweekly testing could not be performed. Detailed equipment and chemical lists were provided by TAG 6 months prior to the dem/val. CCAD stated the necessary chemicals and equipment were ordered but not received in time for the dem/val phase.

2. Product Quality Testing (testing of Tagnite coated panels to measure performance characteristics):

Performance Objective – Coat magnesium test panels on the Tagnite line at CCAD and determine the salt fog corrosion resistance, wear resistance, coating adhesion pull-off testing, paint adhesion pull-off testing. Monitor the stability and maintainability of the Tagnite baths.

Demonstration Success Criteria:

- Performance of Tagnite coated test panels must meet or exceed the performance of the currently used processes at CCAD. The currently used processes are DOW 7 and DOW 19.

Demonstration Success Score: 80 %

- The Tagnite coated panels ***exceeded*** the wear resistance and salt fog performance of the DOW 7 and DOW 19 coated panels.
- The Tagnite coated panels ***met*** the coating and paint adhesion performance of the DOW 7 and DOW 19 coated panels.
- The limited time frame of the dem/val did not allow enough time to collect stability/maintainability data on the Tagnite baths at CCAD.

3. Product Testing (collect data on the repeatability of the chemical stripping/Tagnite process):
Performance Objective – Intent was to use CMM at designated locations on each magnesium component after each Tagnite/chemical stripping cycle to measure the dimensional change over the course of the process.
Demonstration Success Criteria:

- CMM measurements will be in the acceptable dimensional change specification in the DMWR. Determine if the Tagnite/chemical strip process was consistent and repeatable from a dimensional loss standpoint.

Demonstration Success Score: Not Done

- As stated in the JTP (Appendix B), the Tagnite chemical stripping process was not used during the dem/val due to its inability to remove anodize coatings that had Rockhard or other organic coatings embedded in the porosity of the anodize coatings.

4. Product Testing (no adverse effect to the performance of the AH-64 ballistic liners):
Performance Objective – While the Tagnite process will not affect the properties of the AH-64 ballistic liners, there was a strong concern that the high temperature cure range (365 – 375^{o}F) of the Rockhard sealant that needs to be applied after the Tagnite would have an adverse effect on the hardness of the steel liner. Prior to this project, only a DOW 7 chromate conversion coating followed by a Low Temperature Cure Rockhard (Curing temperature $\leq$ 250^{o}F) was allowed to be used on overhauled AH-64 magnesium components.
Demonstration Success Criteria:

- Perform mechanical testing on a ballistic steel liner per Boeing-Mesa specifications after undergoing an extended Rockhard cure cycle.

Demonstration Success Score: Not Done

- After discussions with Boeing-Mesa material engineers about this testing, Boeing-Mesa would not sign off on the testing. As a result, the AH-64 magnesium housings were removed from the priority list and replaced with three (3) H-60 components that do not have ballistic steel liners.

5. Transition from SAFR (BER) parts to actual production components:
Performance Objective – If priority parts coated during the dem/val phase meet the Airworthiness Qualification Criteria set by CCDC AvMC AMA-M, how soon will this process transition to production parts.
Demonstration Success Criteria:

- Meet Airworthiness Qualification Criteria set by CCDC AvMC AMA-M.

Demonstration Success Score: 100 %

- Engineers present during the dem/val phase were extremely pleased at the quality of the parts coated in the Tagnite process after undergoing the masking process. They recommended that the three priority parts be transitioned to production. At this time, MEOs have been written and are being circulated for review. Once the MEOs are signed off, production parts can begin to processed through the Tagnite line. Anticipated production startup date is 1st Quarter of 2019.
- Engineers from the AH-64 program have submitted a list of three (priority parts) that they would like to have processed through the Tagnite line as quickly as possible due to a parts shortage.

6. Reduction of Hazardous Waste Generated:

Performance Objective – To quantify the reduction in hazardous materials (primarily hexavalent chrome) by analysis per EPA standard test numbers during demonstration.

Demonstration Success Criteria:

- > 90 % reduction in hazardous materials usage during the demonstration.

Demonstration Success Score: 25 %

- Review of the MSDS/SDS of the chemicals used in the Tagnite process by CCAD Health and Safety along with AMCOM G-4, gave US Army personnel a high confidence level that hexavalent chrome levels will be drastically reduced by replacing the DOW 7 and DOW 19 processes with the Tagnite process.
- Monitoring of chromium levels at the Tagnite facility in Grand Forks, ND showed extremely low levels of chromium in the waste stream and only a minor buildup in the fluoride activator tank which is never dumped.
- Due to the very limited number of parts processed during the dem/val process, very little analytical information was obtained.

Field Testing Qualitative Performance Objectives

1. Masking Evaluation:

Performance Objective – To visually inspect parts after Tagnite processing for signs of damage to the steel components due to failure of the masking tools or damage to the magnesium component due to an adverse event such as arcing or material loss. In addition, evaluate repeatability of the masking process and estimate lifetime of the masking tools.

Demonstration Success Criteria:

- No rust or damage to steel components after Immersion Tagnite and removal of the masking tools.
- Repetitive use of the masking tools without any failures.
- No visual damage of the masking tools or priority parts after Tagnite

Demonstration Success Score: 80 %

- Masking tools were applied to the priority parts over fifteen (15) times during the dem/val phase and a 1 week follow-up training session. There

were no failures with any of the large covers or bolts. In addition, there was no damage to any of the steel liners.

- There was damage to two (2) small, replaceable steel inserts during the first week of the dem/val due to a masking failure. The masking installation procedure was modified and there were no more failures.
- There was two (2) liner bolts that were stripped during training due to artisan inexperience. Replacement bolts were supplied with the masking kits and the training was modified to prevent a reoccurrence.
- Initial masking lifetime estimates were obtained. Large covers are very robust and can last a minimum of twenty-five (25) uses before needing replacement. Larger bolts have a shorter lifetime of 8 – 15 uses before needing replacement. Small bolts with fine threads will only last 4 – 6 uses before the threads become clogged with dried Tagnite and are unusable.

2. Ease of Use (Masking Tools and Tagnite Process):

Performance Objective – To gather feedback from CCAD plating shop artisans on the clarity of the procedures, parts lists, ease of use of the masking technology/Tagnite process and the time requirements for installing/removing the masking tools.

Demonstration Success Criteria:

- Based entirely on feedback from the artisans.

Demonstration Success Score: 100 %

- Masking procedures: Feedback was entirely positive – the artisans felt that the procedures were well written and easy to follow. They really liked the 1 page masking summaries with a list of masking parts and tools needed to install the masking tools.
- Masking installation: Artisans felt that the installation process was straight forward and required less time to apply than some of other parts that need to be masked for other plating processes.
- According to the artisans, the Tagnite process was simple and straight forward with a minimal number of processing steps.
- There was no negative feedback on any of the masking requirements or Tagnite processing requirements. The majority of the artisans were excited to get this new process and to eliminate time spent near or around any chromate tanks.

4.0 SITES/PLATFORM DESCRIPTION

4.1 TEST PLATFORMS/FACILITIES

The selected demonstration site for this project is the Corpus Christi Army Depot (CCAD) plating shop. They have a decommissioned plating line (known as the D Line). The criteria for selecting the CCAD plating shop are:

- TAG has a long standing relationship with the CCAD plating shop as they were the first military facility to accept a Brush Tagnite touchup unit. TAG personnel have been in this facility on numerous occasions for Brush Tagnite recertification of the plating shop artisans and have developed a strong working relationship with shop and lab personnel
- The CCAD is the primary overhaul facility for the Army Aviation rotary platforms - AH-64 Apache, UH-60 Blackhawk and CH-47 Chinook. They have extensive knowledge and experience in all steps of the overhaul phase on magnesium gearboxes on these platforms including removal of old coatings and application of new coatings and paints.
- The unused D-line at the CCAD plating shop is ideally suited for retrofit as a Tagnite line. This line is configured with the correct amount of tanks, ventilation, heaters and anodization hookups therefore no extensive modifications are needed thereby minimizing capital costs. In addition, all the needed utilities and waste disposal are readily available on site.
- This project has the complete support of the CCAD plating shop management and shop personnel as well as the base command.

The test platform will be the UH-60 Blackhawk. This helicopter platform was chosen because:

- This helicopter platform has already been approved for the use of Immersion Tagnite and Brush Tagnite on magnesium components by the OEM.
- Magnesium components from these platforms were used during the IBIF effort to prove the feasibility of dissimilar metal masking and application of the Tagnite to legacy components. As a result, there is the added benefit of using previously developed masking kits in order to minimize costs for this project.
- The UH-60 components do not have ballistic liners. The lack of ballistic liners will allow for the use of high temperature Rockhard clear sealant application after Tagnite. The high temperature Rockhard will greatly enhance the corrosion resistance of the magnesium components when applied over Tagnite.

4.2 PRESENT OPERATIONS

The current process for treating magnesium aerospace components is:

1. Degrease
2. Glassbead Blasting (If necessary)
3. Bifluoride Pickle
4. Type III (DOW 7) Conversion Coating
5. Rinse and Dry

A process flow diagram for the current process is shown below in Figure 7.

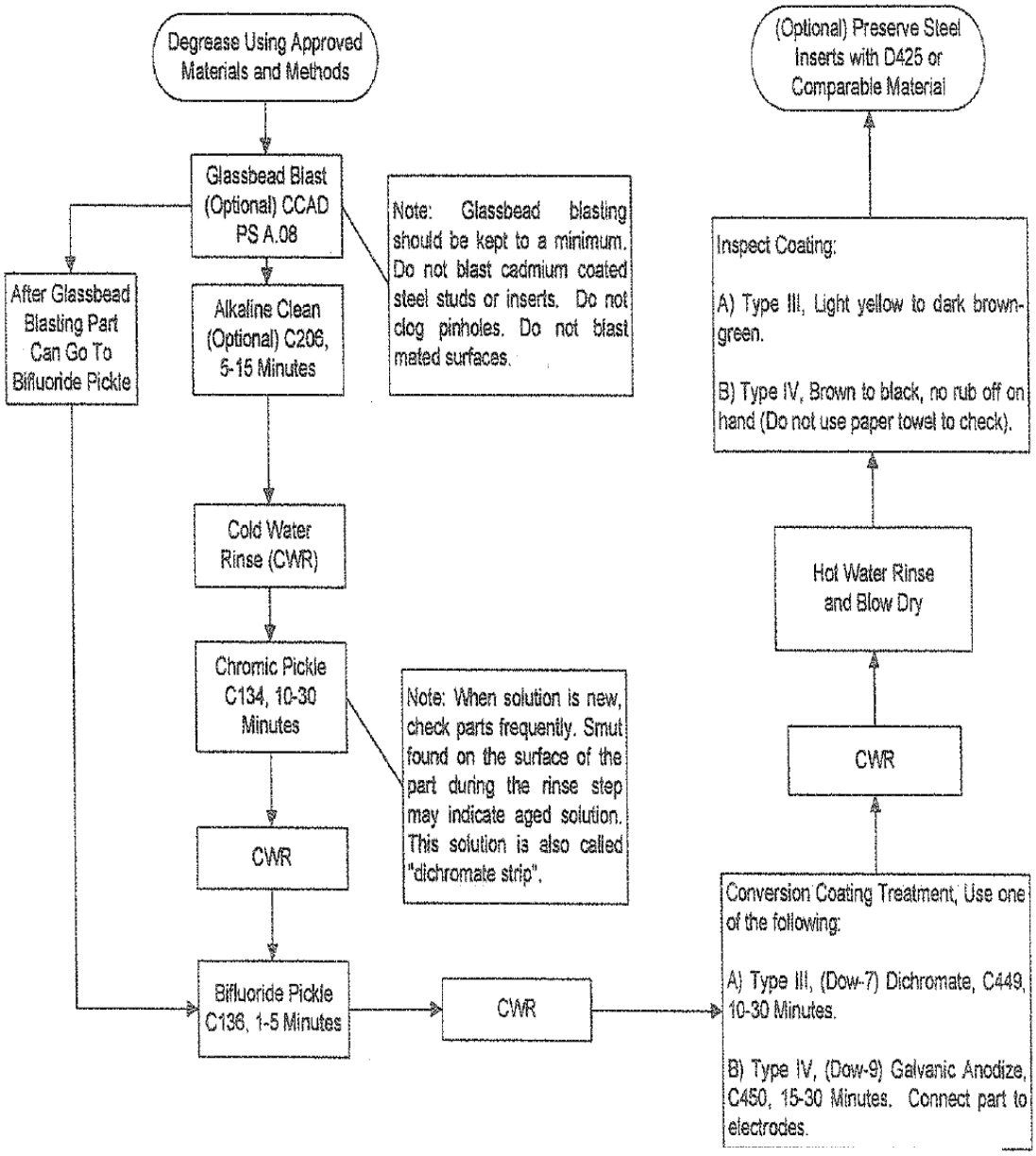


Figure 7: CCAD Process Diagram for Type III and IV Chrome Conversion Coatings

The biggest drawback to this process is the use of the Type III (DOW 7) conversion coating. This bath contains 6.2 % (by weight) hexavalent chromium (Cr^{6+}). In addition, the DOW 7 bath is operated at the boiling temperature and the magnesium component must be submerged in this bath for 10 -30 minutes. The toxic effects of exposure to hexavalent chromium are well documented and the protective characteristics of the DOW 7 coating on magnesium are minimal at best. The principle benefit of this process is the DOW 7 is compatible with the dissimilar metals in the magnesium, thereby eliminating the need to mask off these dissimilar metals.

The primary purpose of the demonstration/validation project at the CCAD plating shop is to replace the Bifluoride Pickle/Type III (DOW 7) baths with a Tagnite anodize coating line. A secondary hope is the Tagnite chemical stripping process will replace the need for glassbeading or chromic acid strip (another hexavalent chrome containing bath).

The Tagnite line was placed in the CCAD plating shop in a unused production line known as the "D-Line". Figure 8 shows the D-Line in its decommissioned state prior to the Tagnite retrofit. The decommissioned line configuration, tank material and heating/cooling capabilities are shown in Figure 9. The proposed modifications to the D-Line are summarized in Figure 10 and Table 5 is a description of the Tagnite process stream after the CCAD D-Line retrofit.

Capital Equipment: Figures 11 – 14 show the new capital equipment installed at the CCAD plating shop in order to complete the D-Line conversion into a Tagnite anodization line.

Table 5: The Tagnite Process Stream in the CCAD D-Line

Tank Number	Solution Type	Chemical Composite	Maintenance Needs
D-1	Mild Alkaline Etch	Borax and Sodium Pyrophosphate	Periodic chemical additions. Bath replacement every 6 – 8 months dependent on usage
D-4	Fluoride Activator	Proprietary Formula	Periodic chemical additions. Bath will last indefinitely
D-7	Tagnite	Mixture of Potassium Salts: Hydroxide, Fluoride, Silicate	Bath replacement every 20 – 45 days dependent on usage.
D-10	Phosphate Post-treatment	Sodium Dihydrogen Phosphate	Periodic chemical additions. Bath will last indefinitely.



Figure 8: CCAD Plating Shop D-Line Prior to Conversion to Tagnite.
(Left) Start of the D-Line at Tank D-1. (Right) End of the line at Tank D-13.

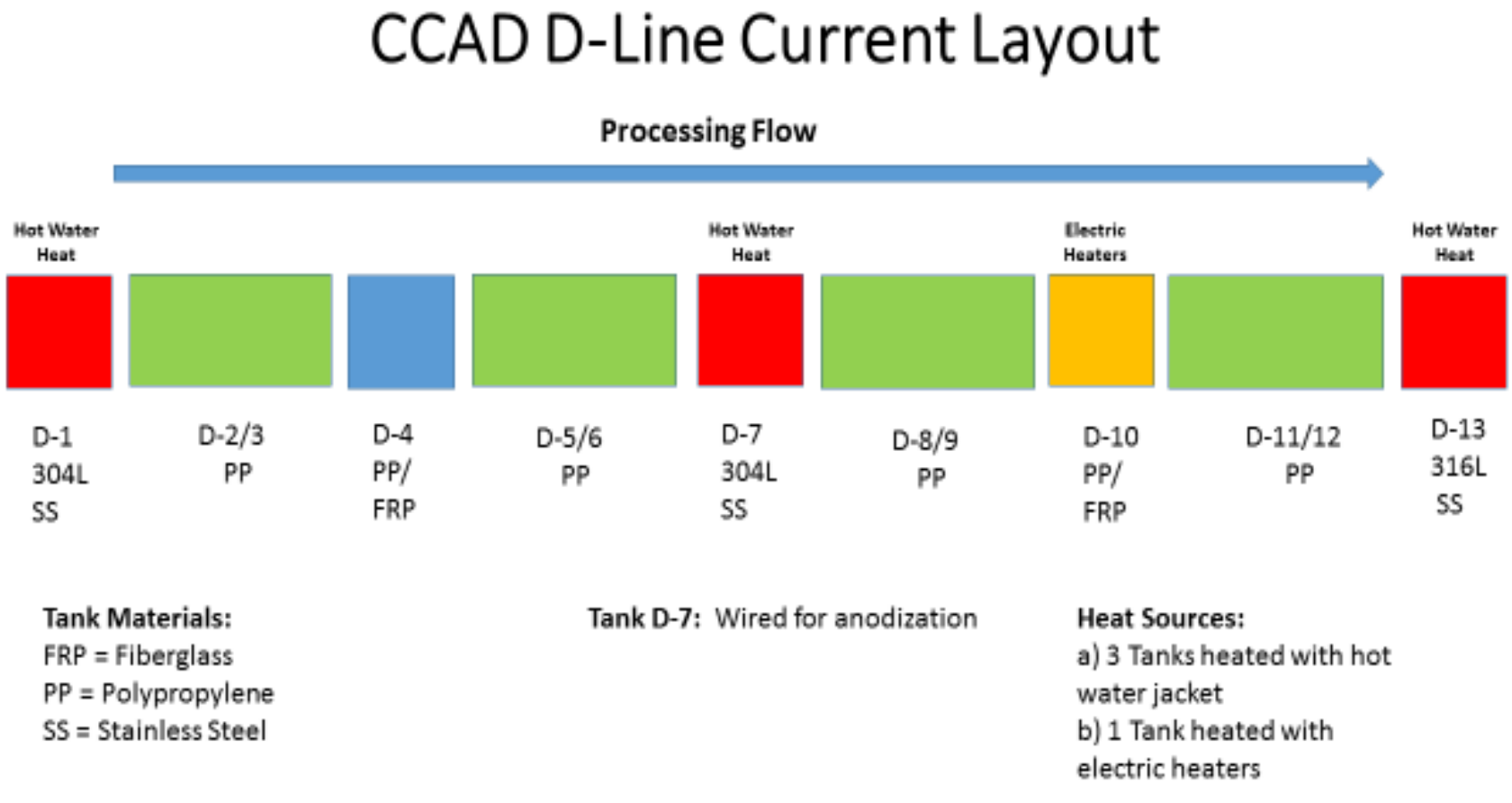


Figure 9: CCAD D-Line Original Layout

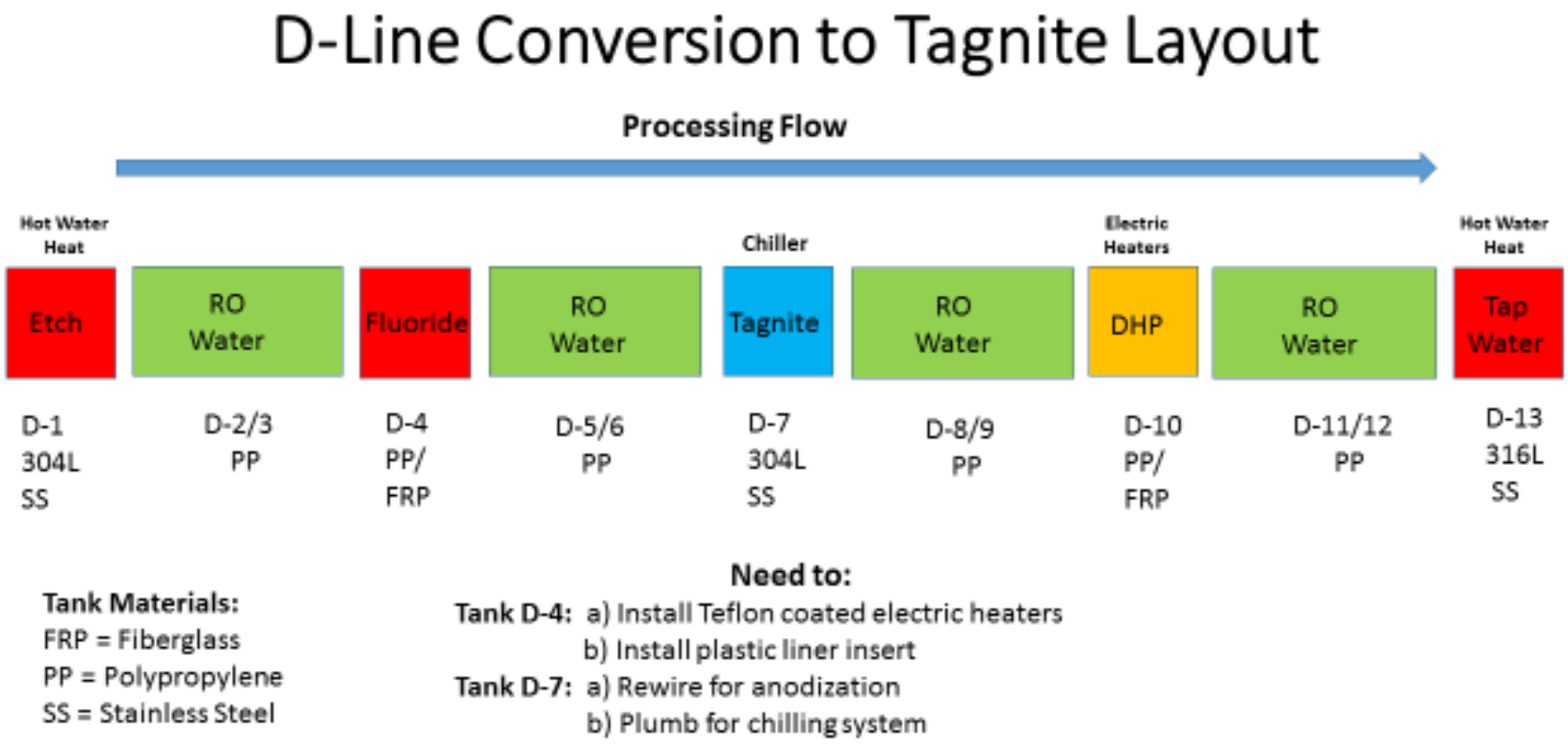


Figure 10: Tagnite Conversion Layout of CCAD D-Line

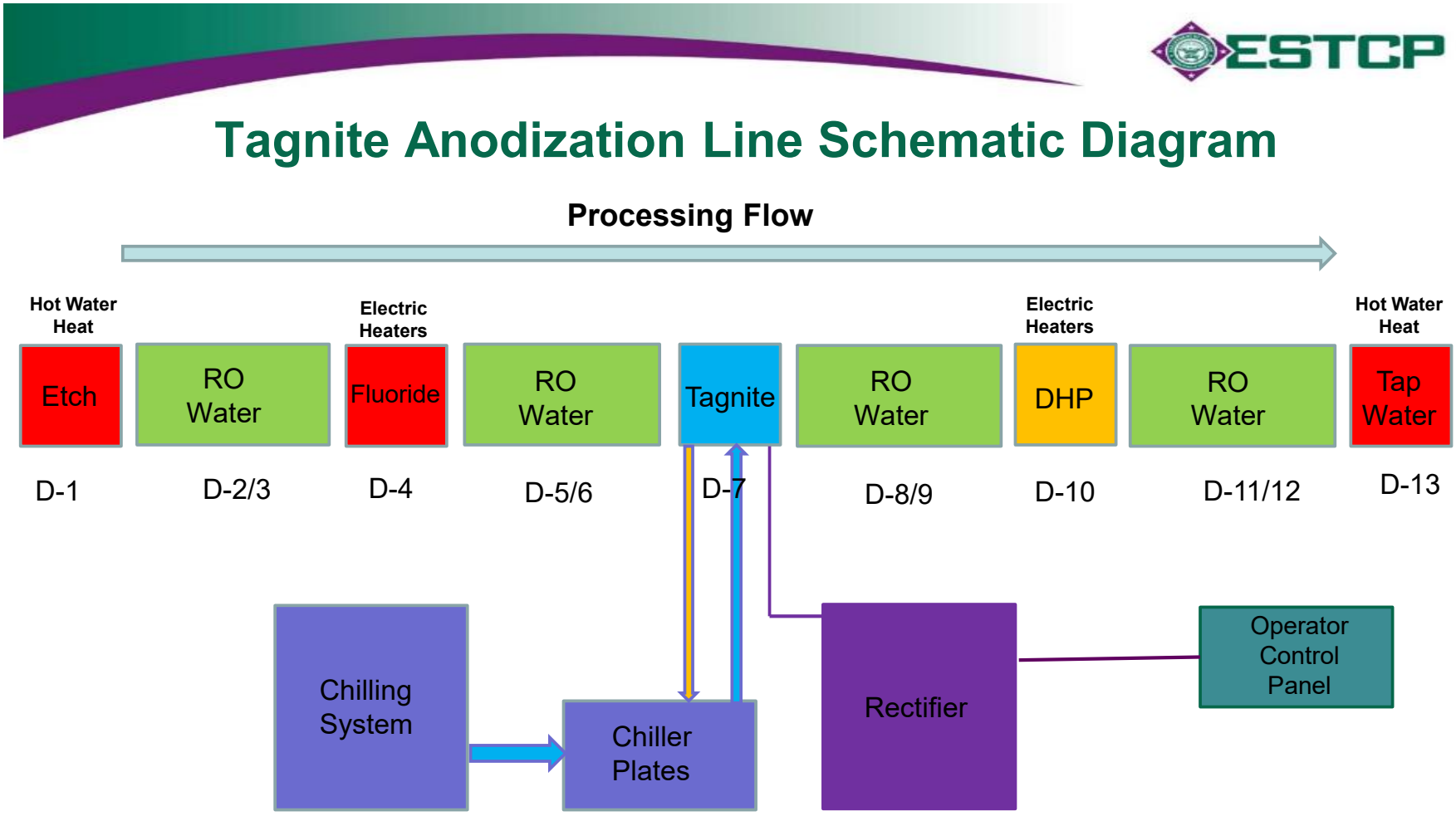


Figure 11: Tagnite Line Schematic with Capital Equipment Needed

ESTCP

Tagnite Tank (D-7) after Modifications



Modifications:

1. New Tank D-7 was constructed from stainless steel.
2. Outside and upper portions of tank were lined with plastic to prevent accidental operator contact with steel.
3. Safety gate on front of tank with interlock. Gate must be in the upright position (as seen in the picture on the left) and interlock must be engaged before rectifier can be turned on.
4. To the left of the safety gate is the process control panel that controls:
   - Heaters for Tank D-4 (Fluoride Activator)
   - Pumps for Tank D-7 (Tagnite)
   - Rectifier
   - Chilling System

Figure 12: Tagnite Capital Equipment – New Tagnite Tank with Process Control Panel

Capital Equipment Upgrades Needed For CCAD D-Line

1. New Rectifier

Due to the higher voltages needed for the Tagnite process, a new rectifier was purchased and installed on the first level of the CCAD Plating Shop, one floor below the D-Line.

a) In order to supply the incoming electrical needs of the rectifier (450 V, 200 A), new electrical lines were run from the main breaker box at the CCAD Plating shop to the new rectifier location.

b) Due to the potential for flooding on the bottom level of the CCAD Plating Shop, the rectifier was placed on an evaluated steel base that is 18" high.



Figure 13: Tagnite Capital Equipment – New Rectifier

Capital Equipment Upgrades Needed For CCAD D-Line

2. New Chilling System

Due to the heating of the Tagnite electrolyte during the Tagnite process, the electrolyte must be chilled to maintain the proper temperature range for the Tagnite anodization process. In order to accomplish this, a chilling system was designed and installed at CCAD.

a) The chilling system compressors were installed outside of the CCAD plating shop.
   a) Prior to installation, a concrete pad was poured to provide the support for the chilling unit.
   b) A security fence was installed after the chilling system was in place.
b) The heat exchanger plates, pumps and glycol storage tank were mounted on skid and placed next to the rectifier on the first level of the CCAD plating shop.





Figure 14: Tagnite Capital Equipment – Chilling System

4.3 SITE-RELATED PERMITS AND REGULATIONS

All needed permits and regulations are in place at the CCAD plating shop.

5.0 TEST DESIGN

5.1 JTP

5.1.1 Tagnite compatibility with current magnesium aerospace component repair techniques.

Rationale for the testing: There are several current magnesium repair techniques that are performed in the field or at the depot level that have not been tested for compatibility with the Immersion Tagnite/Brush Tagnite processes. In addition, one potential repair technique, aluminum cold spray, will be evaluated as well. These repair techniques are used to fill corrosion pits, porosity in the casting and/or restore dimensional loss due to corrosion or excessive wear. The repair techniques to be evaluated are:

- DEVCON Liquid Aluminum
- DEVCON Titanium Paste
- Tungsten Inert Gas (TIG) Weld Repair
- High Velocity Oxy Fuel (HVOF)
- Aluminum (6061) Cold Spray

DEVCON Liquid Aluminum F5 is an aluminum-filled pourable epoxy used to repair shallow corrosion pits. The product is applied using a wooden craft stick or plastic spatula. The product will harden in just over 1 hour. Total cure time is 16 hours. After curing, the product can be machined and/or blended via mechanical means.

DEVCON Titanium Paste is a titanium-reinforced pourable epoxy used to repair shallow corrosion pits. Application, machining and blending are similar to the Aluminum F5 product.

Tungsten Inert Gas (TIG) welding is an arc welding process that uses a non-consumable tungsten electrode to produce a weld. The ZE41-T5 magnesium panels will be repaired using ZE41 welding rods to fill the defects. TIG welding is used to fill in magnesium casting surface porosity.

High Velocity Oxy Fuel (HVOF) is one of the thermal spraying techniques in which melted materials are sprayed onto a magnesium surface. This technique is used to repair severe corrosion loss or dimensional loss due to excessive wear. For this project, the feedstock will be Al-12Si and the oxy-fuel will be propane. The application process and quality control parameters will be followed per Sikorsky SS8491.

Aluminum Cold Spray is another thermal spray technique that has been used to repair porosity and dimensional loss on magnesium castings. For the JTP testing, 6061 Aluminum will be spraying using a high pressure machine and helium gas. The application process and quality control parameters will be followed per MIL-STD-3021.

These repair techniques will be evaluated using test coupons made from ZE41-T5 magnesium alloy, then progressing to scrap magnesium housings, if necessary. The ZE41-T5 test coupons are cut and machined from sand cast blocks. The finished test coupons are 4" x 6" x 0.2" (width x length x thickness) with a surface roughness not to exceed 125 µinches. Repair defects will be machined into one 4' x 6" surface. The orientation and length of this defects are shown in Figures 15 - 17. These evaluations will start by filling the defects in the test panels with the different repair materials. After blending or re-machining the repair areas, the test coupons will receive one of four magnesium pretreatment coatings. These coating involve the application of two of the currently used magnesium pretreatment coatings (DOW 19 and TCP) along with the Immersion Tagnite and Brush Tagnite coatings to the magnesium test coupons followed by 1 coat of MIL-PRF-23377.

DOW 19 is a hexavalent chromate conversion used to touch up magnesium surfaces prior to paint application. The DOW 19 application process is described in AMS-M-3171 Type VI. This process involves brushing the DOW 19 liquid onto the magnesium surface and letting it stand for 1 – 3 minutes until a brown film forms on the surface. The panels are rinsed with cold, running water. Dried in an oven or by exposure to blast of hot air. The DOW 19 liquid is a mixture of Chromic Acid (CrO_3) and Calcium Sulfate ($Ca_2SO_4 \cdot 2H_2O$).

TCP (Trivalent Chromium Preservative) is a hexavalent chrome-free chemical conversion coating developed by NAVAIR. The application process and performance characteristics are described in MIL-DTL-81706B and MIL-DTL-5541F. This process involves the immersion of the magnesium component in a tank containing the propriety chemicals containing trivalent chromium salts mixed with RO or DI water. The immersion time is typically 20 minutes at a temperature of 65-120^{o}F. The magnesium components are rinsed with cold, running water then dried in an oven or by exposure to blast of hot air.

Immersion Tagnite: The need for a superior chromate-free surface finish on magnesium led Technology Applications Group, Inc. (TAG) to develop silicon oxide-containing coatings which have markedly improved corrosion protection and abrasion characteristics relative to the more popular anodize and chromate chemical conversion coatings for magnesium. This silicon oxide coating has been given the trademark TAGNITE^{TM}.

The application of the TAGNITE coating as well as the performance characteristics are summarized in MIL-DTL-32459.

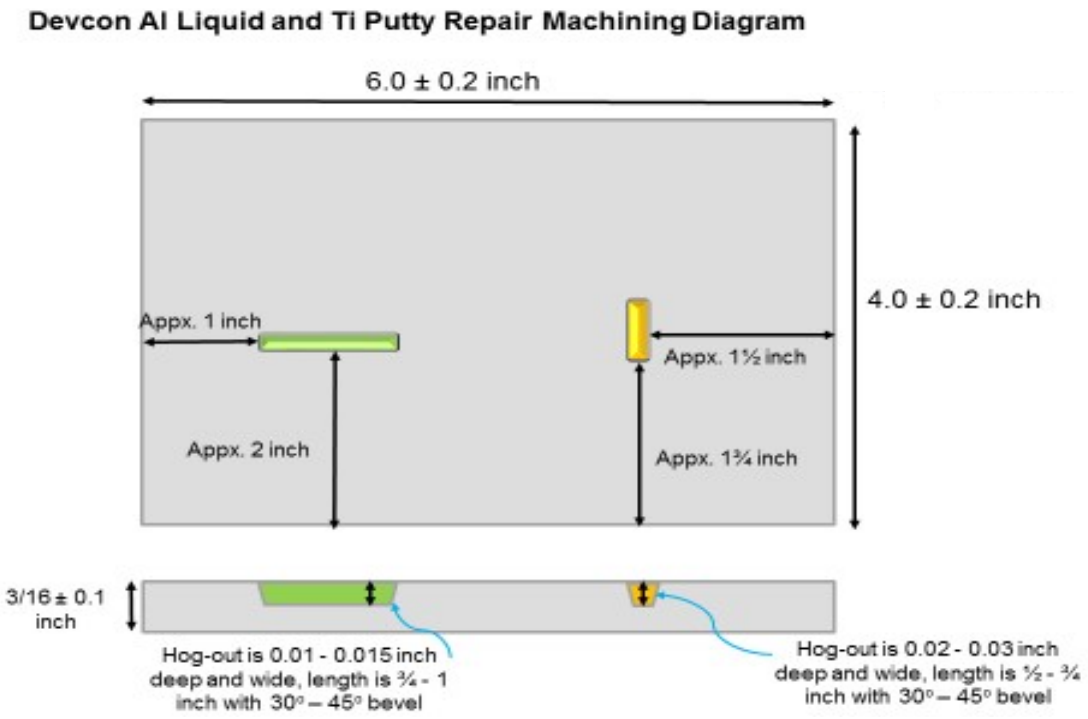


Figure 15: Machining of Defect into Panel for Devcon Al Liquid and Ti Putty Repair

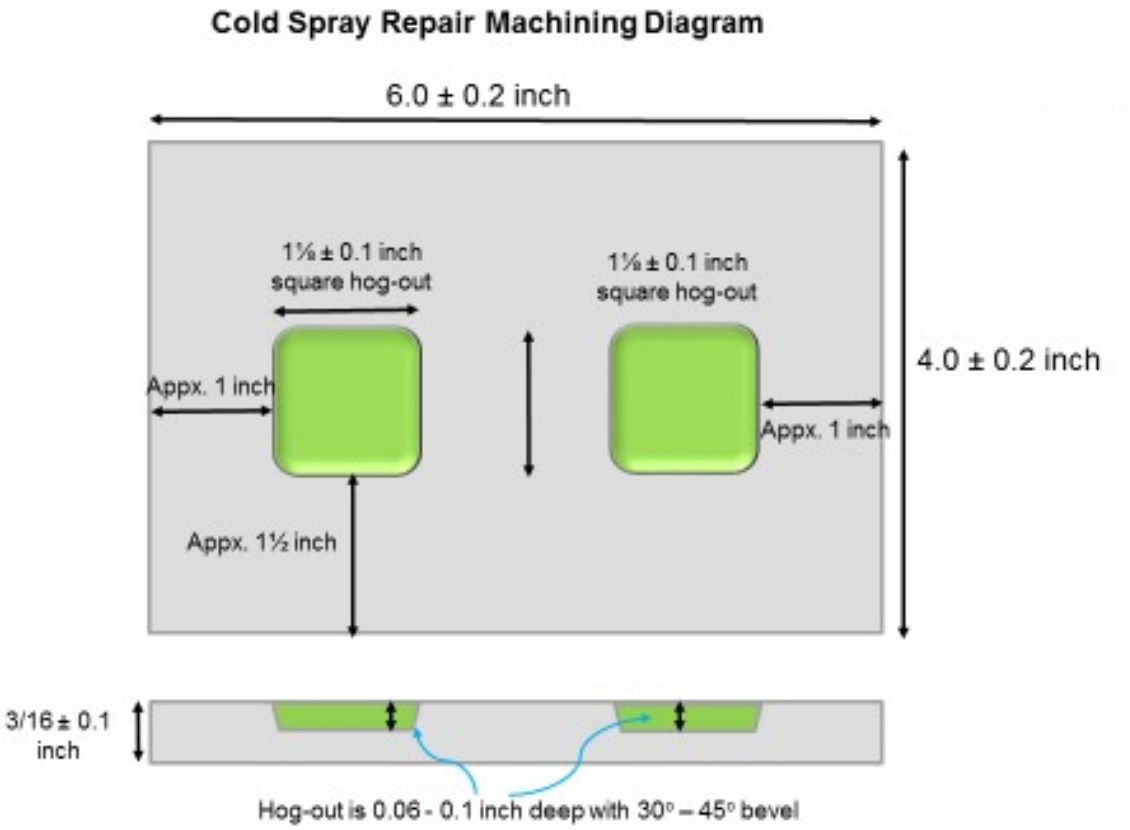


Figure 16: Machining of Defect into Panel for Cold Spray Repair

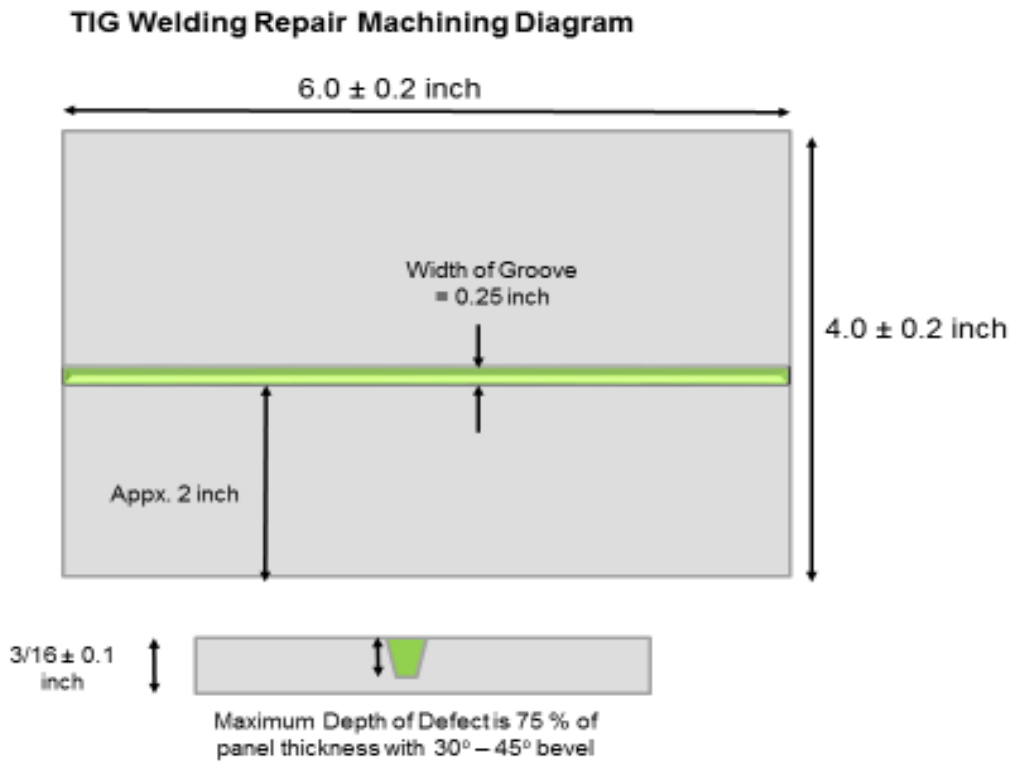


Figure 17: Machining of Defect into Panel for TIG Weld Repair

Typically, the cleaning procedure shown in the process flow diagram (Figure 18) is sufficient to degrease and clean the surface. The coating process itself consists of two steps: (1) a chemical step which produces a barrier film coating that acts as an interface with the metal alloy and prepares the surface for the second step, (2) an electrodeposition step in which the magnesium alloy component is the anode in an electrolytic cell.

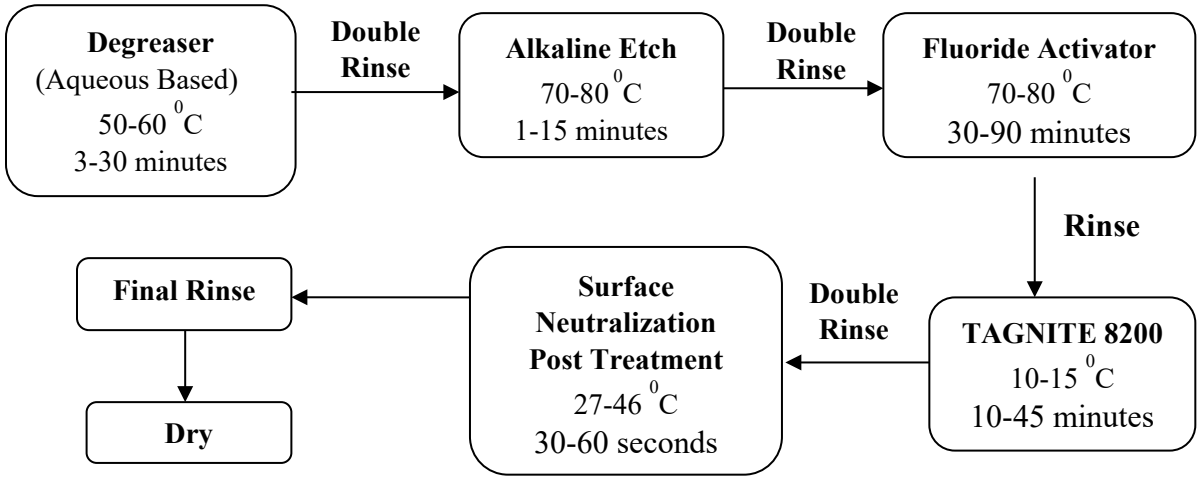


Figure 18: Process Flow Diagram of Immersion Tagnite Line

The first coating step (Fluoride Activator) is a simple chemical process in which the magnesium alloy is immersed into a heated solution containing the fluoride ion. This solution deposits a layer on the magnesium substrate that contains a mixture of magnesium fluoride/oxofluorides and magnesium oxide which serves as a base for the second step. An added benefit of this chemical step is the removal of minor corrosion products.

The second step (Tagnite 8200) is an electrochemical process in which the magnesium alloy is made the anode in an electrolytic cell. The electrolytic process is accomplished using a specially designed high voltage rectifier that supplies a combination AC/DC signal to the electrochemical cell. As in other anodization processes, the magnesium alloy is the anode while the stainless coating tank serves as the cathode. The electrolytic process involves the concurrent anodization or oxidation of the metal substrate and deposition

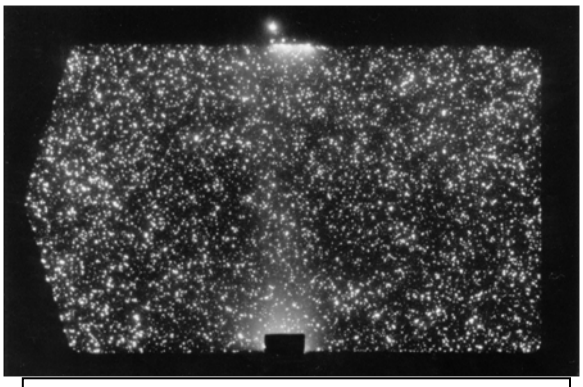


Figure 19: AZ91D magnesium panel during the Tagnite anodic spark deposition

of inorganic species from the silicate-containing electrolyte. As a result of the relatively high voltages, greater than 150V, a spark process develops during the deposition as seen in Figure 19.

Brush Tagnite is a handheld, selective anodization of magnesium castings using a brush or wand to deposit the Tagnite coating on areas that have been re-machined, scratched or left bare after Immersion Tagnite. The operator is able to selectively anodize the areas of exposed magnesium without harming the exposed ferrous components. The Brush Tagnite electrolyte and rectifier waveforms were specifically developed to not harm ferrous components while depositing a coating that has superior corrosion protection compared to the chromate conversion coatings. Figure 20 is a close-up view of the application of the Brush Tagnite coating to a bare area on a magnesium aerospace casting.

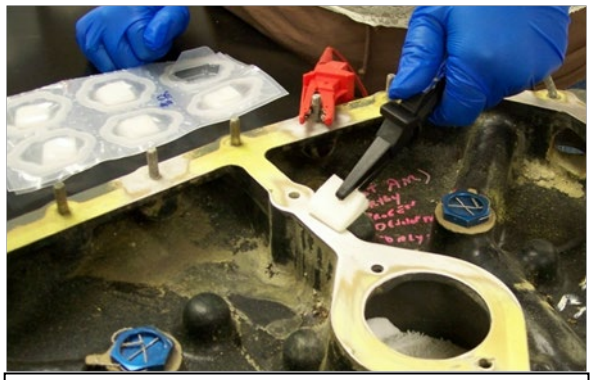


Figure 20: Close-up of Brush Tagnite application to a bare area on a used magnesium aerospace casting

The quality control procedures used to monitor the Immersion Tagnite and Brush Tagnite processes are coating thickness, visual appearance, electrical continuity, salt fog corrosion, wear resistance and paint adhesion. The testing and performance criteria for each of these parameters is detailed in MIL-DTL-32459.

5.1.1.1 Pull-off Adhesion:

Rationale for Testing: The magnesium pretreatments to be tested will leave a coating on the magnesium substrate and the repair area. It is important to determine how well these coatings adhere to the repair areas and how well paint or primer adhere to the repair area. MIL-PRF-23377 non-chromated primer will be sprayed over the entire panel.

ZE41-T5 test coupons will be coated with the four different types of magnesium pretreatment coatings: DOW 19, TCP, Immersion Tagnite and Brush Tagnite. During the Immersion Tagnite and Brush Tagnite coating process, the repair areas will be monitored for softening or lifting to determine if these metal fillers are degraded by the Tagnite pretreatment processes or the anodization step. After the application of the four different coatings, all the panels will receive one coat of MIL-PRF-23377 non-chromated primer. The test matrix is summarized in Table 6.

After primer application, the panels will be tested for pull-off adhesion from the repair area per ASTM D 4541. There will be two testing locations on each panel. Any adhesion failures will be documented such as failure at the repair/coating interface or the coating/primer interface.

Test Description: The Paint Adhesion Test (ASTM D 4541) evaluates the pull-off strength of a coating from metal substrates. The test determines the greatest normal force a coated surface can

bear before a plug of material is detached. The test may also determine whether or not the surface remains intact at a fixed prescribed force.

The Paint Adhesion Test is performed by securing a loading fixture normal to the surface of the coating with an adhesive. After the adhesive is cured, a testing apparatus is secured to the loading fixture. The force on the loading fixture is gradually increased and recorded until the surface fails or a predetermined value is reached. Pull-off strength is calculated based on the maximum load, instrument calibration data, and the tested surface area.

Table 6: Pull-off Adhesion for Repair Compatibility Testing

Repair Description	DEVCON Aluminum Liquid F2	DEVCON Titanium Paste Filler	TIG Welding	Aluminum Cold Spray (6061)	HVOF Spray Coating
Magnesium Alloy	ZE41-T5	ZE41-T5	ZE41-T5	ZE41-T5	ZE41-T5
Panel Pretreatments	DOW 19 TCP Immersion Tagnite Brush Tagnite	DOW 19 TCP Immersion Tagnite Brush Tagnite	DOW 19 TCP Immersion Tagnite Brush Tagnite	DOW 19 TCP Immersion Tagnite Brush Tagnite	DOW 19 TCP Immersion Tagnite Brush Tagnite
Organic Coating	1 Coat of MIL-PRF-23377				
# of Coupons per Pretreatment	3	3	3	3	3
# of Tests per Coupons	2	2	2	2	2
Experimental Control Panels	DOW 19	DOW 19	DOW 19	DOW 19	DOW 19
Acceptance Criteria	Primer Pull-off adhesion strength that is a good or better than DOW 19 Pretreatment				

5.1.1.2 Galvanic Corrosion:

Rationale for Testing: The repair techniques to be used during this testing all contain different metals than magnesium. When dissimilar metals are in contact, there is the potential for a galvanic corrosion cell to form. Applying the four magnesium pretreatment coatings over the repairs may minimize the galvanic interaction. Testing will occur to measure the galvanic interaction between the repair areas and the applied coatings.

The galvanic corrosion behavior of the four magnesium pretreatment coatings will be tested after the coatings are applied to coupons that have received the five (5) different repair techniques. The 4" x 6" ZE41-T5 test coupons will have the same defects machined into one surface of the test coupons as described in Section 5.1.1 and coated with the four magnesium pretreatment coatings as noted in Table 7. There will be no primer on top of the coatings for this evaluation. The test coupons will be tested for galvanic corrosion per ASTM G71.

Test Description: The Galvanic Corrosion Test (ASTM G71) characterizes the behavior of two dissimilar metals in electrical contact in an electrolyte. The test simulates corrosion encountered in service environments. Laboratory testing of galvanic corrosion allows for the controlled study of the environmental variables and material/surface area combinations that contribute to corrosion.

The test specimens are manufactured from the same material as the application being modeled. The ratio of surface areas and basic geometry of the test specimens are also selected to closely model the application.

The test specimens are first immersed in an electrolytic solution. The test specimens are then electrically joined by a low-impedance method which will not corrode itself. This is generally accomplished with simple wires. Control specimens are not electrically joined. During testing, the electric current between the test plates is monitored and recorded. Current data is then used in a theoretical calculation of the corrosion rate.

Table 7: Galvanic Corrosion Test Description for Repair Compatibility Testing

Repair Description	DEVCON Aluminum Liquid F2	DEVCON Titanium Paste Filler	TIG Welding	Aluminum Cold Spray (6061)	HVOF Spray Coating
Magnesium Alloy	ZE41-T5	ZE41-T5	ZE41-T5	ZE41-T5	ZE41-T5
Panel Pretreatments	DOW 19 TCP Immersion Tagnite Brush Tagnite	DOW 19 TCP Immersion Tagnite Brush Tagnite	DOW 19 TCP Immersion Tagnite Brush Tagnite	DOW 19 TCP Immersion Tagnite Brush Tagnite	DOW 19 TCP Immersion Tagnite Brush Tagnite
# of Coupons per Pretreatment	3	3	3	3	3
# of Tests per Coupons	1	1	1	1	1
Experimental Control Panels	DOW 19	DOW 19	DOW 19	DOW 19	DOW 19
Acceptance Criteria	Galvanic Corrosion response that is equal to or better than DOW 19 Pretreatment				

5.1.2 Chemical Stripping of Legacy Coatings.

Rationale for the testing: The ultimate goal of this ESTCP project is to apply Immersion Tagnite to legacy DoD aviation magnesium components. Feedback from engineers at CCDC AvMC AMA-M and TAG has indicated that the successful application of an Immersion Tagnite coating on legacy components is primarily driven by the condition of the parts upon entering the Tagnite process. Experience has shown that all residual paints and coatings must be removed prior to introduction to the Tagnite process in order to apply a high quality Tagnite coating.

The current stripping process at CCAD is a two step process:

1. Removal of organic coatings (Top Coat, primer and sealants) via a chemical stripping process, MIL-DTL-83936
2. Removal of inorganic coatings (anodic and chemical conversion coatings) via immersion in a Chromic Acid tank.

There has been little to no experience at CCAD or TAG stripping organic coatings from Immersion Tagnite coated magnesium components. Part of this testing will allow TAG personnel to collect enough data to determine the effectiveness of this chemical paint stripping process. The primary objective of this ESTCP effort is to remove as much hexavalent chromium as possible from the depots and field service areas. Therefore, another task in this section will strive to develop an environmentally friendly, chemical stripping process to remove legacy inorganic coatings such as HAE, DOW 17 and Tagnite to replace the chromic acid stripping process.

Once stripping processes have been developed for paint and coating removal, testing will progress to determine the effect of these stripping processes on dissimilar metals.

5.1.2.1 Refine chemical stripping procedure used at TAG to remove legacy anodize coatings

Rationale of Testing: TAG has an internal procedure in place to remove the Tagnite coating from aerospace parts using our existing pretreatment baths, the mild alkaline etch and the fluoride activator. By varying the soak time in each tank and alternating between these pretreatment tanks, TAG has developed a means of chemical stripping the Tagnite coating. This procedure was used on the DOW 17 legacy anodize coating with some success, however, this procedure had little impact on the HAE legacy coating. The goal was to modify the current Tagnite chemical stripping process so that DOW 17 and HAE can be removed as well.

Testing: Magnesium test coupons made from the four major aerospace alloys, ZE41A-T5, EV31A-T6, AZ91E-T6 and QE22A-T6, were coated with the DOW 17 and HAE anodize coatings. These coated test coupons were put through the TAG chemical stripping process. Soak time in the mild alkaline etch and fluoride activator was varied. Progress was monitored based on visual observation of the integrity of the legacy coatings and the ability to remove the legacy coatings with minimal mechanical means such as pressure washing or Scotch Bright pads.

In the case of difficult residual coatings, a brief 1 – 3 minutes anodization in the Tagnite bath after the initial chemical strip was be used in an attempt to undermine and loosen any residual legacy coatings. After this brief anodization step, the chemical stripping process was repeated until a satisfactory bare magnesium surface has been reached.

The success of the chemical stripping process was determined by the ability to apply an Immersion Tagnite coating to test coupons that have been stripped of legacy inorganic coatings. These Tagnite coated test coupons will undergo the standard Quality Control (QC) evaluation for Tagnite coatings, including visual inspection of coating, thickness, electrical continuity, salt fog corrosion and wear resistance to verify these Tagnite coatings meet all the QC specifications.

5.1.2.2 Techniques to eliminate residual fluid leakage from porous magnesium aerospace alloys

Rationale for Testing: Past experience at TAG has shown that new and legacy castings made from AZ91C or AZ91E can weep residual fluids after the Tagnite process when subjected to temperatures used to cure Rockhard. These residual fluids do not weep out during the Tagnite processing steps when Tagnite operators perform their water break free testing. The residual fluid will only weep out of the casting during the initial Rockhard part preheat phase (335 – 365ºF for 15 – 30 minutes) and as a result, stain the Tagnite coating. Removal of the staining requires time consuming wipe downs of the Tagnite coating with solvents.

Testing: Magnesium coupons from the porous AZ91 magnesium alloys will be soaked in various fluids such as transmission, hydraulic and lubricating oils. These test coupons will be subjected to vapor degreasing, pressure washing and/or alkaline degreasers along with various heating cycles to determine the best way to remove any residual fluid. Success will be based on the appearance of the Tagnite coated test panels after being subjected to a Rockhard preheat cycle.

Initial trials will start with aviation hydraulic fluid (MIL-PRF-83282) and lubricating oil (DOD-PRF-85734). During these trials, the test coupons will be put into containers and put through several days of cyclic heating and cooling. The test protocol for hydraulic fluid will be 8 hours of immersion at 150±10°F (66 ±5°C), followed by cool down for 16 hours. This cycle will be repeated for 4 days. After the 4th cycle, the panels will be removed and go through the normal Immersion Tagnite pretreatment. At the end of the Tagnite pretreatment, the coupons will be heated to 365±10°F (185±5°C) for 30 minutes which is the part preheat cycle for Rockhard. Upon removal from the oven, the panels will be wiped with paper towels or cotton gloves, looking for the presence of residual fluid on the towels. If fluid is observed, the heating cycle at 365±10°F (185±5°C) for 30 minutes will be repeated until no residual fluid is noted.

The same testing will take place with lubricating oil (DOD-PRF-85734) repeating the same four cycles of heating and cooling, except the lubricating oil heat cycle will be done at 250±10°F (121±5°C).

If there is noticeable residual fluid after the initial Tagnite pretreatment and Rockhard preheating cycle at 365±10°F (185±5°C) for 30 minutes, alternate cleaning methods such as vapor degreasing or pressure washing will be explored. The objective is to find a cleaning protocol that removes all residual fluids prior to the Immersion Tagnite step.

5.1.2.3 Dimensional change to magnesium surfaces due to stripping of legacy coatings.
Rationale for Testing: TAG plans on using a mild alkaline etch to remove legacy coatings and it is a part of the normal Tagnite pretreatment process. This mild alkaline etch is known to remove metal at a rate of 0.0001" per 3 minutes of soak time. In addition, the application of a Tagnite coating will cause a dimensional change as about 50% of the Tagnite coating will penetrate into the base metal. Therefore, dimensional and weight loss information needs to be collected to quantify the effect the TAG stripping procedure and Tagnite re-anodization on legacy parts.

Testing: A detailed test matrix is summarized in Table 8. Test coupons from each of the four aerospace alloys will be divided into groups and treated as stated below. This test matrix will collect data on the current stripping and coating processes of legacy parts and proposed methods going forward. Before and after each process step, each test coupon will be weighed on an analytical balance to $\pm$ 0.0001 grams and dimensions will be measured in at least 3 locations for each dimension using a micrometer. An example panel is shown in Figure 21.

Control Group: No treatment - used to determine variability in weight and dimensions over time due to changing environmental factors.

"Current" Group: This will simulate the current stripping and recoating process at CCAD. Test coupons will be HAE, DOW 17 and Tagnite anodized then:

1. Stripped via the current chromic acid procedure at the CCAD plating shop followed by
2. Submersion in the currently used DOW 7 conversion coating then
3. Stripped a second time using the chromic acid method.

"Future 1": This would be one potential stripping scenario seen at the depot level. Test coupons will be HAE, DOW 17 and Tagnite anodized then:

1. Stripped via the current chromic acid procedure at the CCAD plating shop followed by
2. Tagnite anodization and subsequently
3. Stripped by chromic acid again.

"Future 2": This would be the preferred procedure going forward. Test coupons will be HAE, DOW 17 and Tagnite anodized then:

1. Stripped via the TAG chemical strip procedure developed in 5.1.2 followed by
2. Tagnite anodization and
3. Re-stripping by TAG chemical method.

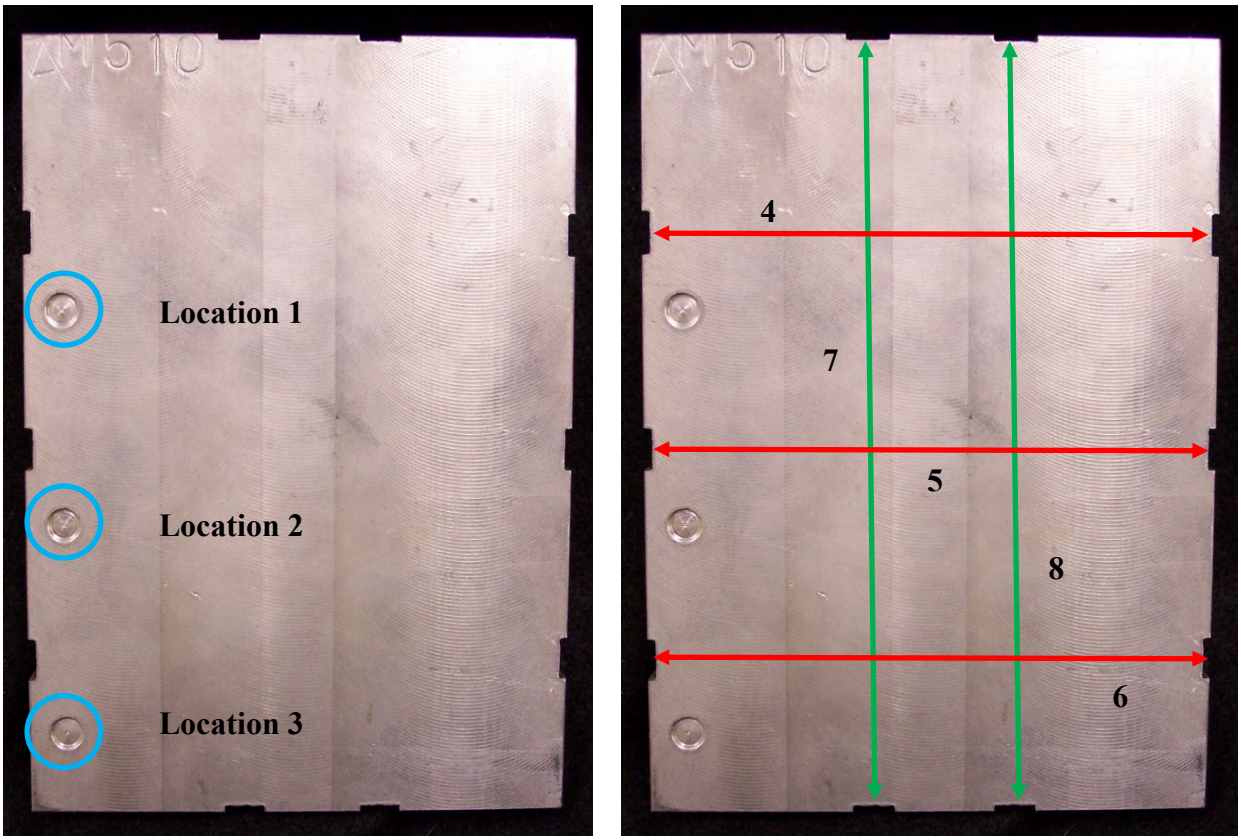


Figure 21: Location of Micrometer Measuring Locations on Dimensional Loss Panels

Table 8: Dimensional Change Test Description for Chemical Stripping of Legacy Coatings.

Treatment Group	Experimental Control				Current Depot Process				Future Process #1				Future Process #2			
Magnesium Alloy	AZ91E-T6	EV31A-T6	QE22A-T5	ZE41-T5	AZ91E-T6	EV31A-T6	QE22A-T5	ZE41-T5	AZ91E-T6	EV31A-T6	QE22A-T5	ZE41-T5	AZ91E-T6	EV31A-T6	QE22A-T5	ZE41-T5
# of Coupons	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Initial Anodize Coating	None				DOW 17 HAE Tagnite				DOW 17 HAE Tagnite				DOW 17 HAE Tagnite			
Initial Stripping Process	None				Chromic Acid				Chromic Acid				TAG Chemical Strip			
Second Coating Process	None				DOW 7				Tagnite				Tagnite			
Second Stripping Process	None				Chromic Acid				Chromic Acid				TAG Chemical Strip			
Acceptance Requirement	Dimensional Loss cannot exceed airworthiness requirements															

5.1.2.4 Effectiveness of MIL-DTL-83936 Paint Stripper on Legacy Coatings

Rationale for Testing: : During a previous trip to the CCAD facility, TAG personnel presented the engine cleaning shop with some test coupons coated with Tagnite + 3 coats of Rockhard sealant and additional test coupons with Tagnite + MIL-PRF-23377 primer. The test coupons were used to test the effectiveness of the paint stripper (Aerostrip 5182) in use at that time in the CCAD engine shop. The test coupons were run through the stripping process and returned to TAG. Visual inspection of the panels at TAG revealed that the top layers of Rockhard and MIL-PRF-23377 primer were gone, however, there appeared to be Rockhard and Primer embedded in the Tagnite pores. TAG personnel used their current Tagnite chemical strip method and attempted to strip the Tagnite off. Initial attempts were unsuccessful at removing the paint embedded Tagnite coating. With extreme efforts, TAG was able to remove the Tagnite embedded with Rockhard. This raises the questions:

1) Do the HAE and DOW 17 legacy anodize coatings absorb paint into their pores similar to Tagnite?
2) How easily can the embedded paint and anodized coating can be stripped?

Since this site visit, a new paint stripping chemical is being used at CCAD and this product's effectiveness needs to be evaluated for this project.

Testing: Magnesium test coupons will be coated with the currently used anodized coatings, HAE, DOW 17 and Tagnite. The test coupons will then receive the sealant, primer and top coat combinations currently being used on the AH-64 and UH-60 platforms. The organic coatings are as follows:

Sealant: High Temperature Rockhard Stoving Enamel, P/N 576-450-002
Primer for AH-64: MIL-PRF-23377
Primer for UH-60: MIL-PRF-85582
Top Coat for AH-64: MIL-DTL-53039
Top Coat for UH-60: MIL-C-46168

Table 9 summarizes the anodize coating and paint combinations to be tested. The painted coupons will be stripped in the MIL-DTL-83936 stripper currently being used at CCAD. After paint stripping, the anodized coatings will be stripped in the chemical stripping process developed in Section 5.1.2.

Table 9: Paint Scheme to Test Effectiveness of MIL-DTL-83936 Paint Stripper on Legacy Coatings

Magnesium Alloy	ZE41A-T6	ZE41A-T6	ZE41A-T6
Panel Pretreatment	HAE	DOW 17	Tagnite
# of Coupons per Pretreatment	15	15	15
Paint Scheme #1	3 Coats of HT Rockhard	3 Coats of HT Rockhard	3 Coats of HT Rockhard
Paint Scheme #2	1 Coat of MIL-PRF-23377	1 Coat of MIL-PRF-23377	1 Coat of MIL-PRF-23377
Paint Scheme #3	3 Coats of HT Rockhard + MIL-PRF-85582	3 Coats of HT Rockhard + MIL-PRF-85582	3 Coats of HT Rockhard + MIL-PRF-85582
Paint Scheme #4	3 Coats of HT Rockhard + MIL-PRF-85582+ MIL-C-46168	3 Coats of HT Rockhard + MIL-PRF-85582+ Sikorsky Top Coat	3 Coats of HT Rockhard + MIL-PRF-85582+ Sikorsky Top Coat
Paint Scheme #5	3 Coats of HT Rockhard + MIL-PRF-23377 + MIL-DTL-53039	3 Coats of HT Rockhard + MIL-PRF-23377 + MIL-DTL-53039	3 Coats of HT Rockhard + MIL-PRF-23377 + MIL-DTL-53039
# of Coupons per Paint Scheme	3	3	3
Acceptance Criteria	MIL-DTL-83936 will remove organic coatings in a manner that allows TAG chemical stripper to remove legacy anodize coatings. If this process is unacceptable, alternate methods will be investigated.		

5.1.2.5 Effect of TAG Chemical Stripping Process on Cad Plated Fasteners

Rationale for Testing: The proposed TAG chemical strip process needs to be properly evaluated on Cad plated studs. There were some casual observations during previous research that the TAG chemical strip process may have an effect on Cad plated materials. A more methodical approach is needed to gather the appropriate data to make a definite decision on the impact of the TAG chemical strip process on Cad plated materials.

Testing: Cad plated studs will be subjected to the TAG stripping process at maximum temperatures and chemical concentrations. Soak times will be twice the time necessary to strip anodic coatings. After immersion in the stripping solution, visual comparison of plating color will be made between a new fastener and a fastener after the stripping process. Any changes in fastener color will be an indication of loss of Cad plating. Samples of the stripping bath will be analyzed after use for cadmium content and quantity via Flame Atomic Absorption Spectroscopy.

Acceptance Criteria: If the TAG stripping process is found to remove Cad plating, Tagnite processing instructions for legacy magnesium aviation components must state that Cad plated fasteners will be masked off prior to the stripping process and Tagnite anodization.

5.1.2.6 Effect of TAG Chemical Stripping Process on Hydrogen Embrittlement of Steel

Rationale for Testing: The proposed TAG chemical strip process needs to be properly evaluated for any potential impact from hydrogen embrittlement of Cad plated studs and other types of steel inserts. The TAG chemical stripping process will be introduced as a new process for implementation at CCAD and hydrogen embrittlement testing is routine for all processes that could potential affect the steel inserts on a magnesium aerospace component.

The Hydrogen Embrittlement Test (ASTM F 519) is designed to test the degree to which steel becomes brittle and fractured following exposure to hydrogen. Specifically, this test will examine the effect TAG production chemicals and processing will have on steel samples.

The test specimens are steel c-rings with notches for load testing. Each trial will consist of four bare steel rings and four cadmium plated steel rings. The first trial will expose the test specimens to the chemical stripping process at maximum temperature and maximum concentration for twice the production time. The samples are then stress tested for embrittlement. The load placed on the samples is 75% of the notch fracture strength (NFS). The samples are stressed by the load for 200 hours. After 200 hours, the specimens are examined for fractures. If two or more specimens have fractured in each of the 4-ring groups, hydrogen embrittlement is indicated. If only one specimen or no specimens have fractured, hydrogen embrittlement is ruled out.

The second trial repeats the above process with pre-stressed rings. The rings are first pre-stressed at 75% of the NFS. The rings are exposed to the same simulated stripping process as stated

above and stress tested with the same 75% load. The criteria for failure and success are the same as indicated above.

Testing: The TAG chemical stripping process shall be evaluated using Type 1d notched C rings per ASTM F519-13, Reference 1c. As stated in Reference 1c paragraph 11.2 of the ASTM standard, a minimum of 4 rings each shall be tested for both the bare and cadmium plated treatments. These rings shall be subjected to the stripping process solutions at maximum temperatures and concentrations allowed by the TAG chemical stripping process specification. Additionally, times in each solution evaluated shall be 2x that allowed by the TAG stripping process specification. Prior to testing, the C ring lot will be validated by taking 10 bare specimens and 10 cad plating specimens and applying stress @ 75% of the notch fracture strength (NFS) for 200 hours at ambient conditions. If the batch testing has no failures, these specimens are to be discarded and the testing in the stripping solution can proceed as described in Table 10.

Table 10: Sampling Plan and Test Conditions for Hydrogen Embrittlement Testing of the TAG Chemical Stripping Process

Specimen Condition	**Bare**	**Bare**	**Cad Plated**	**Cad Plated**
# of Specimens under No Preload Conditions	4		4	
# of Specimens under Preload to 75% NFS Conditions		4		4
# of Specimens for TAG Chemical Strip @ Max Temp - Max Concentration and 2X Soak Time	All	All	All	All
# of Specimens for Post Exposure Stress 200 hrs @ 75% NFS	All	All	All	All
Pass/Fail Criteria	See Section 11 of ASTM F519			

Acceptance Criteria: If the TAG stripping process is found to cause hydrogen embrittlement, Tagnite processing instructions for legacy magnesium aviation components must state dissimilar metals must be masked off prior to stripping process and Tagnite anodization.

5.1.3 Brush Tagnite Qualification on Additional Magnesium Aerospace Alloys
Rationale for Testing: Brush Tagnite units have been in use at CCAD since 2005, however, Brush Tagnite has been limited to touchup on ZE41 magnesium components on the AH-64

Apache that have the Immersion Tagnite anodize as the original coating. As a result of these restrictions, the depots are still using the DOW 19 chromate conversion coating for the vast majority of their repairs. There are other magnesium aerospace alloys such as AZ91C/AZ91E, QE22A, and EV31A which are in use on aviation platforms and Brush Tagnite performance data will be obtained for these alloys in order to expand the use of Brush Tagnite and reduce or eliminate the use of DOW 19 in the services. The touchup coatings to be evaluated are Brush Tagnite, DOW 19 and TCP.

5.1.3.1 Pull-off Adhesion for Brush Tagnite Qualification

Rationale for Testing: The magnesium pretreatments to be tested will leave a coating on the magnesium substrate and the repair area. It is important to determine how well these coatings adhere to the magnesium substrate and repair areas along with the adhesion of applied paints or primers. MIL-PRF-23377 non-chromated primer will be sprayed over the entire panel. Pull-off adhesion testing per ASTM 4541 will be performed on the painted panels. Any adhesion failures will be documented such as failure at the magnesium/coating interface or the coating/primer interface.

AZ91E-T6, EV31A-T6, QE22A-T6 and ZE41-T5 test coupons will be coated with the three different types of magnesium pretreatment coatings; DOW 19, TCP and Brush Tagnite. After the application of these coatings, all the panels will receive one coat of MIL-PRF-23377 non-chromated primer. Table 11 is a test summary of this pull-off test.

After primer application, the panels will be tested for pull-off adhesion per ASTM D 4541. There will be two testing locations on each panel.

Test Description: See Section 5.1.1.1

Table 11: Pull-off Adhesion Test Matrix for Brush Tagnite Qualification Testing

Magnesium Alloy	AZ91E-T6	EV31A-T6	QE22A-T6	ZE41-T5
Panel Pretreatments	DOW 19 TCP Brush Tagnite	DOW 19 TCP Brush Tagnite	DOW 19 TCP Brush Tagnite	DOW 19 TCP Brush Tagnite
Organic Coating	1 Coat of MIL-PRF-23377			
# of Coupons per Pretreatment	3	3	3	3
# of Tests per Coupons	2	2	2	2
Experimental Control Panels	DOW 19	DOW 19	DOW 19	DOW 19
Acceptance Criteria	Primer Pull-off adhesion strength that is equal to or better than DOW 19 Pretreatment			

5.1.3.2 Galvanic Corrosion for Brush Tagnite Qualification

Rationale for Testing: Magnesium components during their services lives will experience wear and damage which can lead to the exposure of bare magnesium. When bare magnesium metal is exposed, there is the potential for a galvanic corrosion cell to form. After application of the three magnesium pretreatment coatings onto test panels, the galvanic interaction will be measured by between exposed bare areas on the panels and the applied coatings.

DOW 19, TCP and Brush Tagnite will be applied to 4" x 6" test coupons of AZ91E, EV31A, QE22A and ZE41A. There will be no primer on top of the coatings for this evaluation. The test coupons will be tested for galvanic corrosion per ASTM G71. Table 12 contains the complete test matrix.

Test Description: See Section 5.1.1.2

Table 12: Galvanic Corrosion Test Matrix for Brush Tagnite Qualification

Magnesium Alloy	AZ91E-T6	EV31A-T6	QE22A-T6	ZE41-T5
Panel Pretreatments	DOW 19 TCP Brush Tagnite	DOW 19 TCP Brush Tagnite	DOW 19 TCP Brush Tagnite	DOW 19 TCP Brush Tagnite
# of Coupons per Pretreatment	5	5	5	5
# of Tests per Coupons	1	1	1	1
Experimental Control Panels	DOW 19	DOW 19	DOW 19	DOW 19
Acceptance Criteria	Galvanic Corrosion response that is equal to or better than DOW 19 Pretreatment			

5.1.3.3 Neutral Salt Fog Performance for Brush Tagnite Qualification

Rationale for Testing: One of the purposes of the magnesium pretreatment coatings is to provide some measure of corrosion resistance. Magnesium is a very active metal and is prone to corrosion when exposed to moisture if no properly protected. Corrosion rates are influenced by alloy components, therefore, magnesium alloys can have drastically different corrosion rates. This testing will assess the corrosion protection characteristics of the three pretreatments: DOW 19, TCP and Brush Tagnite, in a neutral pH salt fog environment on the four different magnesium alloys.

DOW 19, TCP and Brush Tagnite will be applied to 4" x 6" test coupons of AZ91E, EV31A, QE22A and ZE41A. The panels will be painted with one coat of MIL-PRF-23377 non-chromated primer on top of the coatings for this evaluation. The test coupons will be placed in a neutral salt fog chamber operated per ASTM B 117. The salt fog performance will be rated per

ASTM D 1654 at various time intervals until there is differentiation between the coatings. Table 13 describes the testing protocol.

The Salt Fog Cabinet Test is a controlled corrosion environment. The test produces relative corrosion information for metals and coated metal specimens. The test specimens are sealed in a test chamber and exposed to an atomized salt solution. The test chamber simulates atmospheric exposure. The pressure and temperature of the salt spray and temperature in the chamber are controlled to specifications. The test specimens are exposed for a predetermined amount of time. After exposure, the test specimens are removed from the chamber and examined. The corrosion information is compared to material specifications or specifications agreed upon by purchaser and seller.

Table 13: Neutral Salt Fog Corrosion Resistance Testing for Brush Tagnite Qualification

Magnesium Alloy	AZ91E-T6	EV31A-T6	QE22A-T6	ZE41-T5
Panel Pretreatments	DOW 19 TCP Brush Tagnite	DOW 19 TCP Brush Tagnite	DOW 19 TCP Brush Tagnite	DOW 19 TCP Brush Tagnite
Organic Coating	1 Coat of MIL-PRF-23377			
# of Coupons per Pretreatment	5	5	5	5
# of Tests per Coupons	1	1	1	1
Experimental Control Panels	DOW 19	DOW 19	DOW 19	DOW 19
Acceptance Criteria	Neutral Salt Fog Corrosion Resistance that is equal to or better than DOW 19 Pretreatment			

5.1.3.4 SO_2 Salt Fog Performance for Brush Tagnite Qualification

Rationale for Testing: The Navy requires that the corrosion testing be done in a more aggressive atmosphere to simulate the conditions in an ocean environment. The salt fog test is made more aggressive by adding sulfur dioxide gas to the chamber at various intervals. This testing will compare the corrosion protection characteristics of the three pretreatments: DOW 19, TCP and Brush Tagnite, in an aggressive salt fog environment.

DOW 19, TCP and Brush Tagnite will be applied to 4" x 6" test coupons of AZ91E, EV31A, QE22A and ZE41A. After the application of these coatings, all the panels will receive one coat of MIL-PRF-23377 non-chromated primer (See Table 14).

The test coupons will be place in a SO_2 salt fog chamber operated per ASTM G-85, Annex A4. The salt fog performance will be rated per ASTM D 1654 at various time intervals until there is differentiation between the coatings.

Table 14: Acidified (SO_2) Salt Fog Corrosion Resistance Testing for Brush Tagnite Qualification

Magnesium Alloy	AZ91E-T6	EV31A-T6	QE22A-T6	ZE41-T5
Panel Pretreatments	DOW 19 TCP Brush Tagnite	DOW 19 TCP Brush Tagnite	DOW 19 TCP Brush Tagnite	DOW 19 TCP Brush Tagnite
Organic Coating	1 Coat of MIL-PRF-23377			
# of Coupons per Pretreatment	5	5	5	5
# of Tests per Coupons	1	1	1	1
Experimental Control Panels	DOW 19	DOW 19	DOW 19	DOW 19
Acceptance Criteria	Acidified Salt Fog Corrosion Resistance that is equal to or better than DOW 19 Pretreatment			

5.1.3.5 Outdoor Exposure (Beach Front) for Brush Tagnite Qualification

Rationale for Testing: This test is an effort to simulate real world exposure to various factors that influence coating performance. These factors include temperature cycling, UV exposure, humidity and salt cycling.

DOW 19, TCP and Brush Tagnite will be applied to 4" x 6" test coupons of AZ91E, EV31A, QE22A and ZE41A. After the application of these coatings, all the panels will receive one coat of MIL-PRF-23377 non-chromated primer. Table 15 contains the detailed testing protocol.

The panels will be sent to the Applied Science and Technology NASA Materials Testing and Corrosion Technology Branch Kennedy Space Center, Florida. NASA Corrosion Technology Laboratory personnel will secure the panels to the test fixtures at the NASA Beach Corrosion Test Site so that they are at least three feet off the ground at a 30-degree angle. These assemblies will be exposed at the NASA Beach Corrosion Test Site for a two-year duration.

At the beginning of the project, NASA Corrosion Technology Laboratory personnel will inspect and photograph the samples at the end of one week, two weeks and one month of exposure. After this initial month of exposure, NASA Corrosion Technology Laboratory personnel will continue to inspect and photograph the samples for an additional twenty-three (23) months with inspections and photographs performed monthly. Photographs and visual inspection notes will be submitted on a monthly basis via e-mail. NASA Corrosion Technology Laboratory personnel will provide a test report highlighting the performance of the test coupons after each twelve months of exposure.

Table 15: Outdoor Exposure (Beach Front) Testing for Brush Tagnite Qualification

Magnesium Alloy	AZ91E-T6	EV31A-T6	QE22A-T6	ZE41-T5
Panel Pretreatment	DOW 19 TCP Brush Tagnite	DOW 19 TCP Brush Tagnite	DOW 19 TCP Brush Tagnite	DOW 19 TCP Brush Tagnite
Organic Coating	1 Coat of MIL-PRF-23377			
# of Coupons per Pretreatment	3	3	3	3
# of Tests per Coupons	1	1	1	1
Experimental Control Panels	DOW 19	DOW 19	DOW 19	DOW 19
Acceptance Criteria	Outdoor Exposure performance that is equal to or better than DOW 19 Pretreatment			

5.1.3.6 Axial Fatigue Testing for Brush Tagnite Qualification

Rationale for Testing: Whenever a new coating system is proposed for an aerospace application, engineers are concerned about the effect this new system will have on the fatigue strength of the part(s) being coated. The Immersion Tagnite process has a pretreatment step that involves soaking the magnesium component in a mild alkaline etch solution for no longer than 3 minutes. This process will result in a loss of 0.0001" from each surface and since metal loss has occurred, engineers are concerned about fatigue strength. In addition, the Immersion Tagnite deposition process involves a partial deposition into the metal which could also impact fatigue strength.

In this test, Brush Tagnite is being tested. The Brush Tagnite process does not involve a mild alkaline etch pretreatment step, however, the coating process is a deposition process which can disturb the surface of the metal. As a precautionary measure, engineers want to know what impact, if any, the deposition of Brush Tagnite has on fatigue strength.

Fatigue specimens will be machined from AZ91E-T5, EV31A-T5, QE22A-T5 and ZE41A- T6 to the dimensions shown in Figure 22. The three different pretreatments, DOW 19, TCP and Brush Tagnite will be applied to the fatigue specimens. There will be a group of 10 specimens from each alloy that will be left bare (uncoated) for use as control specimens. The machine specimens will be subjected to axial fatigue per ASTM E 466. The test matrix is seen in Table 16.

Test Description: The Axial Fatigue Test is used to determine the effects variations in material, geometry, surface condition etc. have on the fatigue resistance of metallic materials subject to stress. The test subjects a fatigue specimen to multiple cycles at a certain stress level until the

specimen fails or a predetermined number of cycles have passed. The stress is applied as sinusoidally varying tension along the major axis of the sample.

Table 16: Axial Fatigue Test Matrix for Brush Tagnite Qualification

Magnesium Alloy	AZ91E-T6	EV31A-T6	QE22A-T6	ZE41-T5
Panel Pretreatments	Bare DOW 19 TCP Brush Tagnite	Bare DOW 19 TCP Brush Tagnite	Bare DOW 19 TCP Brush Tagnite	Bare DOW 19 TCP Brush Tagnite
# of Specimens per Pretreatment	10	10	10	10
# of Tests per Specimen	1	1	1	1
Experimental Control Specimens	Bare	Bare	Bare	Bare
Acceptance Criteria	Axial fatigue response that is equal to or better than DOW 19 Pretreatment **OR** meets airworthiness requirements			

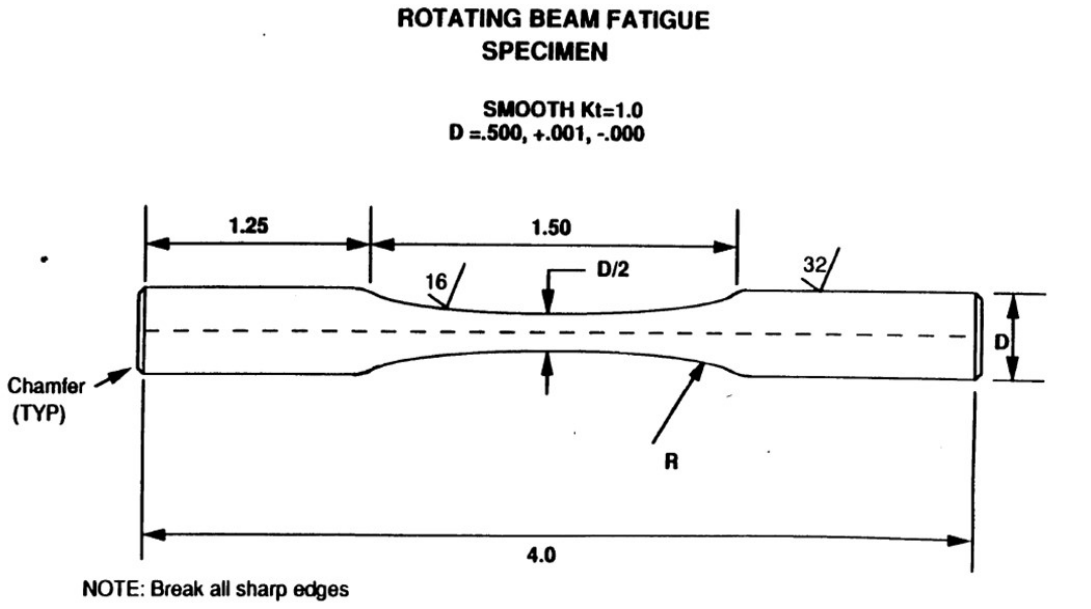


Figure 22: Machining Diagram for Axial Fatigue Specimen

All measurements in inches

Data Analysis: For the purposes of this test, 3 – 4 of the test specimens of each alloy will be used to establish a common stress level. The stress level should be one that causes failure of a

bare metal sample between 10^5 and 10^6 cycles. Once this stress level is established, the remaining test specimens are cycled at this level until failure. The fatigue life of the bare metal control and test specimen are compared statistically using Analysis of Variance (ANOVA) at a ~90% confidence level to determine the effect of the coating on fatigue resistance.

5.2. DEMONSTRATION PLAN - EXPERIMENTAL DESIGN

5.2.1 CONCEPTUAL DEMONSTRATION PLAN EXPERIMENTAL DESIGN

The overall focus of the experimental design for this demonstration project is twofold:

- To prove via routine chemical and physical testing that the quality of the Tagnite coatings generated at Line D of the CCAD plating shop should exceed the performance characteristics of the existing DOW processes currently used at the CCAD plating shop.
- To prove that the masking technology can be transferred to the CCAD plating shop such that parts can be masked and Tagnite coated with the same success as seen at TAG's facility in Grand Forks, ND.

The following operational phases will be covered over the course of this demonstration project as seen is Figure 23:

1. Startup and Testing
    a. Tagnite Training and Evaluation
        i. Controls
            1. Taber Wear Resistance Testing
            2. Salt Fog Corrosion Testing
            3. Coating Tape Adhesion Testing
            4. Primer Adhesion Testing
            5. TAG Personnel Evaluations and Reviews
    b. Masking Procedures and Protocols
        i. Controls
            1. Air pressure leak testing
            2. Checklists
            3. TAG Personnel Evaluations and Reviews
2. Masking - Tagnite Anodization - Chemical Stripping of Scrap Components
    a. Processing of Parts Training and Evaluation
        i. Controls
            1. Taber Wear Resistance Testing
            2. Salt Fog Corrosion Testing
            3. Coating Tape Adhesion Testing
            4. Primer Adhesion Testing
            5. Inspection for arcing/material loss/uncoated areas/damage to steel
            6. Repeatability of process (Acceptable weight and dimensional loss)
            7. Personnel Evaluations and Reviews of CCAD artisans by TAG personnel.
3. Review of Data (Decision Point) by CCDC AvMC AMA-M
    a. Does control data in 2.a.i meet passing criteria (If yes, proceed to processing production components.) If any control data does not meet the passing criteria, there will be an evaluation by the working group to identify and correct the non-passing data.
4. Chemical Stripping - Masking - Tagnite Anodization of Production Components
   Controls same as Section 5.1.2.

Tasks	Month											
	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12
1. Tagnite Line Startup												
2. Analysis of Tagnite Baths – Lab Procedure Training												
3. Tagnite Operator Training												
4. Installation of Masking Tools Training												
5. Evaluation of Masking/Tagnite/Chemical Stripping using Scrap BER Parts												
6. Data Analysis		DP										
7. Demonstration with Production Parts												
8. Reporting											C&P FR	

Figure 23: Gantt Chart – Actual Testing Schedule for Demonstration/Validation at CCAD Plating Shop

5.2.2 PRE-DEMONSTRATION TESTING AND ANALYSES

After manufacture of the rectifier and chilling system, these components will be shipped to TAG's facility in Grand Forks, ND. The rectifier and chilling system will be connected to a small 500 gallon tank filled with Tagnite solution. Scrap magnesium sheet material and scrap parts will be coated in this setup. TAG personnel will thoroughly monitor the operation of the rectifier and chilling system at varying loads to verify that the equipment is operating properly. Once TAG personnel are satisfied with the operation of this equipment, it will disconnected and shipped to CCAD.

5.2.3 DESIGN AND LAYOUT OF TECHNOLGY COMPONENTS

The inactive D-Line at the CCAD plating shop will only need minimal modifications. Capital equipment to be installed for this demonstration will be:

1. **Rectifier:** For this project, DynaPower Corporation is manufacturing a rectifier that operates at 25 % of the capacity of the DynaPower rectifier that is used at TAG's Grand Forks, ND production facility. This downsized rectifier will have the same wave function and programmability as the currently used TAG rectifier.
    a. **Location:** In basement, directly underneath D-Line (See Figure 24)
    b. Additional Services needed:
        i. Incoming Power: 480 V AC, 3 phase, 60 Hz
        ii. Chilled water for cooling
        iii. Base or footing to elevate rectifier 12 – 18" above current floor due to potential flooding in basement
2. **Chilling System (Compressor and Chilling Plates):** A commercially available chilling system will be installed next to the rectifier
    a. **Location:** In basement, near rectifier
    b. Additional Services needed:
        i. Incoming Power: 480 V AC, 3 phase, 60 Hz.
        ii. Ethylene Glycol charging of the system.
        iii. Base or footing to evaluate compressor 12 – 18" above current floor due to potential flooding in basement.

Tank D-4 is designated as the fluoride activator tank (Figure 25). The chemicals used for this solution are corrosive, therefore this tank will need a custom made plastic liner. In addition, in order to heat the tanks, Teflon coated electric heaters need to be installed after the plastic liner. We have requested a ventilation review by CCAD Industrial Health to verify current venting is adequate.

The only tank in the D-Line that will need any type of modification is Tank D-7 which is designated as the Tagnite anodization tank (Figure 26). The modifications needed are:

1. Rewiring or upgrading the current wiring for this tank to deliver the rectifier power to the tank. Due to the power output of the Tagnite rectifier, large gauge wiring and more robust grounding straps will be needed.
2. Plumbing to circulate the warm Tagnite electrolyte from the anodization tank to the chilling system and the return of cooled Tagnite electrolyte.
3. Installation of more robust anodization saddles.



Figure 24 (Left): Picture of basement at CCAD Plating Shop. Green circle is the old rectifier for D-Line. This is the proposed location of Tagnite rectifier and chilling system.

.

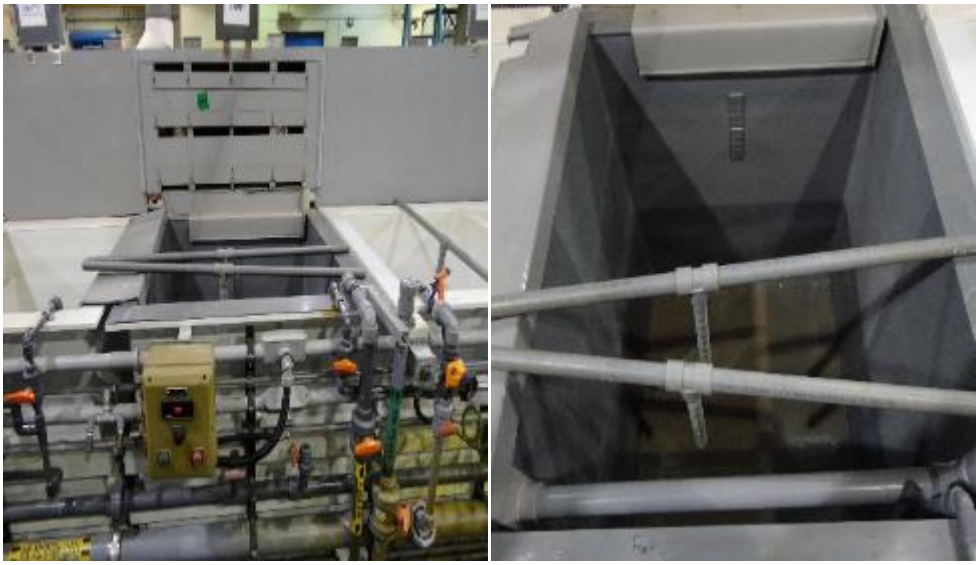


Figure 25: Tank D-4
(Left): Front of Tank D-4 (**Right):** Inside of D-4

This tank will have a custom plastic liner and Teflon coated heaters installed for use as the fluoride activator pretreatment tank.



Figure 26: Tank D-7
(Left): Front of Tank D-7 (**Right):** Inside of Tank D-7
Tank is to be converted to the Tagnite anodization tank. Modifications to this tank will be: 1) Removal of old anode locks, installation of new locks, 2) Removal of old heaters, 3) Plumb for chilling system and 4) Rewired for Tagnite Rectifier

5.2.4 STARTUP, TRAINING AND FIELD TESTING

5.2.4.1 Tagnite Line Check-out: Once all the modifications have been made to the D-Line, the equipment check-out phase of this project will start. TAG personnel along with a third party engineering firm will be responsible for the equipment check-out and initial startup of the Tagnite line. The initial task will be the addition of water to the pretreatment, Tagnite and post-treatment baths. At this stage, the equipment on each individual bath will be powered up. This operation will verify that the bath circulation systems, heaters and chilling system are operating as designed. If all systems are operating properly, chemical will be added to the individual process baths per the TAG provided makeup sheets. When the Tagnite process baths have reached their operating temperatures, samples will be collected and analyzed to ensure that all baths are in the chemical specifications ranges dictated by TAG standards. During this stage, TAG personnel will review the TAG lab procedures with the CCAD chemists and technicians. TAG personnel will monitor and evaluate CCAD personnel as they analyze and calculate the concentrations of the individual chemical components that make up each bath in the Tagnite process. If needed, chemical additions will be made and solutions reanalyzed in order to verify that all Tagnite process baths are in their proper specification range.

5.2.4.2 Rectifier and Chilling System Check-out: The next step is to test and evaluate the Tagnite rectifier. In order to do this, TAG will provide large sheets of AZ31B magnesium to act as practice loads for the rectifier. The magnesium sheets will be sized to allow TAG personnel

to evaluate the performance of the rectifier at 10, 25 50, 75 and 100 % load capacity. These varying load sizes will also help to evaluate the chilling system's response to these loads. As the load size is increased, there is a greater demand for chilling during the Tagnite process. The chilling system should be sized so that the temperature of the Tagnite solution will not exceed the maximum operating temperature defined in the Tagnite standard during the typical 15 – 20 minute time interval used to reach a Type I coating thickness (0.0002 – 0.0004 inches). We will also be monitoring the ability of the chilling system to remove the heat generated during a run and return to the initial startup temperature so that another run can be coated. If the actual temperature of the Tagnite solution exceeds the upper operating limit or the temperature cool down period takes longer than expected, modifications or adjustments may need to be made to the chilling equipment.

5.2.4.3 Tagnite Operator Training: The Tagnite training phases will consist of the following steps using TAG standards, procedures and checklists:

1. A walk through of the Tagnite line with CCAD plating shop artisans while TAG personnel explain the function, operating specifications and safety issues of each Tagnite process tank.
2. Correct startup and shutdown procedures for Tagnite line
3. Operation of the rectifier
4. Initial Tagnite processing of magnesium sheet material
5. Tagnite processing of masked, scrap SAFR BER magnesium components using travelers with detailed processing instructions for each Tagnite processing tank

Methods to ensure uniform and repeatable deposition of the Tagnite coating are:

- Taber wear resistance (Daily)
- Tagnite thickness (Every run)
- Electrical continuity measurement (Every run)
- Visual inspection of coating (Every run)
- Dry Tape Pull Adhesion (Every run)

Taber wear resistance is the quickest and best way for measuring Tagnite coating quality on a daily basis. While hardness testing might be a faster test, TAG researchers have found this test to be difficult to perform due to the friable nature of the coating and the tendency for the magnesium base material to compress before the Tagnite coating breaks. Microhardness testing is even more difficult due to the presence of pores in the coating that are typically 2 – 5 μm in diameter making it difficult to properly position the probe.

Dry tape adhesion is an excellent indicator of the cleanliness of the used components (removal of the legacy paints and coatings) and the quality of the pretreatment part of the Tagnite process. The presence of any legacy coatings will not allow the pretreatment process to properly prepare the magnesium surface for the Tagnite step which will result in a loosely adhered coating. The removal of a Tagnite coating via a dry tape pull is also an indication that the pretreatment process was done incorrectly or one of the pretreatment baths is not being operating correctly. In

addition, this test can also identify post-Tagnite issues. It has been proven that extensive rinsing in high purity deionized or reverse osmosis water will degrade the Tagnite coating.

5.2.4.4 Training for Brush Tagnite: All CCAD artisans that will be applying Brush Tagnite are required to pass a Brush Tagnite training class taught by TAG instructors. The training class consists of:

1. Fundamentals of Electrical Safety
2. Completion of handout on electrical safety
3. Fundamentals of Brush Tagnite process (PowerPoint Presentation)
    a. Part preparation
    b. Brush Tagnite equipment review and preparation
    c. Brush Tagnite application technique
4. Practical application experience on scrap magnesium housing and/or magnesium test coupons
5. Successful application of Brush Tagnite coating to magnesium test coupons

In addition, the Brush Tagnite operators should be wearing PPE consisting of safety goggles, apron or lab coat, electrical insulating gloves and rubber soled shoes or as designated by CCAD health and safety officials.

5.2.4.5 Training for Installation of Masking Components: The masking training phases will consist of the following steps using TAG procedures, hands-on practice under supervision and checklists:

1. Review of masking procedures
2. Masking of scrap part(s) under supervision
3. Leak Testing
4. Checklist review
5. Sign-off sheets
6. Post-Tagnite Inspection after masking removal

Performance of the masking quality will be monitored by:

- Same testing as done for Tagnite
- Visual inspection after Tagnite for arcing, loss of metal, missing areas of Tagnite and rust on steel inserts during unmasking steps

5.2.4.6 Field Testing: During field testing, there will be daily and periodic quality control procedures to ensure that the Tagnite coating being deposited is of the highest quality.

Tagnite Quality: The following QC testing (Table 17) was performed on Tagnite Process Solutions and Tagnite coated test specimens to ensure the Tagnite coating meets the specification requirements of the OEMs.

Table 17: QC Testing during Tagnite Training and Demonstration

Test	Test Method	Frequency
Solution Analysis of Tagnite Process Bath	Per TAG Lab Procedures Manual	Per TAG testing schedule 7LS-020
Taber wear resistance	ASTM D 4060	Daily
Tagnite Thickness	ASTM B 244	Every Run
Visual Inspection	Boeing HP4-134 Sec. 3.4.3.1	Every Run
Tagnite Adhesion by Dry Tape Pull	ASTM D 3359	Every Run

End of Project: Capital Equipment Status
All capital equipment including the rectifier and chilling system that was installed during this project will be left in place at the CCAD plating shop. At the end of the project, if a Tagnite license agreement cannot be reached between CCAD and TAG then TAG will disable the unique Tagnite waveform programmed into the rectifier software. The basic license agreement is currently being negotiated. The equipment release statement is seen in Appendix C.

5.2.5 PERFORMANCE ASSESSMENT PLAN

The performance of the demonstration phase of this project will cover two different areas:

1. Effectiveness of the stripping process to remove legacy coatings
2. Effectiveness of the masking process at protecting the steel components

5.2.5.1 Quality of the Tagnite coatings

The primary objective of this phase is to show that the quality of the Tagnite coating applied at the CCAD plating shop is "as good or better" than the characteristics of the coatings currently used in the CCAD plating shop.

Tagnite Testing: Wear resistance testing will be performed per the ASTM standard and the numerical values calculated were comparted to the historical data from TAG. The wear resistance data to be collected will consist of weight loss at a designated number of cycles as well as weight loss at the endpoint. The endpoint is defined as the presence of 10 % bare metal exposed in the taber track. The wear resistance test is acknowledged in ASTM D 4060 as having a very subjective endpoint determination. There can be up to 50 % difference in the endpoint when comparing intralaboratory results (how different technicians in the lab determine the endpoint) and up to 100 % difference in interlaboratory testing. Therefore, in order to account for this large variation in end point determination, there will be a duplicate set of taber test panels coated concurrently with the CCAD test panels. These duplicate panels will be sent to TAG's facility for taber abrasion testing in order to qualify the testing and evaluation of CCAD lab personnel. In addition, duplicate salt fog and paint adhesion panels will be tested at TAG's facility in order to quantitate any interlaboratory variation. Weight loss at the designated cycles

will be compared to TAG's historical data. The weight loss seen during the CCAD demonstration plan must be within the standard deviation of TAG's historical data.

5.2.5.2 Stability/Maintainability of the Tagnite Process Solutions

In order to apply a quality Tagnite coating, the Tagnite process baths must be maintained per TAG's specifications. These specifications state the need for daily and periodic testing of all process tanks and timely chemical additions when tank parameters exceed the process and/or specifications limits. In addition, there are set criteria when a process bath should be dumped and replaced. In order to proceed with production parts, control charts of all process data will be graphed and reviewed as evidence that the Tagnite process baths at CCAD can be monitored and maintained so that a consistent quality Tagnite coating is produced. The daily/periodic testing, control charts and chemical addition records will be reviewed by TAG personnel on a weekly basis. TAG will work with CCAD chemists to maintain the process baths in order to meet all specification limits.

5.2.5.3 Effectiveness of the Legacy Coating Stripping Process

The effectiveness of the legacy coating stripping process will be based entirely on visual inspection. TAG will supply CCAD with a briefing on determining when a part has been stripping effectively enough for the Tagnite process to deposit a high quality coating. The principle criteria are:

- There can be no residual inorganic or organic coatings present on the magnesium component after stripping
- The magnesium surface must have a bright, metallic, bare metal appearance

Decision Point: If the chemical stripping process developed by TAG is unable to adequately strip off the residual legacy coatings or the repetitive chemical stripping of the Tagnite coating leads to unacceptable dimensional loss than this process may not be used on production parts. At the point, the ESTCP working group will have to determine which course of action needs to be taken to get a legacy magnesium component clean enough for the Tagnite process. Options would be to reconsider current CCAD stripping processes such as chromic acid (chrome pickle) or media blast, or alternate technologies can be investigated as well.

5.2.5.4 Effectiveness of the Masking Process at Protecting Steel Components

During the initial training for the installation of masking, CCAD personnel will be given detailed masking procedures. These procedures are written specifically for each individual part and each masking tool is given a unique number engraved on the tooling. The masking tools for each individual part will be assembled as a kit and placed in a clearly labeled container.

During the masking training, CCAD personnel will undergo individualized training from TAG personnel using scrap BER parts. In addition, the final inspection of the masked component will be done by TAG personnel with immediate feedback to the CCAD artisans.

Performance of the masking tool installation will be based on visual and/or optical inspection. The performance criteria are:

- No arcing
- No material loss
- Coating shall be continuous, smooth and uniform in appearance
- Color shall be white to gray
- No rust on steel liners
- No loss of cad plating on studs and inserts

In the event of a masking failure, every effort will be made to determine the root cause and install a corrective action.

After removal of masking tools, the steel liner covers will be closely inspected for damage such as signs of arcing, metal loss and/or gaps in the sealing surface. Liner covers that are damaged beyond repair will be scrapped and the root cause of the failure will be determined. Bolts and treaded inserts will be inspected after removal for damage to the threads or chemical buildup in the threads that will interfere with installation on subsequent parts. A database will be utilized to determine which masking tools were damaged or deemed unusable in order to estimate tooling lifetimes.

Feedback will be collected from CCAD artisans on the clarity of the masking procedures, ease of masking installation and man-hours needed to mask and unmask the priority parts. The feedback will be analyzed and modifications made, if necessary.

The quality of the Tagnite deposited on the masked aerospace components will be determined by:

- Tagnite thickness measurements on the parts (meets Tagnite specification)
- Electrical continuity testing of the Tagnite coating (Coating shall not conduct electricity)
- Dry Tape Pull of Tagnite on part to check for lack of adhesion of the Tagnite coating (No powder on tape adhesive)

In addition, taber abrasion wear panels will be run concurrently with the masked parts on a daily basis along with periodic salt fog and paint adhesion test coupons to be run alongside the parts.

Processing Production Parts: *Decision Point*

Masking and Tagnite coating of SAFR BER priority parts must pass inspection criteria described above and receive CCDC AvMC AMA-M approval prior to processing production parts.

6.0 PERFORMANCE ASSESSMENT

6.1 JTP Testing and Results

6.1.1 Primer Paint Adhesion Testing of Repair Areas after Immersion Tagnite

6.1.1.1 Batch Testing of Task 1 Paint Adhesion coupons by AFRL

The paint adhesion test panels for this task were shipped to AFRL/UDRI in two batches. Each panel was tested in the two separate areas where the specified repair took place. The testing was done per ASTM D 4541, Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers (PATTI). The test procedure and test results from the first batch are summarized in Appendix D. In this case, the raw data was provided by UDRI and is included in the back of this report. TAG received the first batch of coupons back from UDRI and upon examination, we noticed that some of Devcon Al Liquid and Devcon Ti Paste repair panels were tested on the wrong side as seen in Figure 27. These panels were returned to UDRI for retesting along with a second batch of samples for paint adhesion testing. The test results from this second batch of testing are summarized in Appendix E. The raw data was included in the back of this report. The raw data from both reports was reorganized by TAG in order to show all results from one repair technique on one page along with the retest values. The reorganized data are shown in Tables 18 – 22.

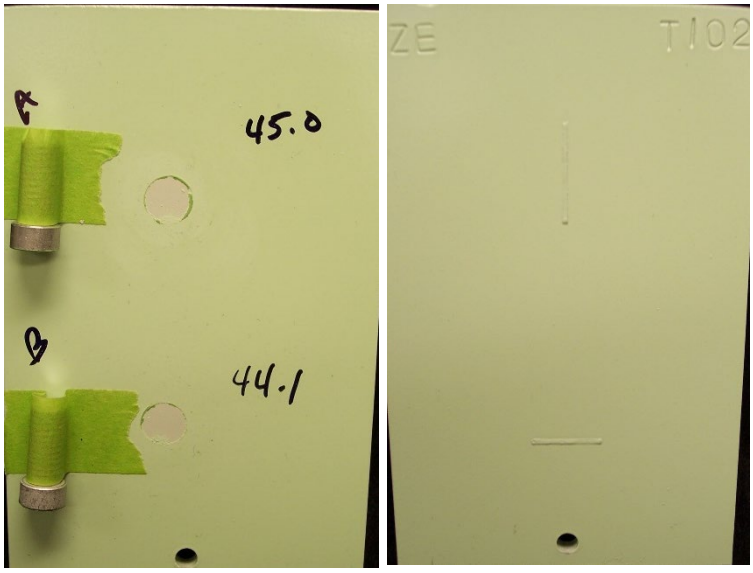


Figure 27:
Left: Paint Adhesion Testing on wrong side of panel
Right: Correct Side with Titanium Paste Repair

Table 18: UDRI Paint Adhesion Testing Raw Data for DEVCON Aluminum Liquid Repair (Includes retest values) where ND = Not Done

Panel Number	Pretreatment	Panel Verification	Gage Pull-off Pressure, psig	POTS (calculated psi)	POTS (calculated psi) (Retest)	% Glue Failure (Adhesion)	% Primer to Primer (Cohesion)	% Primer to Pretreatment (Adhesion)	%Pretreatment to Pretreatment (Cohesion)	% Pretreatment to Substrate (Adhesion)				Remarks
316ZEAL01A	Immersion Tagnite	✔	50.4	2052	2264	5%	95%							
316ZEAL01B	Immersion Tagnite	✔	46.6	1897	2562	5%	95%							
316ZEAL02A	Immersion Tagnite	✔	47.0	1913	2823	5%	95%							
316ZEAL02B	Immersion Tagnite	✔	44.9	1827	2905	5%	95%							
316ZEAL03A	Immersion Tagnite	✔	38.9	1582	2570	5%	95%							
316ZEAL03B	Immersion Tagnite	✔	40.7	1656	2990	5%	95%							
316ZEAL07A	Brush Tagnite	✔	47.1	1917	2884	5%	95%							
316ZEAL07B	Brush Tagnite	✔	57.3	2333	2656	5%	95%							
316ZEAL08A	Brush Tagnite	✔	50.6	2060	2852	5%	95%							
316ZEAL08B	Brush Tagnite	✔	23.9	970	3452	60%	40%							
316ZEAL09A	Brush Tagnite	✔	49.9	2031	2995	5%	95%							
316ZEAL09B	Brush Tagnite	✔	49.6	2019	3093	5%	95%							
316ZEAL13A	DOW 19	✔	44.8	1823	ND		25%	75%						
316ZEAL13B	DOW 19	✔	25.2	1023	ND	25%				75%				
316ZEAL14A	DOW 19	✔	49.0	1995	ND		50%	50%						
316ZEAL14B	DOW 19	✔	44.5	1811	ND		20%	80%						
316ZEAL15A	DOW 19	✔	49.0	1995	ND		50%	50%						
316ZEAL15B	DOW 19	✔	48.5	1778	ND		40%	60%						
316ZE41AL19	TCP	✔	48.0	1954	ND	15%	30%	55%						
316ZE41AL19	TCP	✔	37.7	1533	ND	10%	45%	45%						
316ZE41AL20	TCP	✔	47.2	1921	ND	20%	30%	50%						
316ZE41AL20	TCP	✔	59.7	2431	ND	15%	75%	10%						
316ZE41AL21	TCP	✔	56.0	2280	ND	15%	70%	15%						
316ZE41AL21	TCP	✔	54.9	2235	ND	10%	70%	20%						

Originally the wrong side was tested, re-test by AFRL

Table 19: UDRI Paint Adhesion Testing Raw Data for DEVCON Titanium Paste (Includes retest values) where ND = Not Done

Panel Number	Pretreatment	Panel Verification	Gage Pull-off Pressure, psig	POTS (calculated psi)	POTS (calculated psi) (Retest)	% Glue Failure (Adhesion)	% Primer to Primer (Cohesion)	% Primer to Pretreatment (Adhesion)	%Pretreatment to Pretreatment (Cohesion)	% Pretreatment to Substrate (Adhesion)				Remarks
316ZETI01A	Immersion Tagnite	✔	51.5	2097	3325	5%	95%							
316ZETI01B	Immersion Tagnite	✔	43.3	1762	3113	5%	95%							
316ZETI02A	Immersion Tagnite	✔	45.0	1831	3697	5%	95%							
316ZETI02B	Immersion Tagnite	✔	44.1	1795	3235	5%	95%							
316ZETI03A	Immersion Tagnite	✔	38.3	1558	3513	5%	95%							
316ZETI03B	Immersion Tagnite	✔	39.4	1603	2223	5%	95%							
316ZETI07A	Brush Tagnite	✔	47.8	1946	2595	5%	95%							
316ZETI07B	Brush Tagnite	✔	47.2	1921	2986	5%	95%							
316ZETI08A	Brush Tagnite	✔	52.9	2154	2737	5%	95%							
316ZETI08B	Brush Tagnite	✔	49.2	2003	2799	5%	95%							
316ZETI09A	Brush Tagnite	✔	53.0	2158	3203	5%	95%							
316ZETI09B	Brush Tagnite	✔	47.8	1946	3907	5%		95%						
316ZE41TI13A	DOW 19	✔	43.7	1778	ND	10%	35%	55%						
316ZE41TI13B	DOW 19	✔	46.5	1893	ND		40%	60%						
316ZE41TI14A	DOW 19	✔	36.2	1472	ND		15%		85%					
316ZE41TI14B	DOW 19	✔	38.0	1546	ND		15%		85%					
316ZE41TI15A	DOW 19	✔	35.4	1439	ND		25%	25%	50%					
316ZE41TI15B	DOW 19	✔	38.8	1578	ND	20%	20%		60%					
316ZE41TI19	TCP	✔	48.7	1982	ND	10%	45%	45%						
316ZE41TI19	TCP	✔	48.5	1974	ND	25%	50%	25%						
316ZE41TI20	TCP	✔	46.0	1872	ND	15%	10%	75%						
316ZE41TI20	TCP	✔	54.1	2203	ND	15%	45%	40%						
316ZE41TI21	TCP	✔	58.6	2386	ND	10%	90%							
316ZE41TI21	TCP	✔	48.1	1958	ND	15%	85%							

Wrong side was tested, at AFRL for re-test

Table 20: UDRI Paint Adhesion Testing Raw Data for TIG Weld Repair

Panel Number	Pretreatment	Panel Verification	Gage Pull-off Pressure, psig	POTS (calculated psi)	% Glue Failure (Adhesion)	% Primer to Primer (p/p) (Cohesion)	% Primer to Pretreatment (p/pr) (Adhesion)	%Pretreatment to Pretreatment (pr/pr) (Cohesion)	% Pretreatment to Substrate (pr/s) (Adhesion)				Remarks
316ZEGW01A	**Immersion Tagnite**	✔	46.1	1876	5%	95%							
316ZEGW01B	**Immersion Tagnite**	✔	40.9	1664	5%	95%							
316ZEGW02A	**Immersion Tagnite**	✔	39.6	1611	5%	95%							
316ZEGW02B	**Immersion Tagnite**	✔	40.0	1627	5%	95%							
316ZEGW03A	**Immersion Tagnite**	✔	46.1	1876	5%	95%							
316ZEGW03B	**Immersion Tagnite**	✔	39.9	1623	5%	95%							
316ZEGW07A	Brush Tagnite	✔	43.1	1754	10%	45%	45%						
316ZEGW07B	Brush Tagnite	✔	43.0	1750	10%	45%	45%						
316ZEGW08A	Brush Tagnite	✔	86.1	1756	10%	55%	35%						
316ZEGW08B	Brush Tagnite	✔	35.5	1444	5%	45%	50%						
316ZEGW09A	Brush Tagnite	✔	32.7	1329	5%	50%	45%						
316ZEGW09B	Brush Tagnite	✔	42.6	1733	5%	25%	70%						
316ZE41GW13	DOW 19	✔	35.9	1460		100%							
316ZE41GW13	DOW 19	✔	31.4	1276		95%		5%					
316ZE41GW14	DOW 19	✔	31.8	1293		100%							
316ZE41GW14	DOW 19	✔	4.7	186		10%			90%				
316ZE41GW15	DOW 19	✔	36.2	1472		100%							
316ZE41GW15	DOW 19	✔	34.2	1390		100%							
316ZE41GW19	TCP	✔	34.6	1407	15%	35%	50%						
316ZE41GW19	TCP	✔	39.2	1595	15%	25%	60%						
316ZE41GW20	TCP	✔	43.9	1786	15%	45%	40%						
316ZE41GW20	TCP	✔	33.6	1366	15%	25%	60%						
316ZE41GW21	TCP	✔	41.5	1688	25%	30%	45%						
316ZE41GW21	TCP	✔	35.0	1423	20%	20%	60%						

Table 21: UDRI Paint Adhesion Testing Raw Data for Cold Spray Repair

Panel Number	Pretreatment	Panel Verification	Gage Pull-off Pressure, psig	POTS (calculated psi)	% Glue Failure (Adhesion)	% Primer to Primer (p/p) (Cohesion)	% Primer to Pretreatment (p/pr) (Adhesion)	%Pretreatment to Pretreatment (pr/pr) (Cohesion)	% Pretreatment to Substrate (pr/s) (Adhesion)				Remarks
316ZE41CS01A	Immersion Tagnite	✔	44.0	1790	5%	95%							
316ZE41CS01B	Immersion Tagnite	✔	47.6	1937	5%	95%							
316ZE41CS02A	Immersion Tagnite	✔	44.1	1795	5%	95%							
316ZE41CS02B	Immersion Tagnite	✔	43.9	1786	10%	90%							
316ZE41CS03A	Immersion Tagnite	✔	44.6	1815	5%	95%							
316ZE41CS03B	Immersion Tagnite	✔	37.9	1541	5%	95%							
316ZE41CS07A	Brush Tagnite	✔	42.0	1709	5%	95%							
316ZE41CS07B	Brush Tagnite	✔	41.8	1701	5%	95%							
316ZE41CS08A	Brush Tagnite	✔	42.2	1717	5%	95%							
316ZE41CS08B	Brush Tagnite	✔	42.7	1737	5%	95%							
316ZE41CS09A	Brush Tagnite	✔	42.0	1709	5%	95%							
316ZE41CS09B	Brush Tagnite	✔	42.5	1729	5%	95%							
316ZE41CS13	DOW 19	✔	39.6	1611	0%	85%	15%						
316ZE41CS13	DOW 19	✔	42.1	1713	0%	95%	0%	0%	5%				
316ZE41CS14	DOW 19	✔	43.8	1782	0%	60%	0%	40%					
316ZE41CS14	DOW 19	✔	42.7	1737	0%	50%	0%	50%					
316ZE41CS15	DOW 19	✔	35.7	1452	5%	95%							
316ZE41CS15	DOW 19	✔	38.6	1570		95%	5%						
316ZE41CS19	TCP	✔	59.0	2403	15%	70%	0%	0%	15%				
316ZE41CS19	TCP	✔	62.5	2546	20%	80%							
316ZE41CS20	TCP	✔	61.6	2509	15%	85%							
316ZE41CS20	TCP	✔	59.6	2427	20%	80%							
316ZE41CS21	TCP	✔	51.6	2101	20%	80%							
316ZE41CS21	TCP	✔	59.1	2407	20%	80%							

Table 22: UDRI Paint Adhesion Testing Raw Data for HVOF Repair

Panel Number	Pretreatment	Panel Verification	Gage Pull-off Pressure, psig	POTS (calculated psi)	% Glue Failure (Adhesion)	% Primer to Primer (p/p) (Cohesion)	% Primer to Pretreatment (p/pr) (Adhesion)	%Pretreatment to Pretreatment (pr/pr) (Cohesion)	% Pretreatment to Substrate (pr/s) (Adhesion)				Remarks
316ZE41HV01A	Immersion Tagnite	✔	35.2	1431	5%	95%							
316ZE41HV01B	Immersion Tagnite	✔	37.5	1525	5%	90%	5%						
316ZE41HV02A	Immersion Tagnite	✔	27.1	1101	5%	95%							
316ZE41HV02B	Immersion Tagnite	✔	27.2	1105	5%	95%							
316ZE41HV03A	Immersion Tagnite	✔	30.6	1244	5%	95%							
316ZE41HV03B	Immersion Tagnite	✔	31.8	1293	5%	95%							
316ZE41HV07A	Brush Tagnite	✔	33.8	1374	5%		95%						
316ZE41HV07B	Brush Tagnite	✔	30.1	1223	5%		95%						
316ZE41HV08A	Brush Tagnite	✔	37.0	1505	5%		95%						
316ZE41HV08B	Brush Tagnite	✔	38.7	1574	5%		95%						
316ZE41HV09A	Brush Tagnite	✔	37.9	1541	5%		95%						
316ZE41HV09B	Brush Tagnite	✔	38.3	1558	5%		95%						
316ZE41HV13	DOW 19	✔	28.8	1170		100%							
316ZE41HV13	DOW 19	✔	27.2	1105		95%			5%				
316ZE41HV14	DOW 19	✔	24.5	995		50%			50%				
316ZE41HV14	DOW 19	✔	22.0	893		85%			15%				
316ZE41HV15	DOW 19	✔	27.8	1756	5%	90%			5%				
316ZE41HV15	DOW 19	✔	32.1	1756		95%			5%				
316ZE41HV19	TCP	✔	52.3	2129			50%	50%					
316ZE41HV19	TCP	✔	48.4	1970			50%	50%					
316ZE41HV20	TCP	✔	38.7	1574			50%	50%					
316ZE41HV20	TCP	✔	47.9	1950			100%						
316ZE41HV21	TCP	✔	42.3	1721			10%	90%					
316ZE41HV21	TCP	✔	49.9	2031			100%						

6.1.1.2 Paint Adhesion Data Analysis

The JTP states that the performance criteria for this task is ***Immersion Tagnite and Brush Tagnite Paint Adhesion must be equal to or better than DOW 19***. Based on this criteria, the POTS (calculated psi) was extracted from the UDRI raw data and placed in a Excel spreadsheet and for each type of repair, the average POTS for Immersion Tagnite, Brush Tagnite and DOW 19 was calculated for each repair scheme. The paint adhesion performance of two means were compared. The two means compared were:

a. Immersion Tagnite vs. DOW 19
b. Brush Tagnite vs. DOW 19

Initially, an F-test between the two means was calculated to determine if the variances of the two populations were equal. If the variances were equal, a t-test two sample assuming equal variances was run to determine if the means were different. If the variances were unequal, a t-test two sample assuming unequal variances was run to determine if the means were different. The paint adhesion means testing statistical results are summarized in Table 23. The table is organized by repair technique and lists the average pull-off strength (POTS mean), results of the F-test variance test and results of the t-test for means.

Only the Immersion and Brush Tagnite ***retest*** paint adhesion values were used for the Devcon Al Liquid and Devcon Ti Paste data analysis.

6.1.1.3 Paint Adhesion Performance Results: Table 24 is a paint adhesion results summary. From this results, the following observations were seen:

- When comparing the paint adhesion between Immersion Tagnite and DOW 19 for the five different repair schemes, the majority of the time (3 out 5) Immersion Tagnite had a statistically higher adhesion strength than DOW 19. The other two repair schemes showed the primer adhesion strength to be equal between the two pretreatment processes.
- When comparing the paint adhesion between Brush Tagnite and DOW 19 for the five different repair schemes, the majority of the time (3 out 5) there was no difference in paint adhesion performance while Brush Tagnite out performed DOW 19 on the other two repair schemes.
- For the Devcon Aluminum and Titanium repairs both Immersion Tagnite and Brush Tagnite performed much better than the DOW 19. The paint adhesion values used for this calculation were based on the retest values for the Immersion Tagnite and Brush Tagnite coupons. The retest values were significantly higher than the original values collected on the non-repair side. The reason for this large difference is unknown.

Conclusion: In the cases when there was a statistical difference in the average POTS, the higher average was either Immersion Tagnite or Brush Tagnite. In the cases when there was not statistical differences in the means between Immersion Tagnite and DOW 19 or Brush Tagnite and DOW 19, the performance was considered equal to the DOW 19. Therefore, ***the paint adhesion results met the performance criteria*** where the paint adhesion of Immersion Tagnite and Brush Tagnite must be equal to or better than DOW 19.

Table 23: Summary of Means Testing Statistical Analysis for Paint Adhesion Results

	Devcon Al F2 Liquid		Devcon Ti Paste		TIG Welding	
	Immersion Tagnite	DOW 19	Immersion Tagnite	DOW 19	Immersion Tagnite	DOW 19
POTS Mean (psi)	2685	1735	3184	1618	1712	1180
Variance Testing (F-test)	Equal		Unequal		Unequal	
Means Testing (t-test)	Means are different		Means are different		Means are different	
	Brush Tagnite	DOW 19	Brush Tagnite	DOW 19	Brush Tagnite	DOW 19
POTS Mean (psi)	2989	1735	3038	1618	1628	1180
Variance Testing (F-test)	Equal		Unequal		Unequal	
Means Testing (t-test)	Means are different		Means are different		No Difference	

	Cold Spray		HVOF	
	Immersion Tagnite	DOW 19	Immersion Tagnite	DOW 19
POTS Mean (psi)	1778	1644	1283	1279
Variance Testing (F-test)	Equal		Equal	
Means Testing (t-test)	No Difference		No Difference	
	Brush Tagnite	DOW 19	Brush Tagnite	DOW 19
POTS Mean (psi)	1717	1644	1462	1279
Variance Testing (F-test)	Unequal		Unequal	
Means Testing (t-test)	No Difference		No Difference	

Table 24: Paint Adhesion Performance Summary

	Devcon Al F2 Liquid		Devcon Ti Paste		TIG Welding	
	Immersion Tagnite	DOW 19	Immersion Tagnite	DOW 19	Immersion Tagnite	DOW 19
POTS Mean (psi)	2685	1735	3184	1618	1712	1180
Performance Results	Imm. Tagnite > DOW 19		Imm. Tagnite > DOW 19		Imm. Tagnite > DOW 19	
	Brush Tagnite	DOW 19	Brush Tagnite	DOW 19	Brush Tagnite	DOW 19
POTS Mean (psi)	2989	1735	3038	1618	1628	1180
Means Testing (t-test)	Brush Tagnite > DOW 19		Brush Tagnite > DOW 19		Equivalent Performance	

	Cold Spray		HVOF	
	Immersion Tagnite	DOW 19	Immersion Tagnite	DOW 19
POTS Mean (psi)	1778	1644	1283	1279
Means Testing (t-test)	Equivalent Performance		Equivalent Performance	
	Brush Tagnite	DOW 19	Brush Tagnite	DOW 19
POTS Mean (psi)	1717	1644	1462	1279
Means Testing (t-test)	Equivalent Performance		Equivalent Performance	

6.1.2 Galvanic Corrosion Testing of Repair Areas after Immersion Tagnite

6.1.2.1 Testing of Task 1 Galvanic Corrosion Coupons by NDSU

The galvanic corrosion test panels for this task were shipped to the North Dakota State University (NDSU) Department of Coatings and Polymeric Materials (CPM) in multiple batches. Each panel was tested in the two separate areas where the specified repair took place. The testing was done per ASTM G71, Standard Guide for Conducting and Evaluating Galvanic Corrosion Tests in Electrolytes and the experimental setup is shown in Appendix F. Each panel was tested in the two separate areas where the specified repair took place and the galvanic current was measured for 24 hours. The values used for the data analysis were the average of the galvanic current values measured during stable periods which in this case was between the 15th hour and the 24th hour (10 hour period) of the experiment. There were two trials performed for each repair/coating scheme and the galvanic current values are provided in Table 1 of Appendix F.

6.1.2.2 Galvanic Corrosion Performance Results

The galvanic corrosion performance results summarized in the NDSU report rank the performance based on the galvanic corrosion current values regardless of the repair/coating scheme. The performance criteria listed in the JTP for this test states that the galvanic corrosion performance of Immersion Tagnite and Brush Tagnite must be equal to or better than the DOW 19 performance. The NDSU report states "…*low galvanic current indicate low/reduced corrosion of the more active sample whereas higher current indicated higher/increased corrosion of the more active sample.* ***The lower the galvanic current, the better the corrosion resistance.*** " A negative galvanic current shows that the repair site is acting as a cathode while a positive galvanic current is indicative of the repair site acting as the anode. Regardless of the sign of the galvanic current, the lower the current – the better the corrosion resistance. Based on this criteria, TAG analyzed the galvanic corrosion current response of Immersion Tagnite, Brush Tagnite and DOW 19 for each of the five different repair techniques. TAG looked at the average galvanic currents for Immersion Tagnite, Brush Tagnite and DOW 19 and rated the performance of the pretreatments relative to the magnitude of the DOW 19 galvanic current. The rating system is as follows:

"**Best**": Magnitude of Tagnite/Brush Tagnite Galvanic Current is 3 – 5x less than DOW 19
"**Better**": Magnitude of Tagnite/Brush Tagnite Galvanic Current is 1 – 2x less than DOW 19
"**Equal**": Magnitude of Tagnite/Brush Tagnite Galvanic Current is same magnitude as DOW 19

The galvanic corrosion performance ratings are listed in Table 25.

Conclusion: Based on this rating system and the galvanic current readings, Immersion Tagnite and Brush Tagnite had a galvanic corrosion response that was better or equal to the DOW 19 conversion coating in all five repair schemes and therefore passed the performance criteria specified in the JTP.

Table 25: Summary of Galvanic Corrosion Ratings for Magnesium Pretreatments on Repaired Magnesium Coupons

Repair Technique	Panel Treatment	First Trial		Second Trial	
		Galvanic Current (Amps)	Rating	Galvanic Current (Amps	Rating
Devcon Aluminum F2 Liquid	Imm. Tagnite	-2.53E-08	Best	2.08E-08	Better
	Brush Tagnite	-1.19E-11	Best	-4.83E-06	Equal
	Dow 19	1.51E-05		-1.85E-06	
	TCP	-4.19E-06	Better	4.73E-06	Equal
Devcon Titanium Paste	Imm. Tagnite	1.35E-08	Better	-3.11E-07	Better
	Brush Tagnite	3.64E-06	Equal	-1.31E-06	Equal
	Dow 19	4.16E-06		6.26E-06	
	TCP	4.03E-06	Equal	6.67E-06	Equal
TIG Weld Repair With ZE41 Welding Rod	Imm. Tagnite	-1.81E-11	Best	-1.04E-07	Better
	Brush Tagnite	-2.60E-06	Better	-1.30E-11	Best
	Dow 19	-1.78E-05		-2.25E-05	
	TCP	-1.53E-05	Equal	-5.86E-06	Better
6061 Aluminum Cold Spray	Imm. Tagnite	2.12E-04	Equal	1.43E-04	Equal
	Brush Tagnite	-2.27E-11	Better	1.95E-04	Equal
	Dow 19	1.75E-04		1.37E-04	
	TCP	1.83E-04	Equal	7.41E-05	Better
HVOF With Al 12Si	Imm. Tagnite	1.49E-04	Equal	1.24E-04	Equal
	Brush Tagnite	1.29E-04	Equal	2.33E-04	Equal
	Dow 19	1.82E-04		1.81E-04	
	TCP	8.60E-05	Equal	1.69E-04	Equal

6.1.3 Chemical Stripping of Legacy Anodize Coatings

6.1.3.1 Explanation of Tagnite Chemical Stripping Process

Through the years, scientists at Technology Applications Group have developed a procedure for removing the Tagnite coating using the Tagnite pretreatment process to loosen and/or dissolve the Tagnite coating. This process also allows TAG operators to remove Tagnite that was damaged or improperly applied without any adverse effect on the surface finish or dimensional tolerances of the original casting. Once this process has been completed, the parts can be placed in the Tagnite anodize bath and a new Tagnite coating applied.

The Tagnite chemical stripping process involves two steps:

1. The component that needs to have the Tagnite removed is first placed in the mild alkaline etch solution. The mild alkaline etch is a mixture of sodium borate and sodium pyrophosphate operated at 160 – 180ºF. The process allows for a slow, easily controlled etch process. The component to be stripped is placed in the etch tank for 5 – 15 minutes. The amount of time is dependent on the alloy and the Tagnite thickness. During a typical strip cycle, the Tagnite operator will check on the component every few minutes while in the etch tank. The component will be removed when there is evidence of darkening of the Tagnite along the edges of the component as seen in Figure 28 (Upper Right). At this point, the component is given a quick (< 1 minute) water rinse then transferred to the Fluoride Activator tank.
2. The fluoride activator solution is a fluoride based solution operated at 160 – 180ºF. The purpose of the solution during the stripping process is to dissolve the magnesium oxide layer next to the base metal which softens the coating making it easier to remove. This process can take 1 – 2 hours with the operator checking at frequent intervals for lifting of the coating or a clumpy appearance. If the operator can remove the coating with a gentle wipe from a Scotch Brite non-abrasive pad, then the stripping process is complete (Figure 28 – Lower Right). At this point in time, the component can now be recoated with Tagnite.





Above Left: Test Coupon with Tagnite 8200
Above Right: Test Coupon after 8 minutes in Alkaline Etch. Note darken areas around the edges where Tagnite has been removed.

Below Left: Test Coupon after 1 hour soak in Fluoride Activator. Tagnite appearance is spotty with bare metal present
Below Right: Test Coupon after soak in Fluoride Activator and light scrubbing with Scotch Brite pad on right side. Bare metal is now present.





Figure 28: Visual Summary of Tagnite Stripping Process

6.1.3.2 Effect of Tagnite Chemical Stripping Process on the DOW 17 and HAE Legacy Anodize Coatings

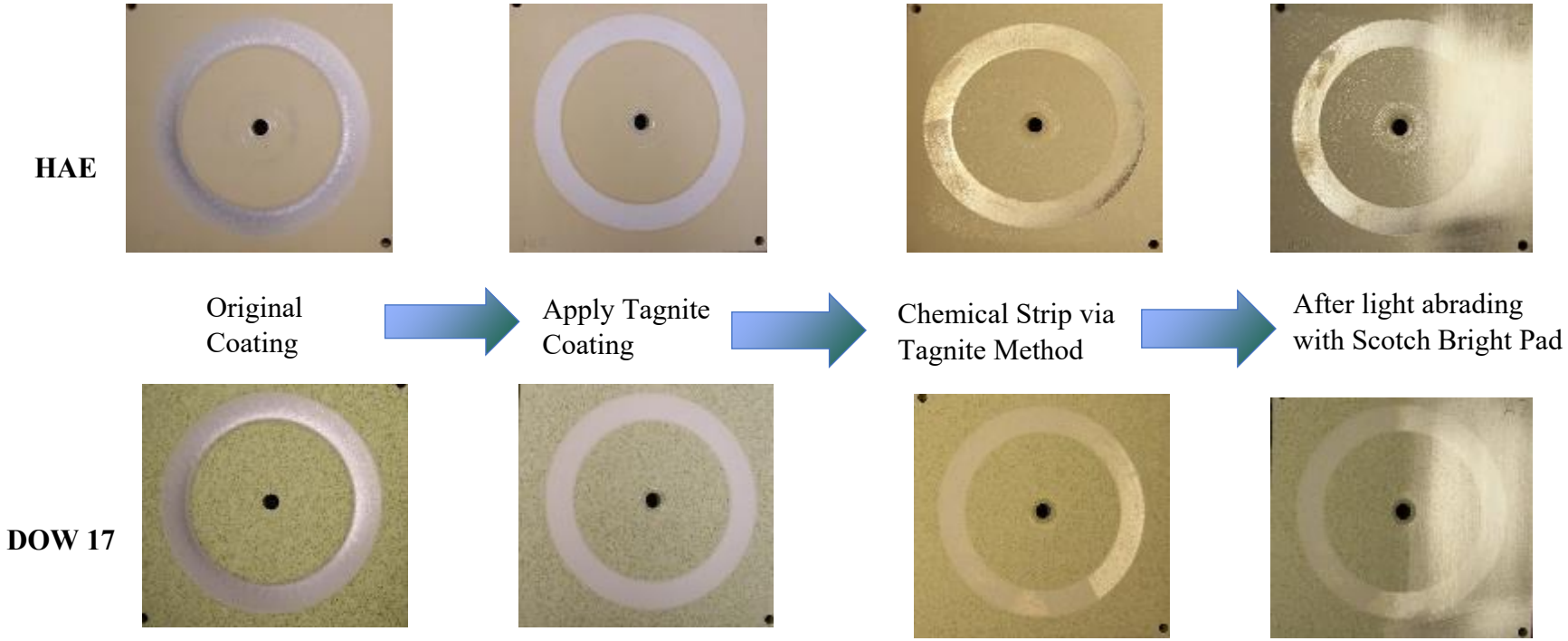
Magnesium test panels that were coated with the DOW 17 and HAE anodize coatings were put through the Tagnite stripping process described in Section 6.1.3.1. Visual examination and scratch testing of the panels showed that neither of the legacy anodize coatings was affected by the Tagnite chemical stripping process. There was no evidence of softening or lifting of the coating. Attempts to remove the legacy coatings with Scotch Brite pads or aluminum oxide were unsuccessful.

At this point in time, TAG scientists decided to use a different approach. It is a proven fact that the DOW 17 and HAE coatings are extremely porous compared to the Tagnite coating. The pores in these legacy coatings are much larger than the pores seen in the Tagnite coating. In addition, these pores channel down and have direct contact with the base metal. The porosity of the Tagnite coating does not allow direct access to the base metal. TAG personnel theorized that we could take advantage of the large pores of the legacy coatings by applying the Tagnite coating while the legacy coatings were in place. The working theory was the high deposition voltages/currents of the Tagnite process would drive the Tagnite solution through the pores down to the base metal and allow a Tagnite coating to build up from the magnesium and lift up the legacy coatings. After this step, the Tagnite chemical stripping process could be used to soften and lift the Tagnite coating next to the magnesium surface and undermine the legacy coatings.

This theory was tested with a series of experiments on some test coupons coated with the DOW 17 or HAE legacy anodize coatings. Prior to applying the initial Tagnite coating, the DOW 17 and HAE panels were placed on a Taber Abraser machine and a track was wore into the coating until only bare magnesium was present in the track. This track would allow us to see the Tagnite deposition and stripping progress. Examples of this process on the HAE and DOW 17 coatings are seen in Figure 29. This approach was somewhat successful in removing the legacy coatings. There was only limited success because of the need to use non-abrasive pads to finish the legacy coating removal process.

Conclusions:

1. The Tagnite chemical stripping process was not successful in removing the legacy HAE and DOW 17 coatings.
2. Incorporating a Tagnite deposition step prior to the chemical stripping process met with more success, however, extra steps were needed to remove the residual legacy coatings.
3. After talking with CCAD engineers and production personnel, the consensus was that the Tagnite deposition/chemical stripping process/non-abrasive pad process was too labor intensive and involved too many processing steps. The decision was made to investigate other means of removing the legacy coatings.



Process Steps for Alternate Chemical Stripping Approach:

1. Use Taber Abraser machine to remove legacy coatings and expose a track of bare magnesium.
2. Process HAE/DOW 17 coated panels through Tagnite pretreatment process
3. Apply thin coating (0.16 - 0.20 mils) of Tagnite. Note gray Tagnite in taber track and slightly gray appearance on DOW 17 and HAE coated areas where Tagnite filled in the pores
4. Strip using Tagnite chemical stripping process. Stripping of Tagnite in the taber track is clearly visible.
5. Light sanding with Scotch Bright pad removed most of legacy coating.

Figure 29: Effect of Tagnite Chemical Stripping Process on Legacy Coatings

6.1.4 Techniques to Eliminate Residual Fluid Leakage from Porous Aerospace Alloys

Original Testing Protocol: The JTP task called out the use of AZ91 magnesium test coupons that were soaked in various rotary wing fluids such as transmission, hydraulic and lubricating oils. TAG scientists soaked the AZ91 coupons in these fluids as called out in Section 5.1.2, however, when processed through the Tagnite pretreatment tanks, no residual fluids were observed after the high temperature drying phase. There are several reasons for the lack of weeping residual fluid from the magnesium test coupons.

1. The panels were not soaked long enough in the fluid.
2. The fluid must be at operating temperature for significantly longer periods before any significant adsorption into the porosity of the magnesium occurs.

This approach was discontinued due to a lack of time for prolonged soak periods and the fact that TAG was not equipped to process these coupons at the operating temperatures of the fluids. Therefore, the focus of the study shifted from test coupons to scrap parts.

Revised Test Protocol: A variety of helicopter scrap parts made from the AZ91 magnesium alloy family were obtained from CCDC AvMC SAFR facility and studied for residual fluid weeping after being processed using typical magnesium degreasing protocols. These protocols were vapor degreasing, pressure washing and alkaline degreasers. TAG's experience has shown that baking the parts at the Rockhard curing temperature range is the best way to force any residual fluids trapped in the porosity of the magnesium component to the surface.

The test protocol was to treat these scrap housings using the magnesium degreasing protocols listed above, then place the components in a curing oven at 375^{o}F for 30 minutes. Once the component has cooled to room temperature, cotton gloves were wiped over the surface and inspected for residual fluids.

Vapor Degreasing Results: The vapor degreasing was done at the CCAD plating shop using their standard vapor degreaser for 15 minute cycles. In a limited number of tests, after one vapor degreasing cycle there was no residual fluid seen after the high temperature drying.

Pressure Washing Results: Parts were pressure washed at 1000 psi using a commercially available pressure washer with a 25^{o} high pressure nozzle for 3 – 5 minutes while adding some Oakite NST degreasing concentrate to the soap container. This process was the least effective as residual fluid was observed even after 3 pressure washer/drying cycles.

Alkaline Degreasing Results: For this test, the TAG degreaser used as the first step in the Tagnite pretreatment process was tested. The TAG degreaser consists of a 10 – 12 % solution of Oakite NST Aluminum Cleaner with the pH adjusted to 10.3 – 12.0 using 50 % sodium hydroxide. Each scrap part was soaked in the TAG degreaser for 20 minutes at 50 – 60^{o}C, rinsed for 5 minutes in RO water and placed in the curing oven. About 50 % of the time, there was no residual fluid on the surface of the part after the high temperature drying. The other half of the time the parts needed at least one additional 20 minute soak in the TAG degreaser to completely remove the residual fluid.

Residual Fluid Conclusions: These conclusions are based on a limited amount of scrap parts and additional testing is recommended.

1. Vapor degreasing appeared to remove the greatest amount of residual fluid based on the lack of weeping residual fluid at the end of the initial vapor degreasing/high temperature drying protocol.
2. Alkaline Immersion Degreasing was the second best option at removing residual fluids, however, a significant number of parts needed a second degreasing cycle before all the residual fluid was removed.
3. Pressure washing had no effect on residual fluid removal and is only recommended for the removal of heavy oil or grease on the surface of the part.

Removal of Weeping Residual Fluid after Tagnite: There will be times regardless of how aggressively the part has been degreased, weeping residual fluid will be found in the Tagnite coating after the initial Rockhard preheating step (typically this step is 335 - 365ºF for 15 – 20 minutes after part reaches temperature). The weeping fluid will darken or discolor the Tagnite coating – it will look like an oil stain.

TAG has developed a procedure to remove the residual fluid from the Tagnite without having to strip the Tagnite coating. The procedure is:

1. Place part in the oven at 335 - 365ºF for 15 – 20 minutes after part reaches temperature.
2. If fluid stain is noticed immediately after being taken out of the oven, allow the part to cool down to $\leq$ 120ºC. Continue to Step 4.
3. If the fluid stain is not noticed until the part is at room temperature, preheat part to 335 – 365ºF for 15 – 20 minutes then allow part to cool down to $\leq$120ºF.
4. Saturate a lint-free cloth with acetone and wipe the stained area. Only wipe the area once then fold the cloth to expose clean cloth for the next wipe. It is very important that you continually fold the cloth and do not use any cloth that has absorbed the oil as it will be easily transferred to a new area.
5. After the stained area has been cleaned to the point where the stained Tagnite looks like the “normal” Tagnite, place the part back in the oven for another preheat cycle of 15 – 20 minutes.
6. Allow to cool down, inspect the part and, if necessary, repeat the acetone wipe and the preheat cycle until no more residual fluid is seen on the Tagnite surface.
7. Part is now ready for Rockhard application per the appropriate specification.

6.1.5 Dimensional and Weight Change due to Stripping of Legacy Coatings

6.1.5.1 Dimensional Change

Original Testing Protocol: A detailed test matrix is summarized in Table 26. Test coupons from each of the four aerospace alloys were to be treated as below. This test matrix would collect dimensional and weight loss data on the current stripping and coating processes of legacy parts and proposed methods going forward. Before and after each process step, each test coupon would be weighed on an analytical balance to $\pm$ 0.0001 grams and dimensions would be measured in at least 2 locations for each dimension using a micrometer. An example panel is shown in Figure 30.

Control Group: No treatment - used to determine variability in weight and dimensions over time and changing environmental factors.

"Current" Group: This will simulate the current stripping and recoating process at CCAD. Test coupons will be HAE, DOW 17 and Tagnite anodize coatings which are coatings applied to the original, new build components, then:

1. Stripped via the current chromic acid procedure at the CCAD plating shop followed by
2. Submersion in the currently used DOW 7 conversion coating then
3. Stripped a second time using the chromic acid method.

"Future 1": This would be one potential stripping scenario seen at the depot level. Test coupons will be HAE, DOW 17 and Tagnite anodize coatings on the magnesium coupons, then:

1. Stripped via the current chromic acid procedure at the CCAD plating shop followed by
2. Tagnite anodization and subsequently
3. Stripped by chromic acid again.

"Future 2": This would be the preferred procedure going forward. Test coupons will be HAE, DOW 17 and Tagnite anodize coatings on the magnesium coupons, then:

1. Stripped via the TAG chemical strip procedure developed in Section 5.1.2 followed by
2. Tagnite anodization and
3. Re-stripping by TAG chemical method.

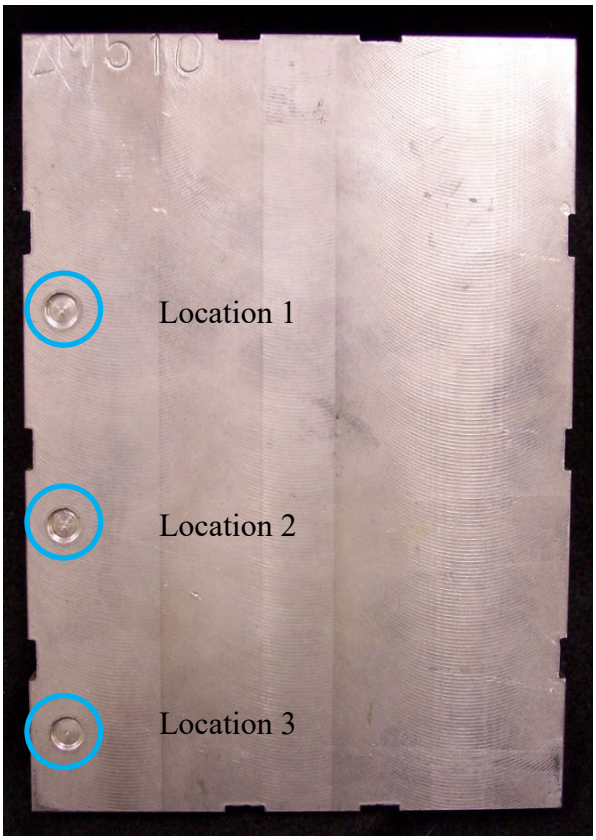


Figure 30: Location of Micrometer Measuring Locations on Dimensional Loss Panels

Table 26: Original Dimensional Change Test Description for Chemical Stripping of Legacy Coatings.

Treatment Group	**Experimental Control**				**Current Depot Process**				**Future Process #1**				**Future Process #2**			
Magnesium Alloy	AZ91E-T6	EV31A-T6	QE22A-T5	ZE41-T5	AZ91E-T6	EV31A-T6	QE22A-T5	ZE41-T5	AZ91E-T6	EV31A-T6	QE22A-T5	ZE41-T5	AZ91E-T6	EV31A-T6	QE22A-T5	ZE41-T5
# of Coupons	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Initial Anodize Coating	None				DOW 17 HAE Tagnite				DOW 17 HAE Tagnite				DOW 17 HAE Tagnite			
Initial Stripping Process	None				Chromic Acid				Chromic Acid				TAG Chemical Strip			
Second Coating Process	None				DOW 7				Tagnite				Tagnite			
Second Stripping Process	None				Chromic Acid				Chromic Acid				TAG Chemical Strip			
Acceptance Requirement	Dimensional Loss cannot exceed airworthiness requirements															

Revised Test Protocol: As this project progressed, the rational behind the dimensional change protocol changed. The "Current" Group testing process was eliminated because the DOW 7 conversion coating tank is being phased out. The "Future 2" testing process was eliminated due to the failure of Tagnite stripper to remove the HAE and DOW 17 anodize coatings. As a consequence, the project group was left with a modified version of the "Future 1" testing process. The modified version is shown in Table 27.

Table 27: Modified Dimensional Change Test Matrix for Chemical Stripping of Legacy Coatings.

Treatment Group	**Experimental Control**			**Future Process #1**		
Magnesium Alloy	AZ91E-T6	EV31A-T6	ZE41-T5	AZ91E-T6	EV31A-T6	ZE41-T5
# of Coupons	3	3	3	6	6	6
Initial Anodize Coating	None			DOW 17 HAE Tagnite		
Initial Stripping Process	None			Chromic Acid		
Second Coating Process	None			Tagnite		
Acceptance Requirement	Dimensional Loss cannot exceed airworthiness requirements					

There were two items left off this modified test matrix.

1. QE22-T5 was left off the matrix because this alloy is not present on H-60 platform.
2. The second chromic acid stripping step was eliminated due to time constraints.

Waypoints for Dimensional Change and Panel Weight Measurements: Dimensional change and panel weight measurements were collected at four different waypoints during this experiment.

1. Bare panel – no pretreatments of coating applied. Due to a technician oversight, the test coupon dimensions for the bare panels prior to the HAE anodize were not done.
2. After original anodize was applied. The anodize coatings were either HAE, DOW 17 or Tagnite.
3. After the chromic acid stripping at the CCAD plating shop.
4. After the application of Tagnite to all of the stripped panels, equivalent to re-anodization of the panel.

Dimensional Change Measuring Protocols:

1. Prior to measuring the control/test panels for dimensional change, the panels were placed in drying oven at 60ºC for 20 minutes, then allowed to cool at room temperature for another 20 minutes prior to measurement.
2. The dimensional change was always measured at the location points #1, 2 and 3 (Figure 30) on every control and test coupon. Each location point was measured six (6) times.
3. The values were entered into a spreadsheet and the average dimensional change at each location was calculated.
4. If there was a dimensional change in the location average of the control panels, this change was applied to the test panel average.
5. The average dimensional change and weight change was calculated for:
    a. Change between the bare panel and original anodize coating.
    b. Change between the original anodize coating and after chromic acid strip.
    c. Change between bare panel and after chromic acid strip.
    d. Change between after chromic acid strip and Tagnite re-anodization.
    e. Change between bare panel and Tagnite re-anodization.

Dimensional Change Results:

The statistical summary of the dimensional change data is seen in Appendices G – I. Figures 31 – 33 summarize the results.

1. The DOW 17 panels had a negative (loss) dimensional change after the DOW 17 coating was applied (difference between bare and anodize). This is unusual and implies that the DOW 17 pretreatment process led to some dimensional loss and that the DOW 17 coating was thinner than the Tagnite coating. Eddy current readings of the thickness showed the DOW 17 coating was < 0.2 mils (0.0002") thick while the Tagnite coating was 0.34 mils (0.00034") thick.
2. TAG has completed studies that show the Tagnite coating thickness consists of 50 % penetration into the magnesium and 50 % buildup. The measured Tagnite thickness was 0.34 mils (0.00034"), therefore the buildup (dimensional change) was 0.17 mils per surface or 0.34 mils overall. The dimensional change in the Tagnite thickness was in the expected range during the Bare to Original anodize step. There is some variation in buildup which is due to the amount of time spent in the mild alkaline etch pretreatment bath. AZ91C and ZE41A test coupons went through the Tagnite process at the same time and had the same dimensional change in the Bare to Original Anodize step. The EV31A had a larger dimensional change due to less time in etch.
3. The largest dimensional change occurred after each original anodize coating was stripped off using chromic acid. This is unusual because chromic acid is not supposed to attack magnesium. However, if there is a significant contaminate level in the chromic acid, it will attack magnesium. If a second chromic acid step was done as originally proposed, the dimensional loss would have been much greater, potentially leading to failure of the dimensional tolerance airworthiness limits.
4. When the panels were re-anodized with Tagnite, there was still dimensional loss (Chromic Acid to After Tagnite bars) for all three original anodize groups. There was a small dimensional loss between the Chromic Acid Strip to After Tagnite step for

EV31A and ZE41A which is probably due to a greater time spent in the mild alkaline etch. The AZ91C panels had a slight dimensional decrease.

5. For panels originally coated with DOW 17 and Tagnite, the overall dimensional loss for all three (3) alloy groups (Bare to After Tagnite bars) showed that the maximum dimensional loss never exceeded 1.0 mils (0.001”). For panels originally coated with Dow 17 and Tagnite, the Bare to After Tagnite readings showed an overall dimensional loss, primarily driven by the large dimensional loss after the chromic acid strip step. The overall dimensional loss was very consistent for all three alloys.

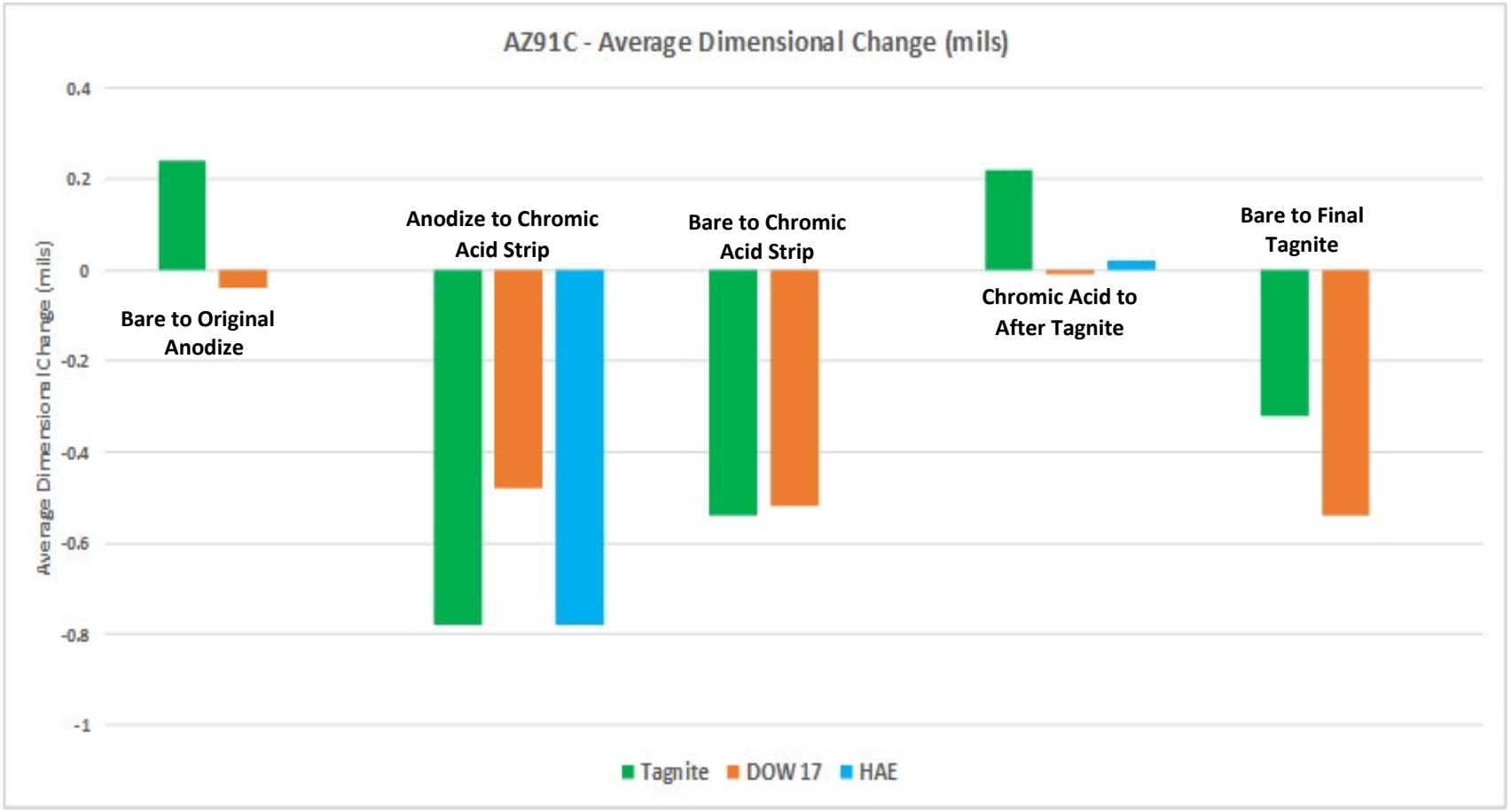


Figure 31: Graph of Dimensional Change for AZ91C over the course of Applying Fresh Anodize Coating, Stripping and Re-anodizing with Tagnite.

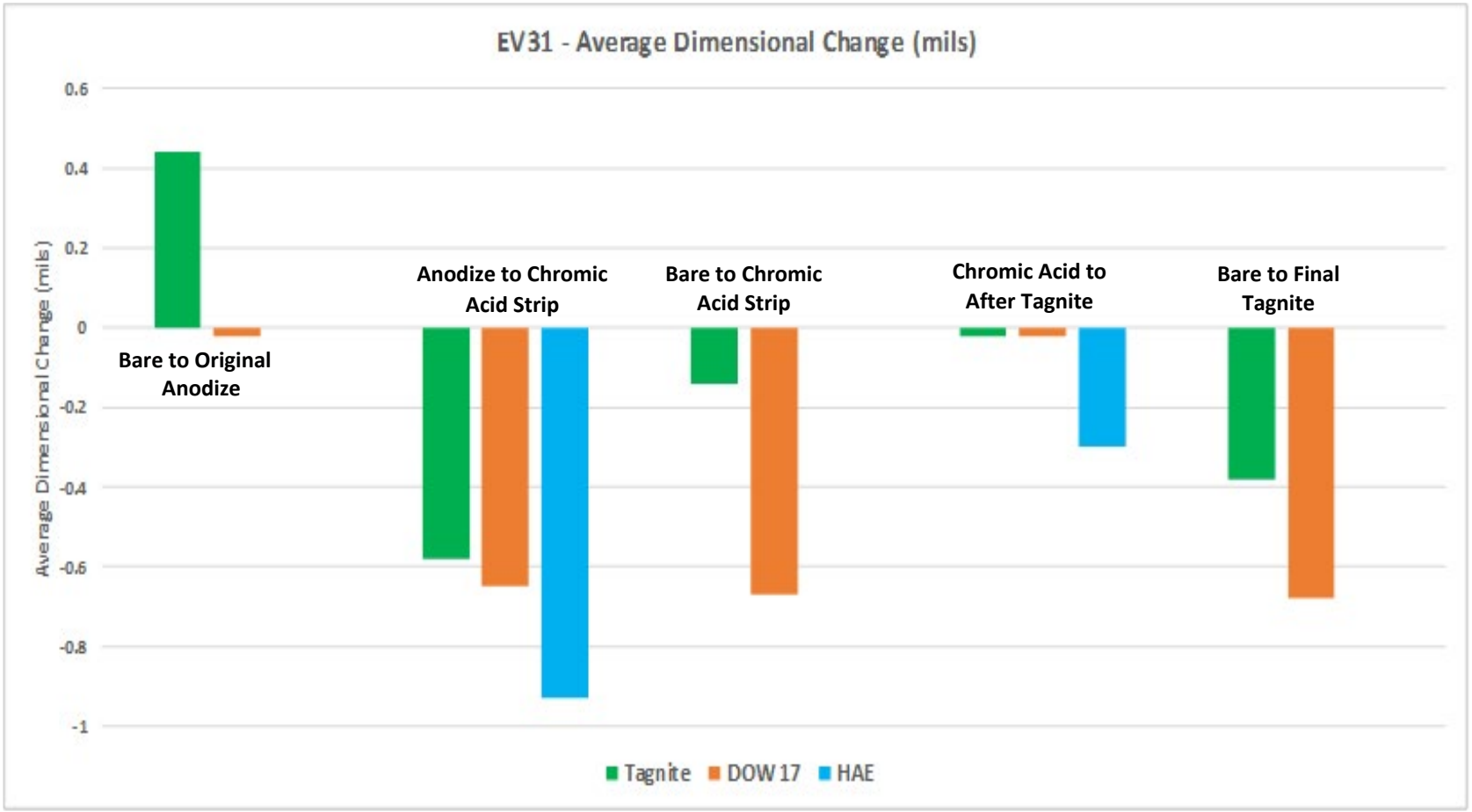


Figure 32: Graph of Dimensional Change for EV31A over the course of Applying Fresh Anodize Coating, Stripping and Re-anodizing with Tagnite.



Figure 33: Graph of Dimensional Change for ZE41A over the course of Applying Fresh Anodize Coating, Stripping and Re-anodizing with Tagnite.

6.1.5.2 Weight Change Results

Weight Change Measuring Protocols:

1. Prior to weighing the control/test panels for weight change, the panels were placed in drying oven at 60ºC for 20 minutes, then allowed to cool at room temperature for another 20 minutes prior to measurement.
2. If there was a weight change of the control panels, this change was used to adjust for the test panel average.
3. Due to the varying test panel weights, the weight change was normalized to the test panel weight and the weight change is expressed as "Average % Weight Change". For example, if you are looking at the Average % Weight Change for **Bare to Anodize** values on the graph, the values were calculated by:

$$\text{Average \% Weight Change} = \frac{(\text{Anodize} - \text{Bare Panel Weight in gms}) \times 100\%}{\text{Bare Panel Weight}}$$

4. The weight values were entered into a spreadsheet and average % weight change was calculated for waypoint measurements.
   a. Change between the bare panel and original anodize coating.
   b. Change between the original anodize coating and after chromic acid strip.
   c. Change between bare panel and after chromic acid strip.
   d. Change between after chromic acid strip and Tagnite re-anodization.
   e. Change between bare panel and Tagnite re-anodization.

Weight Change Results:

The statistical summary of the weight change data is seen in Appendices G – I while Figures 34 – 36 summarize the results.

1. The greatest weight change of the original anodize coatings applied was Tagnite as seen in the Bare to Original Anodize weight change measurements. This verifies that the DOW 17 and HAE coatings were significantly thinner than the Tagnite.
2. There was little to no weight change after the HAE coating was applied which again shows that the HAE coating was thinner than the Tagnite coating.
3. The largest weight change occurred after each original anodize coating (HAE, DOW 17 and Tagnite) was stripped off using chromic acid. In theory, chromic acid should only remove the anodize coatings, leaving the magnesium alone and the panel weight should be close to the original bare panel weight. However, the Anodize to Chromic Acid Strip weight changes show a significant loThese results are significant because it shows that the chromic acid is not only removing the anodize coating but also etching the magnesium. Magnesium etching only occurs in the chromic acid when there is a significant contaminate level in the chromic acid.
4. When the panels were re-anodized with Tagnite, weight gain was very consistent. (Chromic Acid to After Tagnite bars) for all three original anodize groups and all alloys thereby showing that Tagnite is a very controllable process.

5. The overall weight loss (Bare to After Tagnite bars) was highest for the panels originally coated with HAE. The panels that started with Tagnite, stripped and recoated with Tagnite had very consistent weight losses and the EV31A and AZ91C alloys had the lowest weight gain loss.

Overall Dimensional and Weight Loss Conclusions:

1. The test panels that were originally coated with Tagnite, stripped and recoated with Tagnite behaved a very consistent manner in terms of dimensional loss and weight loss.
2. The dimensional loss for the panels that were originally coated with Tagnite, stripped and recoated with Tagnite was the least of the test group. This implies that stripping and recoating with Tagnite can be done in a consistent and predictable manner.
3. Dimensional loss for all the test panel groups did not exceed 1.0 mils (0.0001") from start (bare) to finish (After Final Tagnite).
4. The chromic acid strip had a big impact on the dimensional and weight loss data. The data shows that the chromic acid attacked the magnesium surface and this only occurs when there is significant contamination of the chromic acid bath.
5. The use of the chromic acid bath will not be justified in the future as the DoD moves forward to eliminate all sources of hexavalent chromium. This dimensional and weight loss study will have to be repeated using a more environmentally friendly method of removing the legacy anodize coatings.



Figure 34: Graph of Panel Weight Change for AZ91C over the course of Applying Fresh Anodize Coating, Stripping and Re-anodizing with Tagnite.

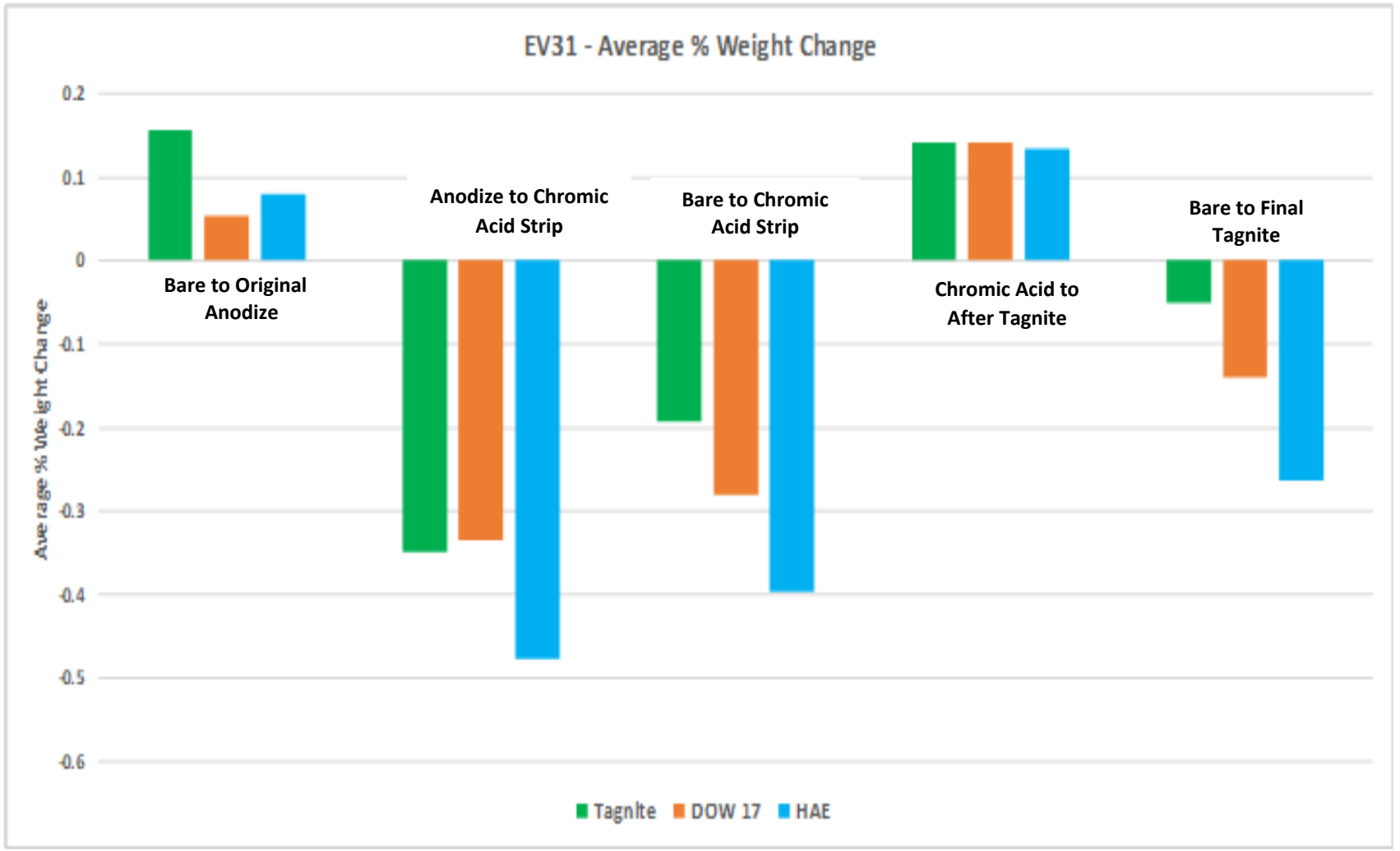


Figure 35: Graph of Panel Weight Change for EV31A over the course of Applying Fresh Anodize Coating, Stripping and Re-anodizing with Tagnite.



Figure 36: Graph of Panel Weight Change for ZE41A over the course of Applying Fresh Anodize Coating, Stripping and Re-anodizing with Tagnite.

6.1.6 Effectiveness of MIL-DTL-83936 Paint Stripper on Legacy Anodize Coatings

Results of Legacy Coatings Painted with Rockhard or Primer: During some early testing, Tagnite coated test panels painted with Rockhard Sealant or MilSpec Primer were placed in a MIL-DTL-83936 chemical stripper at the CCAD plating shop. Inspection of the test panels after the stripping process showed that the top layers of the Rockhard or Primer had been removed. However, based on the color of the Tagnite after the chemical stripping process, Rockhard and/or Primer was still embedded in the Tagnite pores as seen in Figure 37. Attempts to remove the Tagnite using the Tagnite chemical stripper were unsuccessful which verified that residual paint was embedded in the Tagnite pores. TAG also attempted to apply more Tagnite to these panels after Tagnite chemical stripping but this approach was also unsuccessful which again verified that residual paint was embedded in the Tagnite pores.

This same experiment was done to the legacy anodize coatings, DOW 17 and HAE. Magnesium test panels coated with DOW 17 and HAE were painted in the same manner as the Tagnite panels than placed in the same paint stripper. Once the top layers of paint were removed, it was obvious that there was still paint embedded in the pores of the legacy coatings which was similar to the Tagnite coating after paint stripping.

TAG tested a variety of paint strippers, solvents and acids to see what impact these chemicals had on the paint embedded into the porosity of the legacy coatings. None the chemicals tested had any impact on the embedded paint. TAG also attempted the Tagnite re-anodization process described in Section 5.1.2 in an attempt to undermine the legacy coatings with Tagnite. This attempt failed as well because the embedded paint blocked any access to the bare magnesium which preventing the initiation of the Tagnite anodization process.

Conclusions:

1. The MIL-DTL-83936 chemical paint stripping process was successful in removing the Rockhard and MIL-PRF-23377 primer from the anodized magnesium test coupons. However, it was unable to remove the residual paint from the porosity of the Tagnite, HAE and DOW 17 coatings.
2. A brief investigation of other paint strippers and solvents was unsuccessful in removing the paint embedded in the pores of the legacy coatings.
3. After talking with CCAD engineers and production personnel, it became apparent the chemical paint stripping process needed a thorough investigation which was above the scope of this project. The decision was made to utilize baking soda media blast to remove all the legacy coatings on the demonstration parts.



Observations:

1. Paint chemical stripping at CCAD was good at removing surface paint.
2. All anodize coatings showed evidence of residual paint or primer embedded in the porosity.
3. Tagnite chemical stripper was not effective in removing Tagnite coatings embedded with residual paint.

Figure 37: Paint Chemical Stripping Results for Legacy Coatings

6.1.7 Effect of Tagnite Chemical Strip Process on Cad Plating and Hydrogen Embrittlement

Original Testing Protocol: In the original JTP, TAG stated that the effect of the Tagnite chemical strip process on Cad plated hardware would be evaluated by running Cad plated hardware through the stripping process and note any visual changes in the Cad plate color. If the characteristic color were to change during the process, it would be assumed that there was an adverse effect.

After review of the original JTP, AMSAM-ENVI-TI disapproved of this task in a memo (Appendix J) and submitted their own hydrogen embrittlement testing requirement.

Revised Test Protocol (from paragraph 3 of AMSAM-ENVI-TI memo): "The stripping process shall be evaluated using type 1d notched C rings per ASTM F519-13, reference 1c. Per reference 1c paragraph 11.2, a minimum of 4 rings each shall be tested in both the bare and cadmium plated condition. These rings shall be subjected to the stripping process solutions at maximum temperatures and concentrations allowed by the TAG process specification. Additionally, times in each solution evaluated shall be 2x that allowed by the TAG stripping process specification. To validate the specimen batch, prior to testing 4 bare specimen and 4 cad plating specimen shall be stressed @ 75% of the notch fracture strength (NFS) for 200 hours. Provided that there are no failures, these specimens are to be discarded and the testing in the stripping solution can proceed (see chart – Table 28)."

Table 28: AMSAM-ENVI-TI Hydrogen Embrittlement Test Matrix

Specimen Condition	No Preload	Preload to 75% NFS	Strip @ Max Temp - Max Concentration and 2X Time	Post Exposure Stress 200 hrs @ 75% NFS
Bare	4		All	All
Bare		4	All	All
Cad Plated	4		All	All
Cad Plated		4	All	All

C Ring Testing Breakdown: The Type 1D C rings were obtained from Green Specialty Services, Ft. Worth, TX. The order consisted of 18 bare C rings and 18 Cad plated C rings. The testing breakdown was:

1. Two (2) Bare and two (2) Cad plated C rings were used to determine the NFS (Notch Fracture Strength).
2. Four (4) Bare and four (4) Cad plated C rings were used to validate the specimen batch (lot) by stressing the C rings @ 75 % NFS for 200 hours.
3. Four (4) Bare and four (4) Cad plated C rings with no preload were tested in the stripping process at max temp/ max concentration and 2X the maximum allowable soak time for parts.

4. Four (4) Bare and four (4) Cad plated C rings preloaded to 75 % NFS were tested in the stripping process at max temp/ max concentration and 2X the maximum allowable soak time for parts

C Ring Testing Conditions:

1. The NFS was determined by placing an index point on tightening nut, then while slowly tightening the nut, count the number of turns it took to fracture the specimen. All specimens took between 3.75 and 4 turns to fracture.
2. After determining the NFS, four (4) bare and four (4) Cad plated specimens were preloaded to 75 % NFS, set aside for 200 hours.
3. The remaining specimens were put through the strip process under the following conditions.

Table 29 lists the typical Tagnite Stripping Parameters compared to the "Extended" Stripping parameters used in the C Ring Hydrogen Embrittlement Testing

Table 29: Normal Tagnite Stripping Parameters vs. C Ring Hydrogen Embrittlement Parameters

Normal Stripping Process Parameters			
	Working Concentration	**Operating Temperature**	**Allowable time in tank**
Step 1: Mild Alkaline Etch	30 – 36 g/L Pyrophosphate	70 – 80ºC	5 – 15 minutes
Step 2: Fluoride Activator	42.5 – 55.0 g/L Fluoride	70 – 80ºC	30 min – 1.5 hours
C Ring Stripping Process Parameters			
	Actual Concentration	**Operating Temperature**	**Allowable time in tank**
Step 1: Mild Alkaline Etch	35.5 g/L Pyrophosphate	79ºC	30 minutes
Step 2: Fluoride Activator	54.2 g/L Fluoride	80ºC	3 hours

C Ring Testing Results:

4. There were no notch fractures seen on any of the specimens after 200 hours @ 75 % NFS during the specimen batch (lot) validation testing. Therefore, the specimen batch (lot) was validated.
5. After 30 minutes in the mild alkaline etch under the conditions listed above, there were no notch fractures noted.
6. After 3 hours in the fluoride activator under the conditions listed above, there were no notch fractures noted. ***However***, both the bare and Cad plated C rings had softened significantly and were rotating back and forth on the notch. The notch was acting like

a hinge for the two C rings sections to flop up and down. This is considered an adverse event and therefore a failure.

Conclusions:

3. The fluoride activator step of the stripping process had an adverse effect on the Type 1d notched C rings. Therefore, any steel on a magnesium housing should be properly masked off before using the Tagnite chemical stripping process.
4. The fluoride activator is also used during as the final pretreatment step prior to Tagnite anodize. Therefore, all steel on a magnesium housing should be properly masked off before pretreating/anodizing using the Tagnite process.

6.1.8 Brush Tagnite Paint Adhesion Test Results

6.1.8.1 Batch Testing of Task 3 Brush Tagnite Paint Adhesion coupons by AFRL

The paint adhesion test panels were pretreatment and painted with MIL-PRF-23377 non-chromated primer as described in Appendix K. Panels were shipped to TAG for inspection then forwarded to AFRL/UDRI in multiple batches for paint adhesion testing. Each panel was tested in the two separate areas on the same panel side. The testing was done per ASTM D 4541, Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers (PATTI). The test procedure and summarized test results from all the batches are summarized in Appendix D. The raw data was provided by UDRI and is included in the back of Appendix D. This raw data was pulled from a larger report that included paint adhesion raw data from testing in Milestone 1 (Task 1). The raw data from UDRI was reorganized by TAG in order to show all results from one individual alloy in one table. The reorganized data are shown in Tables 30 – 33 where each table summarizes the paint adhesion results for one of the magnesium alloys.

Table 30: UDRI Paint Adhesion Testing Raw Data for the AZ91C Magnesium Alloy and the Three Different Pretreatment Schemes

Panel Number	Pretreatment	Panel Verification	Gage Pull-off Pressure, psig	POTS (calculated psi)	% Glue Failure (Adhesion)	% Pretreatment to Substrate (Adhesion)	% Primer to Pretreatment. (Adhesion)	% Primer to Substrate (Adhesion)	% Primer to Primer (Cohesion)	Remarks
316AZ001A	BT	✔	53.5	2178					100%	
316AZ001B	BT	✔	51.2	2084	65%	30%	5%			
316AZ002A	BT	✔	43.8	1782	10%	50%			40%	
316AZ002B	BT	✔	42.6	1733	15%	75%			10%	
316AZ003A	BT	✔	46.5	1893			30%		30%	
316AZ003B	BT	✔	40.5	1648			70%		70%	
316AZ022A	DOW 19	✔	46.0	1872	10%		90%			
316AZ022B	DOW 19	✔	43.2	1758	10%		90%			
316AZ023A	DOW 19	✔	42.2	1717	10%		90%			
316AZ023B	DOW 19	✔	40.3	1639	10%		90%			
316AZ024A	DOW 19	✔	38.9	1582	10%		90%			
316AZ024B	DOW 19	✔	41.1	1672	10%		90%			
316AZ043A	TCP	✔	39.0	1586				10%	90%	
316AZ043B	TCP	✔	35.1	1427				10%	90%	
316AZ044A	TCP	✔	45.7	1860			90%		10%	
316AZ044B	TCP	✔	43.7	1778			90%		10%	
316AZ045A	TCP	✔	40.5	1648					100%	
316AZ045B	TCP	✔	39.4	1603					100%	

BT = Brush Tagnite
TCP = Trivalent Chromium Preservative

Table 31: UDRI Paint Adhesion Testing Raw Data for the EV31A Magnesium Alloy and the Three Different Pretreatment Schemes

Panel Number	Pretreatment	Panel Verification	Gage Pull-off Pressure, psig	POTS (calculated psi)	% Glue Failure (Adhesion)	% Pretreatment to Substrate (Adhesion)	% Primer to Pretreatment. (Adhesion)	% Primer to Primer (Cohesion)	Remarks
316EV001A	BT	✔	36.3	1476			65%	35%	
316EV001B	BT	✔	42.2	1717	15%		50%	35%	
316EV002A	BT	✔	41.3	1680	5%		95%		
316EV002B	BT	✔	43.4	1766	15%		85%		
316EV003A	BT	✔	39.6	1611			75%	25%	
316EV003B	BT	✔	32.4	1317			30%	70%	
316EV022A	DOW 19	✔	27.3	1109			50%	50%	
316EV022B	DOW 19	✔	28.7	1166			25%	75%	
316EV023A	DOW 19	✔	31.5	1280			40%	60%	
316EV023B	DOW 19	✔	28.3	1150			80%	20%	
316EV024A	DOW 19	✔	27.8	1129	10%		90%		
316EV024B	DOW 19	✔	23.4	950	5%		95%		
316EV043A	TCP	✔	46.7	1901				100%	
316EV043B	TCP	✔	41.1	1672				100%	
316EV044A	TCP	✔	44.2	1799				100%	
316EV044B	TCP	✔	44.6	1815				100%	
316EV045A	TCP	✔	42.8	1741				100%	
316EV045B	TCP	✔	40.5	1648				100%	

Table 32: UDRI Paint Adhesion Testing Raw Data for the QE22A Magnesium Alloy and the Three Different Pretreatment Schemes

Panel Number	Pretreatment	Panel Verification	Gage Pull-off Pressure, psig	POTS (calculated psi)	% Glue Failure (Adhesion)	% Pretreatment to Substrate (Adhesion)	% Primer to Pretreatment. (Adhesion)	% Primer to Primer (Cohesion)	Remarks
316QE001A	BT	✔	46.1	1876		35%		65%	
316QE001B	BT	✔	42.9	1746		25%		75%	
316QE002A	BT	✔	36.6	1488		40%		60%	
316QE002B	BT	✔	38.7	1574		50%		50%	
316QE003A	BT	✔	34.7	1411		30%		70%	
316QE003B	BT	✔	44.1	1795		80%		20%	
316QE022A	DOW 19	✔	45.9	1868	20%		80%		
316QE022B	DOW 19	✔	47.2	1921	20%		80%		
316QE023A	DOW 19	✔	33.7	1370	20%		80%		
316QE023B	DOW 19	✔	39.0	1586	20%		80%		
316QE024A	DOW 19	✔	44.2	1799	20%		80%		
316QE024B	DOW 19	✔	43.5	1770	20%		80%		
316QE043A	TCP	✔	44.9	1827				100%	
316QE043B	TCP	✔	43.3	1762				100%	
316QE044A	TCP	✔	44.6	1815				100%	
316QE044B	TCP	✔	45.2	1839				100%	
316QE045A	TCP	✔	43.0	1750				100%	
316QE045B	TCP	✔	26.4	1072	10%			90%	

Table 33: UDRI Paint Adhesion Testing Raw Data for the ZE41A Magnesium Alloy and the Three Different Pretreatment Schemes

Panel Number	Pretreatment	Panel Verification	Gage Pull-off Pressure, psig	POTS (calculated psi)	% Glue Failure (Adhesion)	% Pretreatment to Substrate (Adhesion)	% Primer to Pretreatment. (Adhesion)	% Primer to Primer (Cohesion)	Remarks
316ZE001A	BT	✔	24.5	995	5%		95%		
316ZE001B	BT	✔	21.9	888	5%		95%		
316ZE002A	BT	✔	42.4	1725	95%		5%		
316ZE002B	BT	✔	39.9	1623			80%	20%	
316ZE003A	BT	✔	38.4	1562	5%		95%		
316ZE003B	BT	✔	35.6	1448	5%		95%		
316ZE022A	DOW 19	✔	45.6	1856	20%		80%		
316ZE022B	DOW 19	✔	44.4	1807	10%		90%		
316ZE023A	DOW 19	✔	39.4	1603	20%		80%		
316ZE023B	DOW 19	✔	41.8	1701	10%		90%		
316ZE024A	DOW 19	✔	42.2	1717	10%		90%		
316ZE024B	DOW 19	✔	44.9	1827	10%		90%		
316ZE043A	TCP	✔	41.8	1701				100%	
316ZE043B	TCP	✔	42.9	1746				100%	
316ZE044A	TCP	✔	39.6	1611				100%	
316ZE044B	TCP	✔	39.8	1619				100%	
316ZE045A	TCP	✔	39.0	1586				100%	
316ZE045B	TCP	✔	40.4	1644				100%	

6.1.8.2 Paint Adhesion Data Analysis

The JTP states that the performance criteria for this milestone testing is ***Brush Tagnite Paint Adhesion must be equal to or better than DOW 19***. Based on this criteria, the Pull-off Tensile Strength (POTS) was extracted from the UDRI raw data and placed in a Excel spreadsheet which allowed the average POTS for Brush Tagnite, DOW 19 and TCP to be calculated for each magnesium alloy. In order to quantify the paint adhesion performance, the average POTS for Brush Tagnite was compared to the average POTS for the other two pretreatments (DOW 19 and TCP) to determine if the POTS means were significantly different. The two sets of means compared were:

a. Brush Tagnite vs. DOW 19
b. Brush Tagnite vs. TCP

In order to determine whether the POTS means were significantly different the following statistical tests were performed.

1. An F-test between the two means was calculated to determine if the variances of the two populations were equal.
2. If the variances were equal, a two sample t-test assuming equal variances was run to determine if the means were different.
3. If the variances were unequal, a two sample t-test assuming unequal variances was run to determine if the means were different.

The paint adhesion means testing statistical results are summarized in Table 34 for Brush Tagnite vs. DOW 19 and Table 35 for Brush Tagnite vs. TCP. These tables are organized by magnesium alloy and lists the average pull-off strength (POTS mean) for each pretreatment, results of the F-test variance test and results of the t-test for means.

Table 34: Paint Adhesion Summary for Brush Tagnite vs. DOW 19 by Means Testing Statistical Analysis

	AZ91C		EV31A		QE22A	
	Brush Tagnite	DOW 19	Brush Tagnite	DOW 19	Brush Tagnite	DOW 19
POTS Mean (psi)	1886	1706	1594	1130	1648	1719
Variance Testing (F-test)	Equal		Equal		Equal	
Means Testing (t-test)	No Difference in Means		Means are different		No Difference in Means	
Performance Results	Equivalent Performance		Brush Tagnite > DOW 19		Equivalent Performance	
	ZE41A (using UDRI Results)		**ZE41A (w/o Panel ZE001) (using UDRI Results)**		**ZE41A (w/o Panel ZE001) After TAG Retest**	
	Brush Tagnite	DOW 19	Brush Tagnite	DOW 19	Brush Tagnite	DOW 19
POTS Mean (psi)	1373	1751	1589	1751	2858	2792
Variance Testing (F-test)	Unequal		Equal		Equal	
Means Testing (t-test)	Means are different		Means are different		No Difference in Means	
Performance Results	DOW 19 > Brush Tagnite		DOW 19 > Brush Tagnite		Equivalent Performance	

Table 35: Paint Adhesion Summary for Brush Tagnite vs. TCP by Means Testing Statistical Analysis

	AZ91C		EV31A		QE22A	
	Brush Tagnite	TCP	Brush Tagnite	TCP	Brush Tagnite	TCP
POTS Mean (psi)	1886	1650	1594	1762	1648	1677
Variance Testing (F-test)	Equal		Equal		Equal	
Means Testing (t-test)	Means are different		Means are different		No Difference in Means	
Performance Results	Brush Tagnite > TCP		TCP > Brush Tagnite		Equivalent Performance	
	ZE41A (using UDRI Results)		**ZE41A (w/o Panel BT01) (using UDRI Results)**		**ZE41A (w/o Panel BT01) After TAG Retest**	
	Brush Tagnite	TCP	Brush Tagnite	TCP	Brush Tagnite	TCP
POTS Mean (psi)	1373	1651	1589	1651	2858	2806
Variance Testing (F-test)	Unequal		Equal		Equal	
Means Testing (t-test)	No Difference in Means		No Difference in Means		No Difference in Means	
Performance Results	Equivalent Performance		Equivalent Performance		Equivalent Performance	

6.1.8.3 Paint Adhesion Performance Results from UDRI Data

Table 34 is a paint adhesion results summary of the comparison of Brush Tagnite vs. DOW 19. From these results, the following observations were seen:

- When comparing the paint adhesion between Brush Tagnite and DOW 19 for the four different magnesium alloys, the alloys AZ91C and QE22A showed no difference in paint adhesion performance between Brush Tagnite and DOW 19. For the EV31A alloy, Brush Tagnite clearly outperformed DOW 19.
- A closer examination of the paint adhesion data for ZE41A revealed that one of the Brush Tagnite panels (ZE BT 01) had significantly lower paint adhesion results than the other two Brush Tagnite panels. During the t-test, this panel lead to the determination that the DOW 19 outperformed the Brush Tagnite in paint adhesion performance. When this panel was removed from the data analysis, the DOW 19 still outperformed the Brush Tagnite. Retesting was performed to verify the Brush Tagnite results on ZE41 and these results are summarized in Section 6.1.8.4.

Table 35 is a paint adhesion results summary of the comparison of Brush Tagnite vs. TCP. From these results, the following observations were seen:

- The paint adhesion performance between TCP and Brush Tagnite was evenly split among the four alloys. TCP has better paint adhesion on EV31A and while Brush Tagnite had better paint adhesion on AZ91E.
- There was no statistical difference in paint adhesion performance between TCP and Brush Tagnite on QE22A and ZE41A.

Conclusion from UDRI Paint Adhesion Results: For three (3) out of the four (4) alloys, Brush Tagnite met or exceeded the paint adhesion performance of DOW 19. For the ZE41A alloy, the paint adhesion of DOW 19 was statistical better than the Brush Tagnite. Therefore, ***the paint adhesion results met the performance criteria*** where the paint adhesion of Brush Tagnite must be equal to or better than DOW 19 for three out of the four alloys.

6.1.8.4 Retest of ZE41A Paint Adhesion Performance Results by TAG

As stated in Section 6.1.8.3, one of the ZE41A panels with the Brush Tagnite pretreatment (BT ZE01) had paint adhesion results that were significantly lower than the other two Brush Tagnite panels. The decision was made to retest these panels along with the ZE41A panels treated with DOW 19 and TCP using pull-off paint adhesion equipment purchased by TAG. The equipment purchased was a PosiTest AT-A instrument made by DeFelsko which is listed under ASTM D4541 as the Type V, Self-Aligning Tester. In addition, TAG coated three new ZE41A panels with Brush Tagnite and they were painted with MIL-PRF-23377 non-chromated primer by NECCI and the paint adhesion of these panels was determined by TAG. The results are listed in Table 36. The results obtained by TAG cannot be directly compared with the results generated by UDRI because TAG used a different tester, dolly size and possibly a different adhesive.

Table 36: TAG POTS Results for the ZE41A Magnesium Alloy and the Three Different Pretreatment Schemes

Panel ID	Pretreatment	POTS (Calculated psi)
316ZE001A	Brush Tagnite	1868
316ZE001B	Brush Tagnite	1272
316ZE002A	Brush Tagnite	2850
316ZE002B	Brush Tagnite	2978
316ZE003A	Brush Tagnite	2873
316ZE003B	Brush Tagnite	2763
ZM591A	Brush Tagnite	2768
ZM591B	Brush Tagnite	2908
ZM592A	Brush Tagnite	2961
ZM592B	Brush Tagnite	3000
ZM593A	Brush Tagnite	2480
ZM593B	Brush Tagnite	3000
316ZE022A	DOW 19	3000
316ZE022B	DOW 19	2525
316ZE023A	DOW 19	3000
316ZE023B	DOW 19	2735
316ZE024A	DOW 19	2652
316ZE024B	DOW 19	2843
316ZE043A	TCP	2536
316ZE043B	TCP	3000
316ZE044A	TCP	2819
316ZE044B	TCP	2936
316ZE045A	TCP	2688
316ZE045B	TCP	2854

The POTS results using the TAG Pull-off Adhesion Tester clearly showed that the ZE BT 01 panel yielded lower POTS values the other two panels in the original set. The POTS results obtained from other two original panels compared well with the adhesion results from the three new panels (Panel ID ZM591, ZM592 and ZM593) pretreated with Brush Tagnite. The POTS values from Panel ZE001 where rejected as an anomaly probably due to poor rinsing of the panel after the Brush Tagnite application.

The POTS values were obtained using the TAG pull-off adhesion tester on

- The two remaining Brush Tagnite panels (ZE002 and ZE003)

- The three new Brush Tagnite panels (ZM191 – ZM593)
- The three original DOW 19 panels (ZE022 – ZE024)
- The three original TCP panels (ZE043 – ZE045)

The POTS values for the two remaining Brush Tagnite panels where averaged with the POTS values from the three new Brush Tagnite panels to calculate the overall average POTS value. The POTS values are summarized in Table 36 and these values were run through the same statistical analysis detailed in Section 6.1.8.2 and the results are summarized in Tables 34 and 35 under the heading "***ZE41A (w/o Panel ZE001) after TAG Retest***".

6.1.8.5 Conclusions from TAG Paint Adhesion Results

1. Pull-off paint adhesion testing by two different instruments clearly showed that the Brush Tagnite Panel ZE001 had consistently lower POTS results than the other Brush Tagnite panels and was rejected as an outlier.
2. Statistical means testing analysis of the ZE41A Brush Tagnite and DOW 19 POTS results showed that there was no difference in the mean POTS values, Therefore, ***the Brush Tagnite paint adhesion results met the performance criteria*** where the paint adhesion of Brush Tagnite must be equal to or better than DOW 19.
3. Statistical means testing analysis of the ZE41A Brush Tagnite and TCP POTS results showed that there was no difference in the mean POTS values, therefore there was no different in the paint adhesion performance between the two pretreatments.

6.1.8.6 General Paint Adhesion Conclusion

Based on the statistical analysis of the POTS results, Brush Tagnite met or exceeded the paint adhesion performance of DOW 19 on all four alloys tested. Therefore, ***the paint adhesion results met the performance criteria*** where the paint adhesion of Brush Tagnite must be equal to or better than DOW 19.

6.1.9 Brush Tagnite Galvanic Corrosion Test Results

6.1.9.1 Testing of JTP Task 3 Galvanic Corrosion Coupons by NDSU

The galvanic corrosion test panels were pretreated at the locations described in Appendix K. Panels were shipped to TAG for inspection prior to shipment to the North Dakota State University (NDSU) Department of Coatings and Polymeric Materials (CPM) in multiple batches for galvanic corrosion testing. The testing was done per ASTM G71, Standard Guide for Conducting and Evaluating Galvanic Corrosion Tests in Electrolytes and the experimental setup is shown in Appendix L. The galvanic current values shown in the NDSU report are the average of the galvanic current values measured during stable periods which in this case was between the 6^{th} hour and the 24^{th} hour (18 hour period) of the experiment. There were four or five trials

performed for each alloy/pretreatment coating scheme and the average galvanic current values are provided in Table 1 of Appendix L and Table 37 below.

6.1.9.2 Galvanic Corrosion Performance Results

The galvanic corrosion performance results summarized in the NDSU report rank the performance based on the galvanic corrosion current values for each of the four magnesium alloys and the three different pretreatment coatings (Brush Tagnite, DOW 19 and TCP). The performance criteria listed in the JTP for this test states that the galvanic corrosion performance of Brush Tagnite must be equal to or better than the DOW 19 performance. The NDSU report states "…*low galvanic current indicate low/reduced corrosion of the more active sample whereas higher current indicated higher/increased corrosion of the more active sample.* ***The lower the galvanic current, the better the corrosion resistance.*** " Based on this criteria, NDSU analyzed the galvanic corrosion current response of Brush Tagnite, DOW 19 and TCP for each of the four different magnesium alloys. When looking at each individual alloy, there was very little variation between the galvanic current readings for the three different pretreatment coatings in each individual alloy. In addition, there was very little variation in the galvanic corrosion between the AZ91C, EV31A and QE22A alloys, regardless of the pretreatment coating. The galvanic corrosion response for ZE41A was consistently lower for all three pretreatment schemes compared to the other three magnesium alloys.

Conclusion: Based on the average galvanic current readings, Brush Tagnite had a galvanic corrosion response that was equal to the DOW 19 conversion coating for all four magnesium alloys and therefore passed the performance criteria specified in the JTP.

Table 37: Summary of Average Galvanic Corrosion Current (Amps) for Different Magnesium Alloys and Three Different Pretreatments

AZ91C Magnesium			EV31A Magnesium		
Pretreatment	**Panel ID #**	**Average Galvanic Current**	**Pretreatment**	**Panel ID #**	**Average Galvanic Current**
Brush Tagnite	AE BT-17	9.65E-5	Brush Tagnite	EV BT-17	1.57E-4
Brush Tagnite	AE BT-19	1.11E-4	Brush Tagnite	EV BT-19	1.36E-4
Brush Tagnite	AE BT-20	1.22E-4	Brush Tagnite	EV BT-20	1.48E-4
Brush Tagnite	AE BT-21	1.24E-4	Brush Tagnite	EV BT-21	3.15E-6
DOW19	AE BT-38	1.24E-4	DOW19	EV BT-38	1.23E-4
DOW19	AE BT-39	1.06E-4	DOW19	EV BT-39	1.49E-4
DOW19	AE BT-40	1.24E-4	DOW19	EV BT-40	1.26E-4
DOW19	AE BT-41	1.24E-4	DOW19	EV BT-41	1.45E-4
DOW19	AE BT-42	2.16E-5	DOW19	EV BT-42	1.33E-4
TCP	AE BT-59	9.22E-5	TCP	EV BT-59	1.13E-4
TCP	AE BT-60	5.19E-5	TCP	EV BT-60	1.68E-4
TCP	AE BT-61	1.11E-4	TCP	EV BT-61	1.32E-4
TCP	AE BT-62	1.21E-4	TCP	EV BT-62	1.18E-4
TCP	AE BT-63	9.66E-5	TCP	EV BT-63	9.82E-5
QE22A Magnesium			**ZE41A Magnesium**		
Brush Tagnite	QE BT-17	1.22E-4	Brush Tagnite	ZE BT-17	7.19 E-5
Brush Tagnite	QE BT-19	1.48 E-4	Brush Tagnite	ZE BT-19	8.11 E-5
Brush Tagnite	QE BT-20	9.29E-5	Brush Tagnite	ZE BT-20	8.10 E-5
Brush Tagnite	QE BT-21	1.12 E-4	Brush Tagnite	ZE BT-21	7.04 E-5
DOW19	QE BT-38	1.40 E-4	DOW19	ZE BT-38	8.75 E-5
DOW19	QE BT-39	1.26 E-4	DOW19	ZE BT-39	8.61 E-5
DOW19	QE BT-40	1.18 E-4	DOW19	ZE BT-40	4.50 E-5
DOW19	QE BT-41	1.37 E-4	DOW19	ZE BT-41	7.03 E-5
DOW19	QE BT-42	1.12 E-4	DOW19	ZE BT-42	7.65 E-5
TCP	QE BT-59	1.29 E-4	TCP	ZE BT-59	7.44 E-5
TCP	QE BT-60	1.26 E-4	TCP	ZE BT-60	8.50 E-5
TCP	QE BT-61	8.38E-5	TCP	ZE BT-61	7.66 E-5
TCP	QE BT-62	1.09 E-4	TCP	ZE BT-62	7.30 E-5
TCP	QE BT-63	1.09 E-4	TCP	ZE BT-63	7.41 E-5

6.1.10 Brush Tagnite Neutral Salt Fog Corrosion Test Results

6.1.10.1 Testing of Brush Tagnite Neutral Salt Fog Corrosion Coupons by TAG

The neutral salt fog corrosion test panels were pretreated followed by MIL-PRF-23377 non-chromated primer at the locations described in Appendix K. Panels were shipped to TAG for inspection followed by neutral salt corrosion testing using TAG's salt fog chamber. Prior to insertion into the salt fog chamber, each panel had an "X" scribed on one of the 4" x 6" surfaces using a carbide tipped scribe. After the scribe, the panels were inspected to verify that bare metal was present in the scribe prior to salt fog exposure. Panels were randomly placed in the salt fog chamber and exposed to neutral salt fog per ASTM B117, Standard Practice for Operating Salt Spray (Fog) Apparatus. Due to limited space in the TAG salt fog cabinet, the neutral salt fog testing was done in two batches. The magnesium alloys, QE22A and ZE41A, have the highest corrosion rate and were run together first in the salt fog cabinet. AZ91C and EV31A have much lower corrosion rates than the other two alloys and therefore, were run together as the second batch.

6.1.10.2 Neutral Salt Fog Corrosion Performance Results

The scribed panels did not act in the expected manner. Most of the corrosion took place away from the scribe, underneath the primer. There was no set criteria for number of hours to run in the salt fog cabinet. TAG personnel exposed the panels to salt fog for a time period that allowed for complete differentiation between the three types of pretreatment – Brush Tagnite, DOW 19 and TCP. For most of the alloys, some of the panels were removed early due to excessive corrosion formation. Once the salt fog exposure was terminated for each alloy, each individual panel was inspected for:

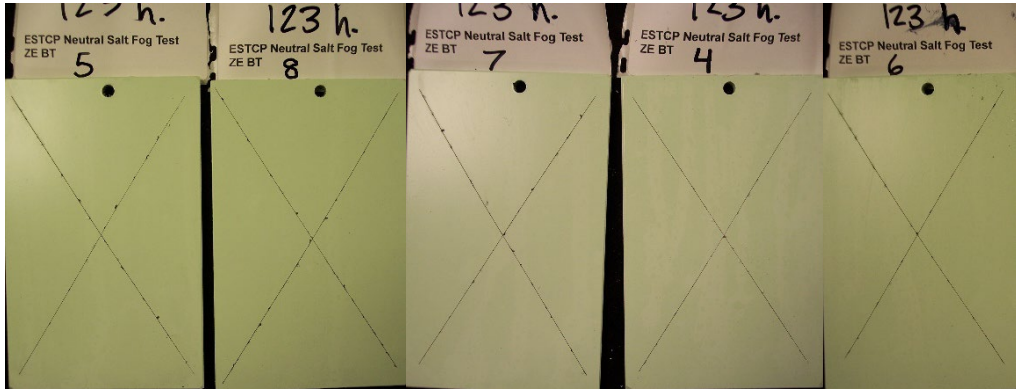
1. Corrosion migration away from the scribe
2. Percentage of overall corrosion pitting on the entire panel or was pulled early
3. Depth of corrosion pitting in the painted areas away from the scribe

After the inspection, the fifteen (15) panels for each alloy were given a grade from 1 (Best) to 15 (worst).

6.1.10.2.1 ZE41A Neutral Salt Fog Corrosion Results

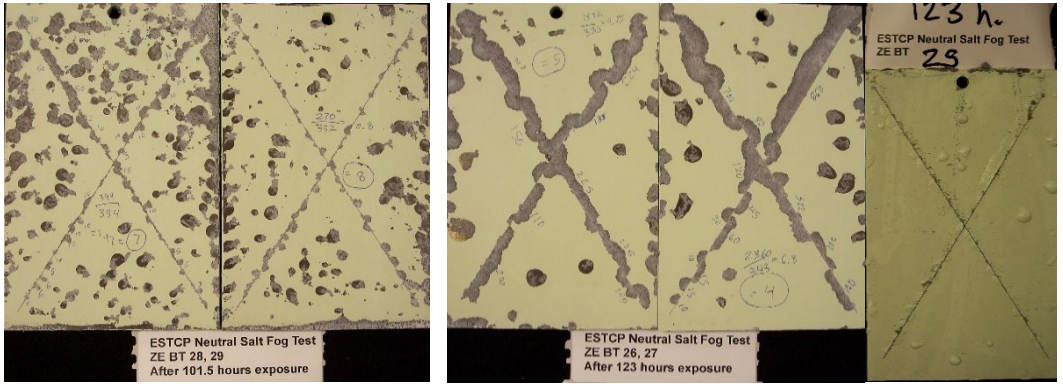
The total exposure time for this alloy was 192 hours. Pictures of the ZE41A panels during at various time intervals are seen in Appendix M. The last time all ZE41A panels were in the salt fog together was at the 46 hour mark. At that time several of the TCP panels were removed due to complete blistering of the primer. Other TCP panels were removed at 69.5 or 71.5 while several DOW 19 panels were removed at 101.5 hours. Figure 38 shows the panels after 123 hours of exposure, also shown are pictures of the panels that were removed at earlier time interval after removal of the corrosion product. Figure 39 shows the Brush Tagnite panels at the completion of the test which was 192 hours of exposure,

The neutral salt fog corrosion ratings for ZE41A are listed in Table 38.



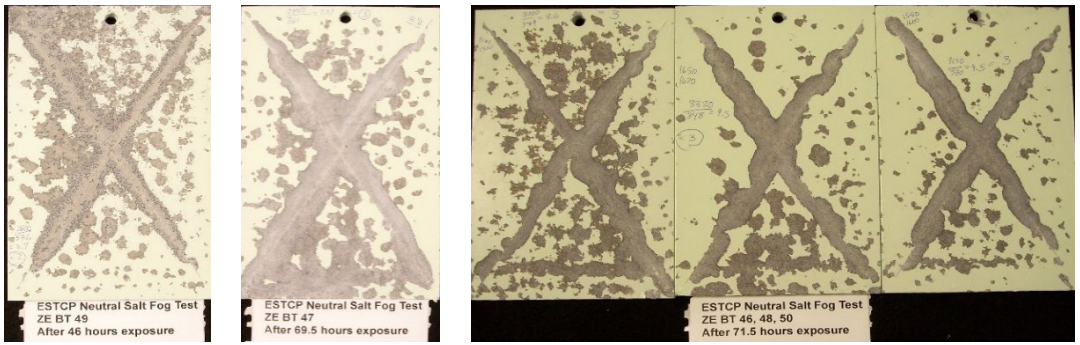
Brush Tagnite with MIL-PRF-23377

All 5 panels exposed for 123 hrs



DOW 19 with MIL-PRF-23377

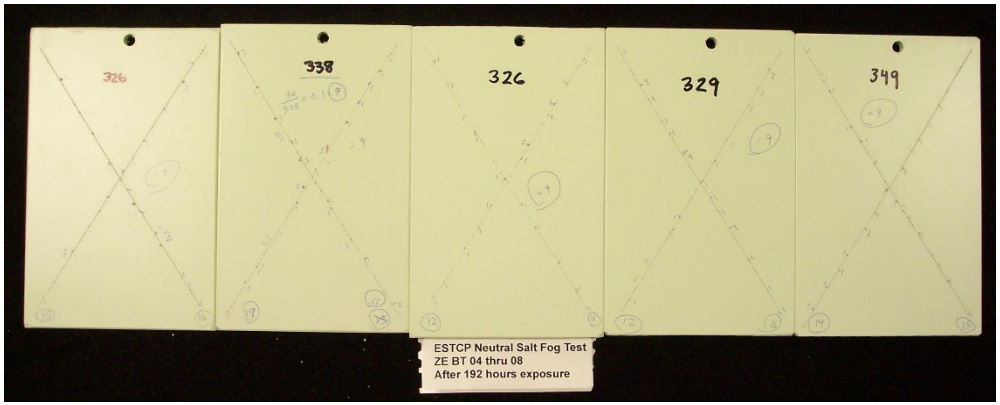
Left: 2 panels removed at 101.5 hrs
Right: 3 panels after 123 hrs exposure



TCP with MIL-PRF-23377

Left: 1 panel removed after 46 hrs
Middle: 1 panel removed after 69.5 hrs
Right: 3 panels removed after 71.5 hrs

Figure 38: ZE41A Neutral Salt Fog Panels with MIL-PRF-23377 Primer after ≤ 123 hours of exposure



Brush Tagnite with MIL-PRF-23377

2 panels removed at 101.5 hours
3 panels removed at 123 hours

DOW 19 with MIL-PRF-23377

Panels removed between 46 and 71.5 hours

TCP with MIL-PRF-23377

Figure 39: ZE41A Neutral Salt Fog Panels with MIL-PRF-23377 Primer after 192 hours of exposure

Table 38: ZE41A Neutral Salt Fog Summary

Panel ID #	Pre-treatment	Hours in Salt Fog	Ranking
ZE BT 04	Brush Tagnite	192	1
ZE BT 05	Brush Tagnite	192	4
ZE BT 06	Brush Tagnite	192	2
ZE BT 07	Brush Tagnite	192	3
ZE BT 08	Brush Tagnite	192	5
ZE BT 25	DOW 19	146	10
ZE BT 26	DOW 19	123	8
ZE BT 27	DOW 19	123	9
ZE BT 28	DOW 19	101.5	7
ZE BT 29	DOW 19	101.5	6
ZE BT 46	TCP	71.5	11
ZE BT 47	TCP	69.5	12
ZE BT 48	TCP	71.5	14
ZE BT 49	TCP	46	15
ZE BT 50	TCP	71.5	13

ZE41 Test Results:

1. The panels pretreated with TCP failed the fastest. One (1) panels was pulled after 46 hours of exposure and another was pulled after 69.5 hours of exposure. The remaining three (3) panels were pulled after 71.5 hours of exposure. The TCP panels had the lowest rankings.
2. The DOW 19 panels were the second group to fail. Two (2) panels were pulled after 101.5 hours of exposure while another two (2) panels were pulled after 123 hours. The remaining panel was left in the salt fog cabinet for 146 hours.
3. The Brush Tagnite coupons received a total of 192 hours of exposure at which point the test was terminated. The BT panels received the highest rankings.
4. The Brush Tagnite panels had the best performance based on visual observation.
    a. Minimal corrosion migration away from the scribe.
    b. Minimal corrosion pitting in the painted areas away from the scribe.

ZE41 Neutral Salt Fog Conclusion: Brush Tagnite clearly outperformed the DOW 19 during this test, therefore, ***Brush Tagnite exceeded the performance objective of the JTP*.**

6.1.10.2.2 QE22A Salt Fog Corrosion Results

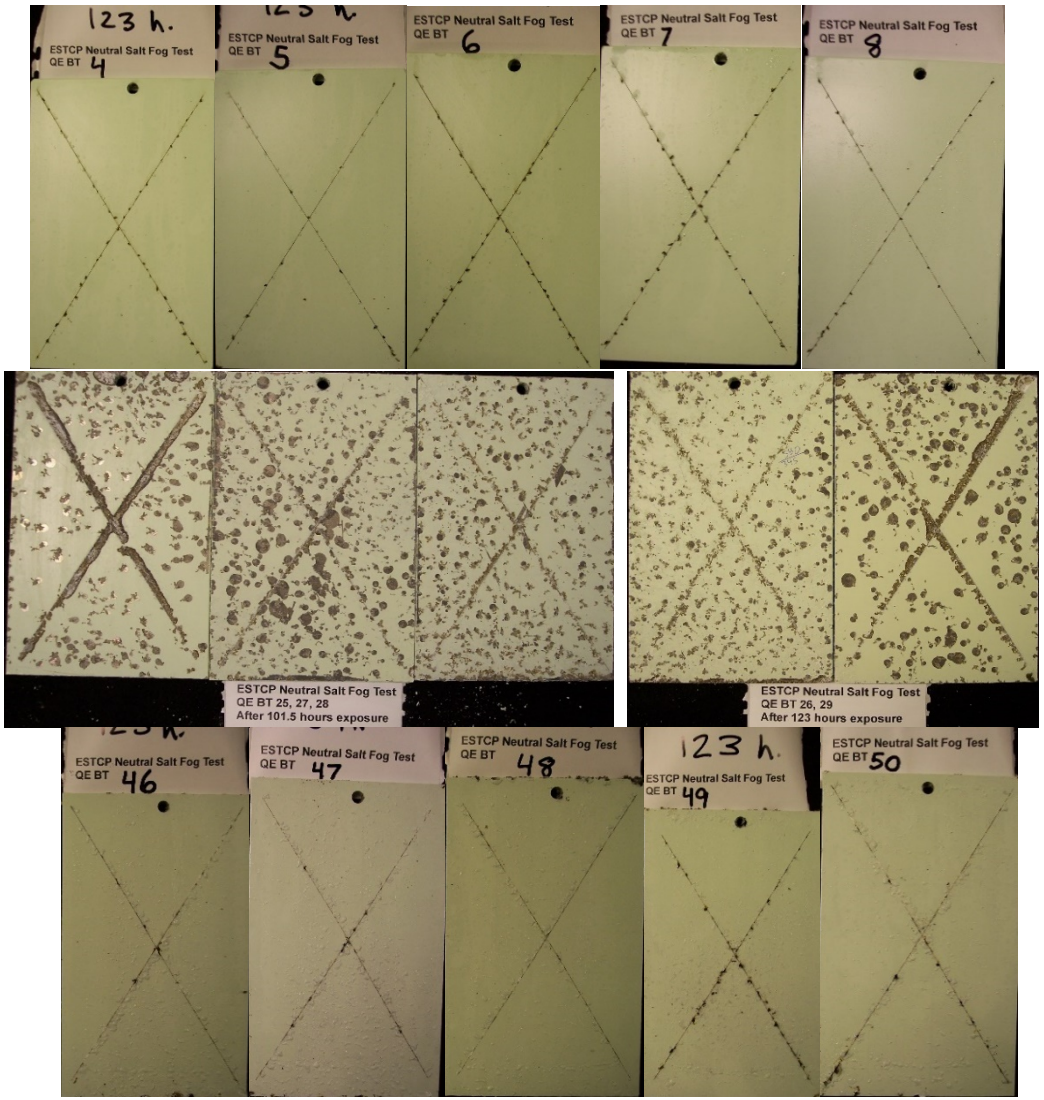
The total exposure time for this alloy was 192 hours. Pictures of the QE22A panels during at various time intervals are seen in Appendix N. The last time all QE22A panels were in the salt fog together was at the 101.5 hour mark. At that time, several of the DOW 19 panels were removed due to complete blistering of the primer. Figure 40 shows the panels after 123 hours of exposure, also shown are pictures of the DOW 19 panels that were removed at earlier time interval after removal of the corrosion product. At 123 hours, the remaining DOW 19 panels were removed while the Brush Tagnite and TCP treated panels had similar corrosion behavior and were left in the salt fog chamber. However, at the 146 hour mark, the TCP panels were

showing increased evidence of corrosion and by 171 hours the remaining TCP panels were removed. Figure 41 shows the panels after 171 hours of exposure.

The neutral salt fog corrosion ratings for QE22A are listed in Table 39.

Table 39: QE22A Neutral Salt Fog Summary

Panel ID #	Pre-treatment	Hours in Salt Fog	Ranking
QE BT 04	Brush Tagnite	192	3
QE BT 05	Brush Tagnite	192	2
QE BT 06	Brush Tagnite	192	5
QE BT 07	Brush Tagnite	192	4
QE BT 08	Brush Tagnite	192	1
QE BT 25	DOW 19	101.5	14
QE BT 26	DOW 19	123	11
QE BT 27	DOW 19	101.5	15
QE BT 28	DOW 19	101.5	13
QE BT 29	DOW 19	123	12
QE BT 46	TCP	146	8
QE BT 47	TCP	146	9
QE BT 48	TCP	171	7
QE BT 49	TCP	146	6
QE BT 50	TCP	171	10



Brush Tagnite with MIL-PRF-23377

All 5 panels exposed for 123 hrs

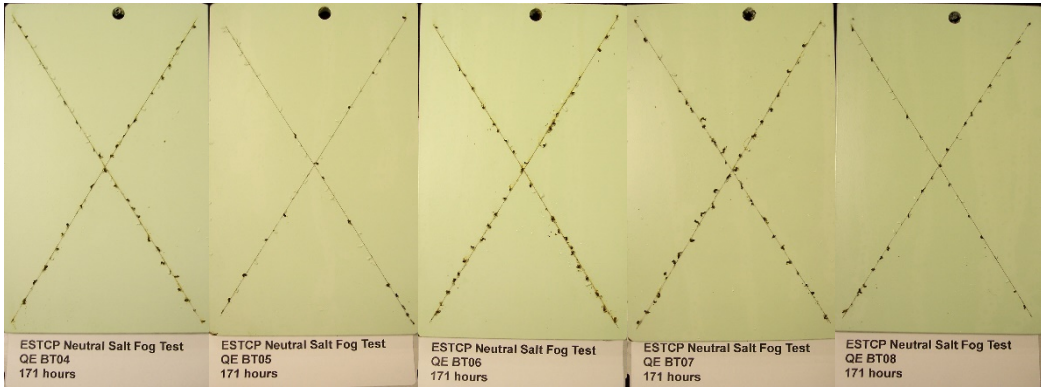
DOW 19 with MIL-PRF-23377

Left: 3 panels removed at 101.5 hrs
Right: 2 panels after 123 hrs exposure

TCP with MIL-PRF-23377

All 5 panels exposed for 123 hrs

Figure 40: QE22A Neutral Salt Panels with MIL-PRF-23377 Primer after ≤ 123 hours of exposure



Brush Tagnite with MIL-PRF-23377

All 5 panels exposed for 171 hrs

All panels removed after 101.5 – 123 hours of salt fog exposure

DOW 19 with MIL-PRF-23377

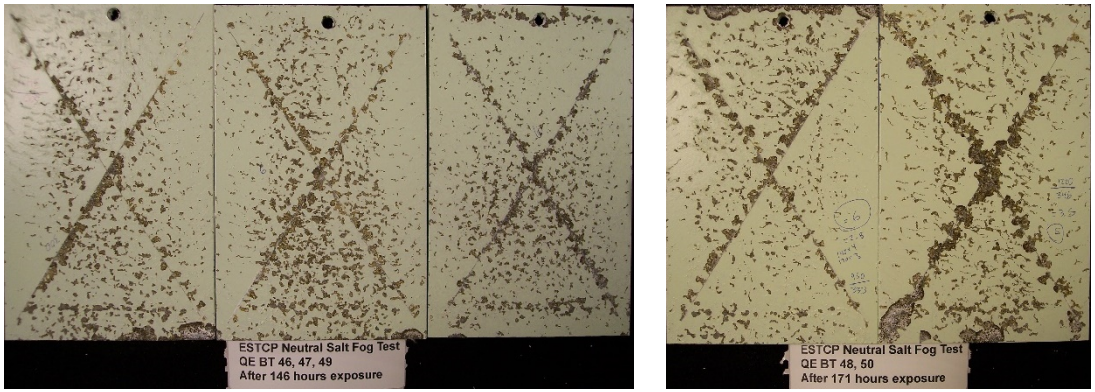


Figure 41: QE22A Neutral Salt Panels with MIL-PRF-23377 Primer after ≤ 171 hours of exposure

QE22 Neutral Salt Fog Corrosion Test Results:

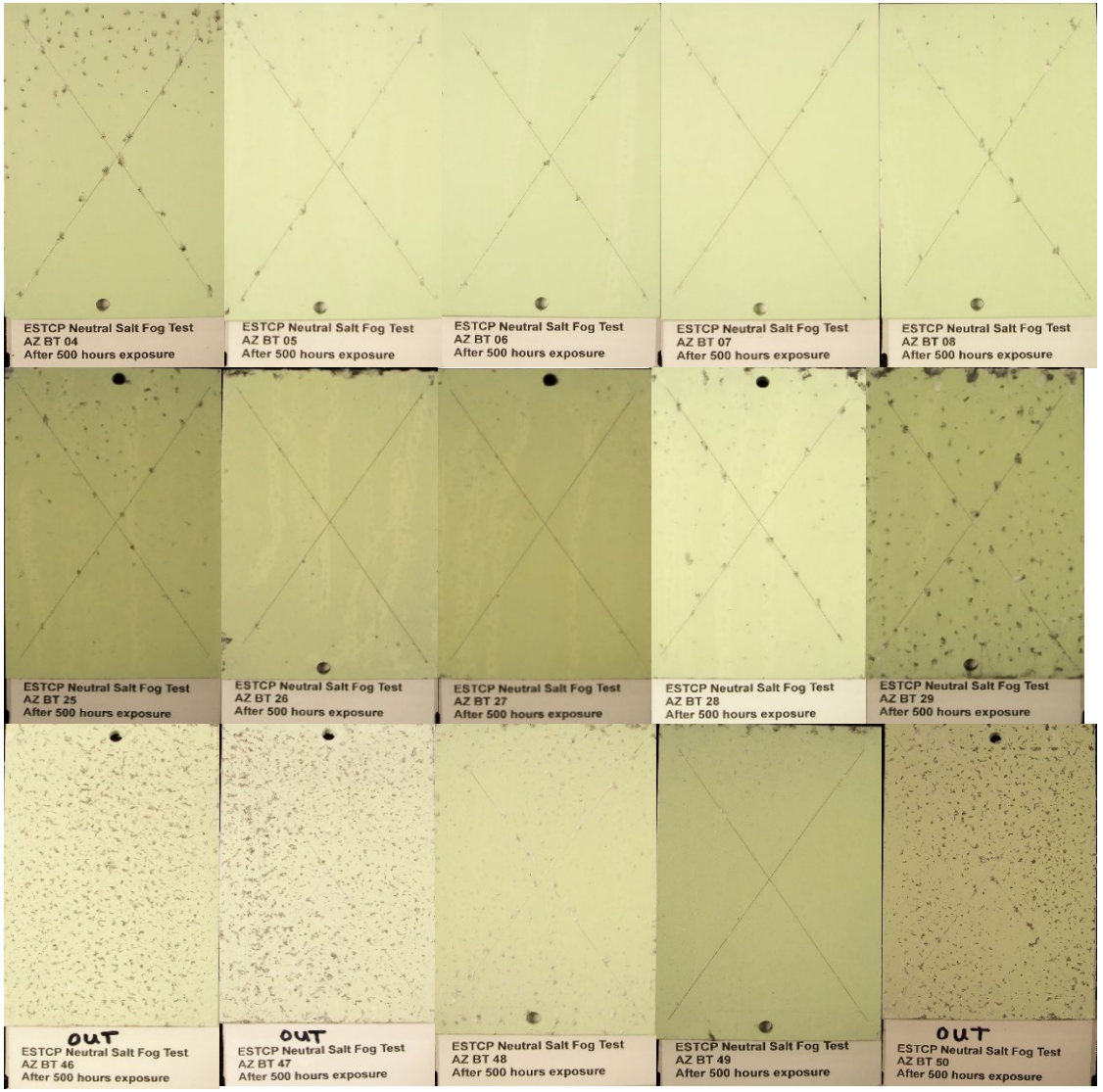
1. The panels pretreated with DOW 19 failed the fastest. Three (3) panels were pulled after 101.5 hours of exposure. The remaining two (2) panels were pulled after 123 hours of exposure. This group received the lowest rankings.
2. The TCP panels were the second group to fail. Three (3) panels were pulled after 146 hours of exposure. The remaining two (2) panels were left in the salt fog cabinet for 171 hours.
3. The Brush Tagnite test coupons were exposed to 192 hours of salt fog after which the test was terminated. The BT panels received the highest rankings.
4. The Brush Tagnite panels had the best performance based on visual observation.
    a. The corrosion migration away from the scribe was the least of the three pretreatments
    b. There was minimal corrosion pitting on the painted surfaces away from the scribe compared to the TCP and DOW 19 panels.
5. The second best performer was TCP while the DOW 19 was the worst performer.

QE22 Neutral Salt Fog Conclusion: Brush Tagnite clearly outperformed the DOW 19 during this test. Therefore, ***Brush Tagnite exceeded the performance objective of the JTP*.**

6.1.10.2.3 AZ91C Salt Fog Corrosion Results

The total exposure time for this alloy was 1150 hours. Pictures of the AZ91C panels during at various time intervals are seen in Appendix O. The last time all AZ91C panels were in the salt fog together was at the 500 hour mark. At that time, three of the TCP panels were removed due to complete blistering of the primer. Figure 42 shows the panels after 500 hours of exposure. At 500 hours, the Brush Tagnite and DOW 19 appeared to have the same general level of corrosion while the TCP panels had more surface corrosion. The remaining panels were left in the salt fog chamber for a total of 1150 hours when the test was terminated and panels ratings were done. Figure 43 shows the panels after 1150 hours of exposure.

The neutral salt fog corrosion ratings for AZ91C are listed in Table 40.

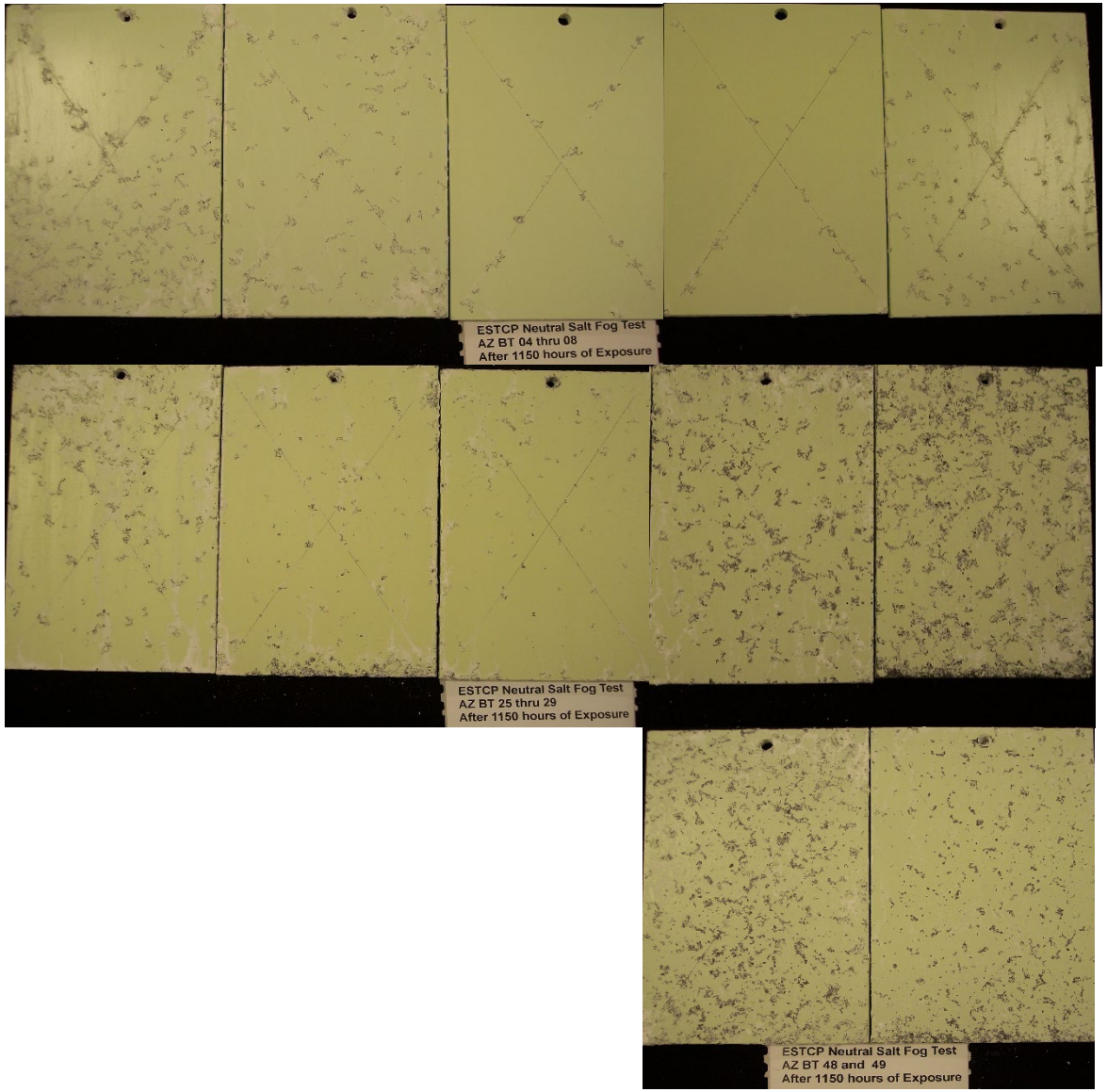


Brush Tagnite with MIL-PRF-23377

DOW 19 with MIL-PRF-23377

TCP with MIL-PRF-23377

Figure 42: AZ91C Neutral Salt Panels with MIL-PRF-23377 Primer after 500 hours of exposure



Brush Tagnite with MIL-PRF-23377

All panels exposed for 1150 hours

DOW 19 with MIL-PRF-23377

All panels exposed for 1150 hours

TCP with MIL-PRF-23377

3 panels removed after 500 hours
2 panels exposed for 1150 hours

Figure 43: AZ91C Neutral Salt Panels with MIL-PRF-23377 Primer after 1150 hours of exposure

Table 40: AZ91C Neutral Salt Fog Summary

Panel ID #	Pre-treatment	Hours in Salt Fog	Ranking
AZ BT 04	Brush Tagnite	1150	7
AZ BT 05	Brush Tagnite	1150	6
AZ BT 06	Brush Tagnite	1150	1
AZ BT 07	Brush Tagnite	1150	2
AZ BT 08	Brush Tagnite	1150	4
AZ BT 25	DOW 19	1150	8
AZ BT 26	DOW 19	1150	5
AZ BT 27	DOW 19	1150	3
AZ BT 28	DOW 19	1150	9
AZ BT 29	DOW 19	1150	11
AZ BT 46	TCP	500	15
AZ BT 47	TCP	500	14
AZ BT 48	TCP	1150	12
AZ BT 49	TCP	1150	10
AZ BT 50	TCP	500	13

AZ91C Neutral Salt Fog Corrosion Test Results:

1. The panels pretreated with TCP failed the fastest. Three (3) panels were pulled after 500 hours of exposure. The remaining two (2) panels completed 1150 hours of exposure when the test was terminated.
2. The DOW 19 panels were the second worst performers. All five (5) panels reached the maximum exposure of 1150 hours but 3 out of the 5 panels were ranked lower that the Brush Tagnite coupons.
3. The Brush Tagnite test coupons were exposed to 1150 hours of salt fog after which the test was terminated and 3 panels ranked in the top 5.
4. The Brush Tagnite panels had the best performance based on visual observation.
    a. The corrosion migration away from the scribe was the least of the three pretreatments
    b. There was minimal corrosion pitting on the painted surfaces away from the scribe compared to the TCP and DOW 19 panels.
5. The second best performer was DOW 19 while the TCP was the worst performer.

AZ91C Neutral Salt Fog Conclusion: Three out of five Brush Tagnite outperformed the DOW 19. However, two DOW 19 panels were rated in the top five at the conclusion of the testing. Therefore, ***Brush Tagnite met the performance objective of the JTP in which the Brush Tagnite performance must meet or exceed the DOW 19 performance***.

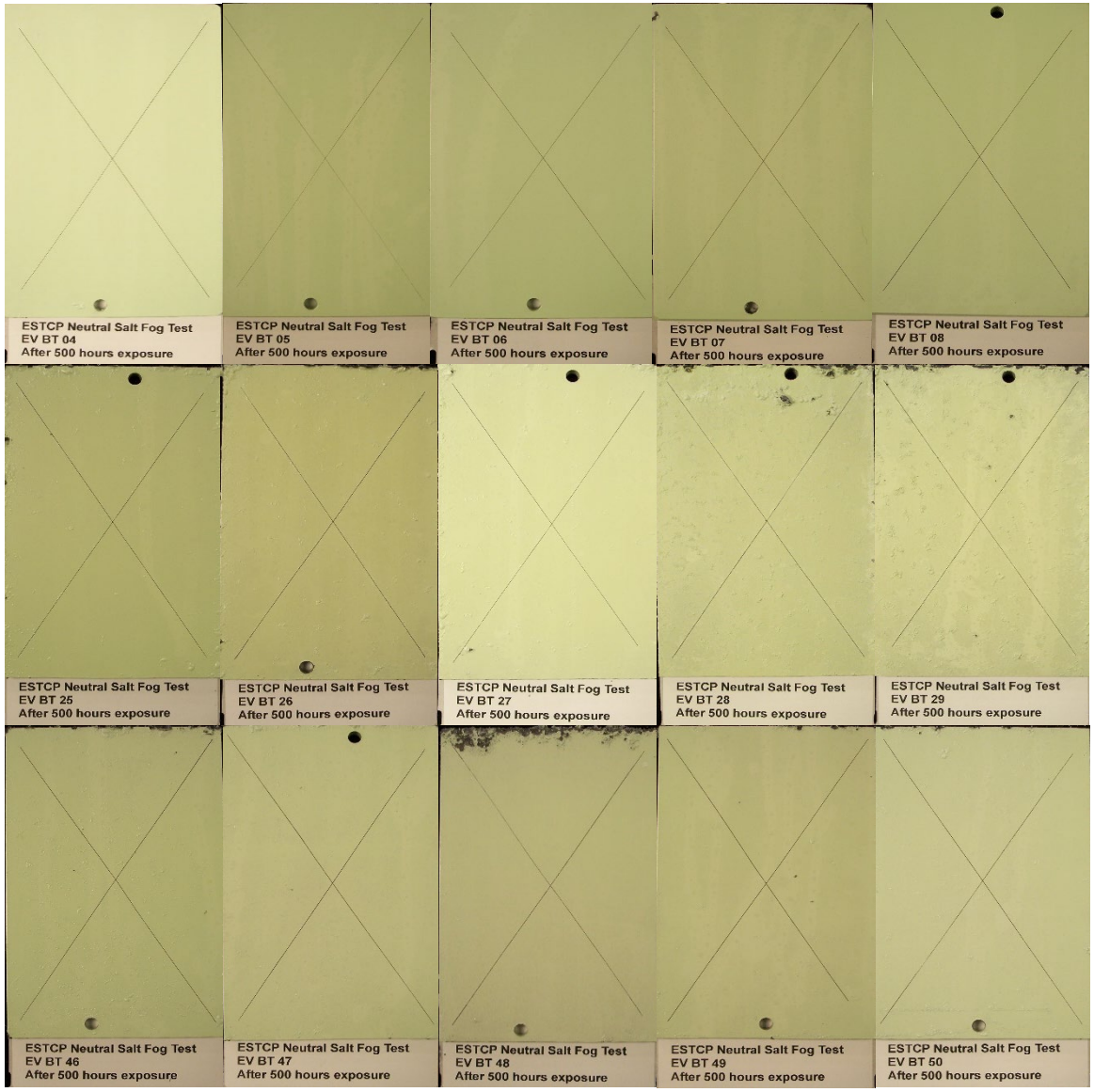
6.1.10.2.4 EV31A Salt Fog Corrosion Results

The total exposure time for this alloy was 1394 hours. Pictures of the EV31A panels during at various time intervals are seen in Appendix P. Every EV31A panel regardless of pretreatment completed the 1394 hours of exposure. At the 500 hour mark, corrosion was starting to form around the outside edges of several DOW 19 and TCP panels as seen in Figure 44. After 1150 hours of exposure, there was some differentiation between the three different pretreatments. Figure 45 shows all the panels after 1394 hours of exposure.

The neutral salt fog corrosion ratings for EV31A are listed in Table 41.

Table 41: EV31A Neutral Salt Fog Summary

Panel ID #	Pre-treatment	Hours in Salt Fog	Ranking
EV BT 04	Brush Tagnite	1394	4
EV BT 05	Brush Tagnite	1394	5
EV BT 06	Brush Tagnite	1394	1
EV BT 07	Brush Tagnite	1394	2
EV BT 08	Brush Tagnite	1394	3
EV BT 25	DOW 19	1394	11
EV BT 26	DOW 19	1394	13
EV BT 27	DOW 19	1394	8
EV BT 28	DOW 19	1394	T 14
EV BT 29	DOW 19	1394	T 14
EV BT 46	TCP	1394	12
EV BT 47	TCP	1394	9
EV BT 48	TCP	1394	7
EV BT 49	TCP	1394	6
EV BT 50	TCP	1394	10

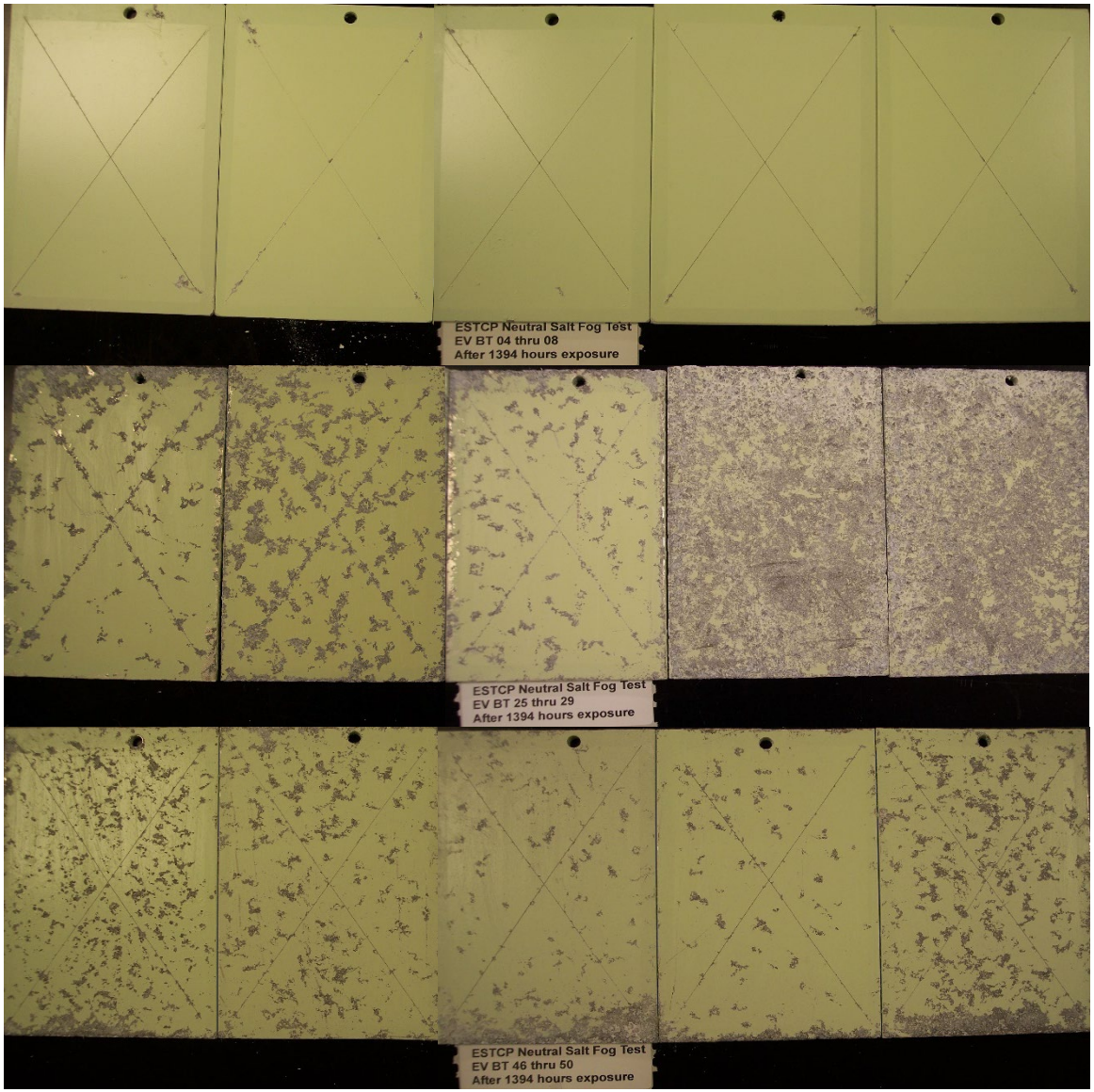


Brush Tagnite with MIL-PRF-23377

DOW 19 with MIL-PRF-23377

TCP with MIL-PRF-23377

Figure 44: EV31A Neutral Salt Panels with MIL-PRF-23377 Primer after 500 hours of exposure



Brush Tagnite with MIL-PRF-23377

DOW 19 with MIL-PRF-23377

TCP with MIL-PRF-23377

Figure 45: EV31A Neutral Salt Panels with MIL-PRF-23377 Primer after 1394 hours of exposure

EV31A Neutral Salt Fog Corrosion Test Results:

1. All three pretreatment schemes (Brush Tagnite, DOW 19 and TCP) made it through the entire testing cycle of 1394 hours of salt fog exposure.
2. The DOW 19 panels were the worst performers with 4 panels receiving the lowest rankings.
3. The second best performer were the TCP treated panels.
4. **The Brush Tagnite panels had the best performance** based on visual observation. All five BT panels received the top 5 rankings.
    a. The corrosion migration away from the scribe was the least of the three pretreatments
    b. There was minimal corrosion pitting on the painted surfaces away from the scribe compared to the TCP and DOW 19 panels.

EV31A Neutral Salt Fog Conclusion: Brush Tagnite clearly outperformed the DOW 19 during this test. Therefore, ***Brush Tagnite exceeded the performance objective of the JTP*.**

6.1.8.3 Overall Conclusion for Neutral Salt Fog Corrosion Testing: For three alloys (EV31A, QE22A and ZE41A) Brush Tagnite clearly outperformed the DOW 19 pretreatment. Testing on the AZ91C alloy showed that DOW 19 and Brush Tagnite had equivalent performance. Therefore, ***Brush Tagnite met or exceeded the JTP performance objective for all alloys tested.***

6.1.11 Brush Tagnite Acidified (SO_2) Salt Fog Corrosion Test Results

6.1.11.1 Testing of Brush Tagnite Acidified (SO_2) Salt Fog Corrosion Coupons by NAVAIR

The SO_2 salt fog corrosion test panels were pretreated then painted with MIL-PRF-23377 non-chromated primer at the locations described in Appendix K. The Brush Tagnite and DOW 19 panels were shipped to TAG for inspection prior to forwarding to NAVAIR for testing. The TCP panels were pretreated and painted by NAVAIR. The JTP called out that each panel be scribed with an "X" prior to SO_2 salt fog exposure, however, due to miscommunication the ***panels were not scribed***. Panels were randomly placed in the SO_2 salt fog chamber and exposed to acidified salt fog per ASTM G 85, Standard Practice for Modified Salt Spray (Fog) Testing, Annex A4. All four alloys were exposed at the same time.

6.1.11.2 SO_2 Salt Fog Corrosion Performance Results

Since the panels were not scribed, most of the corrosion initiated along the edges and undermined the primer. There was no set criteria for number of hours to run in the salt fog cabinet. NAVAIR personnel exposed the panels to salt fog for a length of time that allowed for complete differentiation between the three types of pretreatment – Brush Tagnite, DOW 19 and TCP. At certain time intervals, NAVAIR personnel would remove the panels and photographs were taken when blistering first appeared. The amount of blistering and corrosion was noted and summarized in Appendix Q. At the discretion of NAVAIR testing personnel, some panels were removed early due to excessive corrosion formation. There were fifteen (15) panels per alloy – five (5) with Brush Tagnite, five (5) with DOW 19 and five (5) with TCP. Once the salt fog exposure was terminated for each alloy, the fifteen (15) panels for each alloy were given a rating from 1 (Best) to 15 (worst) by TAG personnel based on:

1. Amount of exposure time in the salt fog chamber
2. Degree of blistering under the primer
3. Depth of corrosion pitting in the painted areas

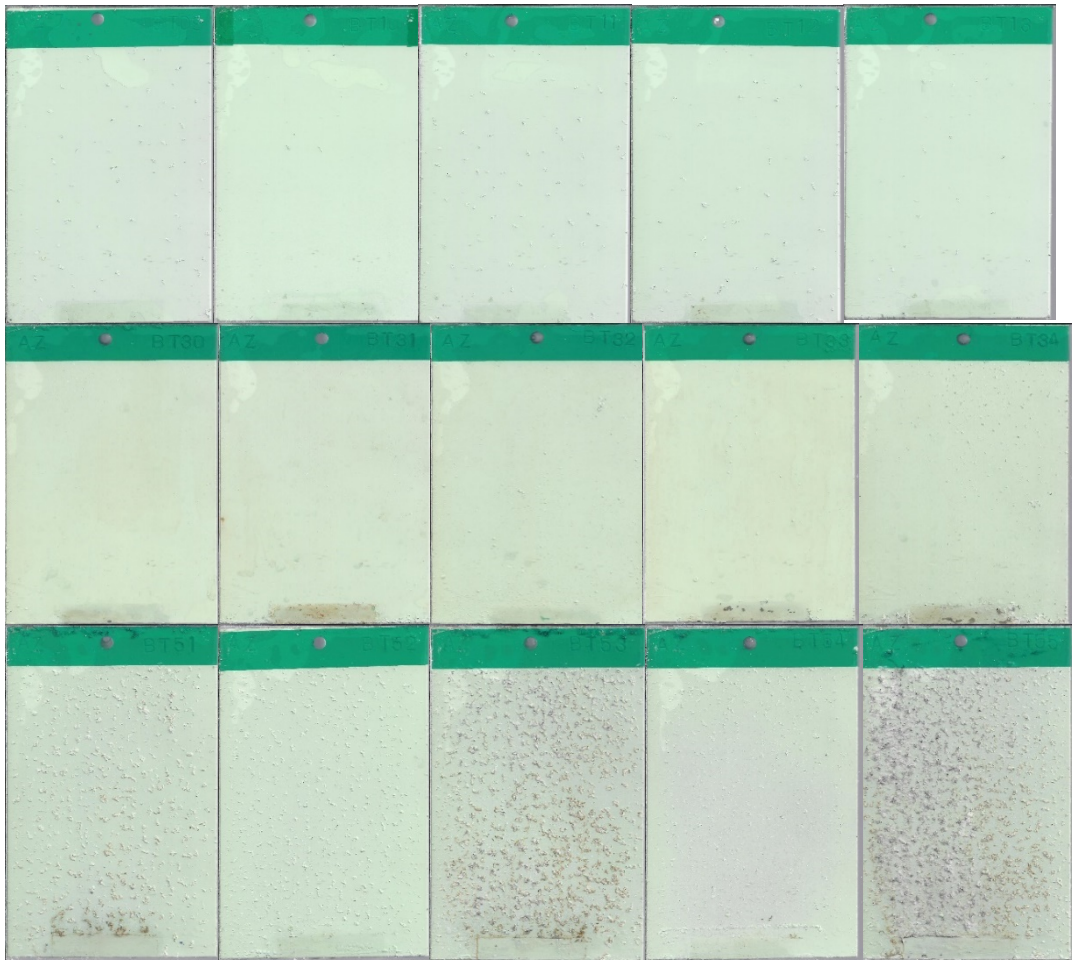
6.1.11.2.1 AZ91C SO_2 Salt Fog Corrosion Results

The total exposure time for this alloy was 1536 hours. Pictures of the AZ91C panels during at various time intervals are seen in Appendix R. The last time all AZ91C panels were in the salt fog together was at the 648 hour mark. At that time, all of the TCP panels were removed due to complete blistering of the primer. Figure 46 shows the panels after 648 hours of exposure. At 864 hours, the Brush Tagnite and DOW 19 appeared to have the same general level of corrosion. The Brush Tagnite and DOW 19 panels were left in the salt fog chamber for a total of 1200 hours after which the DOW 19 panels were removed. Figure 47 shows the panels after 1200 hours of exposure. The Brush Tagnite panels were left in the chamber for a total exposure time of 1536 hours when the test was terminated.

The SO_2 salt fog corrosion ratings for AZ91C are listed in Table 42.

Table 42: AZ91C SO_2 Salt Fog Summary

Panel ID #	Pre-treatment	Hours in Salt Fog	Ranking
AZ BT 09	Brush Tagnite	1536	4
AZ BT 10	Brush Tagnite	1536	1
AZ BT 11	Brush Tagnite	1536	5
AZ BT 12	Brush Tagnite	1536	3
AZ BT 13	Brush Tagnite	1536	2
AZ BT 30	DOW 19	1200	7
AZ BT 31	DOW 19	1200	9
AZ BT 32	DOW 19	1200	8
AZ BT 33	DOW 19	1200	6
AZ BT 34	DOW 19	1200	10
AZ BT 51	TCP	648	13
AZ BT 52	TCP	648	12
AZ BT 53	TCP	648	14
AZ BT 54	TCP	648	11
AZ BT 55	TCP	648	15

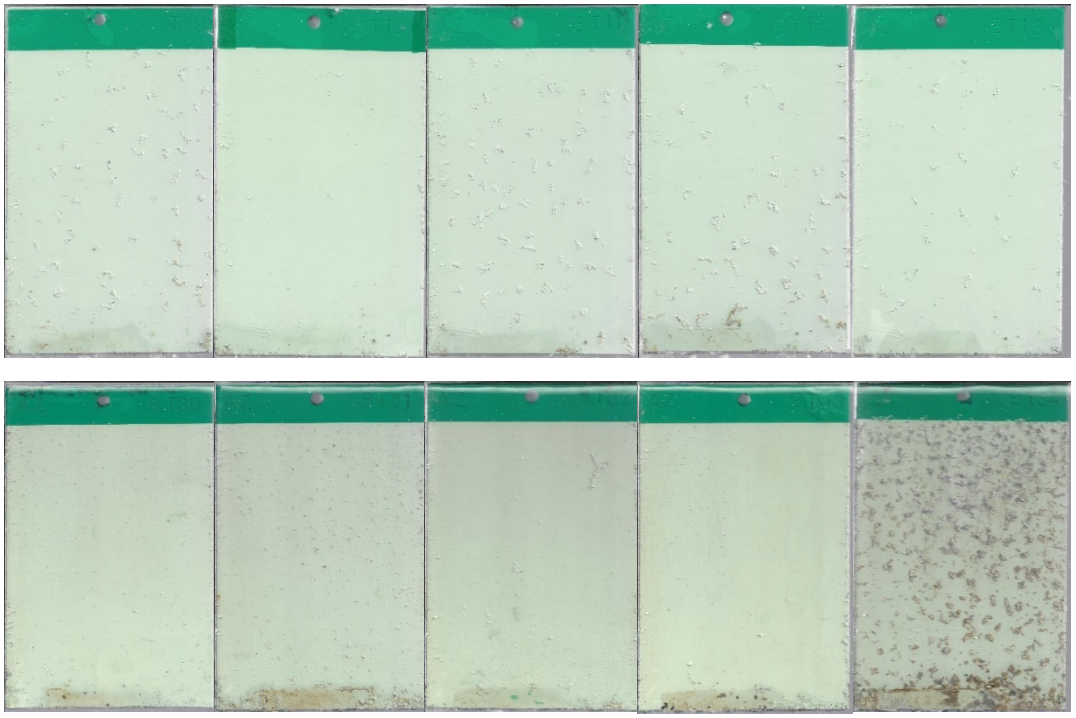


Brush Tagnite with MIL-PRF-23377

DOW 19 with MIL-PRF-23377

TCP with MIL-PRF-23377

Figure 46: AZ91C SO_2 Salt Panels with MIL-PRF-23377 Primer after 648 hours of exposure



Brush Tagnite with MIL-PRF-23377

DOW 19 with MIL-PRF-23377

TCP with MIL-PRF-23377

Panels pulled after 648 hours exposure

Figure 47: AZ91C SO_2 Salt Panels with MIL-PRF-23377 Primer after 1200 hours of exposure

AZ91C SO_2 Salt Fog Corrosion Test Results:

1. The panels pretreated with TCP failed the fastest. All of the TCP panels were pulled after 648 hours.
2. The DOW 19 panels were the second worst performers. They were all pulled after 1200 hours.
3. The Brush Tagnite test coupons were exposed for 1536 hours of acidified salt fog after which the test was terminated. All five (5) BT panels were ranked in the top 5.
4. The Brush Tagnite panels had the best performance based on visual observation as well as:
    a. Longest exposure time in the salt fog cabinet
    b. There was minimal corrosion pitting on the painted surfaces compared to the TCP and DOW 19 panels.

AZ91C Neutral Salt Fog Conclusion: All five Brush Tagnite panels clearly outperformed the DOW 19. Therefore, ***Brush Tagnite met the performance objective of the JTP*** in which the Brush Tagnite performance must meet or exceed the DOW 19 performance.

6.1.11.2.2 EV31A SO_2 Salt Fog Corrosion Results

The total exposure time for this alloy was 1536 hours. Pictures of the EV31A panels during at various time intervals are seen in Appendix S. At the 312 hour mark, corrosion was starting to form around the outside edges of the DOW 19 and TCP panels. After 648 hours of exposure, there was enough blistering on the DOW 19 panels to lead to their removal as seen in Figure 48. The remaining Brush Tagnite and TCP panels were exposed for a total of 1535 hours when the test was terminated. Figure 49 shows all the panels after 1536 hours of exposure. There appeared to be more widespread corrosion on the TCP panels and the primer had little to no adhesion, therefore the Brush Tagnite panels received better ratings.

The SO_2 salt fog corrosion ratings for EV31A are listed in Table 43.

Table 43: EV31A SO_2 Salt Fog Summary

Panel ID #	Pre-treatment	Hours in Salt Fog	Ranking
EV BT 09	Brush Tagnite	1536	6
EV BT 10	Brush Tagnite	1536	2
EV BT 11	Brush Tagnite	1536	5
EV BT 12	Brush Tagnite	1536	1
EV BT 13	Brush Tagnite	1536	3
EV BT 30	DOW 19	648	15
EV BT 31	DOW 19	648	11
EV BT 32	DOW 19	648	12
EV BT 33	DOW 19	648	13
EV BT 34	DOW 19	648	14
EV BT 51	TCP	1536	4
EV BT 52	TCP	1536	8
EV BT 53	TCP	1536	7
EV BT 54	TCP	1536	10
EV BT 55	TCP	1536	9

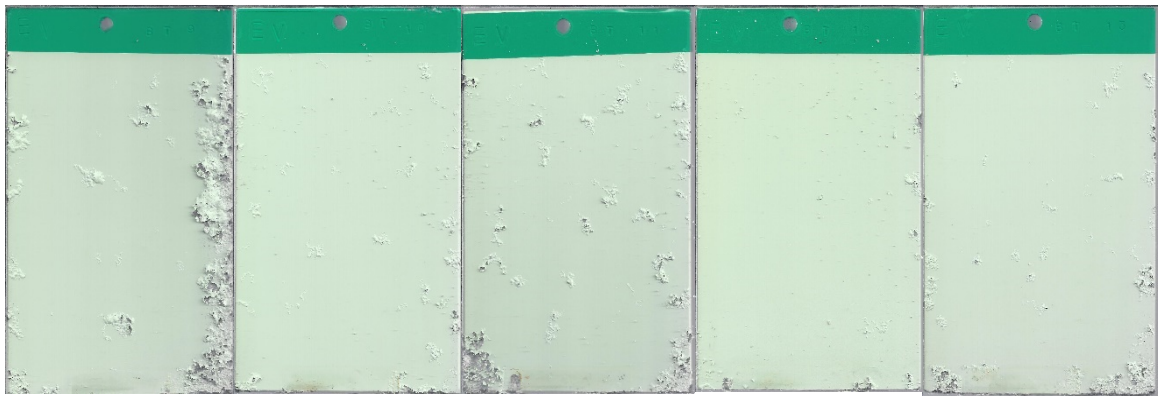


Brush Tagnite with MIL-PRF-23377

DOW 19 with MIL-PRF-23377

TCP with MIL-PRF-23377

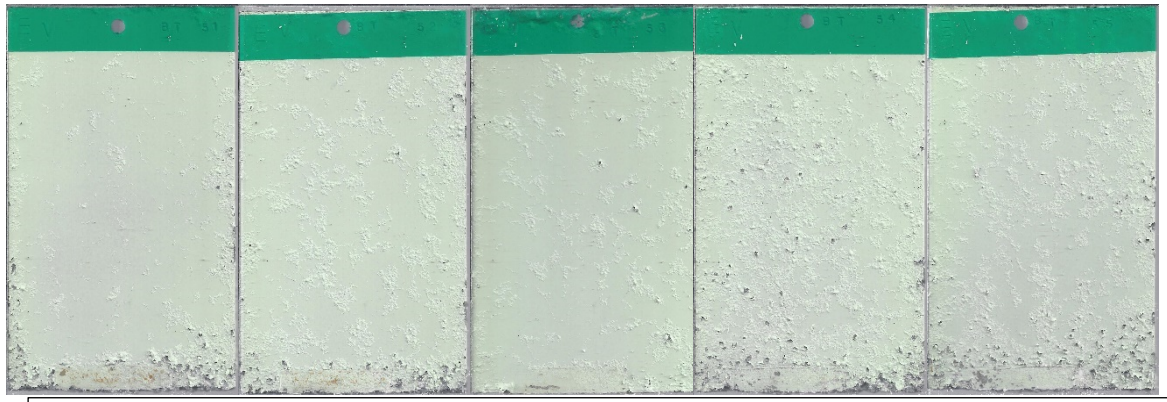
Figure 48: EV31A SO_2 Salt Panels with MIL-PRF-23377 Primer after 648 hours of exposure



Brush Tagnite with MIL-PRF-23377

Panels pulled after 648 hours

DOW 19 with MIL-PRF-23377



TCP with MIL-PRF-23377

Figure 49: EV31A SO_2 Salt Panels with MIL-PRF-23377 Primer after 1536 hours of exposure

EV31A SO_2 Salt Fog Corrosion Test Results:

1. The panels pretreated with DOW 19 failed the fastest. All of the DOW 19 panels were pulled after 648 hours.
2. The Brush Tagnite and TCP coupons received a total of 1536 hours of exposure at which point the test was terminated. The BT panels received 4 of the 5 highest rankings. There was not much difference in the performance of the TCP and Brush Tagnite on the EV31A alloy.
3. The Brush Tagnite panels had the slightest advantage over TCP based on smaller amount of corrosion at the end of the test period (1536 hours).

EV31A SO_2 Salt Fog Conclusion: **All five Brush Tagnite panels clearly outperformed the DOW 19.** Therefore, Brush Tagnite met the performance objective of the JTP in which the Brush Tagnite performance must meet or exceed the DOW 19 performance.

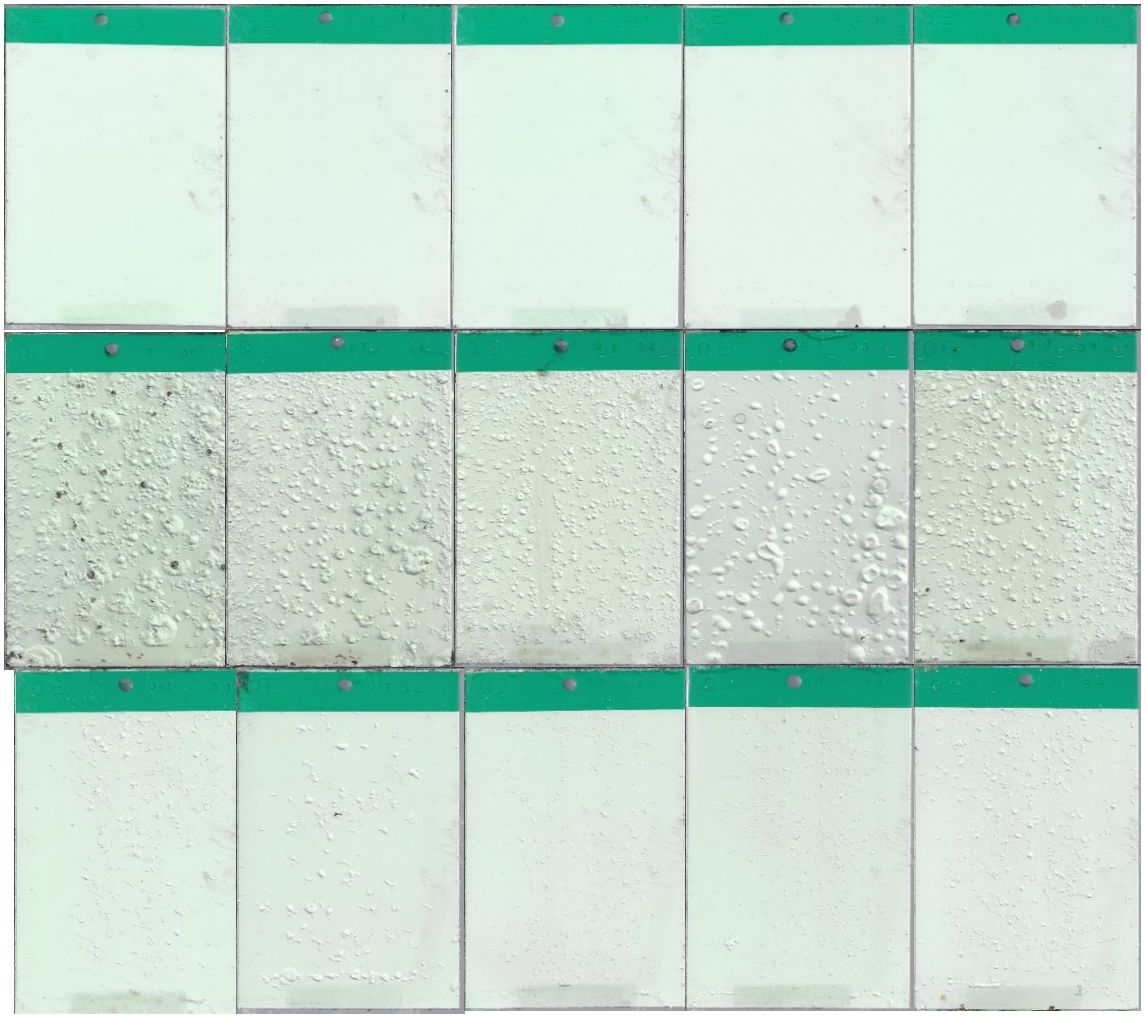
6.1.11.2.3 QE22A SO_2 Salt Fog Corrosion Results

The total exposure time for this alloy was 1536 hours. Pictures of the QE22A panels during at various time intervals are seen in Appendix T. The last time all QE22A panels were in the salt fog together was at the 144 hour mark. At that time, all of the DOW 19 panels were removed due to complete blistering of the primer. Figure 50 shows the panels after 144 hours of exposure. At 312 hours, the TCP panels were removed and Figure 51 shows the panels after 312 hours of exposure. The Brush Tagnite panels remained in the chamber until the test was terminated at 1536 hours of exposure and are seen in Figure 52.

The SO_2 salt fog corrosion ratings for QE22A are listed in Table 44.

Table 44: QE22A SO_2 Salt Fog Summary

Panel ID #	Pre-treatment	Hours in Salt Fog	Ranking
QE BT 09	Brush Tagnite	1536	1
QE BT 10	Brush Tagnite	1536	3
QE BT 11	Brush Tagnite	1536	2
QE BT 12	Brush Tagnite	1536	5
QE BT 13	Brush Tagnite	1536	4
QE BT 30	DOW 19	144	15
QE BT 31	DOW 19	144	14
QE BT 32	DOW 19	144	11
QE BT 33	DOW 19	144	12
QE BT 34	DOW 19	144	13
QE BT 51	TCP	312	8
QE BT 52	TCP	312	10
QE BT 53	TCP	312	7
QE BT 54	TCP	312	6
QE BT 55	TCP	312	9



Brush Tagnite with MIL-PRF-23377

DOW 19 with MIL-PRF-23377

TCP with MIL-PRF-23377

Figure 50: QE22A SO_2 Salt Panels with MIL-PRF-23377 Primer after 144 hours of exposure

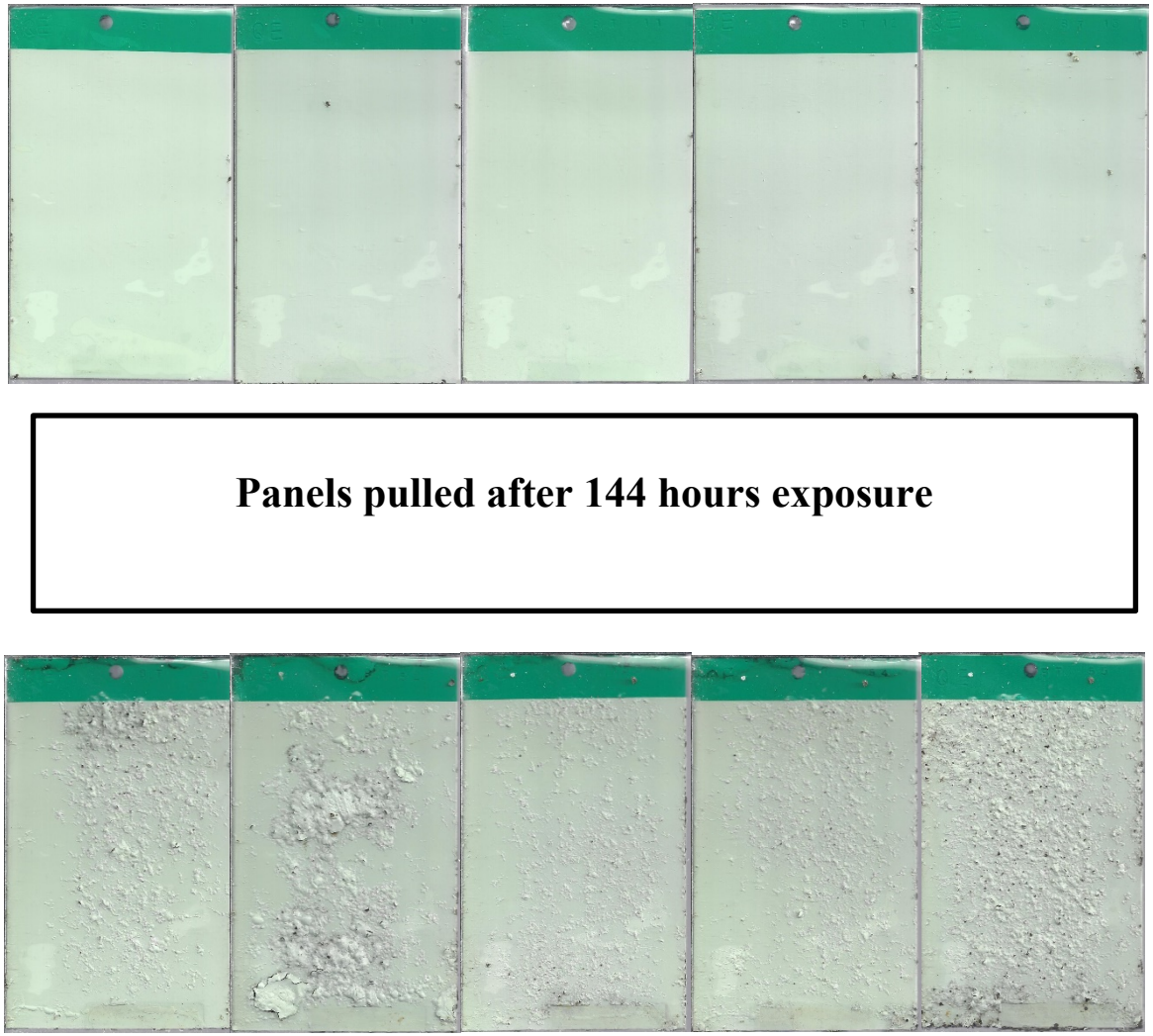
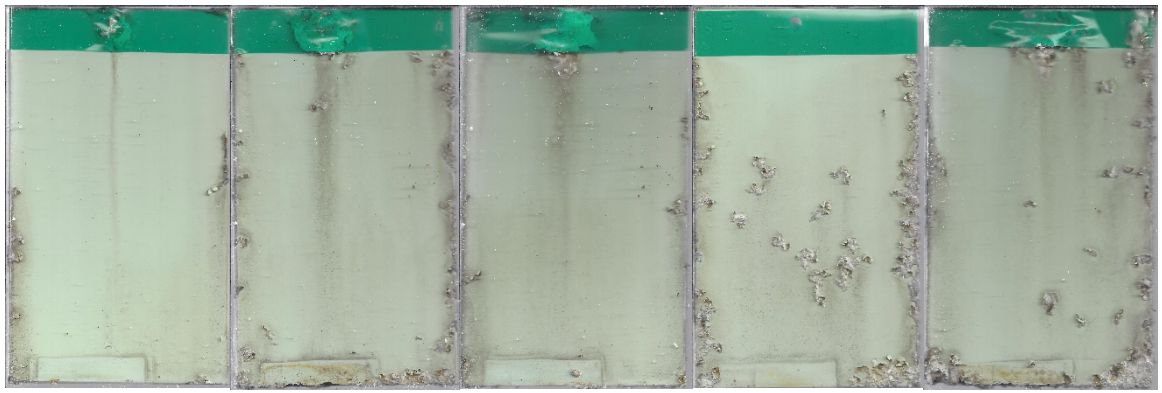


Figure 51: QE22A SO_2 Salt Panels with MIL-PRF-23377 Primer after 312 hours of exposure



Brush Tagnite with MIL-PRF-23377

Panels pulled after 144 hours exposure

DOW 19 with MIL-PRF-23377

Panels pulled after 312 hours exposure

TCP with MIL-PRF-23377

Figure 52: QE22A SO_2 Salt Panels with MIL-PRF-23377 Primer after 1536 hours of exposure

QE22A SO_2 Salt Fog Corrosion Test Results:

1. The panels pretreated with DOW 19 failed the fastest. All of the DOW 19 panels were pulled after 144 hours of exposure.
2. The TCP panels were the second group to fail. All of the TCP panels were pulled after 312 hours of exposure.
3. The Brush Tagnite coupons received a total of 1536 hours of exposure at which point the test was terminated. The BT panels received the highest rankings.
4. ***The Brush Tagnite panels had the best performance*** based on visual observation and time is the salt fog cabinet. The Brush Tagnite panels lasted 5x longer in the salt fog cabinet than TCP and 10x than the DOW 19 panels.

QE22A SO_2 Salt Fog Conclusion: ***All five Brush Tagnite panels clearly outperformed the DOW 19.*** Therefore, Brush Tagnite exceeded the performance objective of the JTP in which the Brush Tagnite performance must meet or exceed the DOW 19 performance by lasting 10x longer in the acidified salt fog than the DOW 19 panels.

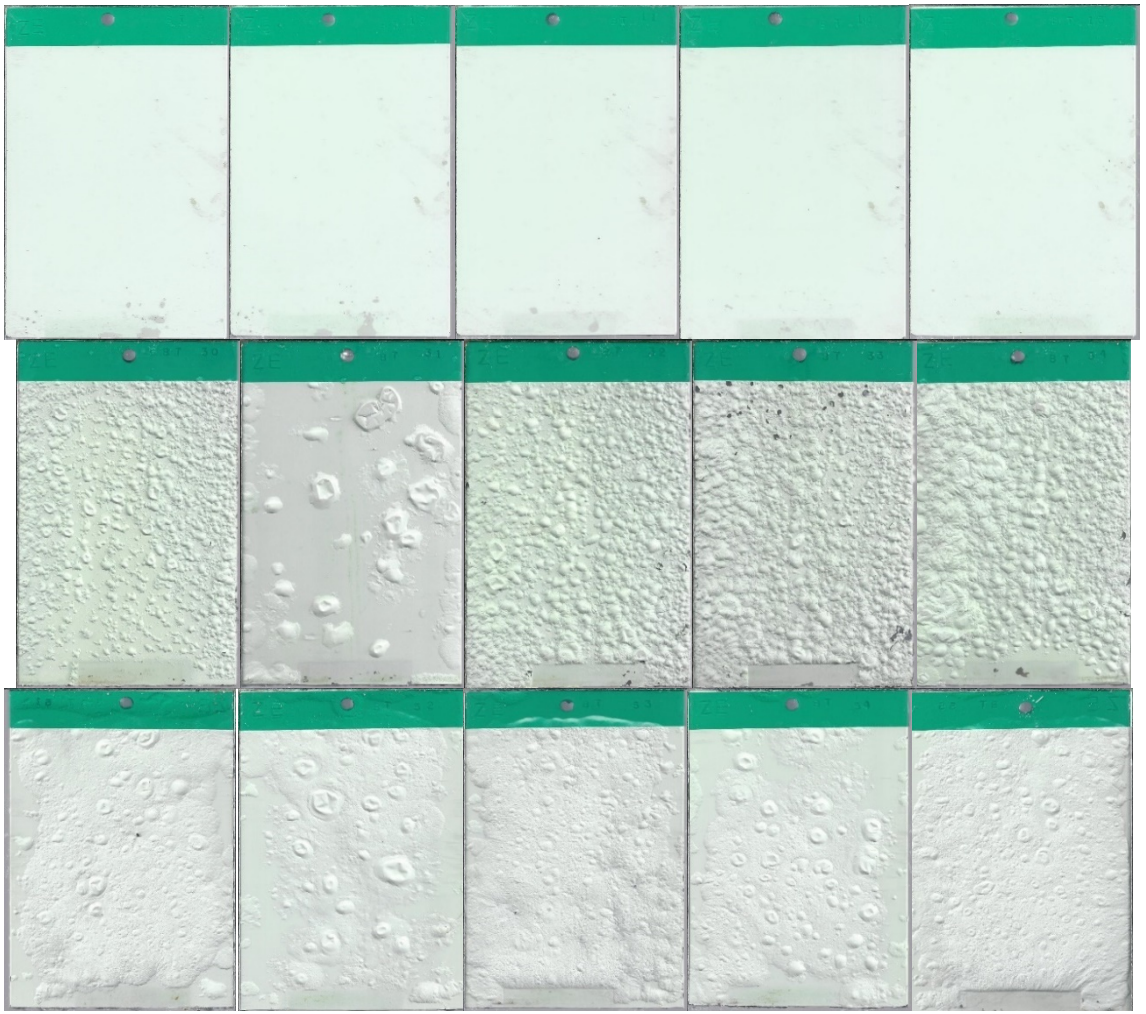
6.1.11.2.4 ZE41A SO_2 Salt Fog Corrosion Results

The total exposure time for this alloy was 1536 hours. Pictures of the ZE41A panels during at various time intervals are seen in Appendix U. The last time all ZE41A panels were in the salt fog together was at the 144 hour mark. At that time, all of the DOW 19 and TCP panels were removed due to complete blistering of the primer. Figure 53 shows the panels after 144 hours of exposure. The testing was continued with the Brush Tagnite panels and the test was terminated after 1536 hours. The Brush Tagnite panels after 1536 hours of SO_2 exposure are seen in Figure 54.

After the test was terminated, the panels were ranked. The SO_2 salt fog corrosion rankings for ZE41A are listed in Table 45.

Table 45: ZE41A SO_2 Salt Fog Summary

Panel ID #	Pre-treatment	Hours in Salt Fog	Ranking
ZE BT 09	Brush Tagnite	1536	2
ZE BT 10	Brush Tagnite	1536	3
ZE BT 11	Brush Tagnite	1536	5
ZE BT 12	Brush Tagnite	1536	4
ZE BT 13	Brush Tagnite	1536	1
ZE BT 30	DOW 19	144	12
ZE BT 31	DOW 19	144	11
ZE BT 32	DOW 19	144	13
ZE BT 33	DOW 19	144	14
ZE BT 34	DOW 19	144	15
ZE BT 51	TCP	144	9
ZE BT 52	TCP	144	7
ZE BT 53	TCP	144	10
ZE BT 54	TCP	144	8
ZE BT 55	TCP	144	6

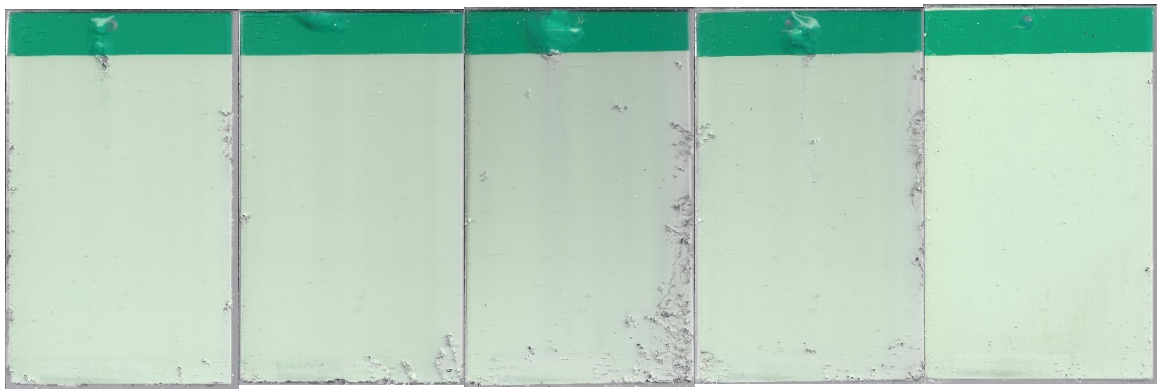


Brush Tagnite with MIL-PRF-23377

DOW 19 with MIL-PRF-23377

TCP with MIL-PRF-23377

Figure 53: ZE41A SO_2 Salt Panels with MIL-PRF-23377 Primer after 144 hours of exposure



Brush Tagnite with MIL-PRF-23377

Panels pulled after 144 hours exposure

DOW 19 with MIL-PRF-23377

Panels pulled after 144 hours exposure

TCP with MIL-PRF-23377

Figure 54: ZE41A SO_2 Salt Panels with MIL-PRF-23377 Primer after 1536 hours of exposure

ZE41A SO_2 Salt Fog Corrosion Test Results:

1. The panels pretreated with DOW 19 and TCP failed the fastest. All of the DOW 19 and TCP panels were pulled after 144 hours.
2. The DOW 19 panels had a significant amount of blistering and were rated lower than the TCP panels based on the photographs.
3. The Brush Tagnite coupons received a total of 1536 hours of exposure at which point the test was terminated. The BT panels received the highest rankings.
4. The Brush Tagnite panels had the best performance based on:
    a. Exposure time in the salt fog cabinet.
    b. Minimal corrosion throughout the test period.

ZE41A SO_2 Salt Fog Conclusion: ***All five Brush Tagnite panels clearly outperformed the DOW 19.*** Therefore, Brush Tagnite exceeded the performance objective of the JTP in which the Brush Tagnite performance must meet or exceed the DOW 19 performance by lasting 10x longer in the acidified salt fog than the DOW 19 panels.

6.1.11.3 Overall Conclusion for Acidified SO_2 Salt Fog Corrosion Testing: The Brush Tagnite pretreatment on all four alloys (AZ91C, EV31A, QE22A and ZE41A) clearly outperformed the DOW 19 pretreatment. Therefore, ***Brush Tagnite met or exceeded the JTP performance objective for all alloys tested.***

6.1.12 Brush Tagnite Axial Fatigue Test Results

6.1.12.1 Manufacture of Axial Fatigue Specimens by Westmoreland

The raw material for the fatigue specimens was round bar stock purchased from Magnesium Alloy Products. Figure 55 shows the appearance of the round bar stock. The approximate dimensions of the bar stock were 8" length x ¾" diameter. In order to make the required amount of fatigue specimens, twenty (20) round bars of each alloy (AZ91C, EV31A, QE22A and ZE41) were purchased.



Figure 55: Picture of Magnesium Round Bar stock used as raw material for axial fatigue specimens.

The round bar stock was shipped to Westmoreland Mechanical Testing and Research, Youngstown, PA for machining in axial fatigue specimens per the diagram in Figure 22. After machining, a unique ID number was engraved on the grip ends of the specimens by Westmoreland. Appendix V lists the ID numbers and their correlation to alloy and pretreatment along with who performed the fatigue testing and data analysis.

The Joint Test Protocol (JTP) stated that UDRI would perform the fatigue testing on two alloys. They were only able to test one alloy (ZE41) due to funding constraints. North Dakota State University (NDSU) was listed in the JTP as fatigue testing site for the two other alloys, however, they determined that their fatigue testing equipment was not configured to perform the required ASTM fatigue testing. Therefore, the remaining three alloys (AZ91C, EV31A and QE22A) had the axial fatigue testing performed by Westmoreland Mechanical Testing (Youngstown, PA) and the data analysis was performed by TAG personnel.

6.1.12.2 ZE41A Axial Fatigue Testing at University of Dayton Research Institute (UDRI)

The ZE41A fatigue specimens were sent to UDRI in two batches for axial fatigue testing per ASTM E 466 – Standard Practice for Conducting Force Controlled Constant Amplitude Axial Fatigue Tests of Metallic Materials. Batch #1 consisted of the uncoated (baseline) and Brush Tagnite (BT) specimens. Batch #2 consisted of the DOW 19 and TCP pretreated specimens. The fatigue testing was performed on an MTS test system equipped with a 22,000 lb actuator and aligned in accordance with ASTM E 466. The stress ratio was R = 0.1 at a cyclic frequency of 30 Hz. The runout cycle was 1×10^6.

The Batch #1 specimens were run at varying stress levels to collect initial data to get an idea on what the optimum stress levels to use. After discussions between ARL, AFRL, TAG and UDRI,

the second batch of specimens was run at stress levels of 22,750 psi and 24,500 psi in order to generate data that could be statistically analyzed with a high degree of confidence. After testing was complete, a report was issued by UDRI (Appendix W). Upon review of the report, personnel at TAG noticed that due to miscommunication, UDRI misidentified the sample pretreatments in Table 11. This issue was clarified and the data was reorganized to align the specimen ID with the proper pretreatment and a revised report was issued (Appendix X). Because of the way the Batch #1 and Batch #2 specimens were tested, there was limited data for the uncoated (baseline) specimens at 22,750 psi and 24,500 psi as well as Brush Tagnite performance at 24,500 psi (Table 1 in Appendix X). Figure 56 shows the fatigue curve for ZE41A at the two different stress levels.

ZE41A Axial Fatigue Results from UDRI

1. There were sufficient data points to compare the fatigue life between the three pretreatment systems at the 22,750 psi stress level. There was no statistical difference in fatigue properties between the Tagnite, DOW 19 or TCP pretreatment systems at 22,750 psi.
2. There was insufficient baseline data at 22,750 psi to determine if there was a statistical difference between the baseline (uncoated) specimens and the three pretreated specimens.
3. There was insufficient data for the baseline or Brush Tagnite at 24,500 psi for statistical comparison.
4. There was no significant difference in fatigue properties found between the DOW 19 and TCP pretreatments at 24,500 psi.

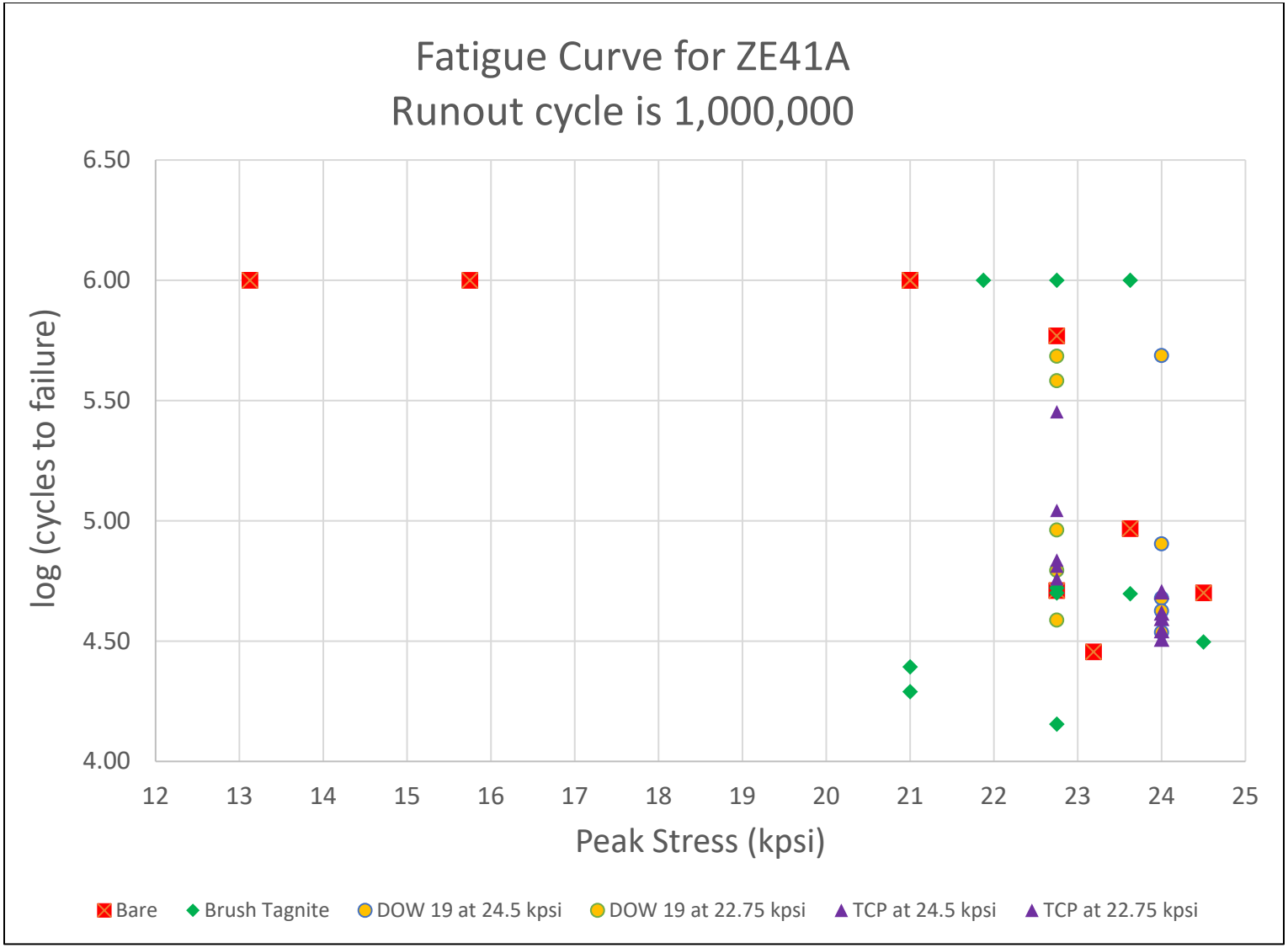


Figure 56: Fatigue Curve for ZE41A

6.1.12.3 AZ91C, EV31A and QE22 Axial Fatigue Testing at Westmoreland Testing

Westmoreland Mechanical Testing & Research, Inc. performed the fatigue testing per ASTM E466 at room temperature in load control on servo-hydraulic test equipment employing a 30 hertz sinusoidal waveform with an R-ratio of 0.1. Run-out was defined as 1,000,000 cycles and any test reaching run-out was discontinued. The stress levels for the test were defined at 22.75 ksi and 24.5 ksi, based upon the values used by UDRI. For each alloy and pretreatment, 50 % of the alloy/pretreatment were run at 22.75 ksi while the other half was run at 24.5 ksi. The testing parameters and test data from Westmoreland Testing are summarized in Appendix Y. The data set was the analyzed independently by personnel at Technology Applications Group.

6.1.12.4 Data Analysis for AZ91C, EV31A and QE22 Axial Fatigue Testing

The ZE41A fatigue data set collected by UDRI was analyzed with the k-factor Anderson-Darling (A-D) test, the Student's t-test assuming unequal variances, and the F-test using a 95% and 90% confidence level. The fatigue data set for AZ91C, EV31A and QE22A from Westmoreland was analyzed using the non-parametric Wilcoxon signed rank test, and Students t-test assuming unequal variances with a 95% confidence level based on consultation with Dr. Gerri Dunnigan, (Associate Professor in Statistics at the University of North Dakota). Dr. Dunnigan recommended that the Wilcoxon test be performed to validate the Student t-test instead of the k-factor Anderson Darling test used by UDRI. The k-factor Anderson Darling test for proving the normality of a data set was not considered for the Westmoreland fatigue data because there was not a large enough sample size to gain any significant knowledge using this test. As a result, the recommendation was made to utilize a Wilcoxon signed-rank test to verify the validity of the t-test statistical analysis. The Wilcoxon signed-rank test is a non-parametric statistical hypothesis test used when comparing two related samples, matched samples, or repeated measurements on a single sample to assess whether their population mean ranks differ.

The F-test of the equality of two variances used by UDRI is also not relevant because it is sensitive to non-normality and is similar to a t-test with enhanced weighting to outliers. With a small sample size, it cannot determine normality because the Anderson Darling test is not relevant, therefore this test also loses its accuracy and is not significant. Based on this rationale, the Students t-test assuming unequal variances was used. Statistical calculations were done using Minitab Statistical Software.

Every data set tested passed the Wilcoxon test with a 95% confidence except one data set - EV31A: BT vs DOW 19 at 22.75 ksi. In this case, every single fatigue specimen for both pretreatments ran to the run-out cutoff of 1,000,000 cycles. The results of the Wilcoxon test implies that the data from the t-test can still be statistically relevant despite the small sample size.

AZ91C Fatigue Results

Uncoated vs. Pretreatment: The test found that at a 95% confidence interval, there was a statistically significant difference between average of log cycles to failure between Brush Tagnite and the uncoated specimens at a max stress of 24.5 ksi and 22.75 ksi. When DOW 19

and TCP fatigue was compared with the uncoated specimens there also was a statistically significant difference between average of log cycles to failure for both 24.5 ksi and 22.75 ksi. Figure 57 shows the fatigue curve for AZ91C at the two different stress levels.

24.5 ksi Stress Load: At 24.5 ksi there is no difference between Brush Tagnite and TCP but there was a difference between Brush Tagnite and DOW 19 where the p value of .045 falls just outside of the 95% confidence interval. If the confidence interval was expanded to 99%, there was no statistically significant fatigue difference between Brush Tagnite and TCP or DOW 19.

22.75 ksi Stress Load: When Brush Tagnite was compared to the rival coatings at 22.75 ksi, there is no statistically significant fatigue difference between Brush Tagnite and TCP or DOW 19.

EV31A Fatigue Results

Uncoated vs. Pretreatment: The test found that when using a 95% confidence interval, there was not a statistically significant difference between average of log cycles to failure between Brush Tagnite/DOW19/TCP and the uncoated specimens at a max stress of 24.5 ksi. Due to the high rate of run-out for the bare and pretreated specimens, no statistical determination can be made at 22.75 ksi. Figure 58 shows the fatigue curve for EV31A at the two different stress levels.

24.5 ksi Stress Load: The values from this data set are slightly difficult to analyze due to the significantly high percentage of the samples that ran to completion. For example, four out of five DOW 19 specimens ran to completion as well as three out of five TCP specimens. If future testing were to be done it might be beneficial to increase the number of cycles to run-out to 10,000,000 instead of 1,000,000 to try and decrease the amount of data that ran to completion. However, testing showed that there was no significant difference between the fatigue strength of bare vs. Brush Tagnite.

22.75 ksi Stress Load: The values from this data set are difficult to analyze due to the significantly high percentage of the samples that ran to completion. For example, all five DOW 19 and Brush Tagnite specimens ran to completion. Based on the high run-out percentage, there is no difference in fatigue strength between DOW 19 and Brush Tagnite.

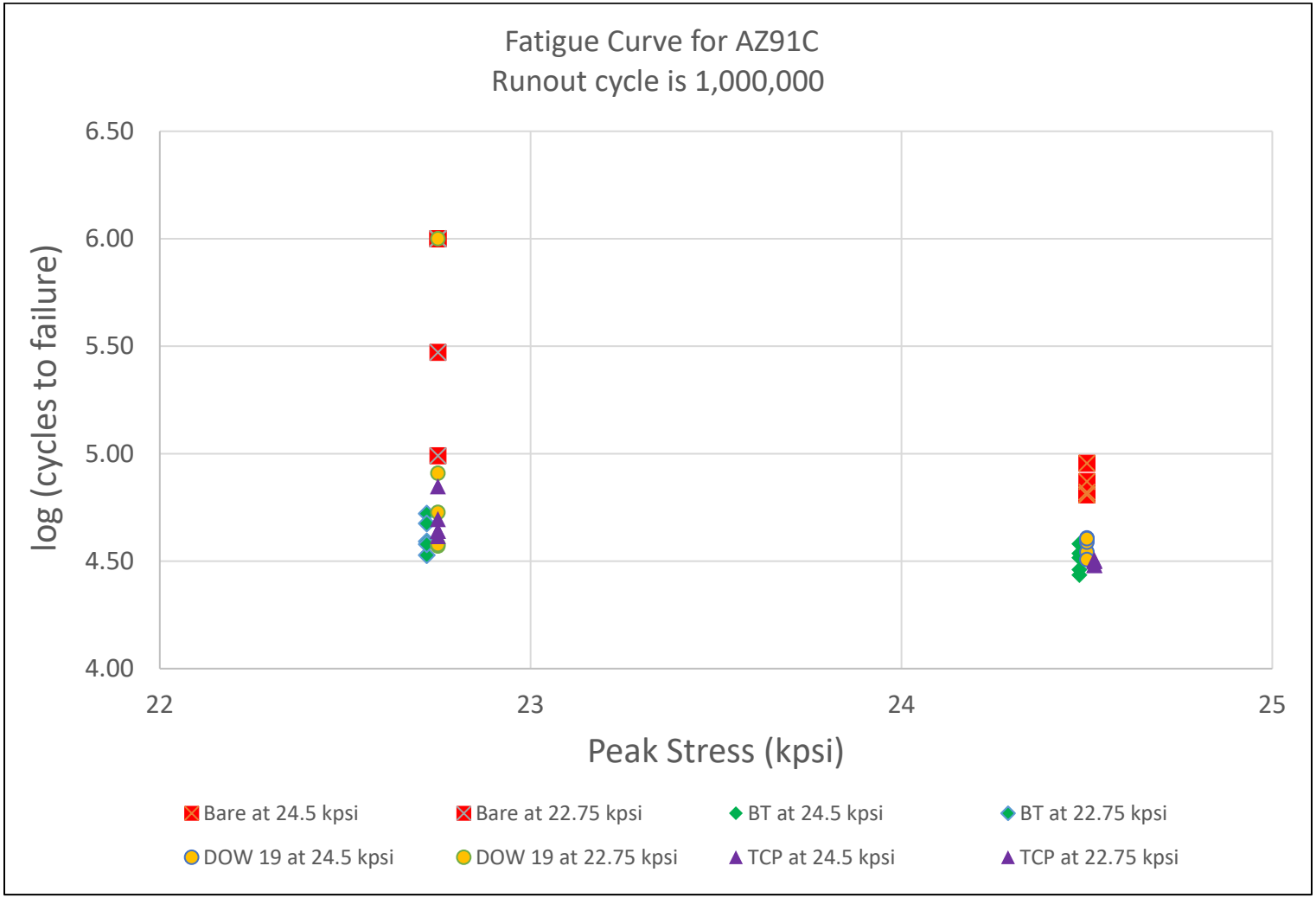


Figure 57: Fatigue Curve for AZ91C

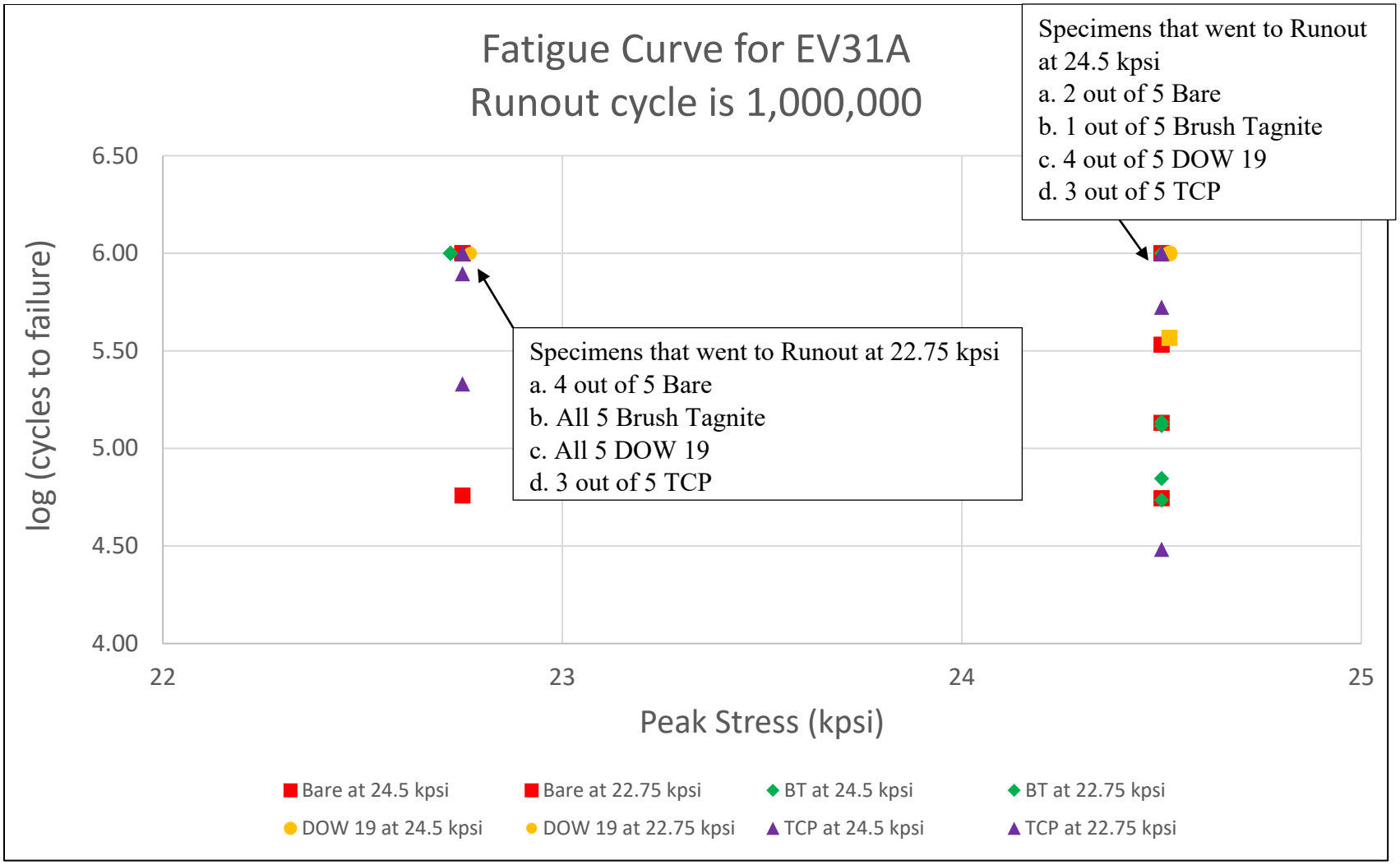


Figure 58: Fatigue Curve for EV31A

QE22A Fatigue Results

Uncoated vs. Pretreatment: The test found that when using a 95% confidence interval, there was not a statistically significant difference between average of log cycles to failure between Brush Tagnite/DOW19/TCP and the uncoated specimens at a max stress of 24.5 ksi. At a max stress of 22.75 ksi, no determination can be made due to the high rate of run-out for both bare and pretreated specimens. Figure 59 shows the fatigue curve for QE22A at the two different stress levels.

24.5 ksi Stress Load: There was a statistical difference between DOW 19 and Brush Tagnite using a 95% confidence interval. This result was due to three out of five DOW 19 specimens went to run-out while all five Brush Tagnite specimens failed prior to run-out.

22.75 ksi Stress Load: The values from this data set are difficult to analyze due to the significantly high percentage of the samples that ran to completion. For example, all five DOW specimens ran to completion along with four TCP and three Brush Tagnite specimens.

6.1.12.5 General Conclusions about Fatigue Testing:

1. For each alloy, there were only 10 specimens per pretreatment scheme and these 10 specimens were divided into two groups, 22.75 ksi and 24.5 ksi maximum stress load. This meant that the sample population was only 5 specimens per max. stress load/pretreatment scheme which made statistical analysis difficult.
2. The specimens tested at Westmoreland had a high percentage of specimens that went to runout at 1,000,000 cycles which also hindered the data analysis.
3. TAG does not have the expertise to analyze this limited data set and will defer to CCDC AvMC AMA-F experts at Redstone Arsenal to determine the fatigue performance of Brush Tagnite vs. DOW 19.
4. The CCDC AvMC AMA-F Branch at Redstone Arsenal reviewed the fatigue data and data analysis. The fatigue experts at CCDC AvMC AMA-M felt strongly that the sample size of fatigue specimens tested was much too small to make any type of definitive statistical conclusions about the fatigue impact pertaining to the use of Brush Tagnite.

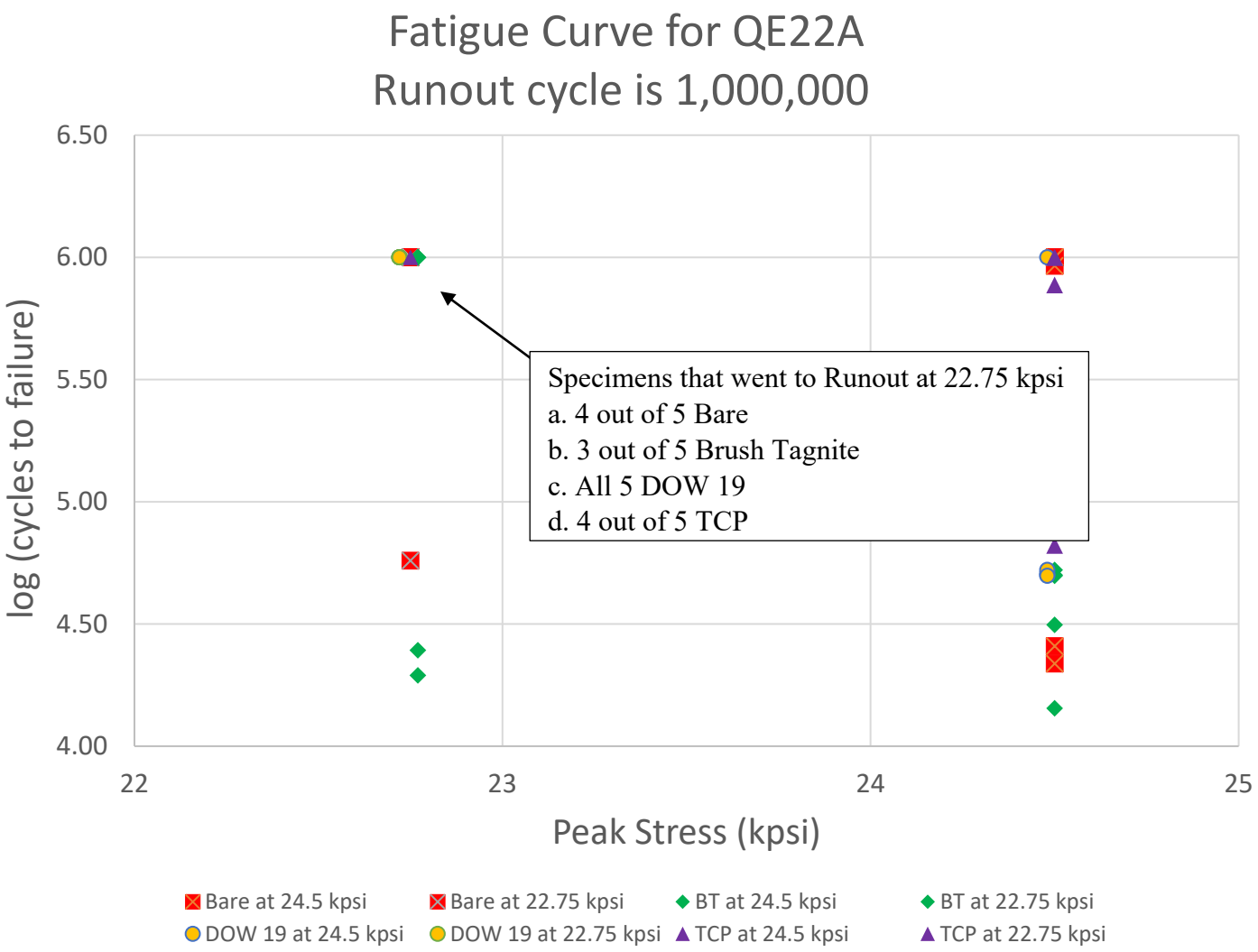


Figure 59: Fatigue Curve for QE22A

6.1.13 Brush Tagnite Outdoor Exposure Test Results

6.1.13.1 Testing of Brush Tagnite Outdoor Exposure Coupons by NASA

The outdoor exposure test panels were pretreated then painted with MIL-PRF-23377 non-chromated primer at the locations described in Appendix K. Panels were shipped to TAG for inspection after which the panels were shipped to NASA Beachside Corrosion Test Site, Kennedy Space Center, FL. The Statement of Work is seen in Appendix Z. Panels were mounted in the test stands arranged by alloy and pretreatment scheme prior to beachside exposure. The period of exposure is 24 months and is still on going at this time. Due to miscommunication, the test panels did not receive an "X" scribe on the exposed 4" x 6" surfaces until 2 months of outdoor exposure.

6.1.13.2 Outdoor Exposure Corrosion Performance Results

NASA personnel took pictures of the panels at the 1 week, 2 week and 3 week marks. After that pictures were taken once per month with the exception of the 12 month interval. No pictures were supplied for the 12 month exposure. As with the other corrosion testing, the scribed panels did not act in the expected manner. Most of the corrosion took place away from the scribe, underneath the primer. This behavior is unusual when compared to anodize coatings such as Immersion Tagnite, DOW 17 and HAE. Anodized coatings act like a corrosion barrier next to the scribe and minimize corrosion migration. Brush Tagnite, DOW 19 and TCP do not have the corrosion barrier properties that anodize coatings have, therefore the paint next to the scribe is easily undermined. TAG personnel reviewed the photos and kept a log of when corrosion first occurred on the panels and determined the time frame when complete differentiation between the three types of pretreatment – Brush Tagnite, DOW 19 and TCP was observed. Once differentiation was noted for each alloy, each individual panel was inspected for:

1. Corrosion migration away from the scribe
2. Percentage of overall corrosion pitting on the entire panel
3. Depth of corrosion pitting in the painted areas away from the scribe

After the inspection, the nine (9) panels for each alloy were given a grade from 1 (Best) to 9 (worst).

6.1.13.2.1 AZ91C Outdoor Exposure Corrosion Results

The total exposure time for this alloy was 24 months. Pictures of the AZ9C panels taken by NASA during various time intervals are seen in Appendix AA.

Observations from the AZ91C Outdoor Exposure:

1. It took several months before any corrosion appeared. Evidence of corrosion started at:
    a. For DOW 19: 3 months
    b. For TCP and Brush Tagnite: 5 months
2. There was not significant differentiation between the three pretreatments until the 18 month mark.

3. At the 24 month mark, **the Brush Tagnite panels had the best performance** based on visual observation and % area corroded.
    a. The corrosion migration away from the scribe was the least of the three pretreatments
    b. There was minimal corrosion pitting on the painted surfaces away from the scribe compared to the TCP and DOW 19 panels
4. At the 24 month mark, there was no clear cut second best performer as the TCP and DOW 19 panels had similar corrosion responses.

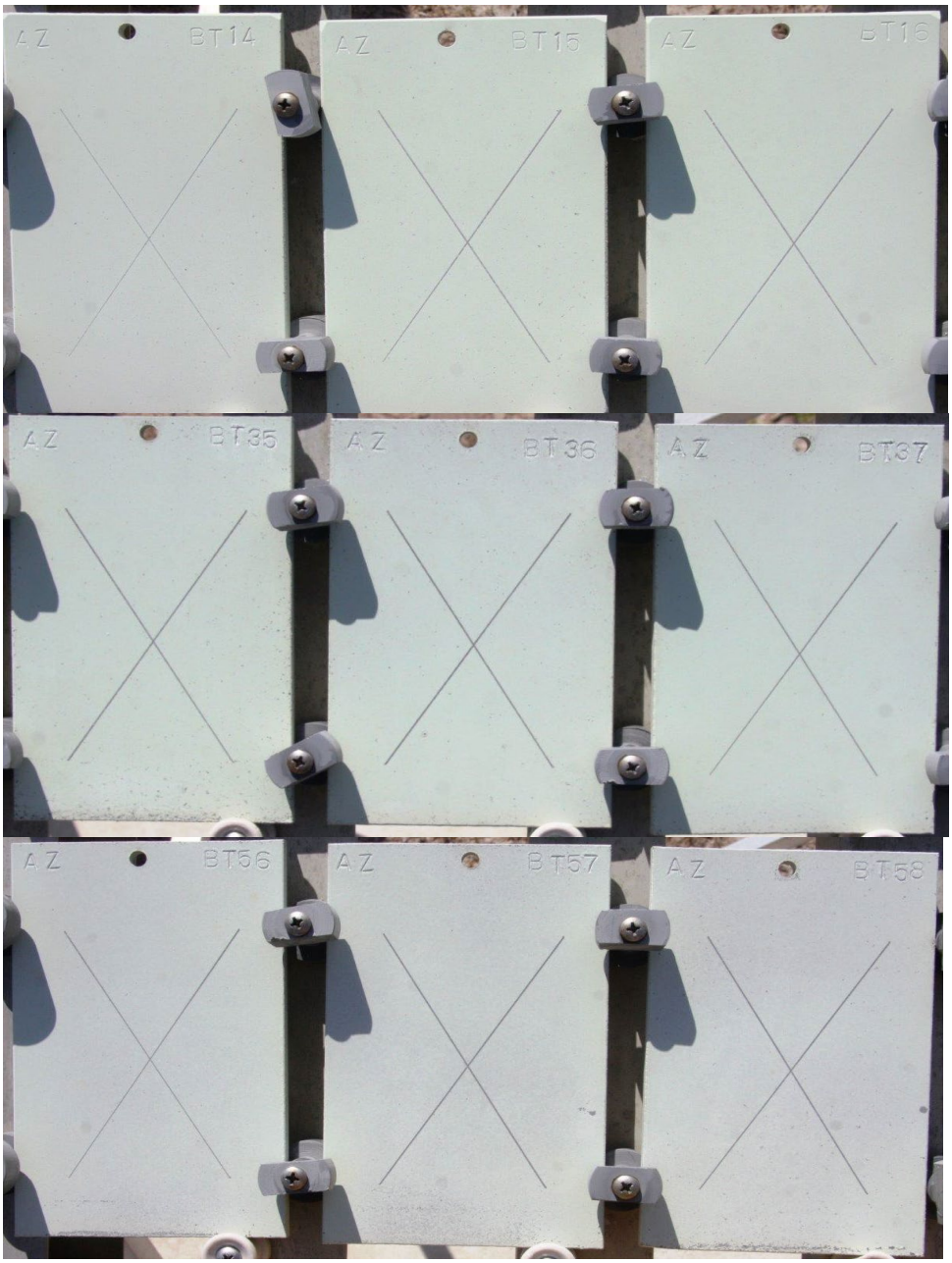
At the 24 month mark, the AZ91C panels were rated. The outdoor exposure ratings for these panels are listed in Table 46.

Table 46: AZ91C Outdoor Exposure Summary

Panel ID	Treatment	Months of Exposure	% Area Corroded	Ranking
AZ BT 14	Brush Tagnite	24	8	3
AZ BT 15	Brush Tagnite	24	5	2
AZ BT 16	Brush Tagnite	24	2	1
AZ BT 35	DOW 19	24	30	9
AZ BT 35	DOW 19	24	25	7
AZ BT 35	DOW 19	24	22	6
AZ BT 56	TCP	24	25	4
AZ BT 56	TCP	24	25	5
AZ BT 56	TCP	24	28	8

Pictures of the AZ91C panels at select outdoor exposure intervals are seen in Figures 60 – 61.

AZ91C Outdoor Exposure Conclusion: All three (3) Brush Tagnite panels outperformed the DOW 19. Therefore, ***Brush Tagnite met the performance objective of the JTP in which the Brush Tagnite performance must meet or exceed the DOW 19 performance.***



Brush Tagnite with MIL-PRF-23377

DOW 19 with MIL-PRF-23377

TCP with MIL-PRF-23377

Figure 60: AZ91C Outdoor Exposure Panels with MIL-PRF-23377 Primer after 14 months of Exposure



Brush Tagnite with MIL-PRF-23377

DOW 19 with MIL-PRF-23377

TCP with MIL-PRF-23377

Figure 61: AZ91C Outdoor Exposure Panels with MIL-PRF-23377 Primer after 24 months of Exposure

6.1.13.2.2 EV31A Outdoor Exposure Corrosion Results

The total exposure time for this alloy was 24 months. Pictures of the EV31A panels taken by NASA during various time intervals are seen in Appendix AB.

Observations from the EV31A Outdoor Exposure:

1. It took several months before any corrosion appeared. Evidence of corrosion started at:
    a. For DOW 19: 5 months
    b. For TCP: 7 months
    c. For Brush Tagnite: 10 months
2. There was not significant differentiation between the three pretreatments until the 18 month mark.
3. At the 22 month mark, **the Brush Tagnite panels had the best performance** by the smallest of margins over TCP based on visual observation and % area corroded.
    a. The corrosion migration away from the scribe was the least of the three pretreatments
    b. On a visual basis, all 3 Brush Tagnite panels were in the top 3 followed by one TCP panel.
4. At the 24 month mark, Brush Tagnite had a slight edge over the TCP panels after looking at the corrosion responses. The poorest performer was DOW 19.

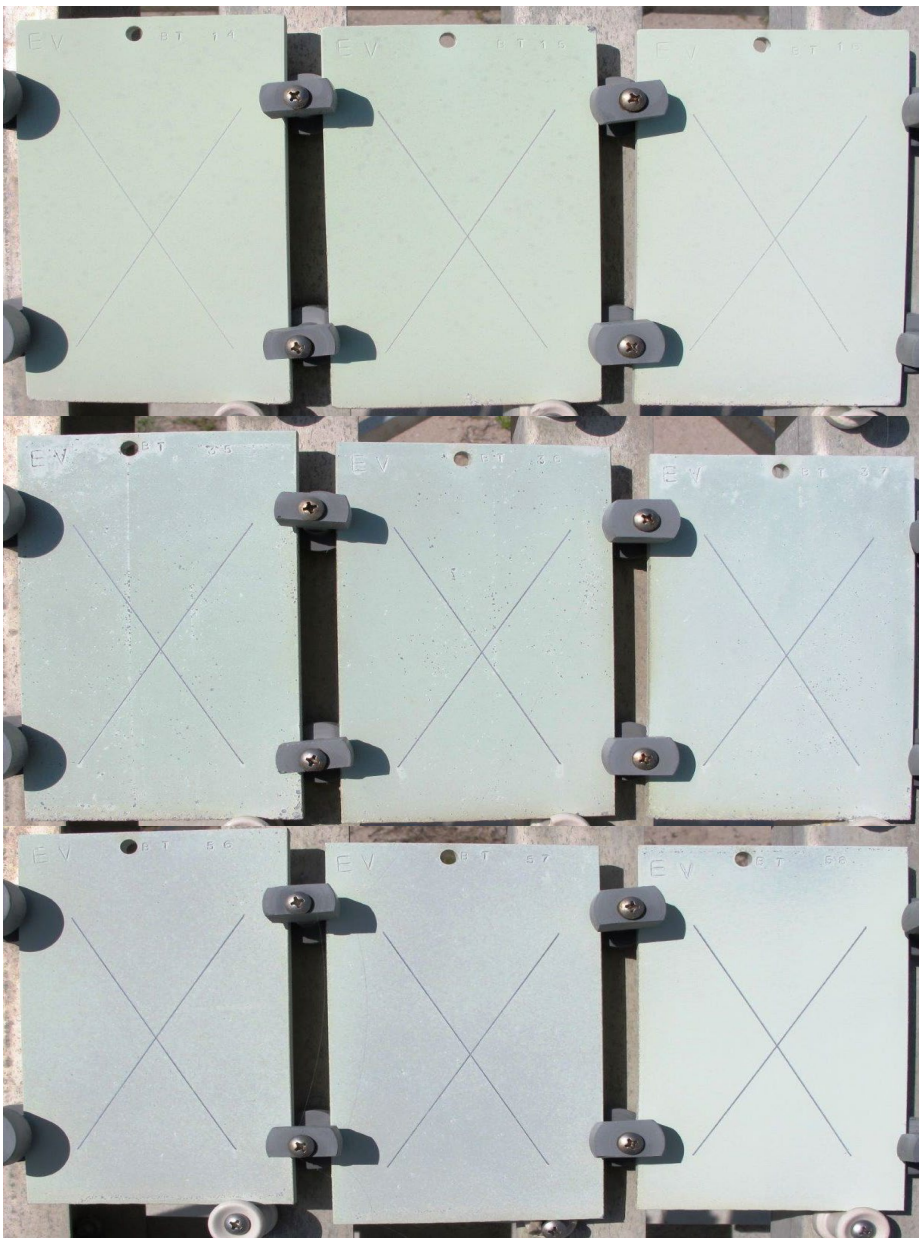
At the 24 month mark, the EV31A panels were rated. The outdoor exposure ratings for these panels are listed in Table 47.

Table 47: EV31A Outdoor Exposure Summary

Panel ID	Treatment	Months of Exposure	% Area Corroded	Ranking
EV BT 14	Brush Tagnite	24	1	1
EV BT 15	Brush Tagnite	24	2	2
EV BT 16	Brush Tagnite	24	3	4
EV BT 35	DOW 19	24	20	9
EV BT 36	DOW 19	24	10	7
EVBT 37	DOW 19	24	15	8
EV BT 56	TCP	24	8	6
EVBT 57	TCP	24	3	5
EV BT 58	TCP	24	2	3

Pictures of the EV31A panels at select outdoor exposure intervals are seen in Figures 62 – 63.

EV31A Outdoor Exposure Conclusion: All three (3) Brush Tagnite panels outperformed the DOW 19 over the course of the 24 month exposure period. Therefore, ***Brush Tagnite met the performance objective of the JTP in which the Brush Tagnite performance must meet or exceed the DOW 19 performance.***



Brush Tagnite with MIL-PRF-23377

DOW 19 with MIL-PRF-23377

TCP with MIL-PRF-23377

Figure 62: EV31A Outdoor Exposure Panels with MIL-PRF-23377 Primer after 15 months of Exposure



Brush Tagnite with MIL-PRF-23377

DOW 19 with MIL-PRF-23377

TCP with MIL-PRF-23377

Figure 63: EV31A Outdoor Exposure Panels with MIL-PRF-23377 Primer after 24 months of Exposure

6.1.13.2.3 QE22A Outdoor Exposure Corrosion Results

The total exposure time for this alloy was 24 months. Pictures of the QE22A panels taken by NASA during various time intervals are seen in Appendix AC.

Observations from the QE22A Outdoor Exposure:

1. It only took a short time for corrosion to appear on this alloy. Evidence of corrosion started at:
    a. For DOW 19 and TCP: ***3 weeks***
    b. For Brush Tagnite: 2 months
2. There was clear differentiation between the three pretreatments at the 10 month mark. At this time, the **Brush Tagnite panels had the best performance** based on visual observation and % area corroded:
    a. The corrosion migration away from the scribe was the least of the three pretreatments
    b. There was minimal corrosion pitting on the painted surfaces away from the scribe compared to the TCP and DOW 19 panels. Most of the corrosion on the Brush Tagnite panels was concentrated along the bottom edge while the DOW 19 and TCP had widely distributed corrosion and loss of primer across the entire panel.
3. At the 20 month mark, Brush Tagnite was the clear leader but there was significantly more corrosion on one of the Brush Tagnite panels. There was no clear cut second best performer as the TCP and DOW 19 panels were corroded on 100 % of the panel face.

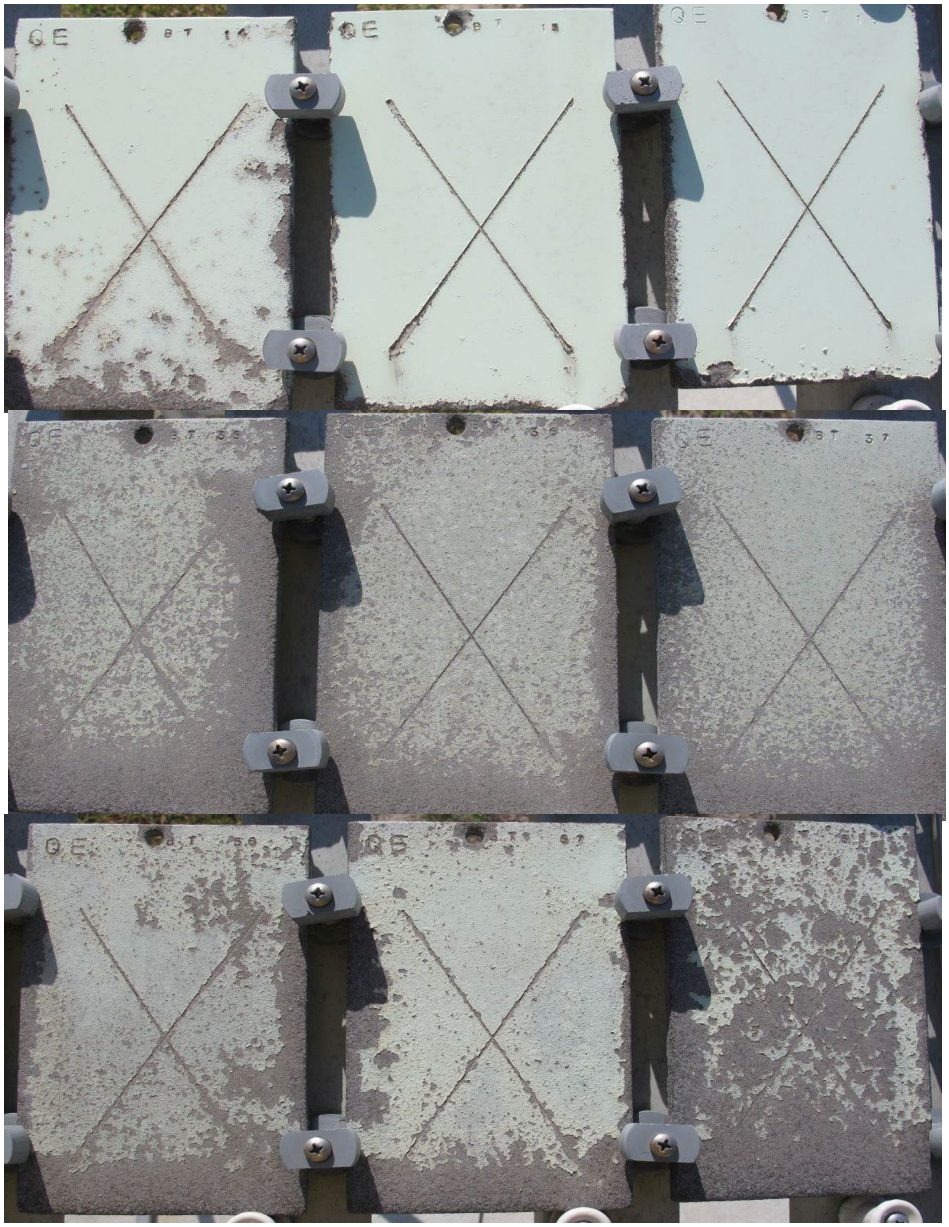
At the 10 month mark, the QE22A panels were rated. The outdoor exposure ratings for these panels are listed in Table 48.

Table 48: QE22A Outdoor Exposure Summary

Panel ID	Treatment	Months of Exposure	% Area Corroded	Ranking
QE BT 14	Brush Tagnite	10	15	3
QE BT 15	Brush Tagnite	10	5	2
QE BT 16	Brush Tagnite	10	5	1
QE BT 35	DOW 19	10	80	8
QE BT 36	DOW 19	10	70	7
QE BT 37	DOW 19	10	60	6
QE BT 56	TCP	10	50	5
QE BT 57	TCP	10	25	4
QE BT 58	TCP	10	80	9

Pictures of the QE22A panels at select outdoor exposure intervals are seen in Figures 64 – 65.

QE22A Outdoor Exposure Conclusion: All three (3) Brush Tagnite panels clearly outperformed the DOW 19 at the 10 and 20 month intervals. Therefore, ***Brush Tagnite met the performance objective of the JTP in which the Brush Tagnite performance must meet or exceed the DOW 19 performance*.**

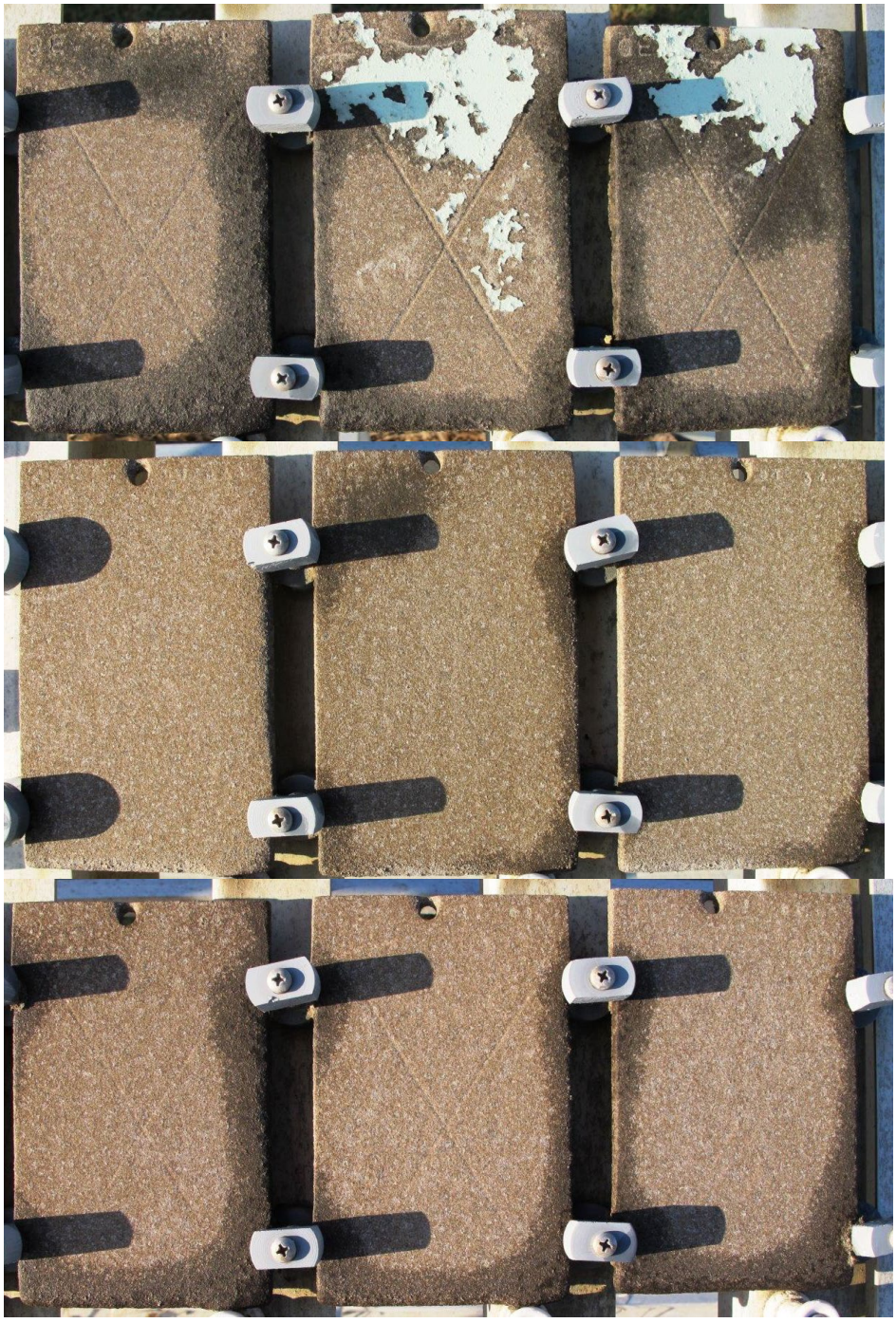


Brush Tagnite with MIL-PRF-23377

DOW 19 with MIL-PRF-23377

TCP with MIL-PRF-23377

Figure 64: QE22A Outdoor Exposure Panels with MIL-PRF-23377 Primer after 10 months of Exposure



Brush Tagnite with MIL-PRF-23377

DOW 19 with MIL-PRF-23377

TCP with MIL-PRF-23377

Figure 65: QE22A Outdoor Exposure Panels with MIL-PRF-23377 Primer after 24 months of Exposure

6.1.13.2.4 ZE41A Outdoor Exposure Corrosion Results

The total exposure time for this alloy was 24 months. Pictures of the ZE41A panels taken by NASA during various time intervals are seen in Appendix AD.

Observations from the ZE41A Outdoor Exposure:

1. It took months before any corrosion began to appear on this alloy. Evidence of corrosion started at:
    a. For DOW 19 and TCP: 5 months
    b. For Brush Tagnite: 11 months
2. There was clear differentiation between the three pretreatments at the 18 month mark.
3. At the 20 month interval, **the Brush Tagnite panels had the best performance** based on visual observation:
    a. The corrosion migration away from the scribe was the least of the three pretreatments
    b. There was minimal corrosion pitting on the painted surfaces away from the scribe compared to the TCP and DOW 19 panels. Most of the corrosion on the Brush Tagnite panels was concentrated along the bottom edge while the DOW 19 and TCP had widely distributed corrosion across the entire panel.
4. At the 22 month mark, Brush Tagnite was the clear leader but significantly more corrosion was apparent on all of the Brush Tagnite panels. There was no clear cut second best performer as the TCP and DOW 19 panels had similar corrosion responses.

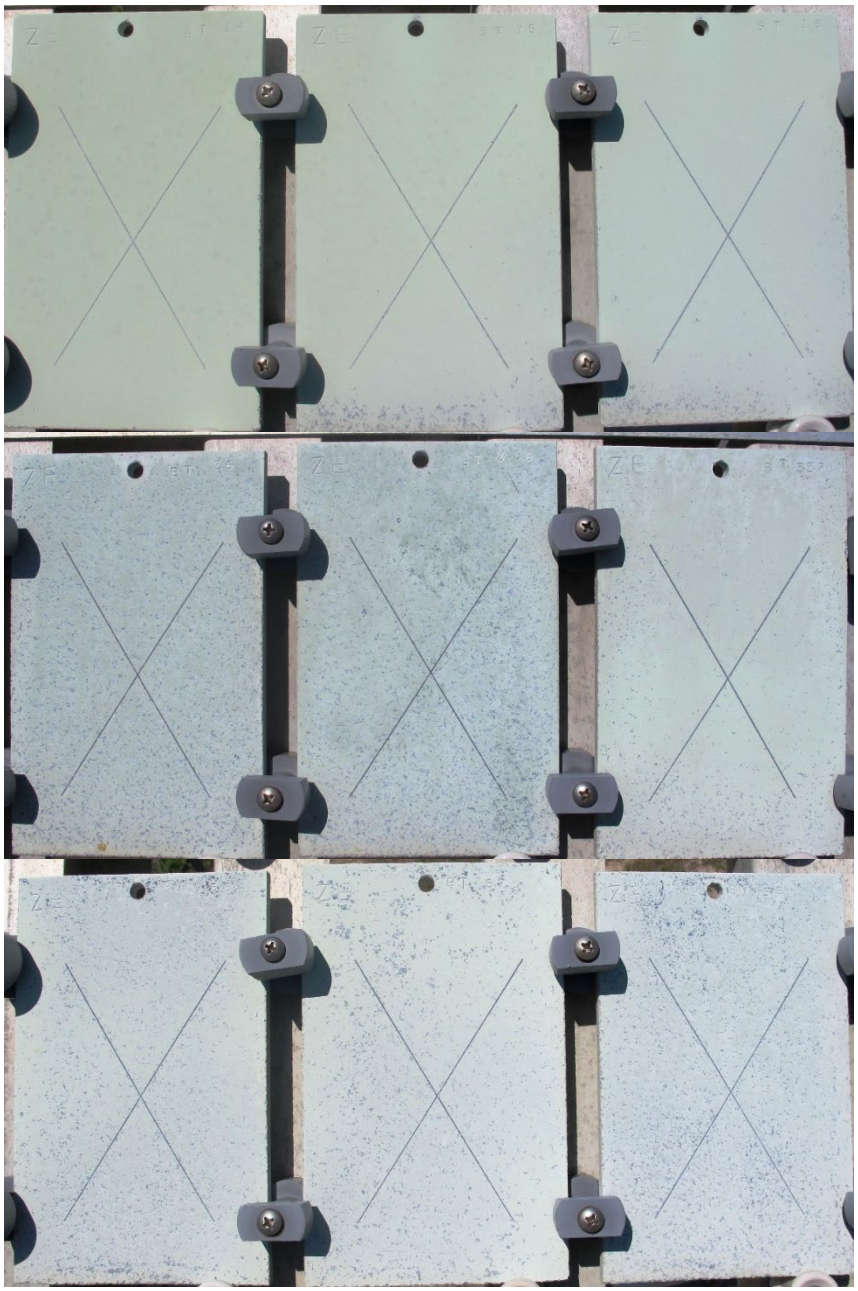
At the 24 month mark, the ZE41A panels were rated. The outdoor exposure ratings for these panels are listed in Table 49.

Table 49: ZE41A Outdoor Exposure Summary

Panel ID	Treatment	Months of Exposure	% Area Corroded	Ranking
ZE BT 14	Brush Tagnite	24	15	1
ZE BT 15	Brush Tagnite	24	30	2
ZE BT 16	Brush Tagnite	24	40	3
ZE BT 35	DOW 19	24	60	7
ZE BT 36	DOW 19	24	60	8
ZE BT 37	DOW 19	24	50	4
ZE BT 56	TCP	24	70	5
ZE BT 57	TCP	24	70	6
ZE BT 58	TCP	24	80	9

Pictures of the ZE41A panels at different outdoor exposure intervals are seen in Figures 66 – 67.

ZE41A Outdoor Exposure Conclusion: All three (3) Brush Tagnite panels clearly outperformed the DOW 19. Therefore, ***Brush Tagnite met the performance objective of the JTP in which the Brush Tagnite performance must meet or exceed the DOW 19 performance***.



Brush Tagnite with MIL-PRF-23377

DOW 19 with MIL-PRF-23377

TCP with MIL-PRF-23377

Figure 66: ZE41A Outdoor Exposure Panels with MIL-PRF-23377 Primer after 16 months of Exposure



Brush Tagnite with MIL-PRF-23377

DOW 19 with MIL-PRF-23377

TCP with MIL-PRF-23377

Figure 67: ZE41A Outdoor Exposure Panels with MIL-PRF-23377 Primer after 24 months of Exposure

6.1.13.3 Overall Conclusion for Outdoor Exposure Corrosion Testing: Even though this test has not reached the 24 month test cycle end, it is clear that the Brush Tagnite pretreatment on all four alloys (AZ91C, EV31A, QE22A and ZE41A) is clearly outperforming the DOW 19 pretreatment. Therefore, ***Brush Tagnite met or exceeded the JTP performance objective for all alloys tested.***

6.1.14 Brush Tagnite Testing Summary

The Joint Test Protocol (JTP) for this milestone involved the evaluation of three different pretreatments – Brush Tagnite, DOW 19 and TCP. The three different pretreatments were applied to four different magnesium aerospace alloys – AZ91C, EV31A, QE22A and ZE41A. The testing consisted of:

- Paint Adhesion Performance of the three different pretreatment schemes after being painted with MIL-PRF-23377 non-chromated primer.
- Galvanic Corrosion Performance of the three different pretreatment schemes without paint.
- Neutral Salt Fog Performance of the three different pretreatment schemes after being painted with MIL-PRF-23377 non-chromated primer.
- Acidified (SO2) Salt Fog Performance of the three different pretreatment schemes after being painted with MIL-PRF-23377 non-chromated primer.
- Axial Fatigue Performance of the three different pretreatment schemes without paint where the baseline was bare (untreated) magnesium.
- Beach Front Outdoor Exposure of the three different pretreatment schemes after being painted with MIL-PRF-23377 non-chromated primer.

The JTP states that the performance criteria for this milestone testing is ***Brush Tagnite Paint performance must be equal to or better than DOW 19***. The JTP testing and performance criteria was approved by the ESTCP working group and these requirements were fully coordinated with and approved by CCDC AvMC AMA-F.

MIL-PRF-23377 Paint Adhesion Testing:

1. For Brush Tagnite vs. DOW 19
    a. There was no difference between the Brush Tagnite and DOW 19 paint adhesion performance for the alloys AZ91C, QE22A and ZE41A.
    b. Brush Tagnite had better paint adhesion than DOW 19 on EV31A magnesium.
2. For Brush Tagnite vs. TCP
    a. Brush Tagnite had better paint adhesion than TCP on AZ91C magnesium.
    b. There was no difference between the Brush Tagnite and TCP paint adhesion performance for the alloys QE22A and ZE41A.
    c. TCP had better paint adhesion than Brush Tagnite on EV31A magnesium.

Therefore, ***the paint adhesion results met the performance criteria*** where the paint adhesion of Brush Tagnite must be equal to or better than DOW 19 on all four magnesium alloys.

Galvanic Corrosion Testing: There was very little variation between the galvanic current readings for the three different pretreatment coatings for each individual alloy. In addition, there was very little variation in the galvanic corrosion between the AZ91C, EV31A and QE22A alloys, regardless of the pretreatment coating. The galvanic corrosion response for ZE41A was

consistently lower for all three pretreatment schemes compared to the other three magnesium alloys. Based on the average galvanic current readings, Brush Tagnite had a galvanic corrosion response that was equal to the DOW 19 conversion coating for all four magnesium alloys and therefore ***Brush Tagnite passed the performance criteria specified in the JTP***.

Neutral Salt Fog Testing:

1. For three alloys (EV31A, QE22A and ZE41A) Brush Tagnite clearly outperformed the DOW 19 pretreatment.
2. Testing on the AZ91C alloy showed that DOW 19 and Brush Tagnite had equivalent performance.
3. Brush Tagnite had much better neutral salt fog performance than TCP for all four magnesium alloys.

Therefore, ***Brush Tagnite Neutral Salt Fog performance met or exceeded the JTP performance objective*** for all alloys tested.

Acidified (SO2) Salt Fog:

1. The Brush Tagnite pretreatment on all four alloys (AZ91C, EV31A, QE22A and ZE41A) clearly outperformed the DOW 19 pretreatment.
2. Brush Tagnite clearly outperformed TCP on the AZ91C, QE22A and ZE41A alloys. Brush Tagnite has slightly better performance than TCP on the EV31A alloy.

Therefore, ***Brush Tagnite met or exceeded the JTP performance objective*** for all alloys tested.

Axial Fatigue Strength: The conclusions summarized below are based on UDRI and TAG data analysis. Neither organization is an expert on fatigue testing and the final determination will be made CCDC AvMC AMA-F.

ZE41A Axial Fatigue Results from UDRI

1. There were sufficient data points to compare the fatigue life between the three pretreatment systems at the 22,750 psi stress level. There was no statistical difference in fatigue properties between the Tagnite, DOW 19 or TCP pretreatment systems at 22,750 psi.
2. There was insufficient baseline data at 22,750 psi to determine if there was a statistical difference between the baseline (uncoated) specimens and the three pretreated specimens.
3. There was insufficient data for the baseline or Brush Tagnite at 24,500 psi for statistical comparison.
4. There was no significant difference in fatigue properties found between the DOW 19 and TCP pretreatments at 24,500 psi.

AZ91C, EV31A and ZE41A Axial Fatigue Data Analysis by TAG

1. For each alloy, there were only 10 specimens per pretreatment scheme and these 10 specimens were divided into two groups, 22.75 ksi and 24.5 ksi maximum stress load. This meant that the sample population was only 5 specimens per max. stress load/pretreatment scheme which made statistical analysis difficult.

2. The specimens tested at Westmoreland had a high percentage of specimens that went to runout at 1,000,000 cycles which also hindered the data analysis.
3. TAG does not have the expertise to analyze this limited data set and will defer to CCDC AvMC AMA-F experts at Redstone Arsenal to determine the fatigue performance of Brush Tagnite vs. DOW 19.

Beach Front Outdoor Exposure:

1. The Brush Tagnite pretreatment on all four alloys (AZ91C, EV31A, QE22A and ZE41A) clearly outperformed the DOW 19 pretreatment.
2. The Brush Tagnite pretreatment on the QE22A clearly outperformed the TCP pretreatment. Brush Tagnite performed slightly better than TCP on the AZ91C, EV31A and ZE41A alloys.

Therefore, ***the Brush Tagnite outdoor exposure results exceeded the performance criteria*** as the Brush Tagnite had much better performance than DOW 19 on all four magnesium alloys.

6.2 Demonstration and Validation

6.2.1 Pre-Demonstration Testing and Analyses

Due to the added expense and time, the rectifier and chilling system were not tested in Grand Forks. These items were shipped direct to CCAD for installation.

6.2.2 Design and Layout of Technology Components

The inactive D-Line at the CCAD plating shop was retrofitted as the Immersion Tagnite line with minimal modifications. Capital equipment installed for this demonstration was:

1. Rectifier: For this project, DynaPower Corporation manufactured a rectifier that operates at 25 % of the capacity of the DynaPower rectifier that is used at TAG's Grand Forks, ND production facility. This downsized rectifier will have the same wave function and programmability as the currently used TAG rectifier.

a. Location: In basement, directly underneath D-Line (Figure 68)
b. Additional Services needed:
   i. Incoming Power: 480 V AC, 3 phase, 60 Hz
   ii. Chilled water for cooling
   iii. Base or footing to elevate rectifier 12 – 18" above current floor due to potential flooding in basement

2. Chilling System (Compressor and Chilling Plates): A commercially available chilling system was installed next to the rectifier

a. Location: In basement, near rectifier (Figure 68)
b. Additional Services needed:
   i. Incoming Power: 480 V AC, 3 phase, 60 Hz.
   ii. Ethylene Glycol charging of the system.
   iii. Base or footing to evaluate compressor 12 – 18" above current floor due to potential flooding in basement.

Tank D-4 is designated as the fluoride activator tank. The chemicals used for this solution are corrosive, therefore this tank had a custom made plastic liner installed. During the startup phase, it was discovered that the single Teflon coated heater did not have sufficient warmup capacity so a second heater was installed (Figure 69).

The original design plan was to modify Tank D-7 as the Tagnite anodization tank. However, during the retrofit stage of the project, the original Tank D-7 was found to have several issues that made the tank unusable. A new tank was fabricated and installed (Figure 70).



Figure 68: Immersion Tagnite Chilling System and Rectifier
Left: **Chilling System and Glycol Storage Tank**
Right: **Heat Exchanger Plates and Rectifier**

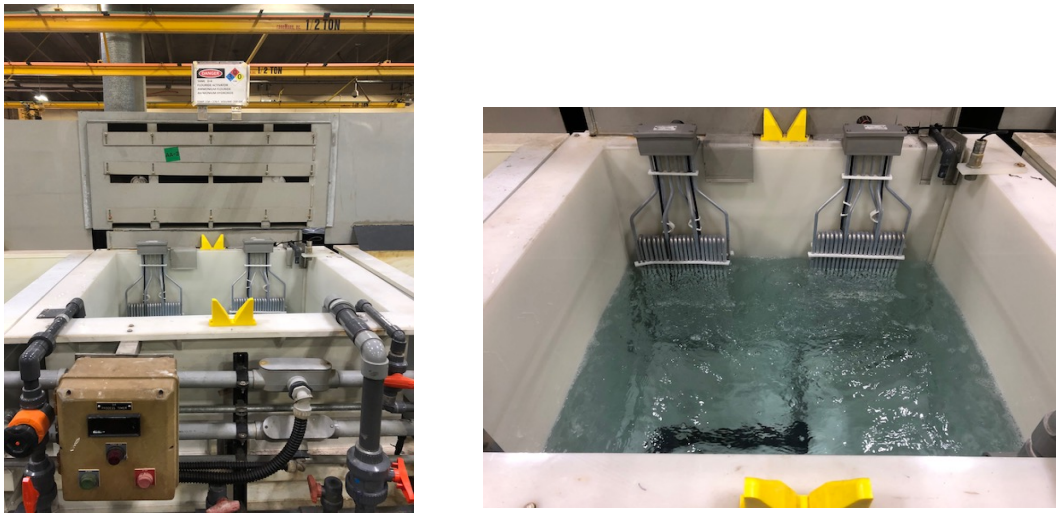


Figure 69: Tank D-4 (Fluoride Activator) after tank modifications.
Left: Front view of modified Tank D-4
Right: Inside view of modified Tank D-4



Figure 70: Tagnite Anodization Tank (D-7) after Modifications

6.2.3 Startup, Training and Field Testing

6.2.3.1 Tagnite Line Check-out: The week of March 19th, 2018 was the original startup date. Two Tagnite professionals (Bill Gorman and Earl Woolsey) along with engineers from AquasGroup (East Providence, RI) arrived on Monday, March 19th and went through the startup process. There were a variety of adjustments that were made during this week:

1. Integration of sensor outputs to central control panel.
2. Level sensor adjustments.
3. Installation of additional heater to Fluoride Activator Tank.

The week of March 26th was devoted to adding chemical to all the Tagnite tanks and testing the rectifier. During this testing period, numerous problems were discovered with the rectifier and the decision was made to bring in a rectifier service technician.

The scheduling of the rectifier service technician took longer than anticipated and TAG personnel returned to the CCAD plating shop the week of April 23, 2018 for a two week block of startup and training. The first few days of the first week were spent replacing a programmable logic controller (PLC) inside the rectifier. The software of the original PLC was somehow corrupted during the attempted startup in March. While attempting to startup the rectifier after installing the PLC, a large popping noise and electrical spark was seen from the inside of the rectifier. After several hours, the source of the noise/sparking was traced to the rectifier cooling system manifold. A replacement part was overnighted and installed. At this point in time, the

rectifier was able to startup and coat some magnesium sheet metal. There were no additional problems with the rectifier.

The coating of the magnesium sheet metal during the rectifier testing acted as a test for the chilling system. During this testing period, several issues were noticed with the chilling system.

1. As the chilling system was cooling the glycol, a heavy amount of condensation was forming on all the plastic piping, metal valves and the glycol storage tank.
2. The chilling system piping running from the chilling sled to the chilling system compressors outside the plating job were routed right over the rectifier and over time, condensation was forming and dripping on to of the rectifier.

During the weekend between the two weeks of training, CCAD personnel worked to correct the chilling system issues by:

1. Installing foam installation on the plastic piping and glycol storage tank. Drip pads were placed underneath the metal valves to collect the condensation.
2. The chilling pipes above the rectifier were rerouted around the rectifier footprint and the pipes were insulated with foam sleeve material.

Lessons learned during the Tagnite Line Startup Phase:

1. The rectifier sat in TAG's facility for 18 months after manufacture due to project delays. This long storage time may or may not have influenced the startup of the rectifier at CCAD. In hindsight, TAG should have had a rectifier service technician on-sight during startup to assist with any rectifier issues. Not having the service rep present during startup led to having to schedule a second, two week of training and the expenses associated with this unplanned trip.
2. We should have budgeted more time for the startup process as there were a lot of electrical issues that needed to be addressed as the system was brought on-line. This was due to the integration of multiple sensors to the Tagnite process controller which was complicated by several faulty level sensors. It took lots of time to integrate the chiller controller with the Tagnite process controller.

6.2.3.2 Tagnite Operator Training: Tagnite Operator Training took place during the week of April 30, 2018. Seven (7) CCAD plating shop artisans were designated by CCAD management to undergo the Tagnite training and each artisan underwent four (4) hours of Tagnite training. The Tagnite training phases consisted of the following steps while using TAG standards, procedures and checklists:

1. A brief Immersion Tagnite video that followed some aerospace parts being processed through the entire Tagnite process at the Grand Forks, ND facility.
2. A walk through of the Tagnite line with CCAD plating shop artisans while TAG personnel explained the function, operating specifications and safety issues of each Tagnite process tank.

3. Correct startup and shutdown procedures for Tagnite line using the process line controller.
4. Operation of the rectifier.
5. How to attach or "fixture" the demonstration parts to the flight bar/rack designed for each specific part.
6. Each CCAD artisan took a masked, scrap SAFR BER magnesium component through the entire Tagnite process using the traveler specific instructions for each demonstration part. Each traveler listed detailed processing instructions for each Tagnite processing tank.
7. After verifying the quality of the Tagnite coating, the CCAD artisans were taught how to strip the Tagnite coating using the Tagnite pretreatment tanks to loosen and remove the Tagnite coating. When the stripping process was complete, the parts were ready to be recoated in the Tagnite anodization tank.

Methods to ensure uniform and repeatable deposition of the Tagnite coating were:

- Taber wear resistance (Daily – done by Plating Shop QC Lab)
- Tagnite thickness (Every run – done by Plating Shop Artisan)
- Electrical continuity measurement (Every run - done by Plating Shop Artisan)
- Visual inspection of coating (Every run - done by Plating Shop Artisan)
- Dry Tape Pull Adhesion (Every run - done by Plating Shop Artisan)

Taber wear resistance is the quickest and best way for measuring Tagnite coating quality on a daily basis but the taber abraser was located in the QC lab. Therefore, this test was supposed to be performed by QC personnel. However, the equipment was not installed at the time of the training, therefore, the taber wear testing was not performed during training.

While undergoing Immersion Tagnite training, CCAD plating shop artisans were taught how to perform the following QC tests to verify the quality and specification requirements for the Tagnite anodize coating:

1. Tagnite thickness is performed after the Tagnite process has been completed in order to determine if the part thickness meets the specified thickness listed on the traveler. An eddy current device is one type of electromagnetic testing used to measure thickness and this device is used to measure the Tagnite thickness.
2. Electrical continuity measurement is another indicator of an acceptable Tagnite coating. Specifications require that the Tagnite coating will not conduct electricity when tested using a multi-meter. CCAD artisans were taught how to handle the multi-meter probes in order to get a consistent reading when placed on the Tagnite coating and what resistance level is acceptable.
3. CCAD artisans were taught how to do a visual inspection of the part after Tagnite, looking for potential defects or unacceptable coating properties such as bare areas, pitting, powder deposits or discolored areas on the part.
4. Dry tape adhesion is an excellent indicator of the cleanliness of the used components (removal of the legacy paints and coatings) and the quality of the pretreatment part of the Tagnite process. The presence of any legacy coatings will not allow the pretreatment process to properly prepare the magnesium surface for the Tagnite step which will result

in a loosely adhered coating. The removal of a Tagnite coating via a dry tape pull is also an indication that the pretreatment process was done incorrectly or one of the pretreatment baths is not being operating correctly. In addition, this test can also identify post-Tagnite issues. One example of poor Tagnite coating issues would be the fact that extensive rinsing in high purity deionized or reverse osmosis water will degrade the Tagnite coating.

Lessons learned during the Immersion Tagnite Training

1. Due to the broad range of plating/coating applications done at CCAD, the CCAD plating shop artisans had no difficulty learning and understanding the Tagnite process.
2. The most intense training involved the deck mounted remote for the Tagnite process that controlled the rectifier, chilling system and process bath heaters/circulation pumps.

6.2.3.3 Brush Tagnite Training: The Brush Tagnite training took place on the week of December 11, 2017. All CCAD plating shop artisans that would be applying Brush Tagnite were required to pass a Brush Tagnite training class taught by TAG instructors. The training class consisted of:

1. Fundamentals of Electrical Safety Review
2. Completion of handout on electrical safety
3. Fundamentals of Brush Tagnite process (PowerPoint Presentation)
    a. Part preparation
    b. Brush Tagnite equipment review and preparation
    c. Brush Tagnite application technique
4. Practical application experience on scrap magnesium housing and/or magnesium test coupons.
5. Each CCAD artisan was required to coat four (4) magnesium test coupons and submit them to TAG for salt fog and primer adhesion testing. All twenty-seven (27) CCAD plating shop artisans passed the qualification testing and were issued Brush Tagnite Operator Certificates prior to Immersion Tagnite training.

During the early May 2018 Tagnite training at the CCAD plating shop, TAG personnel trained a CCAD Plating Lab Chemist to be a Master Brush Tagnite Trainer. This person is now qualified to train and certify any CCAD personnel as Brush Tagnite Operators.

6.2.3.4 Training for Installation of Masking Components: Prior to the initial training, TAG provided the CCAD plating shop with four (4) masking kits for each center housing priority part and two (2) masking kits for the single output housing priority part. Also provided were:

- detailed written instructions for installing the masking tools
- detailed parts lists
- written procedures for applying the UV curable maskant
- written procedures for making the silicone molds used in the masking kits

During the week of March 26, 2018, TAG personnel trained eight (8) CCAD plating shop artisans on how to install the masking on the three (3) priority parts. A second group of two (2) artisans were trained during the second training session during the week of April 23, 2018. The masking training phases consisted of:

1. Review of masking procedures
2. Masking of scrap part(s) under TAG supervision
3. Leak Testing Protocol
4. Checklist review
5. Troubleshooting tips to solve common masking issues
6. Sign-off sheets
7. Post-Tagnite Inspection after masking removal

Observations and Lessons learned during the Masking Components Installation Training

- Due to the broad range of masking/plating/coating applications done at CCAD, the CCAD plating shop artisans had no difficulty learning and understanding the masking process.
- CCAD plating shop artisans were already using UV maskant in the shop and were familiar with applying the material
- They were excited to use the compressed air driven syringe dispenser for the UV masking cartridges. They really liked the fine control available with this syringe dispenser.
- The CCAD artisans were very satisfied with the masking installation training and the documentation.

6.2.3.5 Field Testing: The original demonstration/validation plan was written based on the assumption that the demonstration/validation would occur over a 1 -2 week period. Due to the amount of time spent troubleshooting the Tagnite line/rectifier along with training, very little time was left for the actual demonstration/validation using SAFR parts. As a result, the demonstration/validation only lasted one day and only 1 component of each of the three priority parts were coated.

In addition, the original demonstration/validation plan stated that the quality control testing listed in Table 50 would be performed during the dem/val. This testing was to include daily and periodic quality control procedures to ensure that the Tagnite coating being deposited is of the highest quality. Due to the short time frame for the dem/validation at the CCAD plating shop, very little of the testing listed in Table 50 was performed.

Table 50: QC Testing during Tagnite Training and Demonstration

Test	Test Method	Frequency
Solution Analysis of Tagnite Process Bath	Per TAG Lab Procedures Manual	Per TAG testing schedule 7LS-020
Taber wear resistance	ASTM D 4060	Daily
Tagnite Thickness	ASTM B 244	Every Run
Visual Inspection	Boeing HP4-134 Sec. 3.4.3.1	Every Run

Tagnite Adhesion by Dry Tape Pull	ASTM D 3359	Every Run

a. Solution Analysis of the Tagnite Process Bath: Due to a mix-up between CCAD and DLA, not all of the chemicals needed to do the bath analysis arrived in time for the dem/validation testing. As a result, only pH and specific gravity was performed during the dem/val.
b. Taber Wear Resistance: The taber abraser machine was not fully functional during the dem/val testing, therefore no panels were coated.
c. Tagnite Thickness: The CCAD artisans had prior training in the use of the eddy current instruments to measure thickness and the Tagnite thickness readings obtained during the dem/val were within the specification thickness range.
d. Visual Inspection: The CCAD artisans were given a checklist of items to look for during the visual inspection after Tagnite. Items to look for via visual inspection were powdery areas, bare spots, burning or pitting, discoloration of the Tagnite coating and darkened corners or edges.
e. Tagnite Adhesion by Dry Tape Pull: The CCAD artisans were taught how to perform dry tape pull testing on the Tagnite coating to check for Tagnite quality.

6.3 Performance Assessment Plan

The performance of the demonstration phase of this project focused on four different areas:

5. Quality of the Tagnite Coating
6. Stability/Maintainability of the Tagnite Process Solutions
7. Effectiveness of the stripping process to remove legacy coatings
8. Effectiveness of the masking process at protecting the steel components

6.3.1 Quality of the Tagnite Coatings

The primary objective of this phase is to show that the quality of the Tagnite coating applied at the CCAD plating shop is "as good or better" than the characteristics of the coatings currently used in the CCAD plating shop. In addition, the quality of the Tagnite coating applied at the CCAD plating shop needs to be compared to the Tagnite coating applied at TAG's facility. The quality of the Tagnite coating was to be determined by determining the wear resistance, salt fog corrosion resistance and paint adhesion of CCAD coated Tagnite panels vs. TAG's historical data for these tests.

DOW 19 vs. Tagnite Wear Resistance Performance: The ASTM D4060 Taber Abrasion procedure is used by TAG to measure the wear resistance of the Tagnite coating. The taber abrasion procedure is based on weight loss and the presence of bare metal in the taber track after the panel has been turned a given number of cycles on the turn table while being worn by taber wheels of a specified grit and under a specified weight load (see Figure 71). The currently used process for protection of used magnesium housings after overhaul is DOW 19. The process is a chemical conversion coating that is an extremely thin chemical film and has virtually no weight. Therefore, the weight loss comparison between the two coatings was eliminated.

Testing was done to determine how many cycles of the CS-17 taber wheels under 1000 gram load were needed to expose bare metal. The testing was done at TAG's facility using AZ91C magnesium test panels with the DOW 19 conversion coating and the Tagnite 8200 Type I coating with a thickness around 0.30 mils or 0.0003". It only took 10 – 25 cycles on the taber

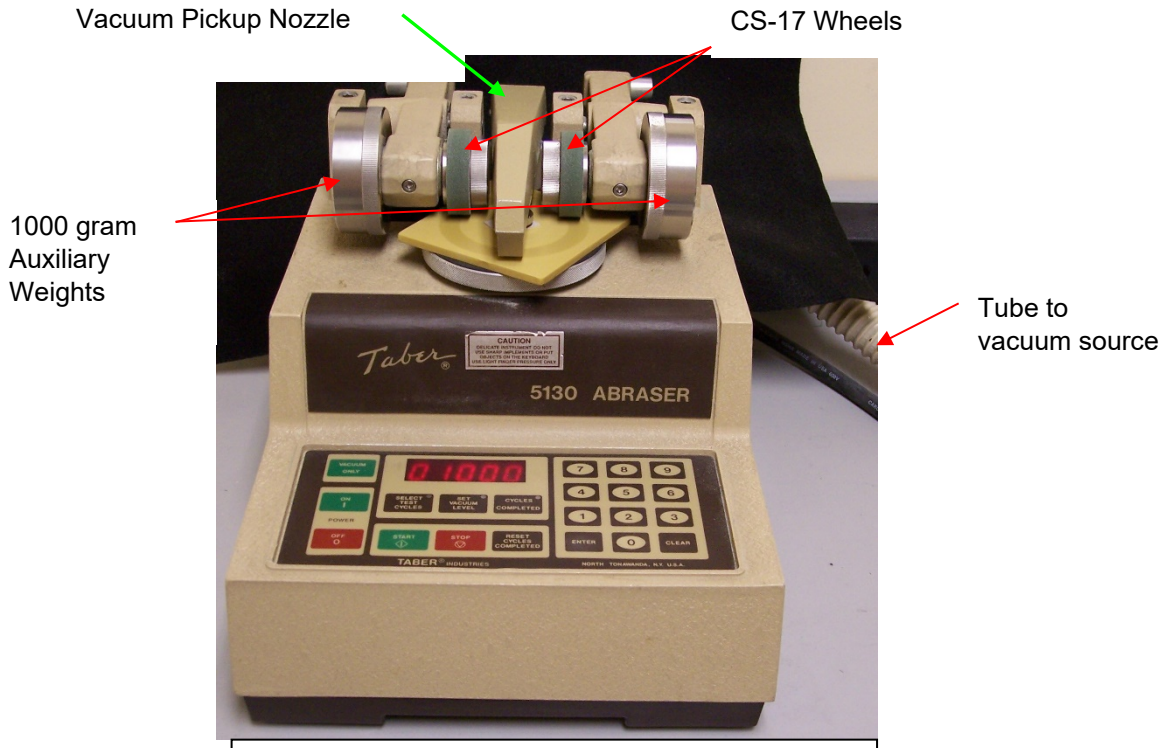


Figure 71: Taber Abraser Model 5130

machine to expose bare metal underneath the DOW 19 coating while it took 1000 – 1500 cycles to expose bare metal under the Tagnite coating. Therefore, the Tagnite coating has several orders of magnitude better wear resistance than the DOW 19 and thereby beating the performance criteria.

CCAD Coated Tagnite vs. TAG coated Tagnite Comparison Studies: This testing was originally designed to:

1. Check the interlaboratory taber endpoint determination between CCAD and TAG using taber panels coated at CCAD.
2. Compare the taber values obtained from CCAD Tagnited panels vs. TAG historical taber data.
3. Compare the salt fog and paint adhesion results from CCAD Tagnited panels vs. TAG historical salt fog and paint adhesion data.

Testing Rationale: The taber endpoint is defined as the presence of 10 % bare metal exposed in the taber track. The wear resistance test is acknowledged in ASTM D 4060 as having a very subjective endpoint determination. There can be up to 50 % difference in the endpoint when

comparing intralaboratory results (how different technicians in the same lab determine the endpoint) and up to 100 % difference in interlaboratory testing. Therefore, in order to account for this large variation in end point determination, there will be a duplicate set of taber test panels coated concurrently with the CCAD test panels. These duplicate panels will be sent to TAG's facility for taber abrasion testing in order to qualify the testing and evaluation of CCAD lab personnel. In addition, duplicate salt fog and paint adhesion panels will be tested at TAG's facility in order to quantitate any interlaboratory variation.

Testing Results: At the time of the demonstration/validation, the CCAD laboratory did not have a functioning taber abraser. In addition, CCAD does not have a supply of test coupons to coat, therefore none of this testing was done. The demonstration parts were thoroughly inspected by CCAD engineers and TAG personnel. TAG personnel stated that the look and feel of the Tagnite was equivalent to the "normal" Tagnite and CCAD engineers agreed with this observation and stated that the parts passed their demonstration/validation criteria.

6.3.2 Stability/Maintainability of the Tagnite Process Solutions

Testing Rationale: In order to apply a quality Tagnite coating, the Tagnite process baths must be maintained per TAG's specifications. TAG specifications state the need for daily and periodic testing of all process tanks and timely chemical additions when tank parameters exceed the process and/or specifications limits. In addition, there are set criteria when a process bath should be dumped and replaced. In order to proceed with production parts, control charts of all process data will be graphed and reviewed as evidence that the Tagnite process baths at CCAD can be monitored and maintained so that a consistent quality Tagnite coating is produced. The daily/periodic testing, control charts and chemical addition records will be reviewed by TAG personnel on a weekly basis. TAG will work with CCAD chemists to maintain the process baths in order to meet all specification limits.

Results: During the dem/val phase, the CCAD lab was able to do the necessary daily analyses and the results were within TAG's specifications. The chemicals needed to do the periodic testing had not been purchased at the time of the demonstration/validation. In addition, the Tagnite process baths were only operated for one week and very little square footage was run through the tanks so very little chemical consumption occurred. TAG personnel spent several hours with the CCAD plating shop chemists during the dem/val phase reviewing the periodic testing procedures and testing schedules. TAG personnel were more than satisfied that CCAD understood the procedures and the testing frequency would be met.

6.3.3 Effectiveness of the Legacy Coating Stripping Process

As stated in Section 5.1.2, the Tagnite chemical stripping process was unable to adequately remove legacy coatings due Rockhard sealant that was embedded in the pores of the anodize coatings. As a result of this finding, engineers at CCAD decided that the best alternative way to remove legacy coatings was through baking soda media blast (aka Sodablast). Prior to the Tagnite dem/val, the demonstration parts were stripped using the sodablast process. TAG personnel were present during this process and gave the CCAD artisans feedback on appearance

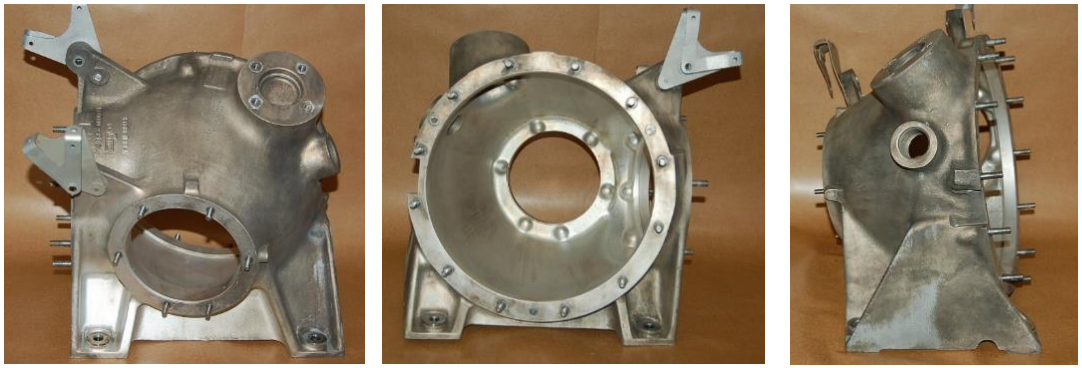
of the parts and when an acceptable level of cleanliness was reached. The effectiveness of the legacy coating stripping process was based entirely on visual inspection. The criteria when determining if the part has been stripping effectively enough for the Tagnite process to deposit a high quality coating was:

- There can be no residual inorganic or organic coatings present on the magnesium component after stripping
- The magnesium surface must have a bright, metallic, bare metal appearance

Decision Point The chemical stripping process developed by TAG was unable to adequately strip off the residual legacy coatings. At this point, the ESTCP working group decided to look into baking soda media blast as an alternative stripping method. With guidance from TAG personnel, the sodablast was able to remove the legacy coatings to a level of cleanliness that was acceptable for the Tagnite process. The demonstration parts after the sodablast process are seen in Figure 72.



P/N: 70357-06308
Center Housing for
Intermediate Gearbox



P/N: 70358-06608
Center Housing for
Tail Gearbox



P/N: 70351-08019
Output Housing for
Input Module

Figure 72: Demonstration Parts after Removal of Legacy Coatings by Sodablast

6.3.4 Effectiveness of the Masking Process at Protecting Steel Components

During the initial masking training, CCAD personnel were given detailed masking procedures and the masking kits. They underwent individualized masking training from TAG personnel while using scrap BER parts. During the demonstration/validation process, the CCAD artisans installed the masking tools under the supervision of TAG personnel. The parts were then run through the Immersion Tagnite process.

After the Tagnite process, the masking tools were removed. The steel liner covers were closely inspected for damage such as signs of arcing, metal loss and/or gaps in the sealing surface. Bolts and threaded inserts were inspected after removal for damage to the threads or chemical buildup in the threads that would interfere with installation on subsequent parts. There was no evidence of damage to the masking tools.

Once the masking tools were removed, the parts were visually inspected with and without the use of hand held magnifiers. The performance of the masking tool installation was graded based on the following performance criteria:

- No arcing
- No material loss
- Coating shall be continuous, smooth and uniform in appearance
- Color shall be white to gray
- No rust on steel liners
- No loss of cad plating on studs and inserts

All three (3) demonstration parts passed the masking performance criteria as no failures were seen. Figure 73 shows the demonstration parts after removal of the masking tools.

After the demonstration, TAG personnel asked the CCAD artisans for their feedback regarding the masking and Immersion Tagnite process. Their observations were:

- The masking documentation and training was very thorough and easy to understand
- They asked that some of the masking tools be modified to make the masking seal better and allow easier removal of the masking tools. These suggestions will be implemented into the next masking revision.
- The CCAD artisans had no problems with the Immersion Tagnite training due to their experience with the other plating type process in their facility.
- The CCAD artisans had multiple concerns about the remote control processor that controlled the fluoride activator tank, Tagnite tank, chilling system and rectifier. There are multiple touchscreens on the control panel that take time to understand. TAG will provide additional documentation about the touch screen controller in the form of a PowerPoint presentation.
- CCAD maintenance personnel needed preventative maintenance documentation for the chilling system and the rectifier. These were provided by AquasGroup and TAG, respectively.

Transitioning from Demonstration to Production Parts: *Decision Point*

The three (3) demonstration parts were thoroughly examined by CCAD engineers after the Tagnite process and after the Rockhard sealant process (Figure 73). They were very happy with the quality of the parts after both processes. They recommended that the Tagnite masking and anodizing process transition to actual production parts. In order to process production parts, maintenance engineering orders (MEO) must be generated and circulated among the CCDC AvMC AMA-M engineers for sign-off approval. This approval cycle could take 6 – 8 months until all the documentation and approvals are collected. TAG is extremely concerned about this large gap between training and implementation on production parts. We are concerned about how much of the training will be retained by the CCAD artisans after this extended time gap between training and production startup.

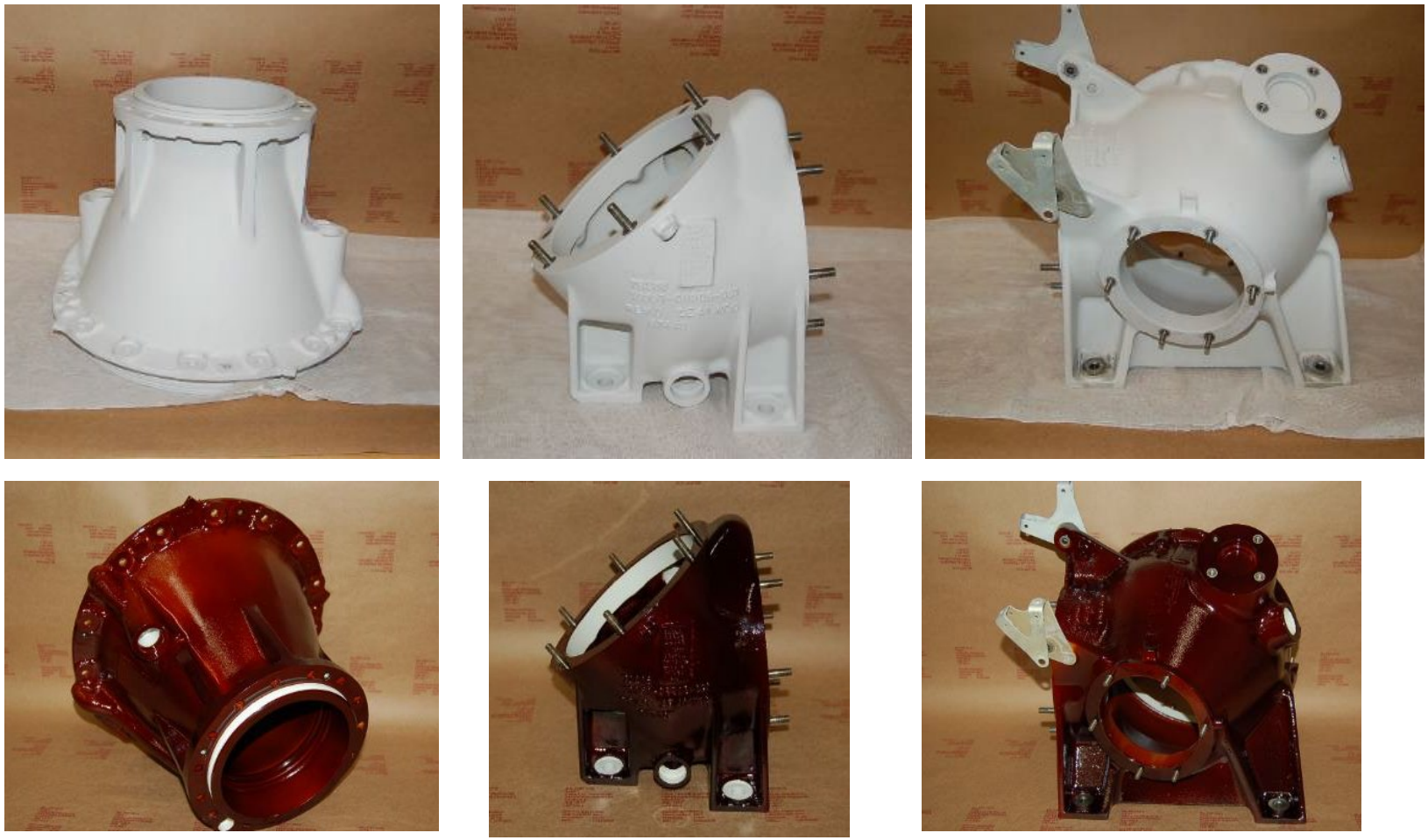


Figure 73:
Top Row: Demonstration Parts after Immersion Tagnite Process and Removal of Masking Tools
Bottom Row: Tagnited Parts after High Temperature Rockhard Sealant

7.0 COST ASSESSMENT

The cost assessment is summarized in a limited distribution document entitled, “Cost Assessment of Final Report Improved Magnesium Protection for DoD Aviation And Weapon Component Technology (ESTCP Project WP-201319)” with a distribution statement “Distribution authorized to DoD components only (Proprietary Information, May 2019). Other request for this document shall be referred to Director, CCDC Army Research Laboratory, FCDD-RLW-MD, Aberdeen Proving Ground, MD 21005” since the cost assessment contains the Technology Applications Group proprietary information.

The cost assessment can be found in the Defense Technical Information Center (DTIC) under accession number AD1074818.

8.0 IMPLEMENTATION ISSUES

Implementation Requirements: The requirements for the acceptance of the Masking/Immersion Tagnite process at CCAD are as follows:

1. Show that the Immersion Tagnite process is compatible with current or potential magnesium aerospace component repair techniques. The repair techniques are:
    - DEVCON Liquid Aluminum F2
    - DEVCON Titanium Paste
    - TIG Weld Repair
    - High Velocity Oxy Fuel (HVOF)
    - Aluminum Cold Spray

    Compatibility testing consisted of primer adhesion strength of the repair areas after being coated with Immersion Tagnite and MIL-PRF-23377 primer. Also, testing the galvanic corrosion behavior of the repair area coated with Immersion Tagnite. The performance criteria is the Immersion Tagnite must have performance that is equal to or greater than the DOW 19 chemical conversion coating (current magnesium protective coating for overhaul parts).

    Results: The Immersion Tagnite met or exceeded the performance criteria.

2. Develop and validate a chemical stripping process that would remove legacy anodize coatings using the Immersion Tagnite pretreatment baths.

    Results: The chemical stripping process was not successful but had no impact on the success of the Masking/Immersion Tagnite process. An alternate stripping technology was identified, tested and approved for the demonstration/validation phase.

3. Design, test and validate the masking tools for the three (3) H-60 demonstration parts.

    The masking tools for the three components were designed and tested at TAG's facility. During the demonstration/validation at the CCAD plating shop, the masking tools were installed on the demonstration parts under the supervision of TAG personnel. The parts were run through the Immersion Tagnite process by CCAD artisans. The masking tools were removed and the parts were visually inspected by CCAD engineers and no evidence of tooling failures were found.

    Results: The demonstration of the masking tool technology at the CCAD plating shop was successful and the process was validated by CCAD engineers.

4. The Masking/Immersion Tagnite process was recommended for transitioning to production parts.

Results: The Masking/Immersion Tagnite process is going through the CCAD production approval process. Maintenance Engineering Orders (MEO) must be written and approved before the processing of production parts can begin. Production is expected in the first half of 2019.

CCAD Production Acceptance Process: CCDC AvMC AMA-M engineering has expressed a strong desire to transition this technology to CCAD production capability. In order to accomplish this task, multiple steps must be taken by various departments at CCAD. The approval process involves the following steps:

1. CCAD or CCDC AvMC AMA-M engineers will identify a need to process certain magnesium helicopter components through the Immersion Tagnite process. Criteria for selecting a certain component are based on:
    - Critical shortage of parts
    - Component is prone to excessive corrosion due to legacy coatings
    - Poor design leading to excessive corrosion.
2. CCAD shall acquire Masking Kits from TAG for the proposed new productions part. Masking kits are part specific and must be designed and approved by TAG.
3. CCAD engineers/QC Lab personnel will submit a frozen process plan to CCAD production.
4. FCDD/CCDC AvMC AMA-M Approval process will commence.
5. After CCDC AvMC AMA-M approval - Demonstration / First Article Inspection will be conducted on subject part
    - Proof of Process using BER scrap parts
    - Successfully coat three (3) production parts
6. CCDC AvMC AMA-M/AMA-F engineers will draft a part specific MEO.
7. Full table top review of MEO for accuracy, routing concerns, etc.
8. MEO is signed out by CCDC AvMC AMA-M/AMA-F leadership.
9. MEO goes through FCDD-AMA induction.
10. CCAD will distribute MEO to appropriate departments or shops.

Regulatory Issues: The Immersion Tagnite process is considered a “green chemistry” process, specifically, this process is chromate free. As a result, the adoption of the Masking/Immersion Tagnite process by the CCAD Plating Shop will allow the Corpus Christi Army Depot to make significant advances in meeting the hexavalent chrome reduction directives. Section 1.3 of this report details the specific regulatory drivers that pertain to this project.

During the design phase of the Tagnite line for the CCAD plating shop, the CCAD Safety Office mandated a physical barrier around the Immersion Tagnite tank to prevent accidental contact with the tank, flight bar or parts during the anodization process. The concern revolved around the high voltages (up to 350 V DC) and high amperage (up to 220 A) during the anodizing process. AquasGroup designed and installed a safety gate in front of the Immersion Tagnite tank. During the demonstration phase, TAG personnel realized that the safety gate design was not robust enough for continuous usage. In addition, the safety gate release was difficult to use.

The design and operation of this safety gate needs to undergo a thorough evaluation prior to the start of normal production.

Procurement, Training and Production Issues: TAG's primary concern about the Masking/Immersion Tagnite process is the extended downtime between the demonstration/validation/operator training periods and the start of product parts. The demonstration/validation took place in late April 2018 and CCAD artisan training was completed in August 2018. Production will probably not start until the 2nd quarter of 2019. This means that there is a 9 – 12 month time gap between training and actual production. TAG is concerned about Tagnite training retention among the CCAD plating shop artisans over this long time period of inactivity.

The Tagnite line at CCAD was installed using a decommissioned line in the CCAD plating shop. The AquasGroup engineers were able to use all of the tanks other than the tank where the Tagnite anodizing process (Tank D-7) was to take place. This tank was replaced due to excessive corrosion. The chilling system and tank heaters were all commercial-off-the-shelf (COTS) items. The only proprietary item was the rectifier and there was no customization of the process line for this demonstration. The masking kits share some common masking tools but most magnesium helicopter parts also need some custom tooling which must be designed and approved by TAG. All of the masking technology is proprietary.

Due to the size limitations of the tanks and rectifier at CCAD, they do not have ability to coat the larger magnesium components on the H-47, H-60 or H-64. However, with their current configuration on the D-Line, CCAD still coat 85 – 90 % of the magnesium components on these helicopter platforms. The primary limitation of the D-Line Tagnite process is some parts can only be processed one part at a time. If they decide that they want to coat all rotorcraft magnesium components, CCAD will have to design a bigger line along with a larger chilling system. These are all COTS items. They would have to also buy a larger rectifier. In addition, they would have to contact TAG for development of the masking kits for these components as well. The Tagnite process is easily scalable provided that the heating and chilling needs are properly engineered.

TAG will use the JTP testing and demonstration/validation data gathered during this project to present talks at major aerospace conferences and publication of the test results in aerospace and/or metal finishing journals about this new process for applying an anodize coating to used/overhauled magnesium components. This technology is currently being used at the TAG facility to process F-35 fighter jet parts and parts for the new Bell Relentless helicopter.

The process can be easily transferred to other depots that overhaul or repair magnesium components such as Hill AFB, Cherry Point NAS and Warner-Robbins AFB. Civilian depots that process large numbers of magnesium components could utilize this process as well. This process could also be incorporated into the machining/manufacturing of new build and spares. By incorporating the masking technology prior to the Tagnite anodize coating, machine shops and OEMs could eliminate several steps from their manufacturing/machining process which would save them time and money.

9.0 REFERENCES

1. "Results of Developmental Testing Conducted to Select an Improved Corrosion-Preventive Finishing System for Apache Magnesium Alloy Gearboxes" by James H. Hawkins, Boeing-Mesa, Report Number: MPS 93LO203 (April 1993).
2. NAVAIR Memo 497000A/7.4911 (April 10, 2006), "Naval Air Systems Command Authorization for Tagnite 8200 Immersion Anodize for Magnesium Surfaces" by John L. Yadon.
3. Army Aviation SBIR Phase I Final Report, Topic Number A00-129, "Advanced Corrosion Protection Scheme for Magnesium Helicopter Components", Contract No: DAAH10-01-C-0020 by William C. Gorman, Jr., Technology Applications Group, Inc. (July 2001)
4. Army Aviation SBIR Phase II Plus Final Report, Topic Number A00-129, "Advanced Corrosion Protection Scheme for Magnesium Helicopter Components", Contract No: DAAH10-02-C-0004 by William C. Gorman, Jr., Technology Applications Group, Inc. (September 2006)
5. Army Research Laboratory Report ARL-CR-717, "Innovative Masking of Ferrous Inserts in magnesium Aerospace Components Prior to Tagnite Anodization" by William C. Gorman, Jr. (July 2013)

Appendixes A–AD appear as separate PDF files attached to this report.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.
PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED (From - To)
18-05-2019	Final	August 2013 - February 2019

4. TITLE AND SUBTITLE
FINAL RTEPORT Improved Magnesium Protection for DoD Aviation And Weapon Component Technology (ESTCP Project WP-201319)

5a. CONTRACT NUMBER
W911NF-13-2-0019

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Dr. William C. Gorman, Jr.
Mr. Kyu C. Cho

5d. PROJECT NUMBER
0010317373

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Technology Applications Group, Inc.
810 S. 48th St.
Grand Forks, ND 58201

8. PERFORMING ORGANIZATION REPORT NUMBER
FR-ESTCP

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Army Research Laboratory
Aberdeen Proving Ground
B4600 Deer Creek Loop
Aberdeen Proving Ground, MD 21005

10. SPONSOR/MONITOR'S ACRONYM(S)
ARL

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
DIST A//Unlimited - Approved for Public Release: The information is approved for public release and does not contain controlled data

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Introduction and Objectives: All military aviation platforms have magnesium castings, however, magnesium is a very electrochemically "active" metal which leads to moisture induced corrosion and galvanic corrosion due to mating with dissimilar metals. During the overhaul phase of the aviation magnesium components the protective coating, primer and topcoat paint are stripped off to allow visual and penetrant inspection of the casting. After passing the inspection, the magnesium castings are dipped in a chemical conversion coating such as DOW 7 or DOW 19 before being placed back into service. Both of these DOW coatings contain hexavalent chromium (Cr6+). The objective of the Tagnite demonstration at th

15. SUBJECT TERMS
Magnesium, corrosion, hexavalent chromium, anodization, overhauled parts, helicopter parts, H-60, CCAD, ESTCP

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					Kyu Cho
a. REPORT	b. ABSTRACT	c. THIS PAGE	UU		19b. TELEPHONE NUMBER (Include area code)
Unclassified	Unclassified	Unclassified			(410) 306-0820

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