EXECUTIVE SUMMARY

Improved Magnesium Protection for DoD Aviation and Weapon Component Technology

ESTCP Project WP-201319

MAY 2019

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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, allowing 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 disposal cost 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.

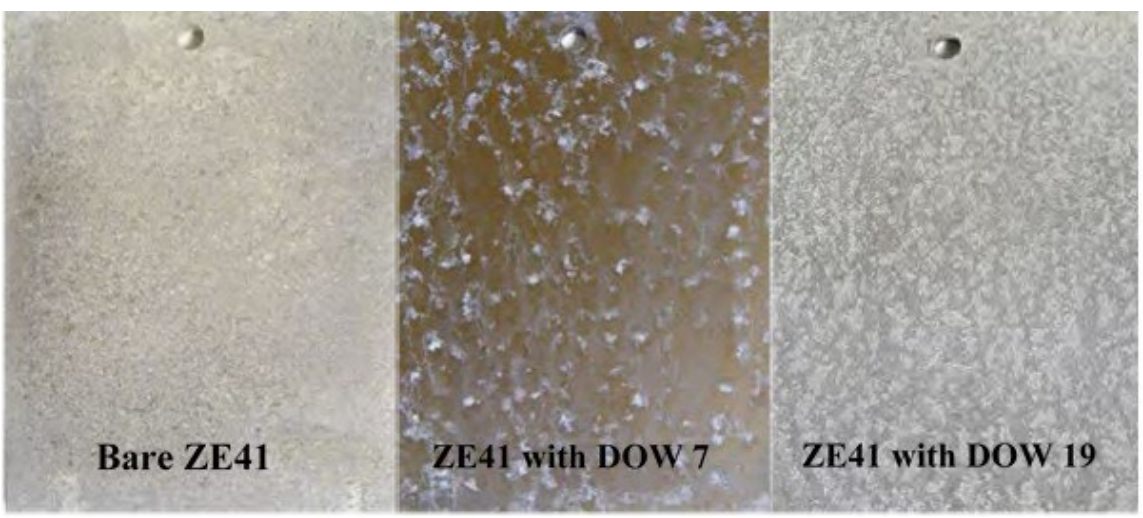

Figure 1. ZE41 Magnesium Panels After 9 Hours of ASTM B 117 Salt Fog

Tagnite was developed as an anodized coating for magnesium that provides superior corrosion resistance, wear resistance, "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) 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 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 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 chosen Department of Defense (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 were 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, and meet current DoD environmental directives, while applying a more robust coating system to the overhauled parts which will lead to lower life cycle costs.

2.0 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.

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3.0 TECHNOLOGY DESCRIPTION

The Tagnite coating process has been approved for DoD magnesium aviation components since 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, and other metals cannot be anodized. If any of these dissimilar metals are 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. As a result, the dissimilar metals will burn away and 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 (36ºF to 180ºF)
- 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 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.

A) **B)**

Figure 2. H-64 Tail Rotor Gearbox: A) Bearing Liner Exposed; B) Bridge in Place to Hold Down Liner Cover

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.

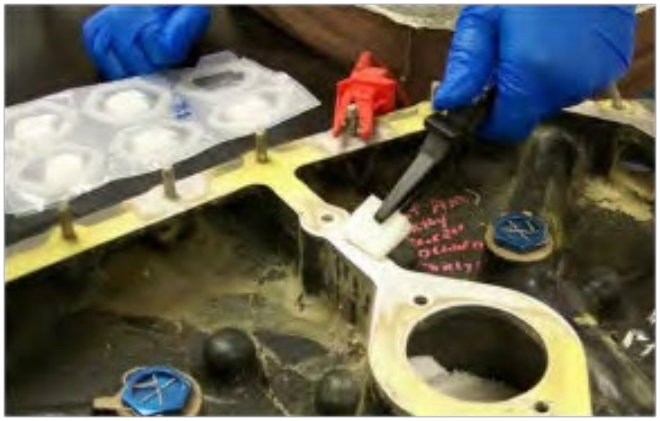

Figure 3. Close-up of Brush Tagnite Application to a Bare Area on a Used Magnesium Aerospace Casting

4.0 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
- Tungsten inert gas (TIG) welding using ZE41A magnesium welding rod and two proposed repair or additive techniques:
  - High velocity oxygen fuel (HVOF) thermal spray using Al-12Si feedstock
  - 6061 aluminum cold spray

The testing involved pull-off adhesion strength per ASTM D4541 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 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 versus 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 Department of Coatings and Polymeric Materials 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 Trivalent Chromium Preservative (TCP). 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 D4541	Brush Tagnite must perform as well or better than DOW 19
	Neutral Salt Fog	ASTM B117 ASTM D1654	
	SO_2 Salt Fog	ASTM G-85, Annex A4 ASTM D1654	
	NASA Outdoor Exposure	24-month exposure in Florida Coast environment	
Brush Tagnite **or** DOW 19	Galvanic Corrosion	ASTM G71	Brush Tagnite must perform as well or better than DOW 19
	Axial Fatigue	ASTM E466	

Table 3. Brush Tagnite (BT) Qualification Results (where Ranking of 1 = Best, Ranking of 15 [Paint Adhesion, Neutral Salt Fog, SO_2 Salt Fog] or 9 [Outdoor Exposure] = Worse)

Treatment	Paint Adhesion		Neutral Salt Fog		SO_2 Salt Fog		Outdoor Exposure	
	POTS Mean (psi)	Performance	Hours of Exposure	Ranking	Hours of Exposure	Ranking	Months of Exposure	Ranking
AZ91C Magnesium Test Panels								
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								
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								
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								
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 TAG 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 and 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% Notch Fatigue Strength (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.

4.1 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

4.1.1 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 dem/val, the CCAD laboratory did not have a functioning taber abraser or 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 dem/val criteria.

4.1.2 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 dem/val. 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.

4.1.3 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.

4.1.4 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 dem/val 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 handheld 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 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.

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5.0 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.

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6.0 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.