ARL-TR-8980 ● June 2020

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High-Build Plural Polyurea Protection for Vehicle Torsion Bars: Final Report

by Thomas A Considine, Thomas E Braswell, and
Brian E Placzankis

NOTICES

Disclaimers

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)* June 2020	**2. REPORT TYPE** Technical Report	**3. DATES COVERED (From - To)** August 2015 – December 2020

4. TITLE AND SUBTITLE
High-Build Plural Polyurea Protection for Vehicle Torsion Bars: Final Report

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Thomas A Considine, Thomas E Braswell, and Brian E Placzankis

5d. PROJECT NUMBER
W14AR03

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
CCDC Army Research Laboratory
ATTN: FCDD-RLW-MC
Aberdeen Proving Ground, MD 21005

8. PERFORMING ORGANIZATION REPORT NUMBER
ARL-TR-8980

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Torsion bars have long been used as part of the suspension system in US Army ground combat vehicles. Torsion bars occasionally suffer catastrophic failures when the load exceeds the tolerance of the bar or due to failure from reduction in critical cross-sectional diameter due to fatigue crack growth. Corrosion can exacerbate the load problem by introducing defect sites for fatigue cracking initiation. The current corrosion mitigation strategy for torsion bars is to clean, shot peen, prime, and apply an electrical insulating polyethylene tape wrap to the torsion bars. The tape damages easily, degrades over time, is not easily removed, and is typically hastily repaired in place. The USMC Amphibious Assault Vehicle (AAV) uses a plural high-build polyurea (HBP) system as an alternative to the polyethylene tape wrapping. This system significantly improved corrosion resistance on the AAV bars versus the original tape, but did not provide a ready in-field capability for touch-up to damaged areas. This study investigates the use of improved and competitive HBP systems on torsion bars for the M2 Bradley Fighting Vehicle and the M1 Abrams main battle tank. Validation of the application and in-field touch-up procedures is discussed, as well as tests for impingement, cure, adhesion, and solvent resistance. Corrosion experiments are performed on test coupons in salt fog and accelerated cyclic corrosion, and on torsion bars placed in outdoor exposure at Cape Canaveral Air Force Station. Two complete sets of torsion bars each for Bradley and Abrams vehicles are fielded as demonstrations. Finally, a certified process is established using the objective quality evidence captured during the application processes.

15. SUBJECT TERMS
torsion bar, high build polyurea, corrosion, impact, adhesion

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Thomas A Considine
Unclassified	Unclassified	Unclassified	UU	36	**19b. TELEPHONE NUMBER (Include area code)** (410) 306-2564

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

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1. Introduction

The M1 Abrams Main Battle Tank and the M2 Bradley Fighting Vehicle employ torsion bar suspension systems. The Bradley torsion bars are currently primed with MIL-DTL-53022 (DOD 2017) (either type II or type III, depending on where it is serviced) and wrapped with MIL-I-15126 (DOD 2005) EF-9 polyethylene electrical insulation tape as the main avenue of corrosion protection. This system has often been criticized for the ease of which the tape is damaged, its rapid breakdown in properties, the difficulty in removing the tape residuals for repair/reset/re-man, and the ineffectiveness of the intended corrosion protection. The Abrams torsion bars are coated with MIL-V-12276 (DOD 1973) Phenolic Baking varnish and covered with a thin, loose-fitting plastic sleeve upon final vehicle assembly. The Amphibious Assault Vehicle (AAV) used by the Marines faced a more significant problem with corrosion in the early 2000s. Because of the extremely aggressive marine environment that the AAV encounters in the field, corrosion issues are more common and could result in catastrophic fracture failure of the torsion bars. To mitigate the danger to the Warfighter, a high-build polyurea (HBP) system was investigated to replace the polyethylene tape system. In lieu of the MIL-DTL-53022 and tape, Devcon 2K XPM urethane primer was applied and then coated with Line-X XS-100 (an HBP) at 90–120 mils dry film thickness (DFT). This new HBP system proved to be more robust than the tape system and lessened the extent of corrosion to a much higher degree. As such, it was successfully implemented by the Marines for the AAV in 2005.

The purpose of this study is to find a competitive HBP system for Abrams and Bradley torsion bars with a performance level equal to or better than the current systems employed on the AAV torsion bars. This competitive system shall be applied using the same equipment and utilize similar process parameters as the AAV platform. One of the drawbacks of the AAV system was that there was no in-field touch-up procedure available at the time of its implementation in 2005. Instead, damaged bars would have to be returned to the applicator's facility in order to be reprocessed. In the years since, methods of touch-up have become available, but have not been fully documented and investigated. The new competitive system shall include a field-friendly touch-up procedure, and the aforementioned touch-up procedures will be investigated by ARL to ensure they conform.

Another major attribute of the competitive system is to include a hexavalent chromium-free pretreatment system qualified to TT-C-490 (DOD 2019). The increase in corrosion inhibition offered by a properly applied pretreatment is crucial to ensuring system stability in the long term. After investigating several HBP coatings in commercial use, the US Army Combat Capabilities Development

Command (CCDC) Army Research Laboratory (ARL) selected PPG's Dragonhide 1000 as a second candidate for use in a competitive system, based on commercial availability and performance on consumer pickup truck beds. This system matrix was composed of an inorganic pretreatment (Henkel Bonderite M-NT 7400, qualified to TT-C-490 Type IV as PT#00008), MIL-DTL-53022 Type IV, and the Dragonhide 1000 as the chip-resistant, high-build coating. This system was tested in conjunction with the Line-X XS100 over XPM system currently employed by AAV. The AAV system, it should be noted, does not have a pretreatment component. The Line-X XS 100 was applied with a "smooth" finish, as is done on AAV bars, and the Dragonhide 1000 system was applied with a stipple textured finish in part to investigate improved safety handling characteristics during installation of the bars or maintenance. Aalberts Surface Treatment (formerly Impreglon Coatings) of Baltimore, Maryland, and the past and current commercial vendor for preparing the USMC AAV bars partnered with CCDC ARL on this project and supported the application of the suggested coating stackups.

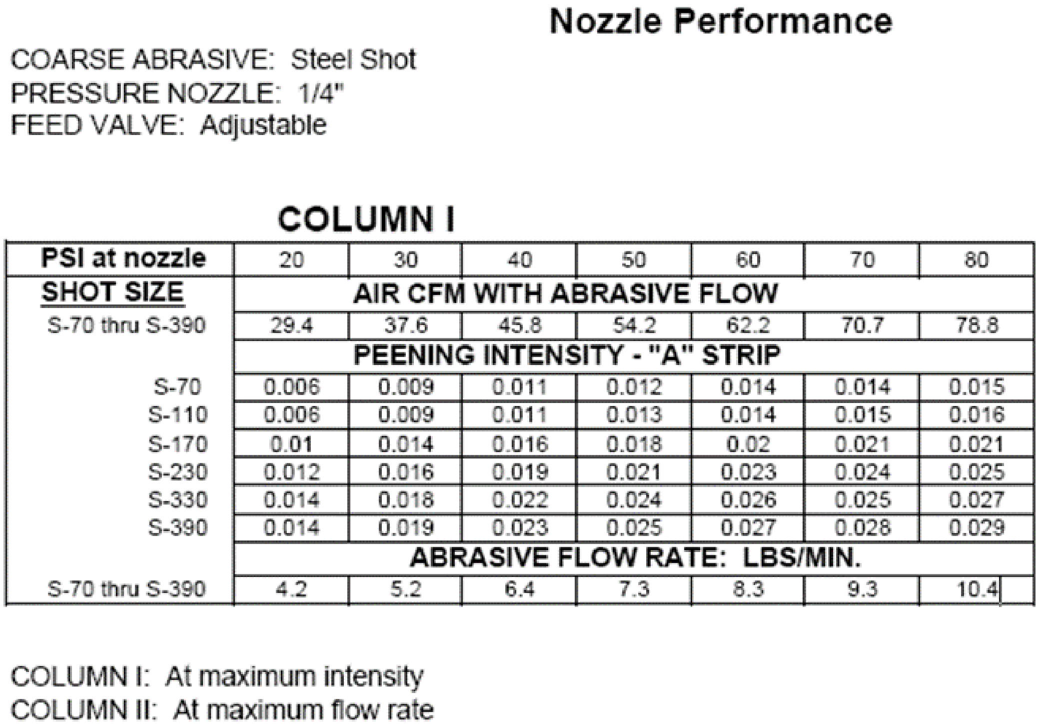
2. Approach

In order to evaluate these commercially available HBP coating systems, an incremental approach to testing was determined. First, laboratory validations of the two HBP systems were performed on test coupons. Concurrently, a pair of AAV bars and several test panels bearing each of the HBP coating systems were placed into outdoor exposure at the ARL test site at Cape Canaveral Air Force Station (CCAFS). Following laboratory testing, a mid-scale validation of the bars and further proofing of coatings in torsion test machines was performed at the BAE Anniston test facility. Finally, a full-scale demonstration was performed at Fort Benning, FMX, utilizing two full sets of bars installed in two Bradleys and two Abrams that are regularly driven as part of training at the Armor School. These bars were demonstrated for a two-year duration.

3. Experimental Procedure

Incorporating the required shot peening intensities designated in the specifications for the Bradley and Abrams torsion bars was a tremendous challenge. Since no technical assistance was available from the current manufacturing and finishing sources, ARL teamed with Wes Prince, general manager and former lead engineer at Aalberts, to develop the shot peening process. The requirements for peening call for a 200% coverage at a specific Almen intensity. A 200% coverage is obtained when the Almen intensity is met on an initial round of peening, and then the operation is repeated at the same intensity. An automated shot peening machine was designed and constructed to encase the torsion bars in a rotating fixture with a robotically controlled blast nozzle. The air pressure, angle of incidence, dwell, and standoff could be adjusted to vary the peening intensity. Shot media of different sizes and hardness were tested on a representative bar in the blast machine to determine the appropriate Almen intensity. The intensity is measured on Almen strips of varying thickness classified as A and C. The A strips are approximately 0.05 inches thick (1.27 mm) and the C strips are approximately 0.929 inches thick (2.36 mm). These strips have a Rockwell Hardness of 44–50C. The intensity of the peening process is determined by measuring the deflection of the Almen strip over the course of the operation. The necessity of using the Almen strips as a process control has been discussed in detail (Miao 2010). Specifications 19207-12358905 Rev. E (FMC 2007) and SC-x131 19B (General Dynamics 1992) call for the Almen peening intensity to be 0.007C to 0.010C on the body and a minimum 0.012A on the splines for the Bradley platform, and a minimum 11C on the body and 4C on the splines for the Abrams platform. Specifications for shot peening, AMS-S-13165A/MIL-S-13165C (SAE International 2007) and AMS2430 (SAE International 1948), were used to set up the procedure for the torsion bars. The published maximum intensity obtainable with shot S170 with a 0.25-inch nozzle is 0.021 inches on an “A” test strip (Table 1). This roughly correlates to a 0.007 C; therefore, shot larger than S170 must be used on the torsion bar bodies. Once that was determined, it was a matter of programming test runs to obtain the correct intensity with 200% coverage. Almen test bars were mounted onto fixture blocks on a representative torsion bar to define and obtain objective quality evidence (OQE). After numerous trial runs with variations on rotational speeds, traverse speeds, pressures, and shot flow parameters, the proper set of parameters were obtained to meet the required intensities.

Table 1 Shot peen nozzle performance



Nozzle Performance

COARSE ABRASIVE: Steel Shot
PRESSURE NOZZLE: 1/4"
FEED VALVE: Adjustable

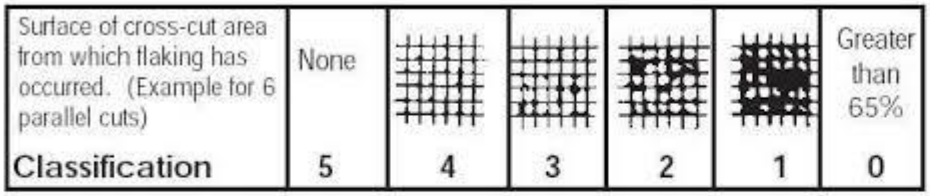
COLUMN I

PSI at nozzle	20	30	40	50	60	70	80
SHOT SIZE	**AIR CFM WITH ABRASIVE FLOW**						
S-70 thru S-390	29.4	37.6	45.8	54.2	62.2	70.7	78.8
	PEENING INTENSITY - "A" STRIP						
S-70	0.006	0.009	0.011	0.012	0.014	0.014	0.015
S-110	0.006	0.009	0.011	0.013	0.014	0.015	0.016
S-170	0.01	0.014	0.016	0.018	0.02	0.021	0.021
S-230	0.012	0.016	0.019	0.021	0.023	0.024	0.025
S-330	0.014	0.018	0.022	0.024	0.026	0.025	0.027
S-390	0.014	0.019	0.023	0.025	0.027	0.028	0.029
	ABRASIVE FLOW RATE: LBS/MIN.						
S-70 thru S-390	4.2	5.2	6.4	7.3	8.3	9.3	10.4

COLUMN I: At maximum intensity
COLUMN II: At maximum flow rate

Once the peening solution had been obtained, a process for coating the AAV bars was created. The basic process and flow was clean/degrease, shot peen, clean, apply pretreatment in accordance with (IAW) TT-C-490 type IV, mask splines, apply primer, cure, apply the chip-resistant HBP coating, cure, de-mask, clean and inspect, apply corrosion inhibitor on the splines, and package. The following SAE Recommended Practice provides uniform procedures for using the standard shot peening test strips reported in SAE J442 (SAE International 2013). Standard test strips are used to establish saturation, determine intensity, monitor repeatability of the shot peening machine operations, and predict a desired result on a part. It is recommended that the standard test strip A be used for intensities that produce arc heights of 0.10 mm A (0.004 inch A) to 0.60 mm A (0.024 inch A). For intensities below 0.10 mm A (0.004 inch A), the standard N strip is recommended, and for intensities above 0.60 mm A (0.024 inch A), the standard C strip is recommended. The process of shot peening, in common with many other processes, cannot at present be adequately controlled by nondestructive inspection of the peened parts; therefore, it is necessary to control the process itself to achieve consistent, reliable results.

Dry tape adhesion tests were conducted at room temperature as defined in ASTM D3359 Method B (ASTM International 2017). Using a sharp cutting tool, an unblemished and clean area of the panel was selected and six parallel cuts at 2-mm spacing were made through the primer to the substrate on both the XPM and 53022 panels. A second series of cuts with the same parameters were made perpendicular to the initial cuts to create a complete grid. These grids were repeated in multiple spots across several panels to establish a sufficient data set. Each set of grid lines was lightly brushed clean to remove detached ribbons and/or flakes of primer material. Two complete laps of the LA-26 Intertape were removed from the roll before applying the lengths of tape used in testing. Tape was placed over the grids and smoothed into place using a finger, then rubbed with the eraser of a pencil to ensure good bonding between the tape adhesive and the primer. After approximately 60 s, the tape was removed by rapidly pulling the tape back upon itself at as close to a 180° angle as possible. After removal of the tape, the remaining grid is evaluated for loss of coating adhesion using the classification from ASTM D3359 Method B as shown in Fig. 1. Two ARL researchers made their own ratings separately, which were averaged together, to ensure accuracy and remove any potential bias.



Surface of cross-cut area from which flaking has occurred. (Example for 6 parallel cuts)	None					Greater than 65%
Classification	5	4	3	2	1	0

Fig. 1 **ASTM D3359 rating system**

Impact testing was performed on test coupons featuring the HBP coatings prepared by Aalberts and a set of test coupons prepared by ARL to represent the taped bars (Fig. 2). These panels were primed with MIL-DTL-53022 Type IV and wrapped in polyethylene electrical tape to approximate the EF-9 polyethylene tape used in the current process. Impact testing was done at 60 cm (~24 inches) and 100 cm (~39 inches) using a 4-lb weight for impacts of 96 inch-lbs and 156 inch-lbs. A second and more severe improvised impact test was then performed by dropping a pipe wrench from 9 ft onto the test panels for an impact force of 972 inch-lbs (Fig. 3). This testing was done based on observations and reports that the bars are easily damaged during shipping, storage, and even installation itself from the installers walking on them (Figs. 4 and 5). Damage was observed and photographed.

Fig. 2 Impact tester

Fig. 3 Improvised impact test

Fig. 4 Taped bar damaged in shipping

Fig. 5 Taped bars damaged during vehicle assembly

Cyclic corrosion was verified using standard mass loss coupons. Because of the nature of the high-build coating, scribing through to the substrate was not performed. It was determined that any such defect incurred in actual usage would be catastrophic and render the bar damaged enough for, at a minimum, rework. As such, two modes of failure were decided upon. The testing was based on TT-C-490 requirements, after 1008 h of salt fog, and 30 cycles of cyclic corrosion, there was to be no more than minimal blistering of the primer and absolutely no delamination of the high-build coating. The samples were nested into polycarbonate racks so that they rested at a 15° angle to the vertical, coating system facing outwards, unprimed section at the bottom. The samples were inspected at 10, 20, 30, 40, and 60 cycles.

Five panels of each system were placed into ASTM B117 (ASTM International 2018) neutral salt fog and GMW14872 (General Motors 2018) cyclic corrosion testing. A Singleton CCT-80 cyclic corrosion chamber (Fig. 6) and an Autotechnology Model 22 salt (NaCl) fog chamber (Figs. 7 and 8) were used for this phase of testing. Both tests were run in accordance with the relevant specifications. Neutral salt fog testing conditions are a continuously atomized 5% NaCl fog at 95 °F and saturated humidity. Salt fog testing was verified using daily fog collection rates, wet and dry bulb temperatures, tower temperature, and the specific gravity and pH of collected fog. Cyclic corrosion was run according to GMW14872, EXT, and C conditions and includes four spray cycles followed by four ambient periods over the course of 8 h, followed by an 8-h high humidity period (120 °F, 100% relative humidity [RH]), and concluded with an 8-h dry period (140 °F, <30% RH). Panels in salt fog were inspected for blistering and delamination at 336, 504, 672, 1008, 1512, and 2016 h and 10, 20, 30, 40, and 60 cycles, respectively.

Fig. 6 Cyclic corrosion test chambers at ARL

Fig. 7 B117 chambers at ARL

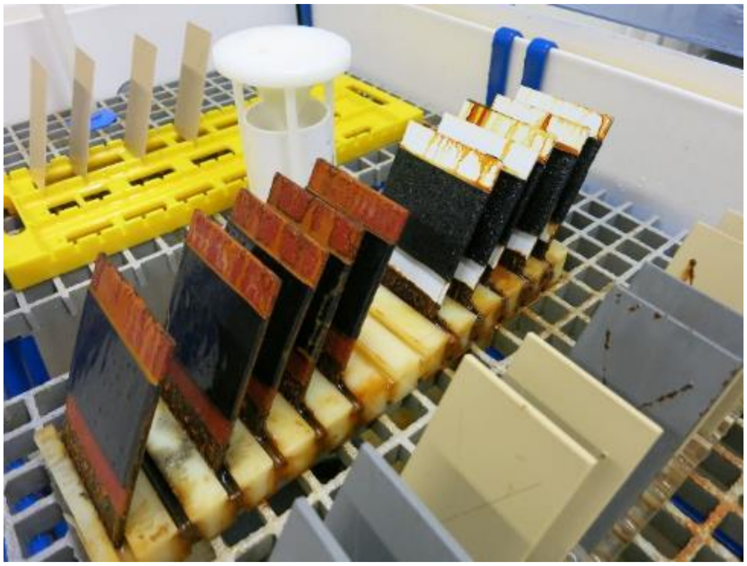


Fig. 8 Panels in salt fog testing

Outdoor exposure testing was performed at ARL's outdoor exposure site on CCAFS (Fig. 9). Cape Canaveral and the surrounding regions in Florida are considered some of the most corrosive environments in the continental United States. ASTM reports a corrosion rate of 5.17 mils per year (MPY) on standard mass loss coupons 55 m inland. The ARL site is 170 m inland and has averaged 5.4 MPY on standard mass loss coupons since 2011. Unscribed test panels were placed on racks in December 2016 and two AAV bars, one with the XPM/Line-X system and the other with the 53022/Dragonhide system, were deployed in March 2017. Panels and bars were evaluated every 3 months for two years, and will remain onsite until failure.

Fig. 9 Satellite image of ARL exposure site on CCAFS

A touch-up procedure was identified and tested by Aalberts and ARL for the Dragonhide 1000 system. As there is no touch-up procedure for either the tape or AAV platform that does not involve sending bars back to a facility for rework, this demonstration was limited in scope. A few decommissioned torsion bars from various programs were made available for Aalberts and ARL to use. Following an empirical approach, ARL and Aalberts were able to provide a viable working touch-up procedure for Dragonhide on torsion bars that can be performed in the field. A pneumatic dual cartridge epoxy gun with static mixing applicator nozzle (Fig. 10) was used to apply the coating to a damaged area of a bar (Fig. 11).

Fig. 10 Pneumatic dual cartridge epoxy gun setup

Fig. 11 Torsion bar used in touch-up testing

4. Results and Discussion

Dry tape adhesion was performed on abrasive blasted and shot peened surrogate panels. The adhesion measured was that of the primer to the substrate. Across all test coupons, not a single panel rated lower than a 5B. It can be ascertained that there were no issues with the application procedure for either system, or with the Bonderite M-NT 7400 used in the Dragonhide stackup. Examples of these adhesion tests can be seen in Figs. 12 and 13.

Fig. 12 Cross hatch on MIL-DTL-53022 type IV

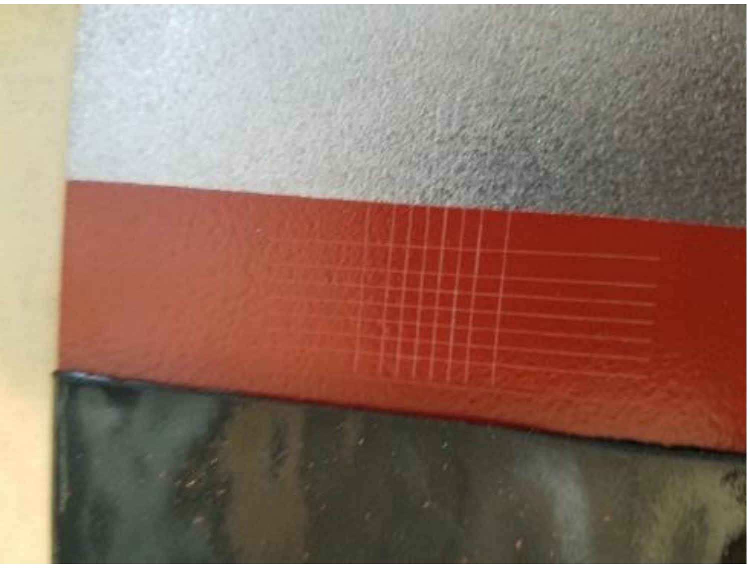


Fig. 13 Cross hatch on XPM primer

Impact testing was conducted on panels representing all three systems. A Byk Gardner Heavy Duty Impact Tester equipped with a 4-lb weight was used in initial testing. Impact strikes were made at 96 inch-lbs and 156 inch-lbs. Figures 14–16 show the results from these impacts.

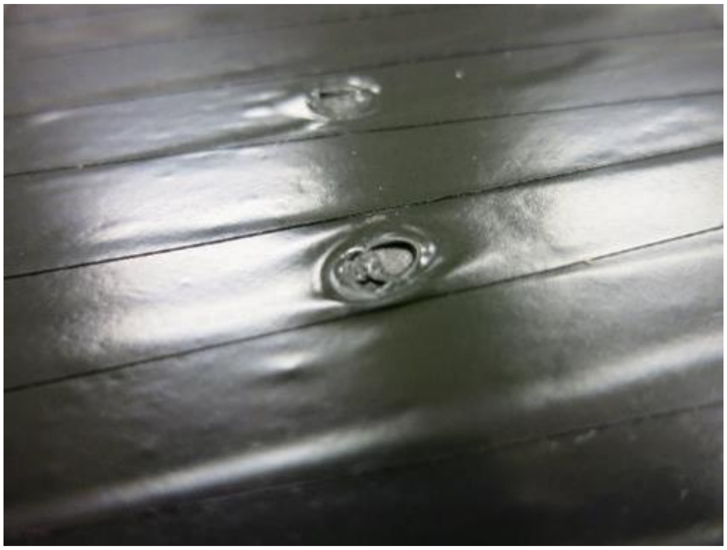


Fig. 14 Impact test results on taped system (top: 96 inch-lbs, bottom: 156 inch-lbs)

Fig. 15 Impact test results on XPM/Line-X System (left: 96 inch-lbs, right: 156 inch-lbs)

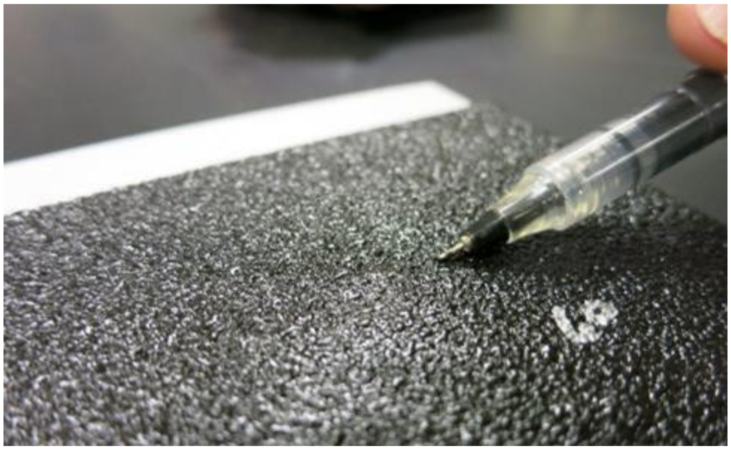


Fig. 16 Impact test results on Bonderite/53022/Dragonhide system (left: 96 inch-lbs, right: 156 inch-lbs)

As can be seen in Fig. 14, both impacts were severe enough to go straight through the tape and primer to the substrate on the legacy taped system analog. It is clear that polyethylene tape does not provide adequate protection against even relatively light impacts. This is of course problematic when it comes to the conditions experienced during installation, refurbishment, and deployment, the overwhelming evidence of which is what led to this study. The Line-X coating offers significantly increased protection from impacts over that of the tape system. As seen in Fig. 15, only two slight depressions were left in the high-build coating, the only difference between them being the diameter of the cratering effect based on the impact strength. It should be noted that these craters had essentially recovered and disappeared within a 24-h period, evidence of the resilient properties of this particular coating. In Fig. 16, the Dragonhide coating with the stippled finish offers even stronger protection from impacts. Neither strike was immediately identifiable and had to be indicated with a pen for photographic purposes. The data generated highlight that both the Line-X and Dragonhide are significantly superior to the tape-based system.

Due to the nearly nonexistent damage noted to both the Line-X and Dragonhide systems in conventional heavy impact testing, a second and much more severe improvised impact test was conducted by dropping a pipe wrench from 9 ft straight down onto the test panels. The pipe wrench had a mass of 3.3 lb and impacted at 972 inch-lbs based upon the vertical orientation and end area of the tool. This additional test was devised to replicate a severe real-world production or maintenance issue in which a tool is accidentally dropped onto a bar and to further assess the mechanical limits of these systems. As noted before, just walking on the currently fielded taped bars is sufficient to damage them. This modified test was approximately 10 times more severe than the previous impact tests, the effects of which can be seen in Figs. 17–19. The damage to the taped samples was quite severe, as before, with the impact penetrating through the tape and primer, damaging the substrate of the panel itself. The tape was torn, distended, and suffered loss of adhesion all around the impact zone. With the Line-X, the impact was absorbed but left two areas of delamination on either side of the impact zone. In contrast with the previous impacts where the coating was able to recover to its original appearance over time, no such healing was observed in the months between testing and the writing of this report. There was no penetration through the coating. Damage to the Dragonhide system was, as before, more difficult to visually observe. A pen was used to indicate the damage in Fig. 15. This damage consists of two small, straight parallel lines, each about 1 mm wide. There was no evidence of delamination or penetration of the coating. Additional testing performed by Aalberts as part of process validation determined the elongation of Dragonhide to be anywhere from 180% to 400%, whereas the elongation of the Line-X had a much narrower window of 140% to 160%. Further testing revealed a shore hardness of Dragonhide to be 45D, and 55D for Line-X. The more elastic Dragonhide, coupled with the fact that it is a softer coating than the Line-X, may explain why the coatings had such visually dissimilar results from a similar impact. The Dragonhide was able to absorb and disperse the force more easily than the Line-X due to those properties discussed previously.

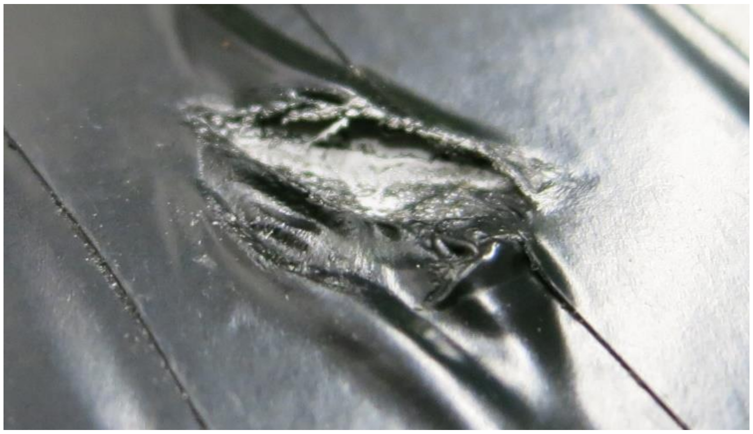


Fig. 17 Improvised impact test on tape

Fig. 18 Improvised impact test on Line-X

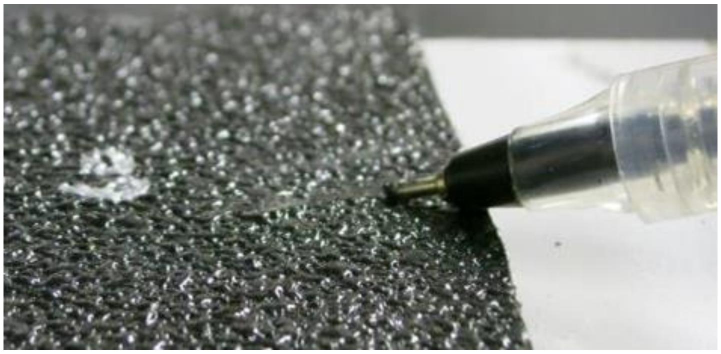


Fig. 19 Improvised impact test on Dragonhide

All testing performed on the taped panels confirmed reports from the field concerning the low durability of the taped system in place currently on the Bradley torsion bars. The tape application is not resilient (as tested) even with minor impacts, and typically delaminates locally when impacted. When this system is penetrated, the primer is left exposed to the impact as well. As seen in Fig. 17, a strike of just under 100 inch-lbs is enough to damage the primer. Without a primer and pretreatment system in place after impact, there is no longer any corrosion mitigation strategy employed to protect these bars in the affected areas. The Line-X and Dragonhide HBP coating systems impart significantly higher impact resistance and therefore create a stronger barrier to potential corrosion than the tape alone.

Cyclic corrosion was initially run to 30 cycles as per the requirements for primers in TT-C-490, and inspected every 10 cycles. The photos of the results at 30 cycles can be seen in Figs. 20 and 21 and in Table 2.

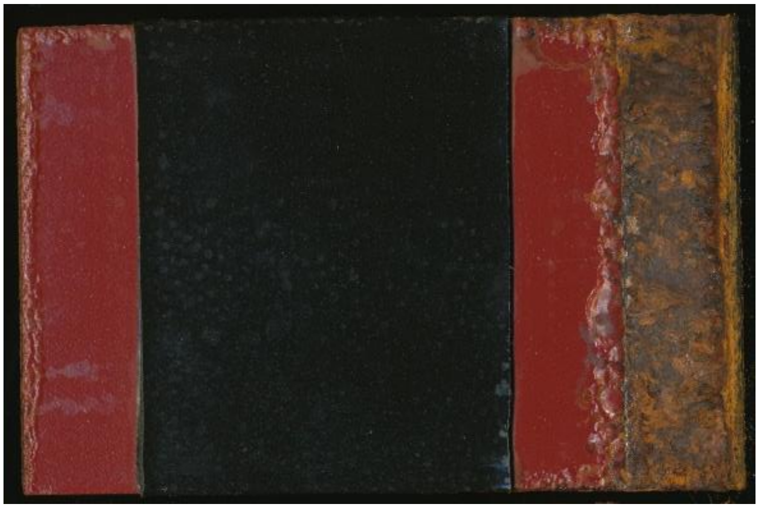


Fig. 20 Representative sample of XPM/Line-X system at 30 cycles GMW14872

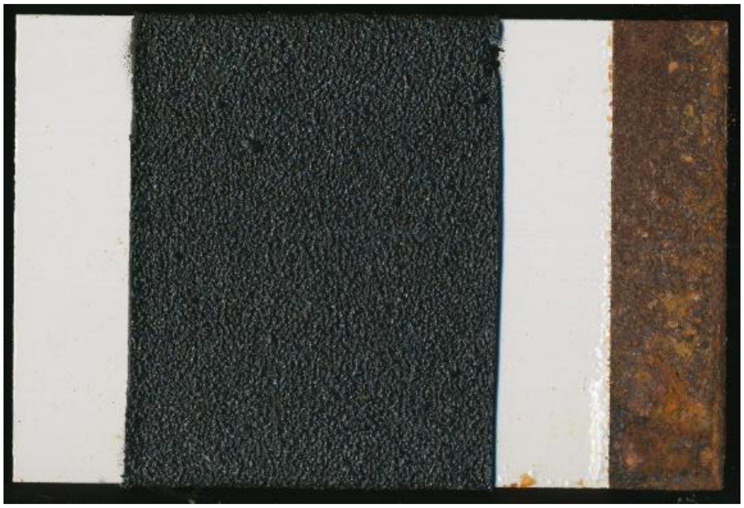


Fig. 21 Representative sample of Bonderite/53022/Dragonhide system at 30 cycles GMW14872

At 30 cycles, there is minimal corrosion in the coated areas. There was more blistering emanating from the uncoated area at the bottom and the edges of the XPM/Line-X panels than there was on the Bonderite/53022/Dragonhide panels, but nothing in the field. Corrosion emanating from those areas was measured in accordance with ASTM D1654, Procedure C. The values obtained are shown in Table 2.

Table 2 Corrosion creep emanating from bare metal at 30 cycles

	ID	Max	Min	Avg	Total Avg
Line-X XS100	1	16	4	10	6.55
	2	7	4	5.5	
	3	18	5	11.5	
	4	6	3	4.5	
	5	2	0.5	1.25	
Dragonhide 1000	1	6	3	4.5	3.85
	2	8	3.5	5.75	
	3	7	3.5	5.25	
	4	3.5	0	1.75	
	5	4	0	2	

As can be determined from Table 2, the Dragonhide system with the pretreatment and enhanced Type 4 CARC primer performed better in cyclic corrosion than the Line-X system with the XPM primer and without pretreatment with respect to creep emanating from the bare area at the bottom of the panel. It should be noted that in the Dragonhide system, this area was treated with the Bonderite M-NT 7400 as it was across the entire surface of the panel, so this space was not necessarily bare. The Bonderite provided some protection from corrosion for a cycle or two, but is not meant to be used without a primer and topcoat. As such, this area began to rapidly corrode after a few cycles. The effects of the pretreatment under the primed area, however, when compared to that of the XPM primer over bare steel, become clear. With blisters extending up to 18 mm on the XPM/Line-X system, compared to 8 mm on the 53022/Dragonhide system panels, the corrosion inhibiting properties of the Bonderite and 53022 Type IV working in tandem are readily apparent. With an overall average of 6.55 mm of blistering, the Line-X stackup has almost two times more corrosion creep than the Dragonhide stackup.

The cyclic corrosion test was extended to 60 cycles to present a worst-case situation. These results are presented in Figs. 22 and 23 and in Table 3.

Fig. 22 Representative sample of XPM/Line-X system at 60 cycles GMW14872

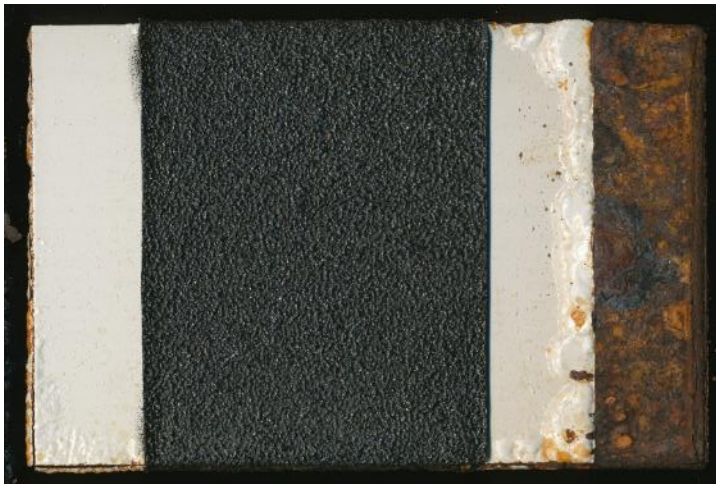


Fig. 23 Representative sample of Bonderite/53022/Dragonhide system at 60 cycles GMW14872

Table 3 Creepage emanating from bare metal at 60 cycles

	ID	Max	Min	Avg	Total Avg
Line-X XS100	1	22	11	16.5	16.1
	2	22	9	15.5	
	3	22	16	19	
	4	22	8	15	
	5	22	7	14.5	
Dragonhide 1000	1	22	4	13	12.4
	2	22	6	14	
	3	22	5	13.5	
	4	19	1	10	
	5	22	1	11.5	

After 60 cycles, the entirety of the XPM primed area is covered in blisters, with large-scale blistering and delamination emanating from the bare, untreated area on the bottom of the panel. Areas coated by the Line-X adjacent to blistering in the primed areas of the panel had begun to lift with the blisters. Though this was double the required duration of cyclic corrosion as per TT-C-490 requirements, this could prove problematic when in the field on assets that are subjected to a marine environment, as in the case of the AAV. The propagation of corrosion on the 53022-primed panels was not as advanced as on the XPM-primed panels. Much of the field remained unblistered, and those blisters that were present originated from the edges and pretreated/bare area at the base of the panel. No portion of the Dragonhide coated area showed signs of blistering under the coating raising any part of it. Working in concert, the combination of the Bonderite M-NT 7400 and the MIL-DTL-53022 Type IV worked considerably well at preventing corrosion at double the required durations specified in TT-C-490.

In neutral salt fog testing, the XPM primer did not meet the requirements of TT-C-490. By 336 h, the minimum salt fog test duration in 490, the entirety of the primed area was covered in blisters (Fig. 24). Several of the panels tested had already begun to show lifting of the Line-X from blistering under the coating. As in the cyclic testing, the stackup of Bonderite 7400, 53022 Type IV, and Dragonhide outperformed the requirements outlined in TT-C-490. Testing on both sets of panels again continued to double the required duration. After 2016 h of salt fog exposure, the Bonderite-pretreated and 53022-primed panels performed exceptionally well. As can be seen in Fig. 25, there is minimal blistering that radiates from the edges of the panel and no blistering in the field at all. Unlike in the cyclic exposure, there is no blistering advancing into the primer from the pretreated/bare area of the panel at the bottom.

Fig. 24 Close up of blistering on XPM primed panels

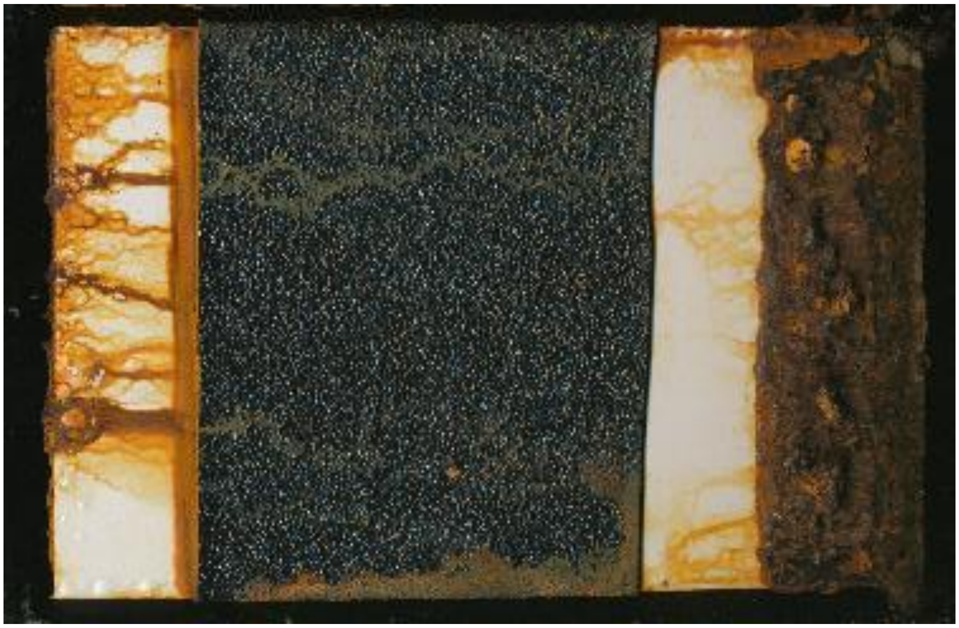


Fig. 25 Representative sample of Bonderite/53022/Dragonhide system at 2016 h B117

A set of AAV torsion bars, one bearing the Line-X stackup system and one with the Dragonhide stackup, were placed in March of 2017 (Fig. 26). Panels of these stackup systems were placed into outdoor exposure 3 months prior. The torsion bars also incurred an unplanned period of seawater immersion, lasting less than 30 days, due to the impact of Hurricane Irma in September 2017 (Fig. 27). Outdoor exposure testing completed two years at CCAFS in December 2018 and March 2019 for panels and bars, respectively. Both sets of bars and panels will continue on in testing until failures are observed. Photographs of the test panels at 24 months are pictured in Figs. 28 and 29. The panels primed with the XPM all show minimal corrosion under the primer near the interface of the primed and unprimed area, but not nearly to the degree seen in cyclic testing. Additionally, there is some corrosion along the other edges of the coupons. The samples primed with 53022 also display some corrosion along the edges and unprimed/primed interface, but to an even lesser degree than seen on the XPM-primed panels. These observations are in line with those from the accelerated testing in the lab. The fifth panel of each set in Figs. 28 and 29 show corrosion in the bottom center of the primed area. These panels were reused from the cross hatch tests, and as such, the scribes go through the coating to the substrate. The severity of the corrosion on the XPM primer is, as expected, much higher than that of the 53022 primer. All 10 test panels do show a degree of color change of the high-build system, with the black fading to a dark gray and a significant amount of dulling of the glossiness of the coating. This change in color and gloss is reflected in the observable results of the bars (Fig. 30).

No failures have been observed on either torsion bar as of December 2019, more than two years after the seawater immersion caused by Hurricane Irma.

Fig. 26 AAV torsion bar set deployed at CCAFS

Fig. 27 Torsion bars emerging from flooded deployment area at CCAFS

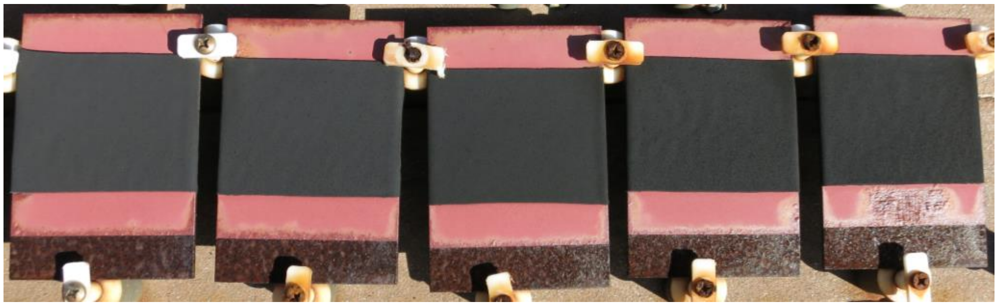


Fig. 28 Line-X system after 24 months of outdoor exposure at CCAFS

Fig. 29 Dragonhide system after 24 months of outdoor exposure at CCAFS

Fig. 30 Dragonhide (top) and Line-X (bottom) bars after 24 months of outdoor exposure at CCAFS

A touch-up procedure utilizing a pneumatic dual part epoxy gun and cartridges was tested by Aalberts and ARL through trial and error, using several scrapped torsion bars. ARL and Aalberts tested various spray patterns, pressures, and techniques in order to obtain the ideal coating surface for touch-up of a contoured surface. The results can be seen in Fig. 31. The procedure for touch-up was written into the certified process used at Aalberts in torsion bar applications. The ARL team then traveled to Line-X headquarters in Huntsville, Alabama, in order to receive training in application procedures, including the Line-X touch-up process. ARL was able to verify that the Line-X touch up procedure was sufficient, resulting in a surface virtually indistinguishable from the original, unblemished surface. This touch-up procedure was also written into a certifiable process to be used by military applicators.

Fig. 31 Torsion bar touch-up procedure result

A partial set of torsion bars for Bradley and Abrams was delivered to BAE systems in Anniston, Alabama, for torsion mechanical testing. During testing, one end of the bar is anchored in place while the other end is rotated between 12° and 70° for Bradley and 10° and 60° for Abrams bars. At a rate between 20 and 30 cycles per minute, the bars are cycled through at least 40,000 times. In one case, a Bradley bar was extended out to 100,000 cycles. No failures of bar or coating were observed in this phase of testing. The results of this phase of testing are displayed in Table 4.

Table 4 Torsion fatigue test results

ID	Vehicle	System	Cycles	Deflection	Pass/Fail
M1-1	M1 Abrams	Line-X	45,000	10º - 60º	PASS
M1-2			45,000	10º - 60º	PASS
M1-3		Dragonhide	40,000	10º - 60º	PASS
M1-4			40,000	10º - 60º	PASS
BFV-1	Bradley	Line-X	40,000	12º - 70º	PASS
BFV-2			40,000	12º - 70º	PASS
BFV-3		Dragonhide	100,000	12º - 70º	PASS
BFV-4			40,000	12º - 70º	PASS

Two full sets each of Bradley and Abrams torsion bars were delivered to the Maneuver Center of Excellence at Fort Benning to be fitted into four vehicles in use at the mechanized infantry school by the Fort Benning TACOM FMX facility in August 2017 (Fig. 32). The hot and humid climate of western Georgia can produce severe corrosion, especially due to condensation inside the hull of vehicles. The torsion bars installed in vehicles were subjected to the repeated wear and tear of the learning environment, school driving terrain courses, increasing the risk of damage to the coatings, which in turn exacerbates the corrosion potential. This constant operating frequency made for an extreme yet realistic environment for validating torsion bars, allowing for the most relevant to real-world data to be obtained. A trip was planned in order to inspect the bars installed in the Bradley and Abrams vehicles, but only one of the Abrams was able to be located at that time. After several months of attempting to locate the other vehicles, no success was had. ARL and Fort Benning personnel were able to determine from maintenance logs that none of the bars provided had failed. Scrap piles were also investigated to further verify that none of the bars provided had been removed without mention in the logs. It can be ascertained that the torsion bars remain in the vehicles they were installed in and that no failures have occurred due to the lack of evidence of failure. The bars will continue to remain in service at Fort Benning until any failure is observed and reported.

Fig. 32 Torsion bar installation at Fort Benning

The use of the improved enhanced HBP system makes a compelling case for its adoption. Not only does it provide superior impact and abrasion protection and increase in-service longevity to the bar but it also for the first time provides a complete CARC stackup in full compliance with the MIL-DTL-53072 CARC application specification. The prior HBP system successfully used by the USMC was already an improvement over the tape-based solution; however, the new system greatly improves upon the USMC system through the use of optimized surface peening procedures, a corrosion-inhibiting surface pretreatment, a greatly improved MIL-DTL-53022 Type 4 primer, and the availability of two qualified HBP coating products under MIL-PRF-32440. During current reset procedures, the current bars are removed and then are often stored outdoors due to indoor space limitations. Due to the prior mentioned shortcomings of the current torsion bar coating systems these outdoor stored bars rapidly corrode and are thereby rendered unserviceable. These bars then must be either reworked or scrapped depending upon the extent of the accrued damage. The adoption of the enhanced HBP coating system for torsion bars can mitigate this level of waste via two reset pathway options: immediate turn around or enhanced protection for outdoor storage. The first option calls for reuse and reinstallation of the same set of bars back into the system it was removed from once it has been reprocessed or remanufactured and is ready for reinstallation. The second option is for outdoor storage, similar to the process that is followed for the current bars but differing by the small but significant addition of protective grease caps to protect the uncoated splines portion of the bars. This level of storage has already been proven successful at the Cape Canaveral beach site and the bars themselves have proven to be quite robust in tolerance to typical handling and various impacts. In the rare and unlikely case of an extreme impact event where the surface was somehow impacted or abraded through to expose the substrate, a repair procedure now exists to prevent reworking of the entire bar.

5. Conclusions

The Line-X and Dragonhide stackups performed significantly better than the tape-based system currently in place on Bradley. Impact testing showed that the Dragonhide system has a slight edge on Line-X XS-100 in terms of protection due to its softer and more elastic nature. These differences could be explained by the stippled surface of the Dragonhide application versus the flat, smooth application given to the LineX. The increased surface area and complex geometry of the surface texture could potentially absorb impacts better than a flat surface. Additional testing of flat versus stippled textures would be required to account for this. It should be noted that a stippled finish is easily attainable on the Line-X product but was not used in this study to purposefully match the AAV high build system. Accelerated corrosion testing yielded more definitive results, showing the Bonderite M-NT 7400 with the enhanced primer MIL-DTL-53022 Type IV to be the superior system in terms of corrosion protection. Though accelerated corrosion laboratory testing is important, the true test of corrosion lies in real-world exposure. Then completion of outdoor exposure testing at CCAFS and the demonstration at Fort Benning continues to demonstrate the durability of both HBP coating systems and reaffirmed the necessity of using a pretreatment and an enhanced primer such as 53022 Type IV. In addition, the testing achieved the original project goal to identify an additional competitive high-build system that offers similar or superior performance to the current system deployed on the AAV. This study also helped to determine an exhaustive template of test criteria for future qualifications of additional competitive systems. As such, ARL took ownership of the specification governing HBP coatings, MIL-PRF-32440, and updated it to adapt to and allow for the implementation of the newer HBP coatings. This specification includes a qualified products database, the first products of which were qualified through this study. Several additional qualifications are in process as of the time of this writing.

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List of Symbols, Abbreviations, and Acronyms

AAV	Amphibious Assault Vehicle
ARL	Army Research Laboratory
CCAFS	Cape Canaveral Air Force Station
CCDC	US Army Combat Capabilities Development Command
DFT	dry film thickness
HBP	high-build polyurea
IAW	in accordance with
NaCl	salt
MPY	mils per year
RH	relative humidity
OQE	objective quality evidence
USMC	US Marine Corps

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