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Corrosion Control for Navy Ships (CCNS): Improving the Performance of Protective Coatings

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14. ABSTRACT

The following document provides the final results for work package (WP) 3 of the Corrosion Control for Navy Ships (CCNS) program. WP3, Improving the Performance of Protective Coatings, included 3 separate studies to evaluate baseline performance of standard Navy coatings in various accelerated and natural weathering environments; characterization of corrosivity and weathering effects of a shipboard environment, and an evaluation of different abrasives for surface preparation. The contributions to this document are from the U.S. Navy only and are provided through International Exchange Agreements (IEA) and Data Exchange Agreements (DEA) operated by the Department of Defense and Department of the Navy.

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Table of contents

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1 Project overview

The following document provides the final results for work package (WP) 3 of the Corrosion Control for Navy Ships (CCNS) program. WP3, Improving the Performance of Protective Coatings, included 3 separate studies to evaluate baseline performance of standard Navy coatings in various accelerated and natural weathering environments, characterization of corrosivity and weathering effects of a shipboard environment, and an evaluation of different abrasives for surface preparation. The contributions to this document are from the US Navy only and are provided through International Exchange Agreements (IEA) and Data Exchange Agreements (DEA) operated by the Department of Defense and Department of the Navy. The full list of international organizations contributing to WP3 is listed in Table 1.

Table 1: WP3 participating partners

Organization	Nation	Short name
Institute de la Corrosion	France	IC
DGA AS	France	DGA AS
DCNS	France	DCNS
BWB WIWEB	Germany	WIWEB
BAE Systems	UK	BAES
University of Southampton	UK	UoS
Centro Sviluppo Materiali	Italy	CSM
Consiglio Nazionale delle Ricerche	Italy	CNR-ISMAR
Naval Research Laboratory	US	NRL

WP3 includes eight Work Elements (WE) listed below and identify the involved partners (WE leads and participants). NRL is contributing as a participant to WE 3.2, 3.6 and 3.7.

WE 3.1 Selection of coating systems for manufacture of samples

Leader: BAES; Participants: IC, DGA, DCNS, WIWEB, CSM, CNR-ISMAR

WE 3.2 Accelerated ageing of coatings for atmospheric exposure

Leader: IC; Participants: DGA, WIWEB, BAES, CSM, CNR-ISMAR, NRL

WE 3.3 Accelerated ageing of coatings for immersion

Leader: BAES; Participants: IC, WIWEB, CSM, CNR-ISMAR

WE 3.4 Evaluation of alternative/emerging coating systems

Leader: CSM; Participants: IC, DGA, WIWEB, BAES, CSM

WE 3.5 Database design

Leader: IC; Participants: WIWEB, BAES, CSM, CNR-ISMAR

WE 3.6 Coating degradation mechanisms

Leader: WIWEB; Participants: IC, DCNS, WIWEB, BAES, CSM, CNR-ISMAR, NRL

Manuscript approved October 8, 2019.

WE 3.7 Surface preparation and paint application

Leader: BAES; Participants: WIWEB, CSM, NRL

WE 3.8 In-situ monitoring of coating behaviour/importance

Leader: BAES; Participants: IC, DGA, WIWEB

WORK UNDERTAKEN:	WE3.2 • Completed accelerated aging testing of topcoats in accordance with ASTM G155, Cycle 1 (xenon-arc), ASTM G154, Cycle 1 (UV-A) and ASTM G154 Cycle 2 (UV-B). • Completed natural exposure testing in Key West, FL. • Completed shipboard exposure testing on an LPD 17 San Antonio class ship. • Measured coating properties data as panels were removed from accelerated and natural exposures at specified intervals. • Finished data analysis. WE3.6 • Design, preparation, and deployment of sample and sensor panels on an LPD 17 San Antonio class ship. • Removed test samples and sensors from LPD 17 class ship. WE3.7 • Abrasive blasting of steel with a variety of abrasive materials to determine effect of process parameters on resultant surface morphology and subsequent coating performance.
MAIN RESULTS:	WE3.2 • Completed data collection for the following coating properties: color, gloss, lightness, contact angle, glass transition temperature, and hardness • When compared to shipboard data, coating properties degrade 1.6 times faster in Key West, 5.4 times faster in xenon-arc, 7.4 times faster in QUV-A, and 10.8 times faster in QUV-B • Coatings should be tested for 270 days in Key West, 2000 hours in xenon-arc, 2000 hours in QUV-A and 1000 hours in QUV-B to represent 1-year shipboard testing for a ship home ported in Norfolk, VA. • All data collected at the above time intervals correlated well with shipboard test data. Correlation coefficients ranged from 0.83 – 0.96. • For the accelerated test methods, natural exposure in Key West, FL and xenon-arc data produced the lowest percent error when compared to the shipboard data. WE3.6

	• Panels were prepped with 7 coating systems and deployed to 5 locations on one ship (along with corrosion sensor, temp/rh sensor, silver, and steel coupons. • Steel corrosion rate was on average 127 and 367 g/m^2 for the 6 and 10 month exposures, respectively. The Key West mass loss was 50 and 183 g/m^2 for 6 and 12 months, respectively. (KW was approximately half the rate of corrosion on the LPD 17 class ship.) WE3.7 • Abrasive particle size has the largest effect of all variables on the resultant surface profile and density of roughness peaks. • Enhanced measurement techniques provide additional value in quality assurance of prepared surfaces. • Scale up abrasive blasting confirmed blasting between 80-100 psi and 18-24 inch standoff had only nominal effect on profile produced by any given type/size of abrasive. • Once through blasting with Garnet and Aluminum Oxide abrasives showed ability to recapture and reuse approximately 60-70% of abrasive in an effective manner.
FUTURE WORK TO BE UNDERTAKEN:	WE 3.2 • None WE 3.6 • None WE 3.7 • None
ON SCHEDULE (*YES/NO*):	YES
PROBLEMS ENCOUNTERED:	NONE
CORRECTION – ACTIONS:	N/A
PUBLICATIONS – PATENTS:	NONE

2 Deliverables and milestones

Milestone	USWE	Responsible	Original Comp. Date	Actual Comp. Date	Description	
M1	3.2	NRL/Tagert	DEC 2014	DEC 2014	Coating test matrix	☑
M2	3.2	NRL/Tagert	FEB 2015	FEB 2015	Delivery of painted samples for testing (accelerated, atmospheric and shipboard)	☑
M3	3.2	NRL/Tagert	SEP 2015	DEC 2015	Finish accelerated testing	☑
M4	3.2	NRL/Tagert	FEB 2016	MAY 2017	Finish atmospheric testing (2 years)	☑
M5	3.7	NRL/Kogler	APR 2015	AUG 2015	Complete comparative abrasive blasting testing and measurement: lab scale	☑
M6	3.7	NRL/Kogler	MAY 2015	DEC 2015	Complete abrasive blasting productivity study	☑
M7	3.7	NRL/Kogler	DEC 2016	DEC 2015	Complete testing of coating performance on abrasive blasted variants	**Did not complete**
M8	3.6	NRL/Sanders	DEC 2014	DEC 2014	Identify candidate ship and 4-5 locations onboard for 1st year corrosivity/weathering map	☑
M9	3.6	NRL/Sanders	DEC2014	DEC 2014	Design test set-up for 1st year ship-based testing	☑
M10	3.6	NRL/Sanders	MAR2015	SEP2015	Install experiment package to 4-5 locations onboard 1st year ship	☑

M11	3.6	NRL/Sanders	MAR2016	SEP 2016	Finish 1st year ship-based testing	☑
M12	3.6	NRL/Sanders	OCT2015		Identify candidate ships (3-4) and 1-2 locations onboard for 2nd year corrosivity/weathering (cross-platform) test (6 month)	**Did not complete**
M13	3.6	NRL/Sanders	OCT2015		Design test set-up for 2nd year ship-based testing	☑
M14	3.6	NRL/Sanders	FEB2016		Install experiment package to 3-4 ships and 1-2 locations onboard 2nd year ship	**Did not complete**
M15	3.6	NRL/Sanders	AUG2017		Finish 2nd year ship-based testing	☑
M16	3.6	NRL/Sanders	JUN2017		Design standardized “improved geometry” test specimens	**Did not complete**
M17	3.6	NRL/Sanders	AUG2017		Deploy improved geometry samples on-board ships, at atmospheric sites, and accelerated testing	**Did not complete**
M18	3.6	NRL/Sanders	FEB2018		Finish testing improved geometry specimens	**Did not complete**

Deliverable	**Responsible**	**Estimated Due Date**	**Actual Due Date**	**Content**	
D1	NRL/Tagert	DEC 2015	DEC 2015	Accelerated testing data package for exterior topcoats (weathering)	☑
D2	NRL/Tagert	JUN 2016	MAY 2017	Atmospheric testing data package for exterior topcoats (weathering)	☑
D3	NRL/Tagert	JUN 2016	SEP 2016	Shipboard testing data package for exterior topcoats (weathering)	☑
D4	NRL/Tagert	SEP 2016		Comparison of accelerated, atmospheric and shipboard exterior topcoats	☑
D5	NRL	APR 2015	APR 2015	Progress Report 3 (meeting presentation)	☑
D6	NRL	SEP 2015	NOV 2015	Progress Report 4 (CCNS format)	☑
D7	NRL	APR 2016		Progress Report 5 (CCNS format)	**Did not complete**
D8	NRL	SEP 2016		Final Report (CCNS format)	☑
D9	NRL/Kogler	APR 2015	DEC 2015	Initial Report on Surface Preparation Comparative Study: Abrasives and Profile Measurement	☑
D10	NRL/Kogler	OCT 2015	DEC 2015	Final Report on Surface Preparation Comparative Study: Abrasives and Profile Measurement	☑
D11	NRL/Kogler	FEB 2016	DEC 2015	Surface Preparation Report: Profile and Contamination vs. Adhesion and Performance	☑

3 Scientific and technical achievements

3.2 WE 3.2 Accelerated ageing of coatings for atmospheric exposure

*3.2.1 **Background***

The legacy United States Navy (USN) topside coatings—silicone alkyds—have proven to have poor color and gloss stability resulting in aesthetically unattractive ships that are difficult to clean. Given that ship appearance is the predominant component in maintenance decision making and is related to the pride and professionalism of Ship's Force, the USN needlessly expends significant dollars and time cosmetically over coating ship topside areas due to "pinking", chalking, and staining (running rust). This problem is further exasperated by the fact that frequent over coating by Ship's Force leads to additional coating failures, such as cracking and delamination, due to poor surface preparation and excessive build up in coating thickness. This leaves maintenance decision makers with one option of removing the existing coating system to bare metal and represerving the entire topside and freeboard during dry dock availabilities.

Recent efforts in the US have focused on the implementation of polysiloxane coatings for improved UV resistance, color retention, gloss retention and cleanability. NRL has been studying the weathering performance of such coatings along with fluoropolyurethanes and silicone alkyds for some time. This work has resulted in valuable insights into the utility of traditionally specified accelerated tests vs. other commercially available testing regimes. Of particular interest are the effects of UV-A vs. UV-B exposure methods under ASTM G154. Closely related to this question is the relative utility of xenon-arc exposure as described in ASTM G155. Prior results have been encouraging in terms of characterizing the relative weatherability of marine topcoats using these methods. NRL proposes to continue these evaluations on the coatings of interest to the subject program.

*3.2.2 **Approach***

In this effort, NRL expanded the scope of the study to determine the appropriate accelerated test methodology for the determination of weathering resistance for USN ships. NRL exposed topcoats of various chemistries according to standard and modified methods for UV-A, UV-B and xenon-arc (i.e., full spectrum UV) exposures. NRL executed the above accelerated tests in conjunction with replicate panels placed on NRL's marine exposure test racks in Key West, FL. Coating properties measured included:

- Color change – color degradation caused by several variables including chalking, yellowing and pigment degradation
- Lightness – change in lightness of coating caused by chalking
- Gloss – resin degradation and surface roughness
- Contact angle – surface degradation
- Glass transition (Tg) – brittleness caused by increasing cross-link density
- Hardness – indication of cross-link density

In addition to natural exposures in Key West, FL, an identical set of coupons were deployed on board an active USN ship for comparison. The first set of shipboard exposure racks were deployed on a ship on the east coast of the United States in the Norfolk, VA area. After all of the accelerated, atmospheric and shipboard exposure data was collected, the data was analyzed to determine which exposure method most closely simulated the shipboard exposure environment.

3.2.3 Coatings

The following topcoats were selected for testing:

Table 2 – Topcoats applied for testing

Paint	Manufacture	Product Name	Abbreviation	Specification	Chemistry
1	NCP Coatings	N-9677	1K Poly	N/A	One component, moisture curable N-substituted urea siloxane
2	International Paint	Interfine 979SG	2K Poly	MIL-PRF-24635	Two component, hybrid amine/acrylic with moisture curable siloxane
3	Amercoat	MILP	2K Epoxy	MIL-DTL-24441	Two component, polyamide epoxy
4	Sherwin Williams	Silicone Alkyd	1K Alkyd	MIL-PRF-24635	One component, silicone alkyd
5	Sherwin Williams	LSA Silicone Alkyd	1K LSA Alkyd	MIL-PRF-24635	One component, silicone alkyd
6	PPG	PSX-700SG	2K Poly	MIL-PRF-24635	Two component, hybrid amine/epoxy with moisture curable siloxane

3.2.4 Sample fabrication

Test coatings were applied directly to 2”x3” aluminium panels for testing, as seen in Figure 1. A total of 420 panels were coated by drawdown for testing. A primer was not included as part of the coating system, therefore, the panels were power sanded using 80-grit sandpaper to improve the adhesion of the coating to the test panel.

*The standard size test panel used for accelerated weathering tests is 3”x6”, however, due to the number of coating systems and replicates required, a smaller test panel was selected so all test panels could fit in the accelerated test chambers at the same time.

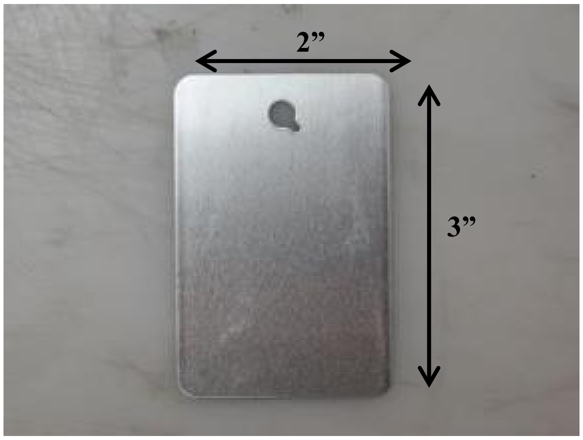


Figure 1 – Bare test panel

The drawdowns were made using an adjustable drawdown bar, as seen in Figure 2. The gap clearance of the drawdown bar was adjusted for each coating in order to apply the desired wet film thickness (WFT). Typically, the edges of a drawdown bar will slide on the test panel being coated, however, due to the small size of the CCNS test panels the edges of the drawdown bar slid outside the panels. To control film thickness, spot WFT measurements were taken using a notched WFT gauge. The final dry film thickness results are provided in Table 3.

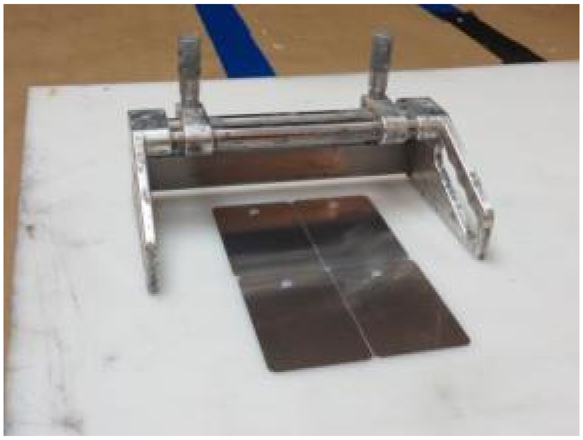


Figure 2 – Adjustable drawdown bar used for coating application

Table 3 – DFT measurements

	Paint #1	Paint #2	Paint #3	Paint #4	Paint #5	Paint #6
Average	2.6	5.6	4.2	3.6	3.2	5.3
Maximum	9.2	9.1	7.2	5.9	5.0	8.0
Minimum	0.9	1.5	0.9	1.0	1.0	1.8
Stdev	1.2	1.5	1.5	1.1	1.2	1.7

3.2.5 Exposure methods

Both accelerated and natural exposure methods were utilized to evaluate performance of the topcoats. The accelerated test methods selected were ASTM G155 and ASTM G154, which are commonly found in coating specifications for evaluating the performance of exterior topcoats. Natural exposure testing was performed in Key West, FL, as well as on an active USN ships. At the conclusion of testing the accelerated test data was compared to the natural test data to determine which accelerated test method had the best representation of the shipboard exposure environment. For the purposes of this study and data evaluation, the shipboard exposure will be the baseline data set that all accelerated methods will be compared to. Key West will be considered, and referred to, as an accelerated method from this point forward.

3.2.5.1 ASTM G155

ASTM G155 is the "Standard Practice for Operating Xenon Arc Light Apparatus for Exposure of Non-Metallic Materials." The test chamber uses a xenon light source and daylight filter to produce a light spectrum that closely matches natural sunlight from 300-800 nm. Other adjustable parameters that affect coating deterioration include irradiance, temperature, moisture and filter type. The test chamber settings used for this program are provided in Table 4.

Table 4 – Test settings for ASTM G155, Cycle 1

Duration	4000 hours
Filter	Day light
Irradiance	0.35 W/m^2
Step 1	102 minutes light at 63°C
Step 2	18 minutes light and water spray
Step 3	Return to Step 1

A picture of the test panels in the xenon arc test chamber is provided in Figure 3. During exposure testing, the panels lay on a flatbed tray that is slightly angled to allow for water runoff. All surfaces inside the chamber are lined with mirror like sheeting to maximize light reflection.

Figure 3 – Test panels in xenon arc test chamber

3.2.5.2 ASTM G154

ASTM G154 is the "Standard practice for Operating Fluorescent Ultraviolet (UV) Lamp Apparatus for Exposure of Nonmetallic Materials." Two cycles were selected for testing, Cycle 1 and Cycle 2 (modified – condensation at 40ºC). Both use a combination of UV light, condensing water and heat to degrade the coatings. The main difference between the two exposure methods is the type of fluorescent bulb used. Cycle 1 uses a UV-A bulb with a peak intensity of 340 nm and Cycle 2 (modified) uses a UV-B bulb with a peak intensity of 313 nm. Like the xenon arc light, the UV-A bulb has a light spectrum close to natural sunlight, but only up to 340 nm before the irradiance begins dropping back to zero. The UV-B light spectrum contains wavelengths of light less than 300 nm, which are responsible for rapid degradation of polymers. The chamber settings for Cycle 1 and Cycle 2 (modified) are provided in Table 5 and Table 6, respectively.

Table 5 – Test settings for ASTM G154, Cycle 1

Duration	4000 hours
Filter	None
Irradiance	0.89 W/m^2
Step 1	8 hours UVA light at 60ºC
Step 2	4 hours condensation at 50ºC
Step 3	Return to Step 1

Table 6 – Test settings for ASTM G154, Cycle 2 (modified)

Duration	4000 hours
Filter	None
Irradiance	0.71 W/m^2
Step 1	4 hours UVB light at 60ºC
Step 2	4 hours condensation at **40ºC**

Step 3	Return to Step 1

A picture of the test panels in the UV test chamber is provided in Figure 4. The same chamber is used for both Cycle 1 and Cycle 2, the only difference are the type of bulb used inside the chamber and exposure settings. To maximize space within the test chamber, four test panels were placed sideways within the standard panel holder for the UV chamber. Typically the panel holder would accommodate two 3"x6" panels; however, because of the smaller size test panel and placement orientation a standard panel holder could accommodate four test panels.


(a) (b)

Figure 4 – Test panels in UV chamber (a) and test panel holder (b)

3.2.5.3 Key West, FL

Test panels were exposed in Key West, FL on a test fence with a 45-degree south facing rack located less than 100 feet from the ocean high tide line per the requirements of MIL-PRF-24635. The average temperature in Key West varies between 68 and 86ºF (20 and 30ºC) depending on the time of year, with the highest average temperature in August and lowest average in January. On a normal, sunny day the average solar radiation will fluctuate between 800 and 1000 W/m^2 between 11am and 3pm. A picture of the exposure rack and test panels is provided in Figure 5.

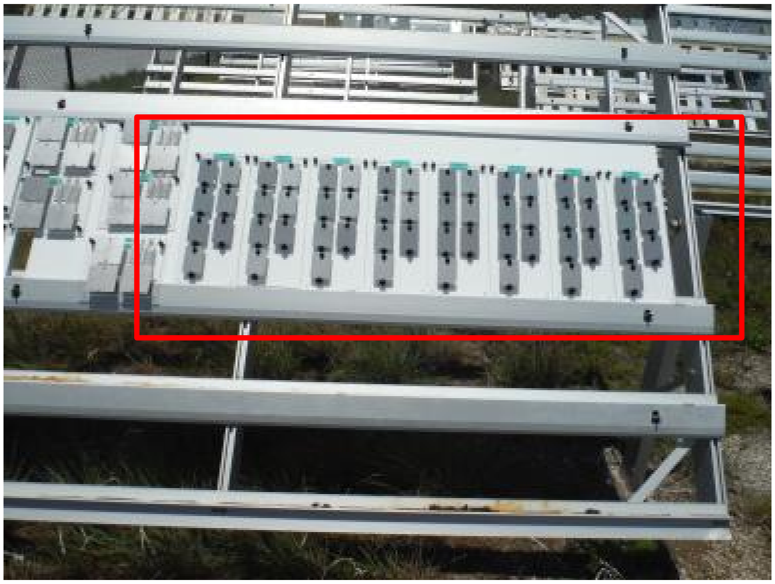


Figure 5 – Test panels on exposure fence in Key West, FL

3.2.5.4 <u>Shipboard exposure</u>

Test panels were also deployed in 5 different locations on an LPD 17 San Antonio class ship. This provides a unique opportunity to determine how paint degradation and aging on a mobile platform compares to static test panels from either accelerated or natural exposures. The conditions (temperature, solar radition, time of wetness, etc.) of each exposure location are unknown, however, the placement of the exposure racks in each location should provide information about rate of degradation depending on the exposure conditions. For example, one exposure rack was placed on a catwalk beneath an overhead structure so it should be exposed to less UV light and temperature cycling than the exposure racks placed on an upper level deck that are not sheltered.

Figure 6 – Exposure rack deployed on an LPD 17 class ship

<u>3.2.6 Test panel measurements</u>

Test panels were removed from exposure testing at specified intervals in order to obtain degradation data. Panels in accelerated testing were removed every 500 hours until 4000 hours was complete. Panels in natural exposure were removed at 30, 60, 90, 180, 270, 360, 540 and after 720 days (or 2 years) of testing. The test panels deployed on board ship were removed at a time that the ship was accessible (docked pier side), with the hope of being able to retrieve samples at 6 and 12 months. At each time interval the following measurements were made:

Table 7 – Test panel measurements

Property	Specification	Instrument	Comments
Color	ASTM E1347	Hunter MiniScanEZ Model 4000L and 4500L D65 light source, 10° observer	Average of 3 measurements
Gloss	ASTM D523	BYK Gardner 60° micro-gloss	Average of 5 measurements
Contact angle	ASTM D7334	Rame-Hart Instrument Company Model H90-F4	Average of 6 angle measurements 10µL droplet size
Glass transition tempearture	ASTM E1356	TA Instruments Q100 DSC	Equilibrate at -50.00°C Modulate +/- 1.00°C every 60 seconds Isothermal for 5.00 min Ramp 3.00°C/min to 150°C
Hardness	ASTM D4366	Paul N. Gardner Co., Inc. Model HA-5854	König Start 6°, end 3°
Lightness (chalking)		Hunter MiniScanEZ Model 4000L and 4500L D65 light source, 10° observer	Average of 3 measurements

3.2.7 ***Test results***

Data for the measurements listed in Section 3.2.6 are provided below. Data was measured at various intervals. For accelerated test methods, panels were measured every 500 hours for a total of 4000 hours total exposure time. For accelerated exposure in Key West, panels were measured at 30, 60, 90, 180, 270, 365, 540, and 720 days. Shipboard test panels were installed on an LPD 17 class ship for 365 days (1 year).

After all data was collected, the rate at which the coating properties degraded in each of the exposure conditions was determined by regression analysis and compared to the shipboard data. This provided an estimation for the recommended amount of testing time that would be equal to 1-year of shipboard testing for the accelerated exposures. Once the estimated testing time was calculated, the closest set of actual test data that corresponds to the estimated test time was pulled from the dataset and used to calculate the percent error between the shipboard data and accelerated test data to determine the best accelerated test method.

The graphs provided in sections 3.2.7.1 – 3.2.7.7 were created by calculating the difference between the initial value for each coating property and value measured at each measurement interval to give the overall change. Then, the differences were added together for all of the coatings tested to determine the total degradation caused by each exposure method for the entire panel set.

For example, the data in Table 8 is the color difference measured at each measurement interval for all coatings in xenon-arc exposure. The column highlighted in yellow is the summation of dE for all coatings, which represents the total color change for the panel set. The column highlighted in yellow is an example of the data used to generate the line graphs in section 3.2.7.1 – 3.2.7.6.

Table 8 – Color difference (dE) data for six coatings tested in xenon-arc

dE	1K Poly	2K Poly	Epoxy	SA	SA	2K Poly	All
0	0	0	0	0	0	0	0
500	0.57	0.74	5.59	1.68	2.25	0.33	11.16
1000	0.83	0.82	6.38	2.15	3.07	0.42	13.67
1500	1.53	1.46	6.25	2.78	4.69	0.76	17.47
2000	1.26	1.1	6.04	2.38	3.51	1.11	15.4
2500	1.91	2.11	7.01	3.31	5.57	2.91	22.82
3000	2.24	1.92	7.15	3.77	6.48	1.61	23.17
3500	2.57	2.46	7.19	4.16	7.66	2.34	26.38
4000	3.07	3.2	7.35	4.82	8.91	2.9	30.25

3.2.7.1 Color

The color of each test panel at different time intervals is measured using CIELab three dimensional coordinates. The magnitude of the color change was determined by calculating the distance between the initial color of the test panel and the color measured at the inspection time interval. The magnitude of color change is referred to as delta E (dE). The data provided in Figure 7 is the summation of dE for all six coatings taken at each measurement interval. The data is organized by exposure method in order to compare severity. The horizontal blue line represents the average value of 3 measurements taken from panels exposed topside on an LPD 17 San Antonio class ship after 1 year of exposure. During that time period, the ship was either pier side or deployed to an unknown location. It was estimated the ship was pier side for 6 months and deployed for 6 months (this applies to all shipboard data in sections 3.2.7.1 – 3.2.7.6). The raw data is provided in Appendix 1.

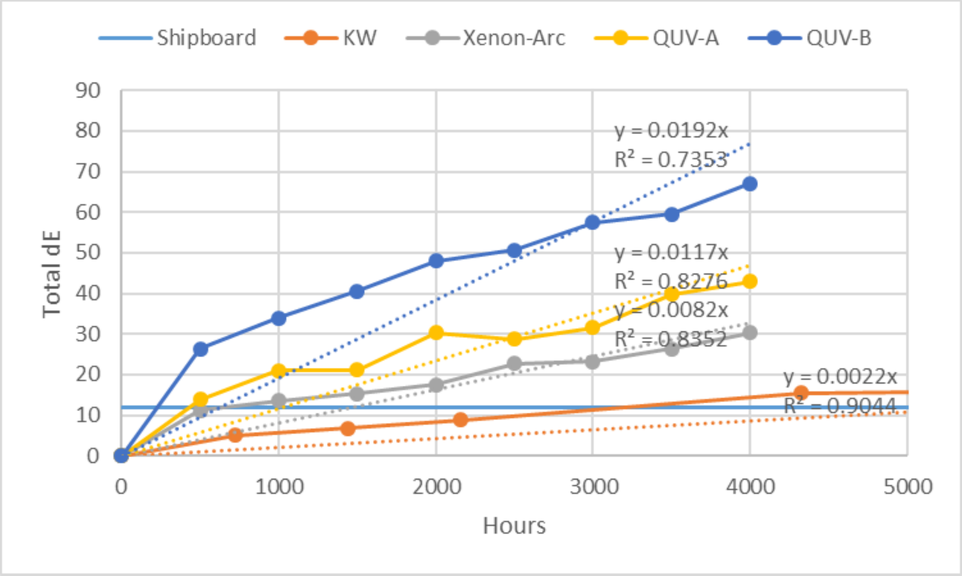


Figure 7 – Total color change (dE) by exposure method

The total dE for the panel set for the shipboard exposure after 1 year was 11.91. Linear regression was used to fit a line to each set of data to determine a rate of change (or slope, m, of the line). The rate of change for each line was then used to estimate the amount of time it took in each exposure method to equal 11.91 (total change divided by slope). The data for each exposure method is provided in Table 9 below.

Table 9 – Rate of change of dE for various accelerated methods

	Total dE after one year on ship	**Rate of change for each accelerated method**	**Estimated amount of time for accelerated method to equal 1 year on ship**
Key West (KW)	11.91	0.0022	5413
Xenon-arc	11.91	0.0082	1452
QUV-A	11.91	0.0117	1017
QUV-B	11.91	0.0192	620

3.2.7.2 Gloss

Each gloss measurement taken was an average of 5 readings per test panel. A 60° gloss meter is recommended for semi-gloss coatings and each of the test panels except for the epoxy (paint #3) had an initial gloss in the semi-gloss range. For consistency, the 60° gloss meter was used for all measurements even when the test panels degraded to low gloss coatings. The data provided in Figure 7 is the summation of dE for all six coatings taken at each measurement interval. The data is organized by exposure method in order to compare severity. For the purposes of improving the linear regression model, the accelerated data was truncated at 2000 hours. The horizontal blue line represents the value measured after 1 year of shipboard exposure. The raw data is provided in Appendix 1.

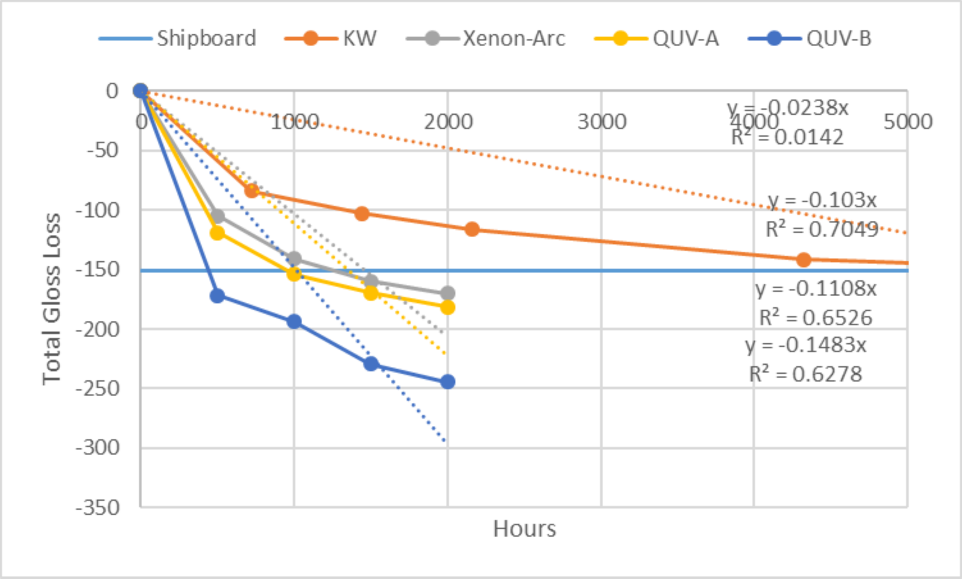


Figure 8 – Total gloss loss data by exposure method

The total gloss loss for the panel set for the shipboard exposure after 1 year was -150.9 gloss units (GU). Linear regression was used to fit a line to each set of data to determine a rate of change (or slope (m) of the line). The rate of change for each line was then used to estimate the amount of time it took in each exposure method to equal -150.9 (total change divided by slope (m)). The data for each exposure method is provided in Table 10 below.

Table 10 – Rate of change of gloss for various accelerated methods

	Total gloss loss after one year on ship	Rate of change for each accelerated method	Estimated amount of time for accelerated method to equal on year 1 ship
Key West (KW)	-150.9	-0.0238	6340
Xenon-arc	-150.9	-0.1030	1465
QUV-A	-150.9	-0.1108	1362
QUV-B	-150.9	-0.1483	1018

3.2.7.3 Contact angle

Each contact angle measurement was an average of 6 angle measurements per test panel. The test panel was wiped clean using high purity water and a wiping cloth before each measurement. The droplet volume was 10 µL and the angle on each side of the droplet was measured and averaged together to provide a single contact angle. For each droplet measured, if the opposing angles were significantly different additional droplets were tested. The data provided in 9 is the summation of contact angle change for all six coatings taken at each measurement interval. The data is organized by exposure method in order to compare severity. For the purposes of improving the linear regression model, the accelerated data was truncated at 3000 hours. The horizontal blue line represents the value measured after 1 year of shipboard exposure. The raw data is provided in Appendix 1.

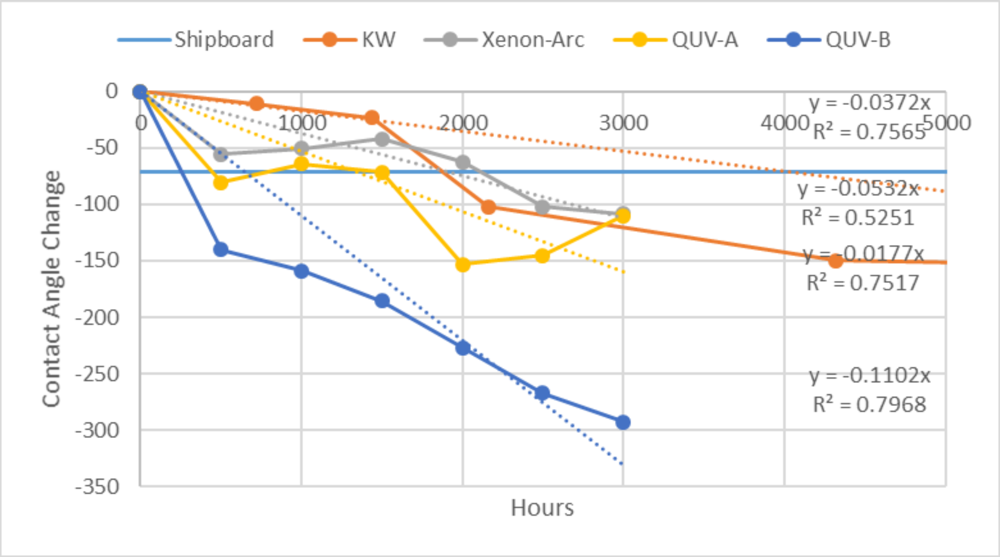


Figure 9 – Total contact angle change by exposure method

The total contact angle change for the panel set for the shipboard exposure after 1 year was -70.8 gloss units (GU). Linear regression was used to fit a line to each set of data to determine a rate of change (or slope (m) of the line). The rate of change for each line was then used to estimate the amount of time it took in each exposure method to equal -70.8 (total change divided by slope (m)). The data for each exposure method is provided in Table 11 below.

Table 11 – Rate of change of contact angle for various accelerated methods

	Total contact angle change after one year on ship	**Rate of change for each accelerated method**	**Estimated amount of time for accelerated method to equal 1 year on ship**
Key West (KW)	-70.8	-0.0177	4000
Xenon-arc	-70.8	-0.0372	1903
QUV-A	-70.8	-0.0532	1331
QUV-B	-70.8	-0.1102	642

3.2.7.4 Glass transition temperature (Tg)

The Tg is measured in degrees Celsius and the value reported is the midpoint glass transition based on the inflection point of the curve. Samples of coating were removed from the lower half of the test panels using shears in order to obtain a free film. The coating was either peeled or scraped from the cut panels. The data provided in 10 is the summation of Tg change for all six coatings taken at each measurement interval. The data is organized by exposure method in order to compare severity. The horizontal blue line represents the value measured after 1 year of shipboard exposure. The raw data is provided in Appendix 1.

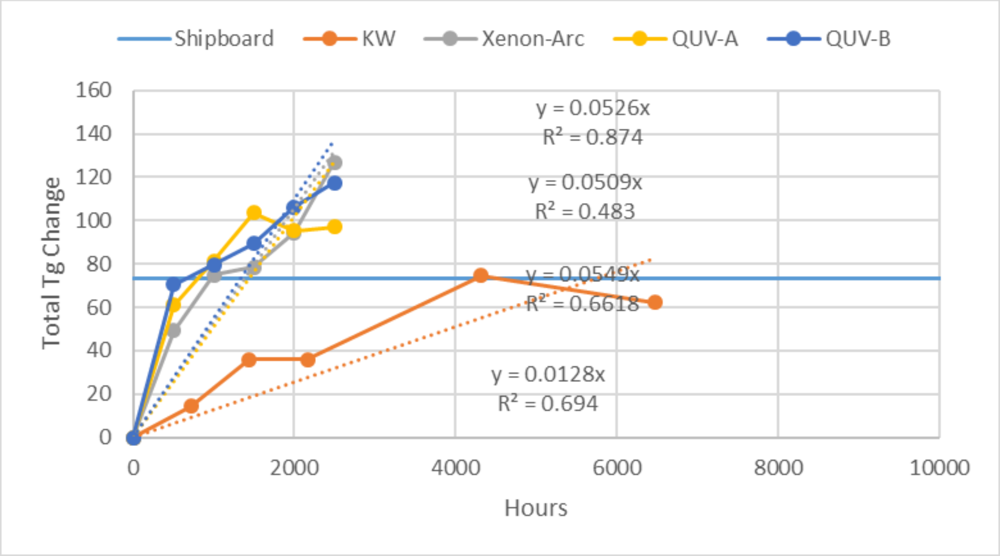


Figure 10 – Total Tg change by exposure method

The total Tg change for the panel set for the shipboard exposure after 1 year was 73.2. Linear regression was used to fit a line to each set of data to determine a rate of change (or slope (m) of the line). The rate of change for each line was then used to estimate the amount of time it took in each exposure method to equal 73.2 (total change divided by slope (m)). The data for each exposure method is provided in Table 12 below.

Table 12 – Rate of change of Tg for various accelerated methods

	Total Tg change after one year on ship	Rate of change for each accelerated method	Estimated amount of time for accelerated method to equal 1 year on ship
Key West (KW)	73.2	0.0128	5719
Xenon-arc	73.2	0.0526	1392
QUV-A	73.2	0.0549	1333
QUV-B	73.2	0.0509	1438

3.2.7.5 Hardness

Pendulum hardness was determined as another means of evaluating cross-link density change of the coating as a result of temperature and moisture exposure. A König type pendulum was used to determine the number of oscillations required for the coating to dampen the swinging pendulum from 6° to 3°. A softer coating will dampen the swinging pendulum faster, where as a harder coating will take longer. For reference, the calibration surface glass and it takes approximately 175 oscillations to dampen the pendulum from 6° to 3°. The data provided in Figure 11 is the summation of hardness change for all six coatings taken at each measurement interval. The data is organized by exposure method in order to compare severity. The horizontal blue line represents the value measured after 1 year of shipboard exposure. The raw data is provided in Appendix 1.

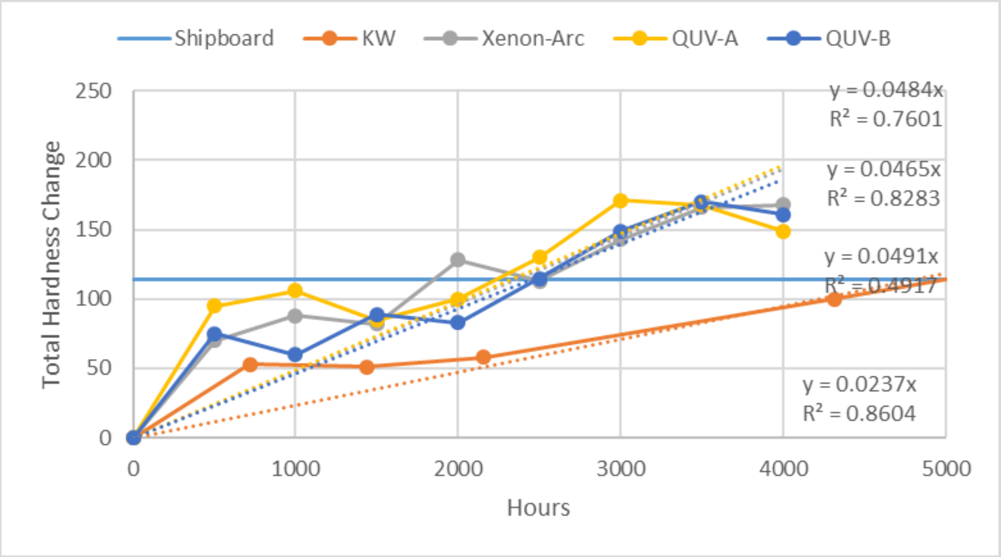


Figure 11 – Total hardness change by exposure method

The total hardness change for the panel set for the shipboard exposure after 1 year was 114. Linear regression was used to fit a line to each set of data to determine a rate of change (or slope (m) of the line). The rate of change for each line was then used to estimate the amount of time it took in each exposure method to equal 114 (total change divided by slope (m)). The data for each exposure method is provided in Table 13 below.

Table 13 – Rate of change of hardness for various accelerated methods

	Total Hardness change after one year on ship	Rate of change for each accelerated method	Estimated amount of time for accelerated method to equal 1 year on ship
Key West (KW)	114	0.0237	4810

Xenon-arc	114	0.0484	2355
QUV-A	114	0.0491	2322
QUV-B	114	0.0465	2452

3.2.7.6 Lightness

Lightness, or delta L, was isolated in the CIELab color measurement and used as an indicator for coating chalking. Chalking is the migration The data provided in Figure 12 is the summation of hardness change for all six coatings taken at each measurement interval. The data is organized by exposure method in order to compare severity. The horizontal blue line represents the value measured after 1 year of shipboard exposure. The raw data is provided in Appendix 1.

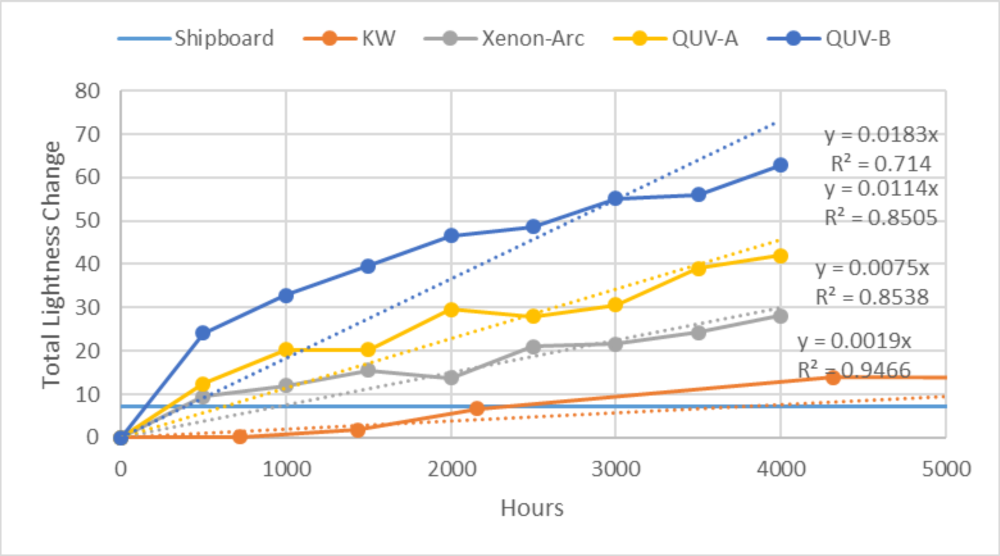


Figure 12 – Total lightness change by exposure method

The total lightness change for the panel set for the shipboard exposure after 1 year was 7.08. Linear regression was used to fit a line to each set of data to determine a rate of change (or slope (m) of the line). The rate of change for each line was then used to estimate the amount of time it took in each exposure method to equal 7.08 (total change divided by slope (m)). The data for each exposure method is provided in Table 14 below.

Table 14 – Rate of change of lightness for various accelerated methods

	Total lightness change after one year on ship	Rate of change for each accelerated method	Estimated amount of time for accelerated method to equal 1 year on ship
Key West (KW)	7.08	0.0019	3726
Xenon-arc	7.08	0.0075	944
QUV-A	7.08	0.0114	621
QUV-B	7.08	0.0183	387

3.2.8 Percentage error

The main objective of the study was to compare different accelerated test methods, including exposure in Key West, FL, to determine which accelerated method simulates 1 year of shipboard exposure testing most accurately and how long the test should be performed. This was done by measuring various coating properties to determine how they change over time, but rather than use a single property, such as dE, to determine which accelerated test method best simulates the shipboard environment, the study evaluated seven different coating properties to make a more robust comparison. To do this, the following steps were taken:

1. Determine the rate of change for each coating property using the total data for each panel set. This information is provided in Tables 9 – 14.
2. Use the rate of change to estimate the amount of testing time required for the accelerated methods to equal the data collected during 1 year of shipboard testing and average. This information is compiled in Table 15.

Note: up to this point, total data has been used to determine degradation rates and to calculate the estimated amount of testing time.

Table 15 – Estimated amount of time (hrs) a coating must be tested in an accelerated method to equal 1 year of shipboard testing

	dE (hrs)	Gloss (hrs)	Contact angle (hrs)	Tg (hrs)	Hardness (hrs)	Lightness (hrs)	Average (hrs)
Key West	5413	6340	N/A*	5719	4810	3726	5201
Xenon-arc	1452	1465	N/A	1392	2355	944	1524
QUV-A	1017	1362	N/A	1333	2322	621	1268
QUV-B	620	1018	N/A	1438	2452	387	1183

*Contact angle measurements after 1 year shipboard testing were not available to make estimation

3. Now that a suggested testing time has been established, the closest set of test data for each accelerated method that corresponds to the estimated test time was used to calculate the percent error between 1 year of shipboard data and accelerated test data. The estimated testing time for each exposure method is as follows:
    - Key West – 5201 hrs, which equals 217 days, rounded up to 270 days
    - Xenon-arc – 1524 hrs, rounded down to 1500 hrs
    - QUV-A – 1268 hrs, rounded up to 1500 hrs
    - QUV-B – 1183 hrs, rounded down to 1000 hours

4. The percent error was calculated by using the following equation:

$$\text{Percent Error} = \frac{(X_{\text{accelerated}} - X_{\text{shipboard}})}{X_{\text{shipboard}}} \quad X\ 100$$

5. The data used for calculating percent error is provided in Tables 16 – 19.

Table 16 – Percent error between 270 day Key West and 1 year shipboard data

1 yr ship vs. 270 days KW	1K Poly			2K Poly			Epoxy			Alkyd			LSA Alkyd			2K Poly		
	1 yr ship	270 days KW	% error	1 yr ship	270 days KW	% error	1 yr ship	270 days KW	% error	1 yr ship	270 days KW	% error	1 yr ship	270 days KW	% error	1 yr ship	270 days KW	% error
dE	0.90	1.36	51%	1.03	1.26	22%	4.00	6.35	59%	2.43	3.00	23%	2.17	3.65	68%	1.38	0.60	57%
Gloss	-25.50	-31.50	24%	-6.10	-2.00	67%	-3.70	-4.90	32%	-42.50	-47.00	11%	-43.20	-45.00	4%	-29.90	-20.00	33%
Tg	17.28	22.43	30%	4.10	-0.11	103%	-1.76	-8.02	356%	18.18	16.87	7%	15.31	9.11	40%	20.05	21.97	10%
CA	Missing contact angle measurement after 1 year on ship																	
Hardness	-8.00	10.00	225%	23.00	26.00	13%	15.00	20.00	33%	35.00	41.00	17%	63.00	37.00	41%	-14.00	11.00	179%
Lightness	0.26	0.93	258%	0.21	0.38	81%	3.11	6.04	94%	2.41	2.94	22%	1.71	3.47	103%	-0.62	-0.02	97%
Overall Percent Error: 72%																		

Table 17 – Percent error between 1500 hours xenon-arc and 1 year shipboard data

1 yr ship vs. 1500 hrs xenon-arc	1K Poly			2K Poly			Epoxy			Alkyd			LSA Alkyd			2K Poly		
	1 yr ship	1500 hrs xenon	% error	1 yr ship	1500 hrs xenon	% error	1 yr ship	1500 hrs xenon	% error	1 yr ship	1500 hrs xenon	% error	1 yr ship	1500 hrs xenon	% error	1 yr ship	1500 hrs xenon	% error
dE	0.90	1.26	40%	1.03	1.10	7%	4.00	6.04	51%	2.43	2.38	2%	2.17	3.51	62%	1.38	1.11	20%
Gloss	-25.50	-27.20	7%	-6.10	-10.80	77%	-3.70	-4.00	8%	-42.50	-45.90	8%	-43.20	-45.20	5%	-29.90	-26.50	11%
Tg	17.28	21.23	23%	4.10	-0.19	105%	-1.76	4.90	378%	18.18	19.86	9%	15.31	14.34	6%	20.05	34.43	72%
CA	Missing contact angle measurement after 1 year on ship																	
Hardness	-8.00	8.00	200%	23.00	20.00	13%	15.00	19.00	27%	35.00	31.00	11%	63.00	27.00	57%	-14.00	23.00	264%
Lightness	0.26	0.90	246%	0.21	0.49	133%	3.11	5.79	86%	2.41	2.29	5%	1.71	3.37	97%	-0.62	0.94	252%
Overall Percent Error: 76%																		

Table 18 – Percent error between 1500 hours QUV-A and 1 year shipboard data

1 yr ship vs. 1500 hrs QUV-A	1K Poly			2K Poly			Epoxy			Alkyd			LSA Alkyd			2K Poly		
	1 yr ship	1500 hrs QUV-A	% error	1 yr ship	1500 hrs QUV-A	% error	1 yr ship	1500 hrs QUV-A	% error	1 yr ship	1500 hrs QUV-A	% error	1 yr ship	1500 hrs QUV-A	% error	1 yr ship	1500 hrs QUV-A	% error
dE	0.90	1.11	23%	1.03	1.22	18%	4.00	12.31	208%	2.43	4.33	78%	2.17	5.17	138%	1.38	6.21	350%
Gloss	-25.50	-33.70	32%	-6.10	-16.70	174%	-3.70	-4.40	19%	-42.50	-47.70	12%	-43.20	-46.90	9%	-29.90	-32.20	8%
Tg	17.28	22.60	31%	4.10	-4.99	222%	-1.76	14.20	907%	18.18	19.78	9%	15.31	17.25	13%	20.05	26.48	32%
CA	Missing contact angle measurement after 1 year on ship																	
Hardness	-8.00	-2.00	75%	23.00	8.00	65%	15.00	17.00	13%	35.00	40.00	14%	63.00	38.00	40%	-14.00	-1.00	93%
Lightness	0.26	0.92	254%	0.21	1.00	376%	3.11	12.16	291%	2.41	4.22	75%	1.71	5.15	201%	-0.62	6.18	1097%
Overall Percent Error: 116%																		

Table 19 – Percent error between 1000 hours QUV-B and 1 year shipboard data

1 yr ship vs. 1000 hrs QUV-B	1K Poly			2K Poly			Epoxy			Alkyd			LSA Alkyd			2K Poly		
	1 yr ship	1000 hrs QUV-B	% error	1 yr ship	1000 hrs QUV-B	% error	1 yr ship	1000 hrs QUV-B	% error	1 yr ship	1000 hrs QUV-B	% error	1 yr ship	1000 hrs QUV-B	% error	1 yr ship	1000 hrs QUV-B	% error
dE	0.90	1.04	16%	1.03	1.71	66%	4.00	13.00	225%	2.43	5.29	118%	2.17	7.38	240%	1.38	5.52	300%
Gloss	-25.50	-37.90	49%	-6.10	-14.30	134%	-3.70	-4.40	19%	-42.50	-48.10	13%	-43.20	-47.10	9%	-29.90	-41.90	40%
Tg	17.28	22.61	31%	4.10	0.34	92%	-1.76	7.17	507%	18.18	15.54	15%	15.31	9.11	40%	20.05	24.84	24%
CA	Missing contact angle measurement after 1 year on ship																	
Hardness	-8.00	3.00	138%	23.00	13.00	43%	15.00	13.00	13%	35.00	22.00	37%	63.00	25.00	60%	-14.00	-16.00	14%
Lightness	0.26	1.03	296%	0.21	0.88	319%	3.11	12.93	316%	2.41	5.25	118%	1.71	7.29	326%	-0.62	5.46	981%
Overall Percent Error: 153%																		

3.2.9 <u>Pictures</u>

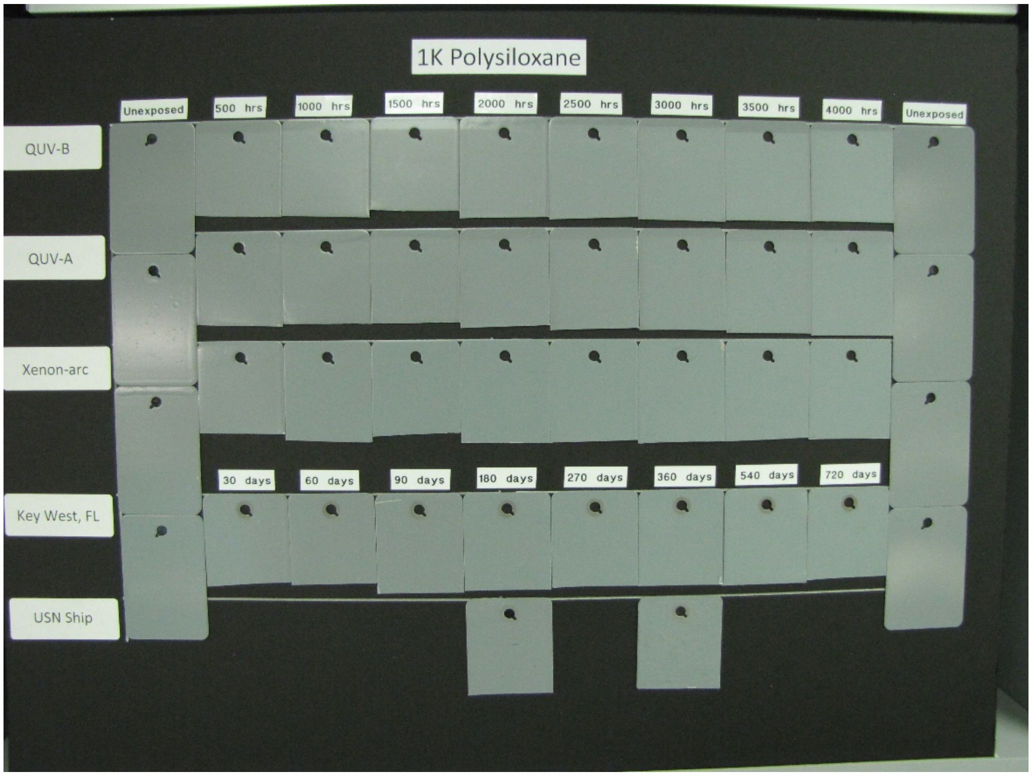


Figure 13 – All test coupons of 1K polysiloxane (Paint #1)

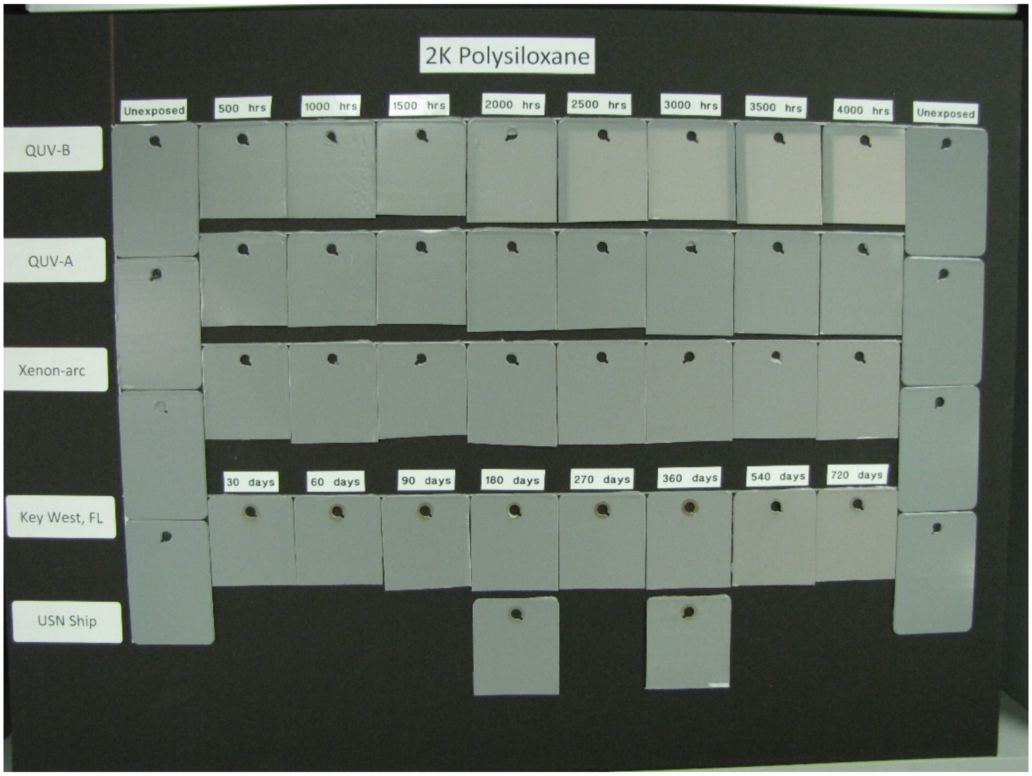


Figure 14 - All test coupons of 2K polysiloxane (Paint #2)

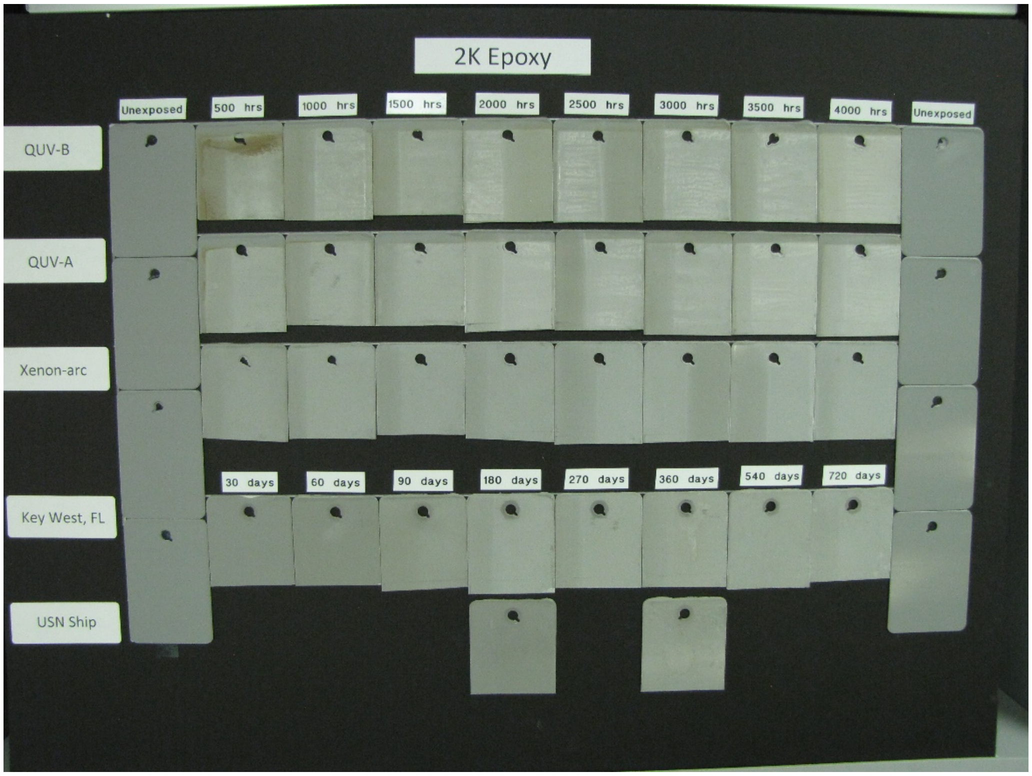


Figure 15 - All test coupons of 2K epoxy (Paint #3)

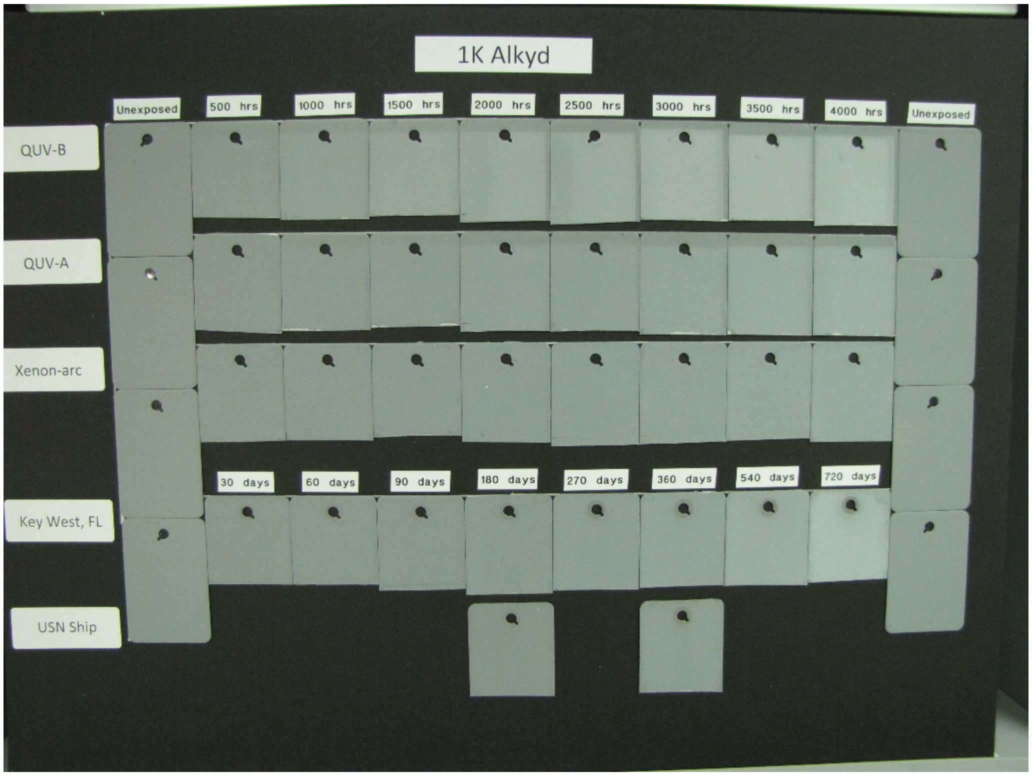


Figure 16 - All test coupons of 1K alkyd (Paint #4)

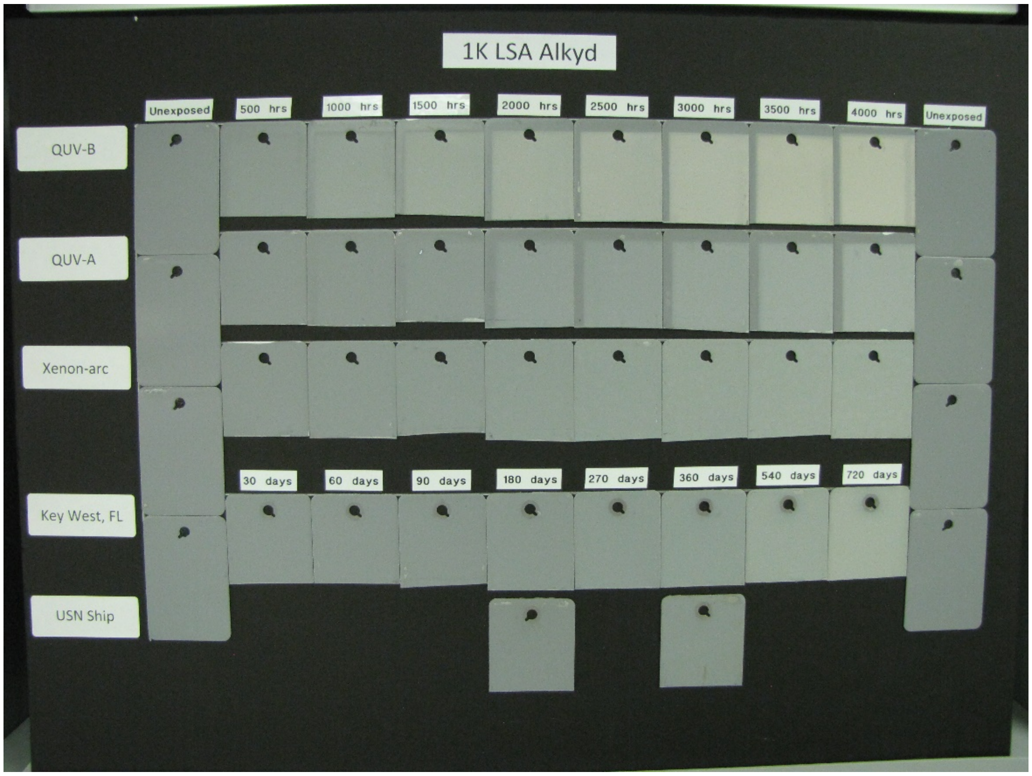


Figure 17 - All test coupons of 1K LSA alkyd (Paint #5)

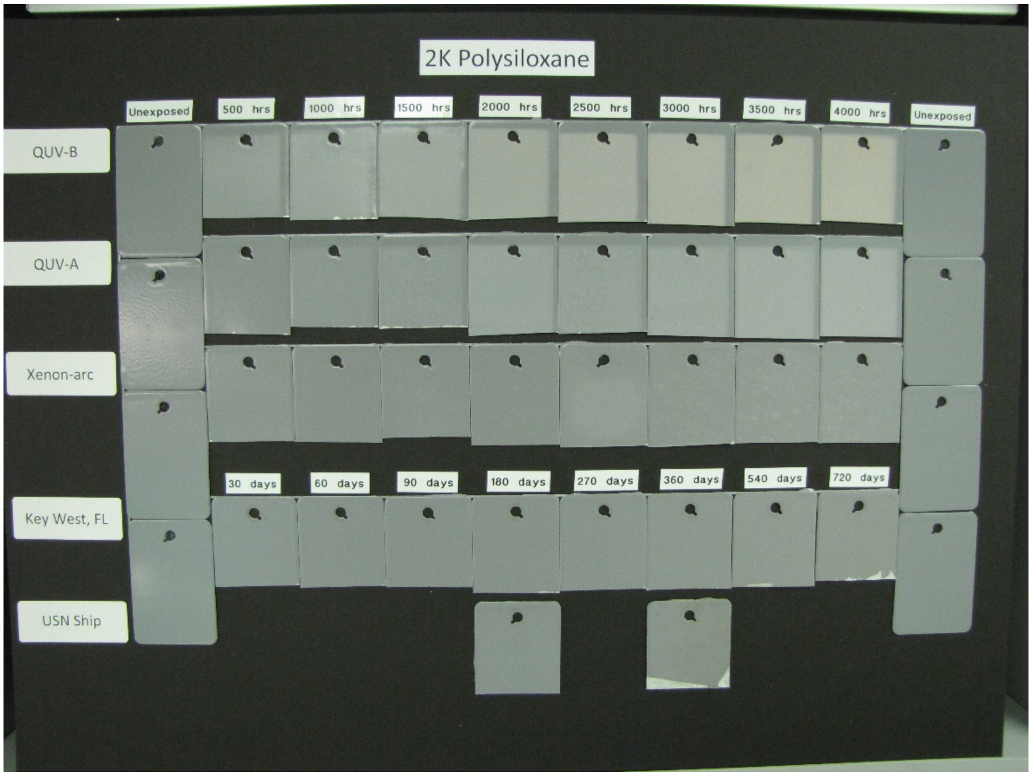


Figure 18 - All test coupons of 2K polysiloxane (Paint #6)

3.2.10 Conclusions

This study evaluated the degradation of seven different coating properties over time using four different accelerated exposure methods. This data was then compared to 1-year of shipboard data collected on an LPD 17 class ship home ported in Norfolk, VA to determine which accelerated exposure method simulates the natural shipboard environment best through the use of UV light, moisture, and temperature. The coating properties measured were color change (dE), gloss loss, glass transition temperature (Tg), contact angle, hardness, and lightness (an indication of chalking). After data collection was complete, the time required for the accelerated test methods to equal one year of shipboard testing was determined to provide an estimate for the amount of time the accelerated test should be performed to get an accurate representation of the coating degradation measured on ship. The percent error was then calculated using the 1-year ship data and the test data from each of the accelerated test methods.

The exposure method that produced the least amount of error was Key West, FL, which was 72 percent. Xenon-arc testing provided the next lowest error at 76 percent, which is encouraging because the error is comparable to Key West, but provides the convenience of using standard test equipment. When reviewing the data more closely, the greatest amount of error was introduced by the lightness property, followed by Tg and hardness for Key West and xenon-arc.

- For lightness, the ship data was consistently about half the value measured in the accelerated tests, which could be attributed to the fact the ship is not stationary and the panels were likely shaded more frequently by other ship structures. Also, the data in Table 14 suggests for lightness only, the xenon-arc should be tested for 944 hours and Key West should be tested for 3726 hours (155 days). This is about half of the estimated testing time suggested when considering all properties, 2000 hours and 6480 hours (270 days), for xenon-arc and Key West.

- Tg and hardness are both properties that give an indication of cross link density and as the coating ages over time they progressively become more cross linked and less flexible. The measurements require precision lab equipment that are sensitive to factors like temperature, thickness, and other variables that could affect the measurements.
- For ASTM G154, QUV-A and QUV-B, dE measurements had greater percent error than Key West and xenon-arc. This is likely due to the greater amount of damaging UV light at shorter wavelengths resulting in unrealistic coating degradation. This can be confirmed by analysing the photographs of the test panels in Figures 13 – 18.

QUV-A and QUV-B had 116 percent and153 percent error, respectively. Across the board, more error is introduced for every coating property measured. This is likely related to the fact that the QUV weathering test uses the UV spectrum of light to degrade the coatings, which is more damaging than natural sunlight. A good example of this influence is dE, which can be confirmed visually by reviewing the photographs of the test panels in Figures 13 – 18.

3.2.11 __Recommendations__

- Additional "resolution" could be obtained about how representative each accelerated exposure method is compared to shipboard testing if the analysis were separated by coating type. For example, coatings could be separated by curing mechanism, solvent evaporation vs. chemical curing. This would result in significantly different curing profiles as the coatings aged in the different accelerated methods which could provide additional insight (the same applies for Tg).
- The current accelerated testing requirements for USN haze gray topcoats are contained in MIL-PRF-24635E. The tests consist of QUV-B for 300 hours and 1-year outdoor exposure (typically in Florida). Based on the findings of this study, it is recommended that the accelerated testing requirements be updated to be representative of 1-year shipboard testing:
    - 270 days on an exposure rack in south Florida
    - 1500 hours in ASTM G155, Cycle 1 (xenon-arc)

3.6 WE 3.6 Coating degradation mechanisms

The intent of this task was 1) to develop a weathering and corrosivity map for a USN surface combatant, 2) to the extent possible, identify the sources of corrosivity in each zone (e.g. well decks, hangars, forecastle, stacks, etc…) and 3) to correlate these studies to the laboratory studies. To this extent, NRL worked to deploy corrosivity monitors on a USN ship. These also included coating specimens for correlation to laboratory studies.

Five locations on the ship were selected depending on the shipboard accessibility. Identification of corrosivity sources were focused on 1 or 2 ship locations, and, to the extent practicable, atmospheric chemistry, chloride deposition, time of wetness and UV irradiance were measured.

The outcome for this task was 1) recommended accelerated test methods for assessing shipboard weathering (i.e. color and gloss retention), 2) data on the change of coating weathering properties with time and 3) a shipboard corrosivity and weathering map. The results were used to project likely correlations in degradation mechanisms between accelerated laboratory, natural test site and shipboard exposures.

Objectives for the reporting period

- Design and fabricate sample exposure system
- Preparation and coating of panels
- Deployment of test panels in Key West, FL (as control)
- Deployment of test panels in 5 locations on single ship (to generate corrosion map)

3.6.1 __Shipboard testing__

The same coatings listed in section 3.2.1 were applied to aluminium substrates for this test.

Coated aluminum samples (2 in. x 3 in.) were tested in triplicate. C1010 steel (3 in. x 3 in.) was used to determine weight loss information and silver (0.5 in. x 3 in.) was used to gather chloride loading information. There was also a temperature/relative humidity sensor (Dataq) and a corrosion sensor (Aircorr). These can all be seen in the following figure which shows a test rack after installation on the ship.

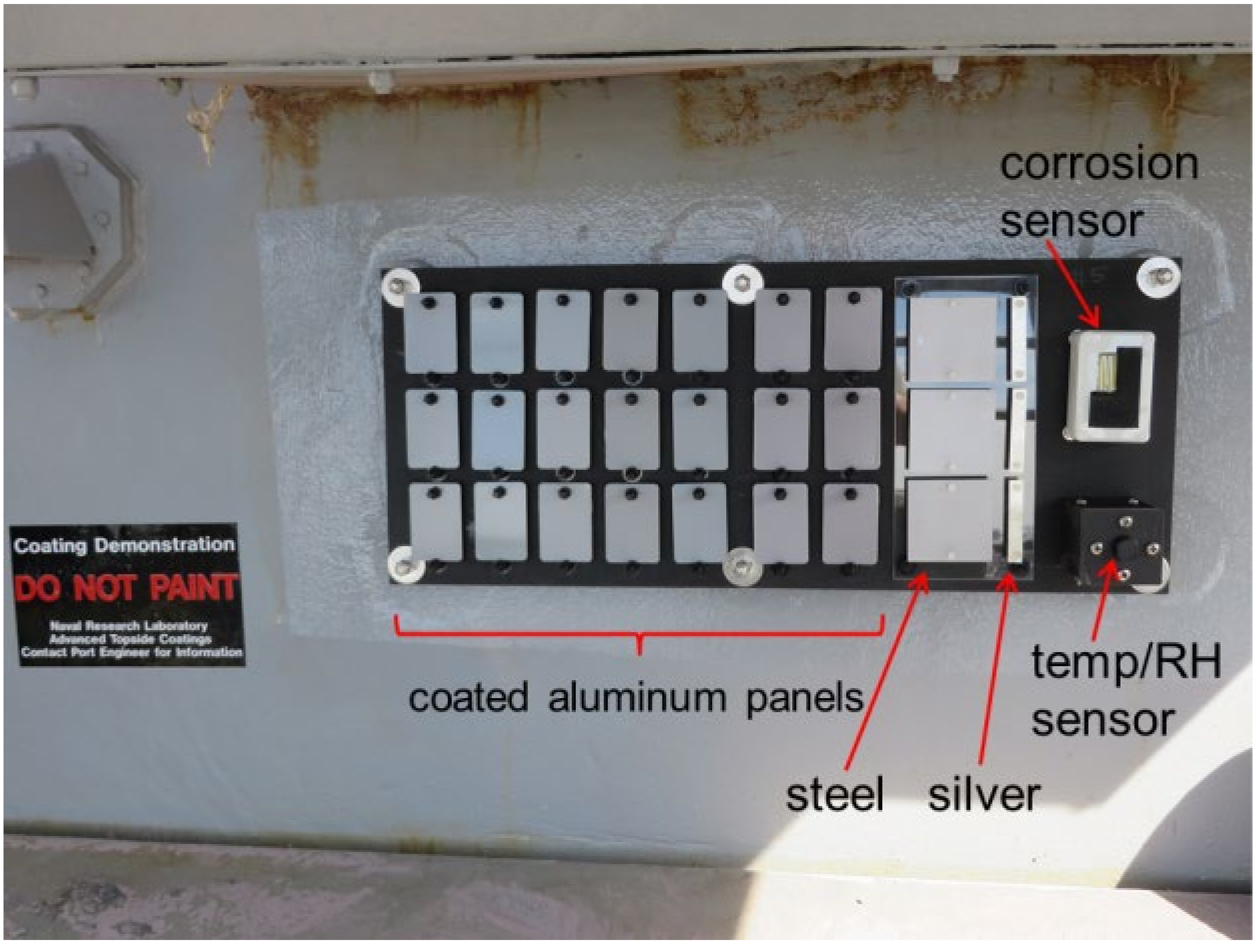


Figure 19 – Exposure racks deployed on an LPD 17 class ship

These panels were placed in 5 locations on an LPD 17 class ship (in the vertical orientation) on 17SEP2015 and again on 08MAR2016.

- 3 boldly exposed on an upper level exterior bulkhead, ~100-120 feet from waterline, 1 facing forward, 1 along slip stream, 1 facing aft (Board 4, 1, and 2, respectively)
- 1 sheltered in well deck, highly corrosive environment, no UV (Board 3)
- 1 partial exposure (sheltered by overhead structure), ~40-50 feet from waterline, along slip stream (likely more misting in higher sea states than the upper level), no rinsing from rain water, very low UV (Board 5)

These locations are shown in Figure 20 and Figure 21.

http://www.freewebs.com/jeffhead/worldwideaircraftcarriers/sanantonio-17.jpg

Figure 20 – Exterior locations of exposure racks on an LPD 17 class ship

http://www.freewebs.com/jeffhead/worldwideaircraftcarriers/sanantonio-95.jpg

Figure 21 – Location of exposure racks in the well deck of an LPD 17 class ship

3.6.2 Results

Mass loss rates from steel coupons were less severe in Key West than on any location on the ship. This was expected from previous data. (It could be increased in future tests with the use of natural seawater spray addition to the exposure test protocol.) An example of the condition of the boards after exposure is shown in Figure 22. Mass loss (g/m^2) of C1010 steel samples exposed in Key West, FL and on-board an LPD 17 San Antonio class ship are shown in Figure 23. The samples exposed for ~180 days were exposed from SEP2015-MAR2016, The subsequent samples exposed for ~320 days were exposed from MAR2016-JAN2017; these were 2 separate sets of samples and were not exposed during the same time.

The silver samples were galvanostatically reduced to calculate AgCl and Ag_2S film thicknesses. These film thicknesses can be used to calculate deposition rates of chloride and sulfide using the following equations:

$$Q_s = I_s t = 1000\ \mathrm{s}\ \times 0.1\frac{\mathrm{mA}}{\mathrm{cm}^2} = 100\ \mathrm{mC/cm}^2$$

$$N_s = \frac{Q_s}{F} = \left(\frac{100\ \mathrm{mC/cm^2}}{96454.56\ \mathrm{C/mol}}\right) \times \frac{0.001\ \mathrm{C}}{\mathrm{mC}} \approx 1.03 \times 10^{-6}\ \mathrm{mol/cm^2}$$

$$d = \frac{N_s M_{\mathrm{AgCl}}}{\rho_{\mathrm{AgCl}}} = \left(\frac{1.03 \times 10^{-6}\ \mathrm{mol/cm^2} \times 143.32\ \mathrm{g/mol}}{5.56\ \mathrm{g/cm^3}}\right) \times \frac{10^7\ \mathrm{nm}}{\mathrm{cm}} \approx 270\ \mathrm{nm}$$

The AgCl and Ag_2S film thickness calculated from the Ag coupons are given in Figure 24 and Figure 25, respectively. The two sets of shipboard data were separate exposures. The data shows that the film thicknesses on the ship were (overall) less than those seen in Key West. The combination of an observation of a higher mass loss rate on steel and thinner film thickness on Ag from the shipboard data is consistent with more surface rinsing and time of wetness on the samples exposed on the ship. Boards 1, 2, and 4 tend to track with each other which is consistent with their similar exposure locations. Board 5 exhibited the highest corrosion rate of steel which is consistent with a sheltered location which has a longer time of wetness and will promote corrosion through a thin film for a longer period of time. The Ag samples exposed in the well deck had very small film thicknesses, even though they are closer to a water source. This is likely a result of less sunlight in the area of the board which is necessary for Ag corrosion reactions. [1-3]

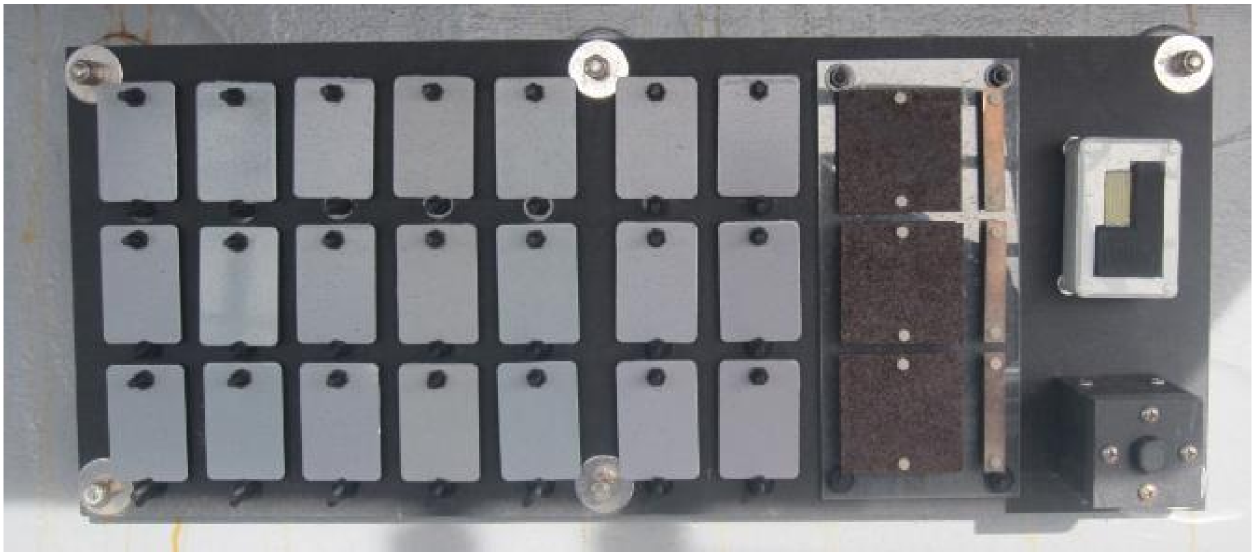


Figure 22 – Example of condition of board after exposure

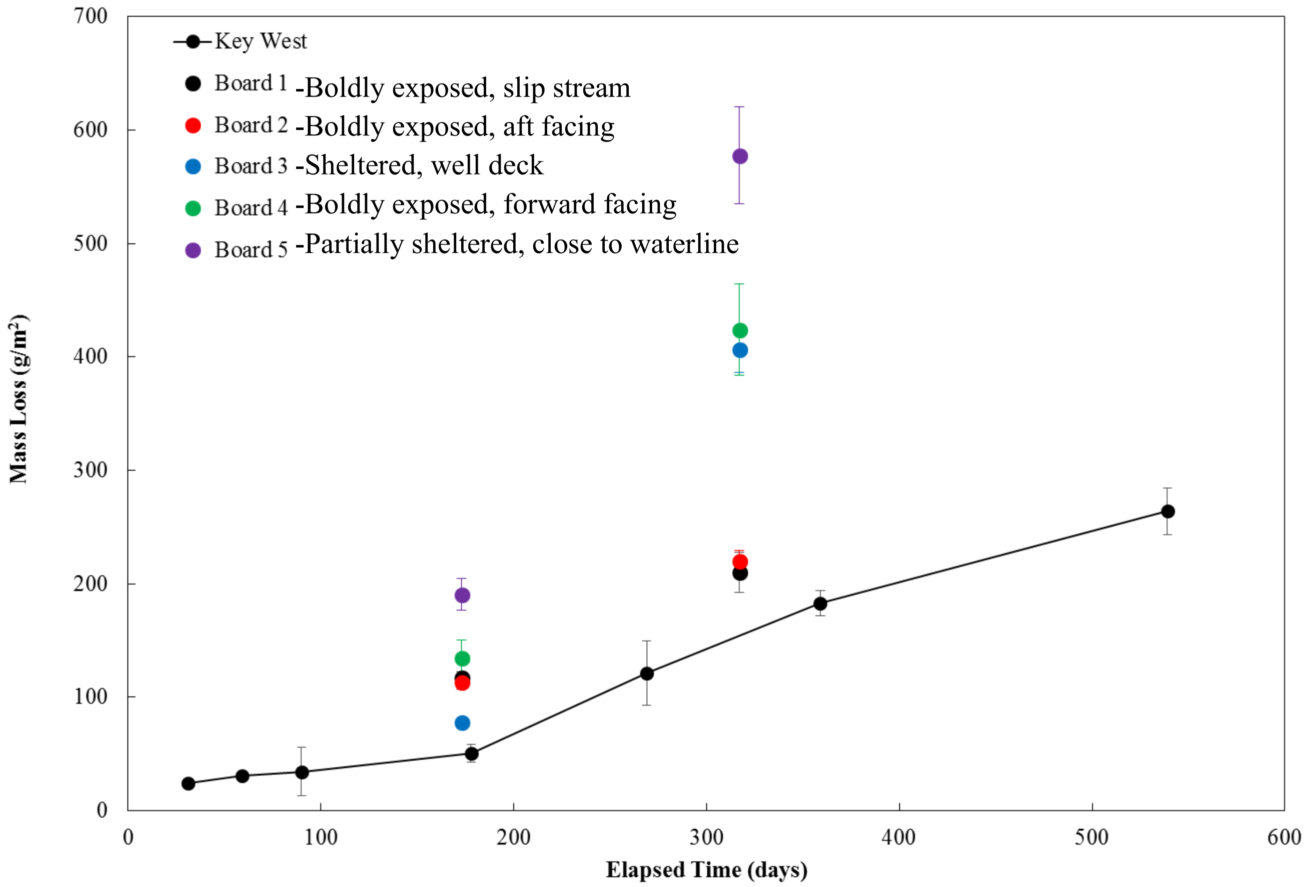


Figure 23 – Mass loss (g/m^2) of C1010 steel samples exposed in Key West, FL (black line) and on-board an LPD 17 San Antonio class ship (colored points). The samples exposed for ~180 days were exposed from SEP2015-MAR2016. The subsequent samples exposed for ~320 days were exposed from MAR2016-JAN2017. These were 2 separate sets of samples and were not exposed during the same time.

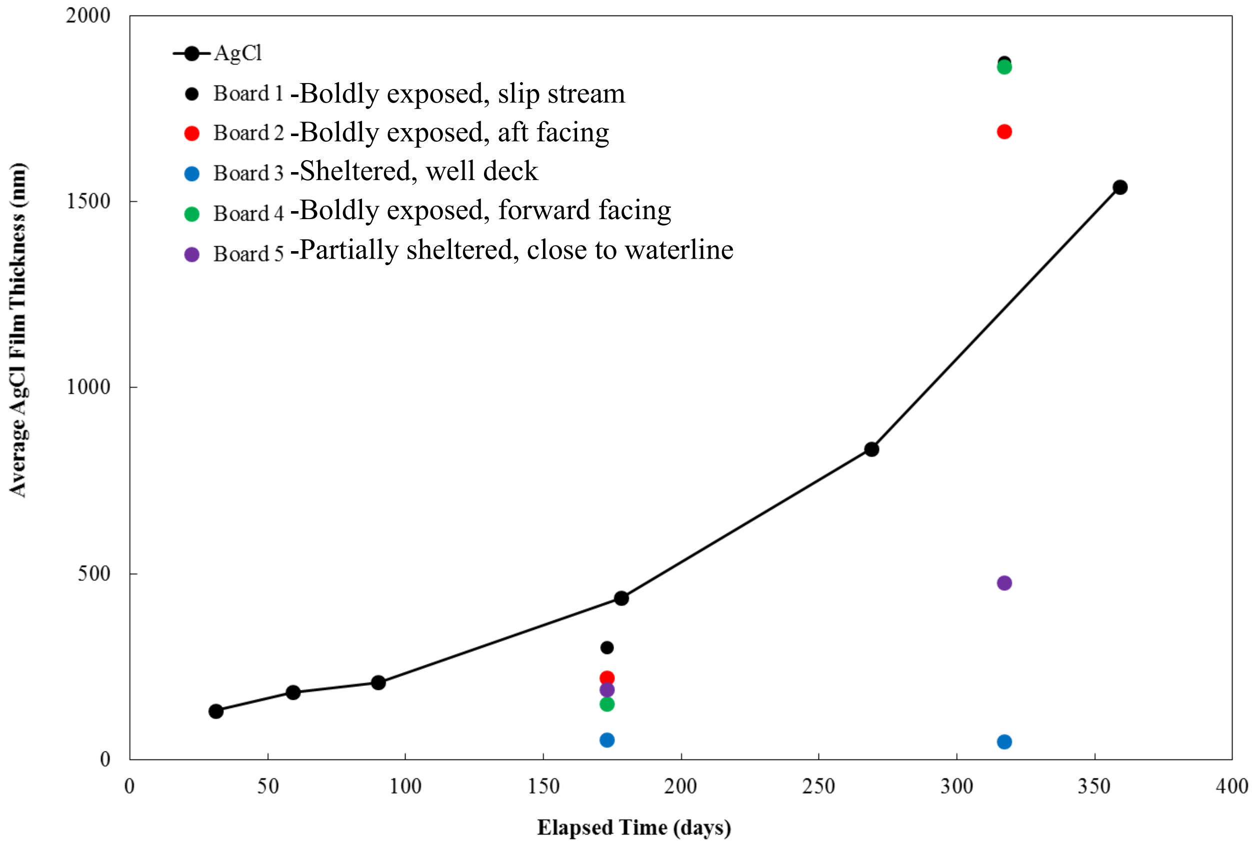


Figure 24 – Average AgCl film thickness (nm) of Ag samples exposed in Key West, FL (black line) and on-board an LPD 17 San Antonio class ship (colored points). The samples exposed for ~180 days were exposed from SEP2015-MAR2016. The subsequent samples exposed for ~320 days were exposed from MAR2016-JAN2017. These were 2 separate sets of samples and were not exposed during the same time.

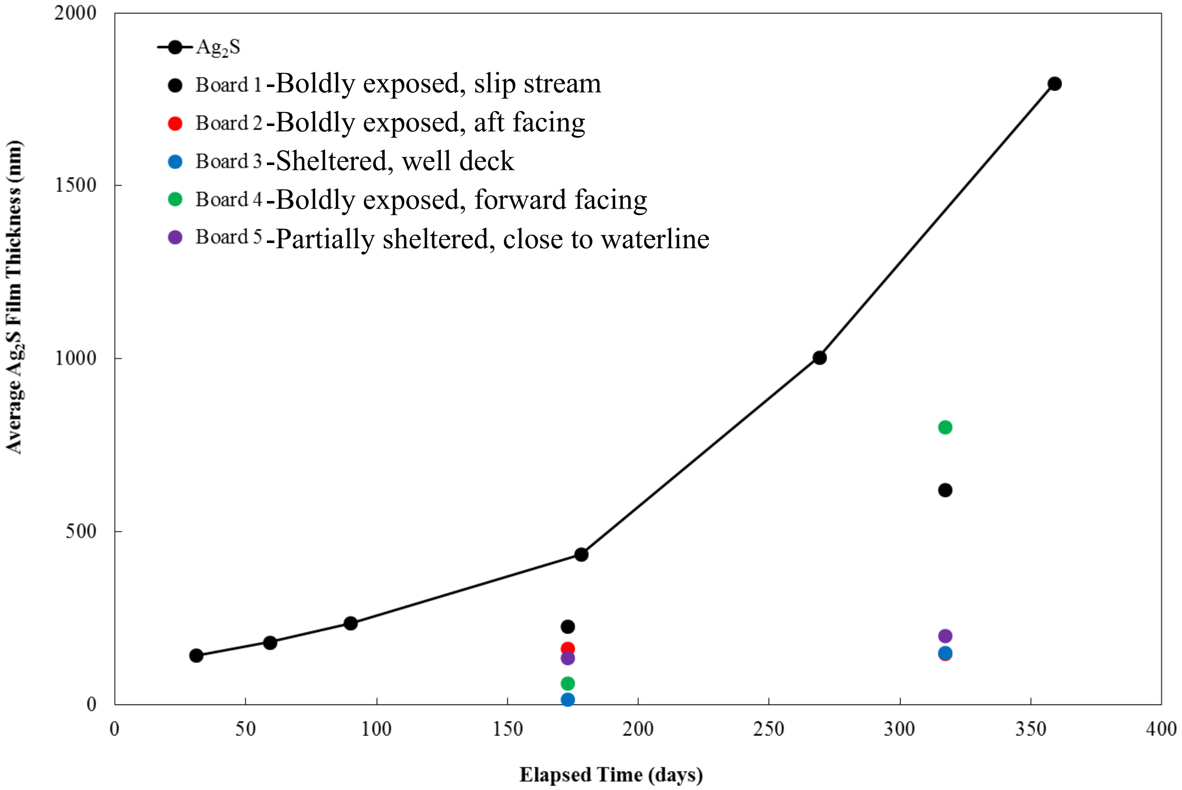


Figure 25 – Average Ag_2S film thickness (nm) of Ag samples exposed in Key West, FL (black line) and on-board an LPD 17 San Antonio class ship (colored points). The samples exposed for ~180 days were exposed from SEP2015-MAR2016. The subsequent samples exposed for ~320 days were exposed from MAR2016-JAN2017. These were 2 separate sets of samples and were not exposed during the same time.

Table 20. Corrosion Rate Data from the nke Corrosion Sensors placed on the US Naval Ship.

		nke Corrosion Rate (mm/year)	
	Location	Round 1	Round 2
Board 1	04 Level, Inboard Bulkhead	3.5	17.571 (end 3/30/16)
Board 2	04 Level, Aft Bulkhead	3.7	No data
Board 3	Well Deck	6.3	54.195
Board 4	04 Level, Forward Bulkhead	4.6	13.298 (end 3/30/16)
Board 5	Flight Deck (sheltered)	10.5	53.789

3.6.3 Conclusions

- Higher steel corrosion rates onboard ship compared to Key West for the same length of exposure:
    - Believed to be related to time of wetness – disturbance of oxide
    - Steel corrosion on FWD facing bulkhead 50% greater than INBD or AFT facing bulkheads
- Lower silver sulfide and silver chloride deposition rates onboard ship compared to Key West for the same length of exposure:
    - Also believed to be related to time of wetness – solubility and cleaning effect

Problems and deviations from schedule

- In lieu of testing on different ships in the second phase of the study, it was decided to repeat the measurements from the same locations on the original ship. This allows for a better understanding of the variability in corrosion severity due to different operational conditions.

3.7 WE 3.7 Surface preparation and paint application

It is well known that surface preparation prior to paint application has a fundamental impact on the protection properties and durability of coatings. The presence of impurities (such as rust, soluble and insoluble salts) or inadequate mechanical preparation can seriously affect the useful service life of coatings. Additionally, in a typical coating operation, the surface preparation step is often the most costly and time consuming step.

The objective of this work element is to evaluate the influence of surface preparation on the durability of coatings, in-particular with respect to their effect on early delamination, blistering and corrosion.

This work element aims to correlate coating adhesion and accelerated corrosion performance to surface roughness morphology and surface cleanliness (i.e., salt concentration). NRL is examining the inherent variability of surface morphology resultant from a variety of blasting materials and process parameters inherent in the abrasive blasting operation. This work examines several of the many parameters and variables that are all within the “acceptable” limits of present processes and specifications – rather than testing of any new or particularly innovative materials or machines. This is being accomplished using relatively small (15cm x 15cm) steel panels in the laboratory with additional complimentary data acquired from larger (60cm x60cm) steel panels blasted in a shop production environment. Two grades of steel samples (typical (50ksi) and high strength (100ksi)) were prepared with various abrasive types, size and shape and characterized by various physical surface metrics such as replica tape, linear profilometer and microscopic methods.

Objectives for the reporting period

- Measure and evaluate the morphological differences between test panels blasted with a variety of MILSPEC qualified abrasive materials.
- Compare and contrast several competing methods of measurement for surface profile.
- Apply US Navy epoxy primers to test panels of varying surface profile and evaluate the difference in expected performance of those coatings based on the variable surface morphology created.
- Compare the surface profile of panels blasted in a small laboratory glove blast box with larger test panels blasted in a production blast shop using a controlled blasting device.
- Apply surface chloride solutions to large test panels and evaluate measurable effects on performance parameters.

3.7.1 Testing approach

Two separate strengths of steel panels were used for testing, notionally 50KSI and 100KSI. Nine (9) 6”x6” (15cm x 15cm) panels of each grade of steel were blasted in a controlled, glove box cabinet set up (Figure 24) for once through use of the grit size and type selected for that set. Each set of panels was blasted using both 100PSI and 80PSI (measured with a needle gauge at the nozzle) air pressure using a #6 straight bore nozzle. Several different grit types were tested. These are listed in the Table 21 below.

Table 21 – Grits tested

Grit Type	Grit Size (per label)
Coal Slag	Medium
Coal Slag	Fine
Garnet Vendor #1	30/60
Garnet Vendor #2	30/60
Mineral Abrasive (garnet by-product)	80
Steel Grit	G25
Steel Grit	G40

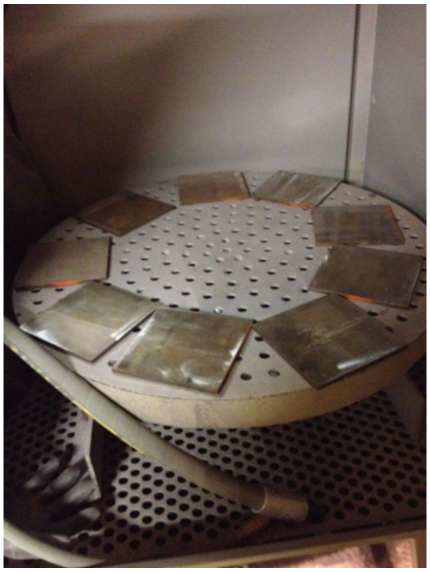


Figure 26 – Panels arranged for blasting in glove box blasting cabinet

For this work, the blasting was done by hand, but due to the configuration of the blast cabinet the standoff distance between nozzle and steel was typically quite controlled at between 4”-6”.

Grits were sieved for size characterization prior to, and after one pass of blasting to assess breakdown of the various grits after a single pass on the steel.

Blasted panels were measured for profile referring to SSPC PA-17 for guidance and using three different methods in parallel to compare results: ASTM D4417 Methods B (single point micrometer measurement) and C (replica tape) and ASTM D7127 (stylus) were used. Additionally, advanced microscopy was used to image and quantify the surface morphology of the various panels.

Following surface characterization, the panels were painted with an array of typical Navy primers. Adhesion testing per ASTM D4541 was performed to attempt to differentiate coating adhesion based on surface profile parameters.

For additional performance testing, these panels will be exposed to test environments (a relatively short duration ASTM B117 salt fog testing for 500 hours) to sort out any performance differences that arise due to the different surface profiles for each panel. These results will be reported after completion at a later date.

Larger test panels were also blasted using the same set of abrasive materials in a larger shop environment. This blasting was performed using a hand held blast nozzle mounted to a mechanical rastering device to keep the horizontal speed of the blast nozzle constant (Figure 25). A constant standoff distance of 24-inches was used for the blasting. Blasting pressures of 100 psi and 80 psi at the nozzle were used just as in the smaller scale cabinet testing. From this work, relative productivity of the various abrasives was measured and differences between nozzle pressures with similar abrasives were compared while removing any inconsistencies in nozzle dwell time inherent in the hand held blasting technique used in the smaller cabinet.

Larger test panels were contaminated with chlorides on one half of the panel, and then primed. These panels will be exposed to accelerated corrosive testing and tested for adhesion differences before and after exposure testing.

Figure 27 – Semi automated blast nozzle for blasting larger test panels at controlled rates

3.7.2 ***Results***

3.7.2.1 Grit size and breakdown

Results in Figure 31 show that the size of “30/60” garnet obtained from two vendors was similar, but not exactly the same. After one pass, these garnets both showed breakdown below a 100 mesh of less than 20% for most samples. This is encouraging when considering the possibility of systematically recycling mineral grits to reduce waste streams in the future. Presently, mineral type abrasives (e.g., garnet) are used frequently in Navy applications, but typically only in once through type of use at the waterfront. These types of abrasives are sometimes recycled in controlled blast rooms. The results of this study indicate that there is a large potential for expanded recycling efforts for garnets and other mineral abrasives. Additionally, subsequent work has shown the excellent potential for recycling and multiple pass use of aluminum oxide abrasive. Aluminum oxide abrasive can be recycled at least four (4) times while maintaining angularity. Results using a 16/24 alunimun oxide mix (50% each size) shows an initial profile on 100ksi steel of just over 3 mils (75 microns) reducing to about 2 mils (50 microns) after four passes with the same load of abrasive. This is a 50% reduction in profile height, but still remains within the specification limits of 2-4 mils for profile. Approximately 20% of the abrasive load is lost to fines and dust on each blasting pass.

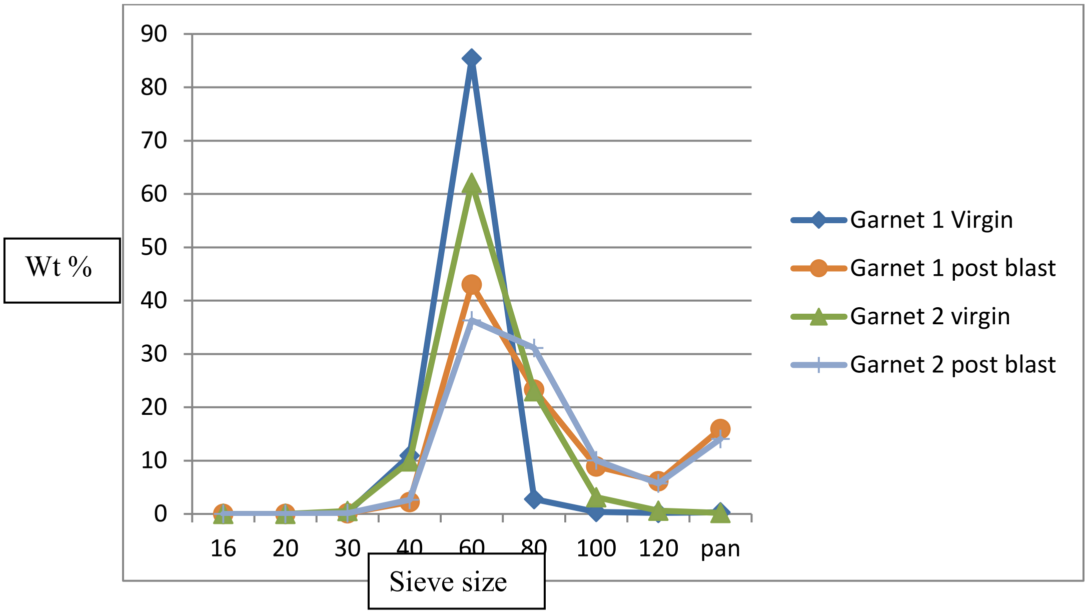


Figure 28 – Initial and post blast size average distribution of garnet grits

Other grits tested showed results primarily as expected with steel grits showing a high degree of stability (although not 100%) and coal slag abrasives showing very little stability in once through blast operations. That is, although coal slag grits and mineral abrasives are both specified and purchased under the same milspec (MIL-A-22262) their performance and breakdown factors are quite different with slags becoming unusable after once through use, while mineral abrasives show attrition of perhaps 20% each time through. This potential benefit should be further explored.

3.7.2.2 Surface profile results

Surface profile measurements showed various differences in measured profile for the panels based on the abrasive used and the measurement techniques employed to measure profile. Preliminary analysis of the data indicates that while each of the blasting process variables examined in the testing has at least a small impact on the resultant profile, the primary controlling variable is the mean size of the grit used for blasting (Figure 27). Additionally, an inverse relationship between mean grit size and number of peaks per inch is clear as well, as seen in Figure 28 below.

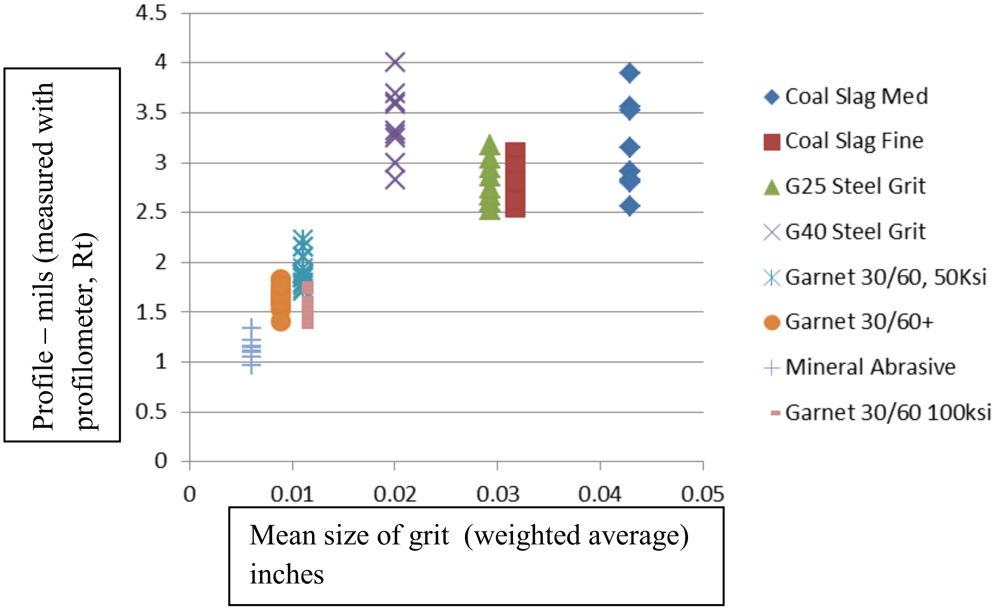


Figure 29 – Mean grit size relationship to profile

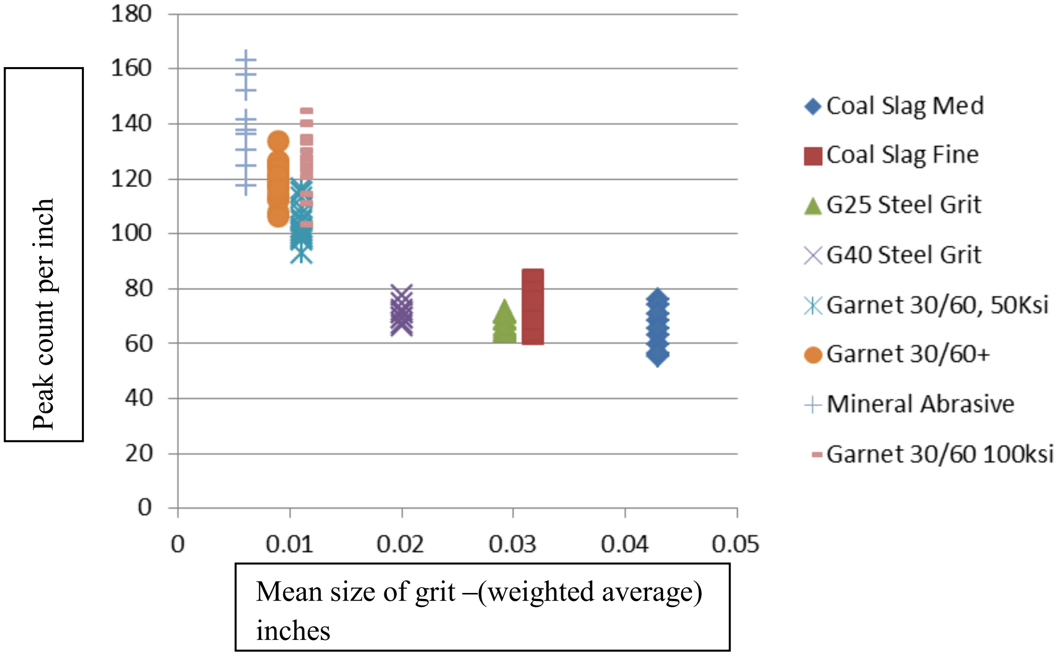
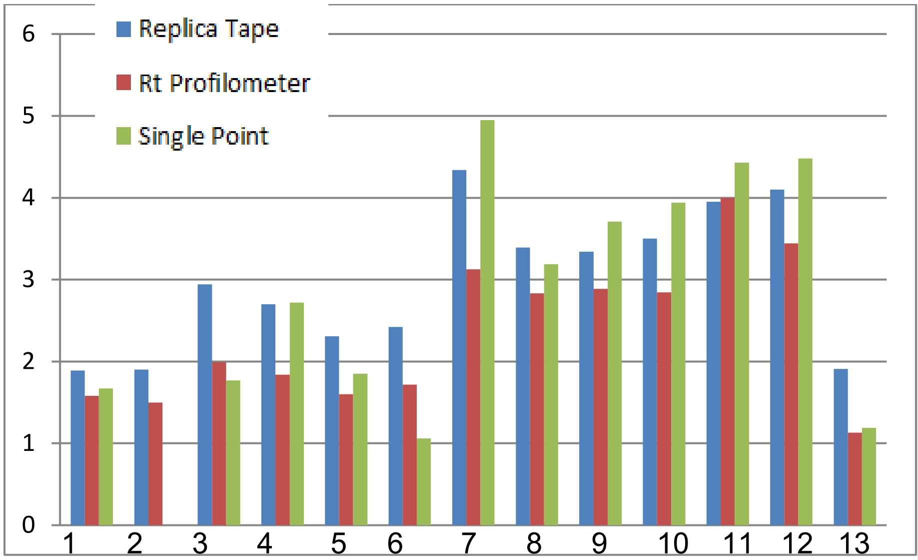


Figure 30 – Mean grit size relationship to peak count per inch

From Figure 27Figure 28, it is clear that there is a general (not quite linear) relationship between the size of the grit and the profile produced. However, upon closer examination of Figure 27, it is interesting to note that the size/profile relationship seems to hold for the coal slag abrasives ("medium" provides a slightly deeper profile than "fine"), the same cannot be said of the steel grits tested where G40 grit provides slightly deeper profiles than the larger G25 grit. The direct relationship between size and profile depth also seems to hold for the mineral abrasives (garnet and garnet by-product).

Also of interest is the data in Figure 28. The mineral abrasives, as a group provide a significant increase in peak height density (Rpk) than the larger (and generally less angularly shaped) slag and steel abrasives. Although, the mineral abrasives tested provide a lower depth of profile, the increased surface complexity provided by the large number of peaks produced provides a surface quality of interest.

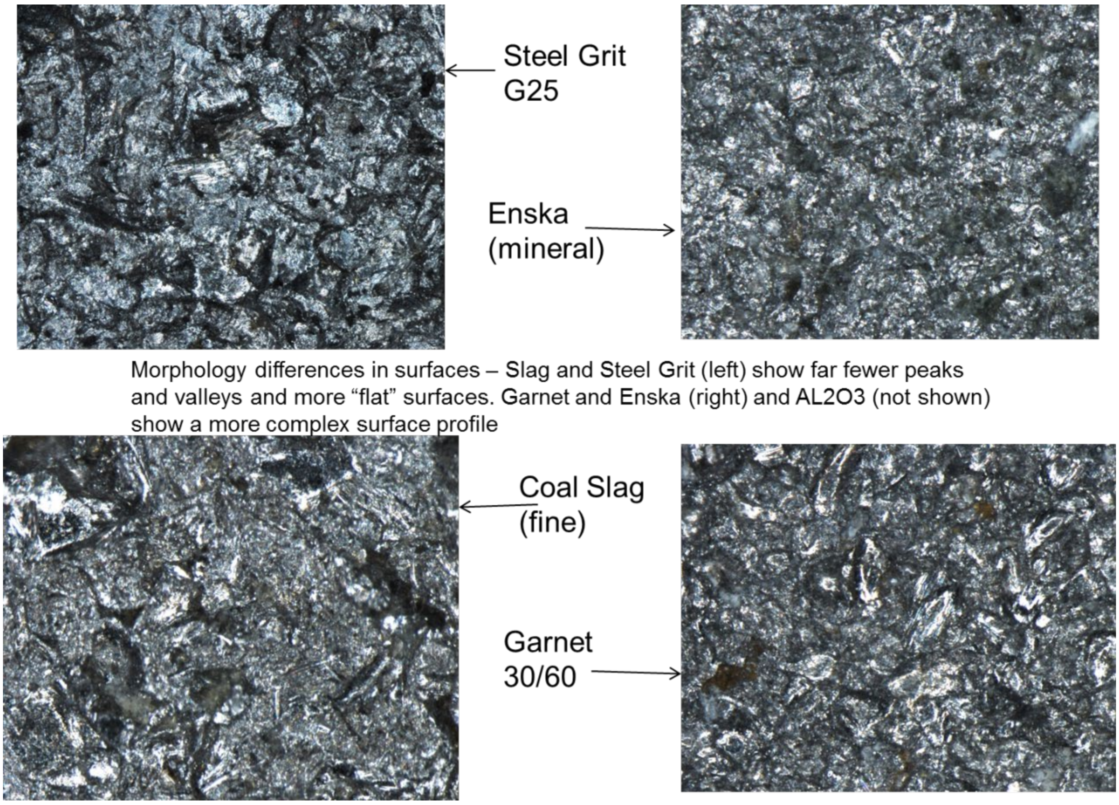
Measurement of profile varied depending on the specific technique used as seen in Figure 29. The replica tape typically provided a measurement that was higher (by 0.5 to 1 full mil) than the stylus and the single point micrometer. Although the single point measurements were sometimes averaged to be higher than the replica tape.



1. Hard rock Garnet 3060 100ksi/100psi
2. Hard rock Garnet 3060 100ksi/80psi
3. Hard rock Garnet 3060 50ksi/100psi
4. Hard rock Garnet 3060 50ksi/80psi
5. Alluvial Garnet 100ksi/100psi
6. Alluvial Garnet 100ksi/80psi
7. Coal Slag Med 50ksi/100psi
8. Coal Slag Fine 100ksi/100psi
9. Coal Slag Fine 100ksi/80psi
10. Steel Grit G25 100ksi/100psi
11. Steel Grit G40 100ksi/100psi
12. Steel Grit G40 50ksi/100psi
13. Mineral Abrasive Fine

Figure 31 – Profile Depth Method Analysis

Images were also taken of the various surfaces produced using an optical microscope. The four images representing Figure 30 shows that in addition to depth of profile and peak density, as reported above, there is clearly a shape factor in each specific abrasive that affects the resultant profile. The hope of this program is to find a measurement technique that relates directly to subsequent performance of Navy coatings, while still maintaining the practicality and simplicity of present measurement methods used in quality assurance operations. However, it is clear from the data that simple characterization of surfaces produced through abrasive blasting is not always simple. A wide variety of surface morphologies are produced, even under relatively consistent process parameters.

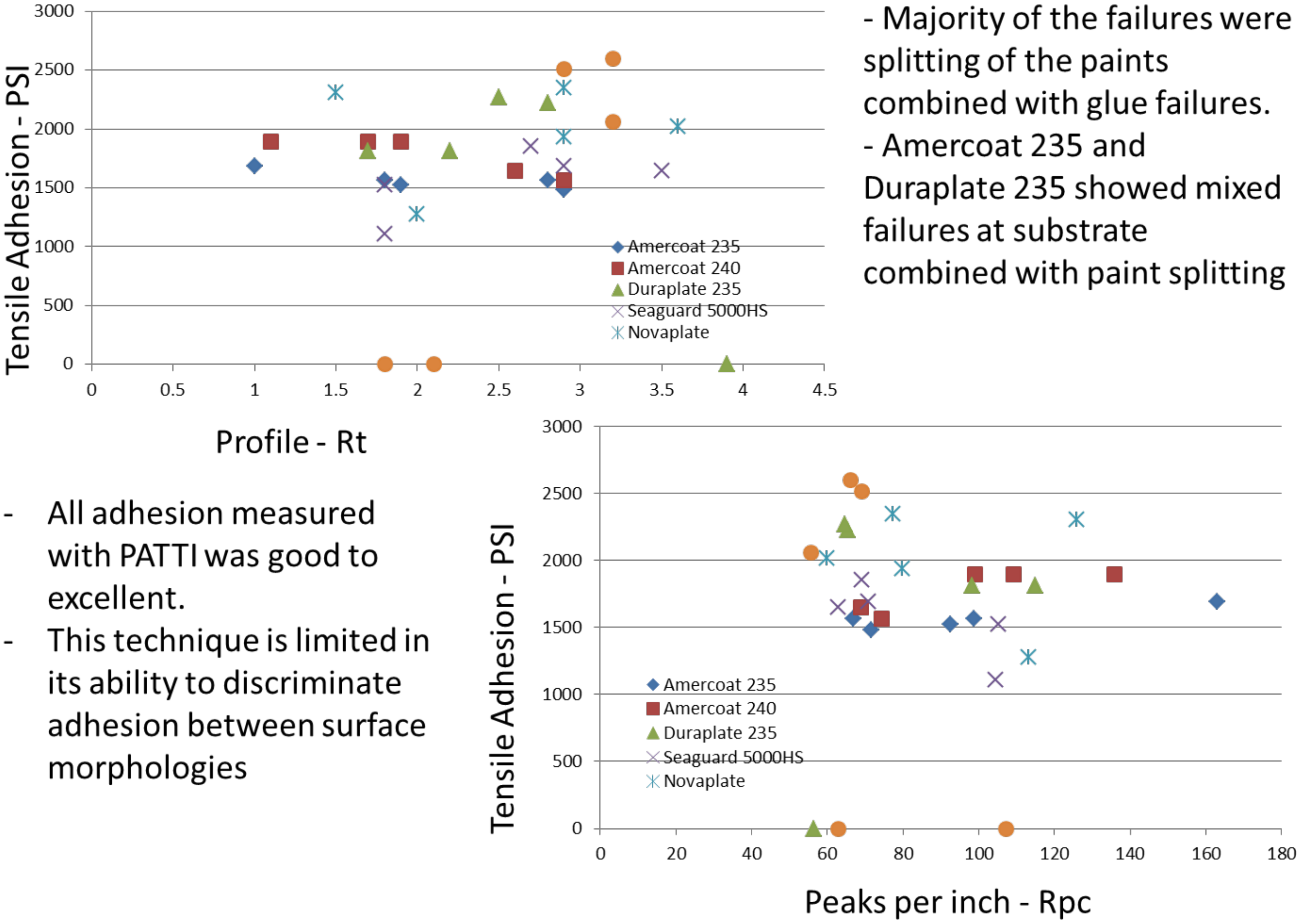


Morphology differences in surfaces – Slag and Steel Grit (left) show far fewer peaks and valleys and more “flat” surfaces. Garnet and Enska (right) and AL2O3 (not shown) show a more complex surface profile

Figure 32 – Micrograph Images of steel surfaces blasted with various abrasives (540X)

3.7.3 Coating performance over varying surfaces

The initial effort to screen coating performance versus surface morphology used ASTM D4541 pneumatic tensile adhesion testing. This testing showed very little (no significant) difference in adhesion of 4 separate non-skid epoxy primers to surfaces that varied from 1.5 up to 4 mils in profile, peak densities from 50 to over 100 peaks per linear inch, and abrasive morphologies from garnet to steel grit, to slag, to steel shot. The primary conclusion regarding this initial data finds that the adhesion of modern Navy coatings, when applied over chemically clean surfaces that are blasted to roughen and remove millscale – is very good. But this scenario is not indicative of the common scenario that results in early failures of Navy primer coatings. These failures likely involve an external driving force for the loss of adhesion. This driver can be mechanical stress from flexing or temperature cycling of the steel/coating system, or intrusion of water or other chemical contaminants. Additionally, more severe mechanical forces can be applied to primers in some applications (e.g., wear, impact, peel stresses from overlays or attachments).



- Majority of the failures were splitting of the paints combined with glue failures.
- Amercoat 235 and Duraplate 235 showed mixed failures at substrate combined with paint splitting

- All adhesion measured with PATTI was good to excellent.
- This technique is limited in its ability to discriminate adhesion between surface morphologies

Figure 33 – Adhesion versus depth of profile and peak density, showing no clear relationship.

The panels tested for initial applied adhesion with be exposed to accelerated (salt fog) testing for an initial exposure period and then retested for adhesion. Such a test regime is hoped to mimic the combined effects of differences in surface morphology and initial stress on the coating to show separation between the various levels of surface preparation and performance of the applied coatings. Additionally, panels doped over half of their surface with salt will be tested similarly for adhesion before and after expose to stress the coating.

3.7.4 ***Conclusions***

- The results of this study indicate that there is a large potential for expanded recycling efforts for garnets and other mineral abrasives. Additionally, subsequent work has shown the excellent potential for recycling and multiple pass use of aluminum oxide abrasive. Aluminum oxide abrasive can be recycled at least four (4) times while maintaining angularity.
- The primary controlling variable for surface profile depth is the mean size of the grit used for blasting
- The replica tape typically provided a measurement that was higher (by 0.5 to 1 full mil) than the stylus and the single point micrometer.

4 References

[1] Liang, D.; Allen, H. C.; Frankel, G. S.; Chen, Z. Y.; Kelly, R. G.; Wu, Y.; Wyslouzil, B. E. *J. Electrochem. Soc.* **2010**, *157*, C146–C156.

[2] Abbott, W. H. *A Decade of Corrosion Monitoring in the World's Military Operating Environments*; Columbus, OH: Battelle Columbus Operations, 2008.

[3] Lemon, C. Atmospheric Corrosion of Silver Investigated by X-ray Photoelectron Spectroscopy. Ph.D. Thesis, The Ohio State University: USA, 2012.

5 APPENDIX 1

Xenon-arc test data:

ID	dE*	Gloss	DSC	CA	Hardness	Lightness
1K Poly	0	64.4	53.86	81.9	101	0
500 hrs	0.57	55.1	57.78	77	100	0.47
1000 hrs	0.83	42.7	77.8	78.8	100	0.56
1500 hrs	1.26	37.2	75.09	70.3	109	0.9
2000 hrs	1.53	33	76.7	81.4	99	1.17
2500 hrs	1.91	24.5	76.45	72.4	106	1.62
3000 hrs	2.24	20.6	77.07	67.2	100	2
3500 hrs	2.57	19.4	75.55	73.9	102	2.4
4000 hrs	3.07	18	75.26	77.2	105	2.92

ID	dE*	Gloss	DSC	CA	Hardness	Lightness
2K Poly	0	34.6	51.02	78.9	65	0
500 hrs	0.74	41.6	52.83	77.6	75	0.01
1000 hrs	0.82	25	52.5	82.1	82	0.15
1500 hrs	1.1	23.8	50.83	75.9	85	0.49
2000 hrs	1.46	19.5	51.52	77.7	80	0.74
2500 hrs	2.11	20	51.77	66.4	77	1.12
3000 hrs	1.92	17.2	51.61	65.3	89	1.4
3500 hrs	2.46	18.9	45.11	66.9	83	1.45
4000 hrs	3.2	15.3	50.27	76.3	93	2.17

ID	dE*	Gloss	DSC	CA	Hardness	Lightness
2K Epoxy	0	6.2	60.08	96.2	69	0
500 hrs	5.59	1.9	52.33	54.2	78	5.38
1000 hrs	6.38	1.5	54.55	59.3	85	6.24
1500 hrs	6.04	2.2	64.98	47.6	88	5.79
2000 hrs	6.25	1.5	56.2	62.3	84	6.09
2500 hrs	7.01	1.5	72.46	49.4	89	6.92
3000 hrs	7.15	1.4	69.78	50.1	89	7.07
3500 hrs	7.19	1	72.43	47.5	94	7.09
4000 hrs	7.35	1.5	72.92	49.2	90	7.23

ID	dE*	Gloss	DSC	CA	Hardness	Lightness
1K Alkyd	0	51.2	0	69.6	11	0
500 hrs	1.68	11.4	11.75	78.5	28	1.59
1000 hrs	2.15	8	13.29	66.5	32	2.02
1500 hrs	2.38	5.3	19.86	78.2	42	2.29
2000 hrs	2.78	4.3	14.75	79.9	35	2.7
2500 hrs	3.31	4.4	29.99	67.2	48	3.17
3000 hrs	3.77	3.3	28.18	67.8	57	3.68
3500 hrs	4.16	3.3	31.18	63.2	65	4.11
4000 hrs	4.82	3.2	38.42	72.9	71	4.79

ID	dE*	Gloss	DSC	CA	Hardness	Lightness
1K LSA Alkyd	0	49.3	5.8	79	11	0
500 hrs	2.25	6.9	15.69	76	37	2.24
1000 hrs	3.07	5.2	14.94	78.5	34	3.03
1500 hrs	3.51	4.1	20.14	88.4	38	3.37
2000 hrs	4.69	2.5	15.65	80.3	32	4.49
2500 hrs	5.57	2.1	29.75	73	38	5.37
3000 hrs	6.48	2	24.95	66.1	54	6.18
3500 hrs	7.66	1.9	30.05	67.3	64	7.22
4000 hrs	8.91	2	41.8	83	72	8.39

ID	dE*	Gloss	DSC	CA	Hardness	Lightness
2K Poly	0	67.3	55.26	92.7	110	0
500 hrs	0.33	51.4	84.94	79.2	119	-0.17
1000 hrs	0.42	49.5	87.95	82.6	122	-0.01
1500 hrs	1.11	40.8	89.69	75.7	133	0.94
2000 hrs	0.76	42.3	89.62	74.6	119	0.36
2500 hrs	2.91	36.6	92.43	67.7	122	2.74
3000 hrs	1.61	37	93.11	73.2	121	1.33
3500 hrs	2.34	37.7	93.63	65.3	125	2
4000 hrs	2.9	36	93.96	69.8	104	2.63

QUV-B test data:

ID	dE*	Gloss	DSC	CA	Hardness	Lightness
1K Poly	0	64.4	53.86	81.9	101	0
500 hrs	0.58	30	77.54	64.3	104	0.57
1000 hrs	1.04	26.5	76.47	65	104	1.03
1500 hrs	1.74	16.7	76.42	62.5	102	1.71
2000 hrs	1.98	12.8	78.17	58.3	100	1.96
2500 hrs	2.52	10.5	77.15	45.6	97	2.49
3000 hrs	2.79	9.7	78.71	46.6	101	2.78
3500 hrs	3.08	8.2	78.85	70.1	104	3.07
4000 hrs	4.02	5.7	78.02	52.2	106	4.01

ID	dE*	Gloss	DSC	CA	Hardness	Lightness
2K Poly	0	34.6	51.02	78.9	65	0
500 hrs	2.16	29.1	53.74	69.1	82	0.13
1000 hrs	1.71	20.3	51.36	68.4	78	0.88
1500 hrs	2.88	14.2	51.83	54	83	2.51
2000 hrs	5.09	6.5	52.51	35.2	80	4.7
2500 hrs	7.01	3.7	51.54	19.8	86	6.47
3000 hrs	8.09	2.8	49.13	20.4	92	7.34
3500 hrs	8.69	2.5	40.2	32.1	92	7.65
4000 hrs	10.21	2.1	44.44	24.1	94	8.88

ID	dE*	Gloss	DSC	CA	Hardness	Lightness
2K Epoxy	0	6.2	60.08	96.2	69	0
500 hrs	11.12	2.1	52.99	47.1	81	10.88
1000 hrs	13	1.8	67.245	56.5	82	12.93
1500 hrs	12.9	1.8	62.61	54.4	85	12.79
2000 hrs	13.59	1.8	65.57	48.7	85	13.43
2500 hrs	11.17	1.6	70.48	55.4	86	11
3000 hrs	12.67	1.4	72.87	37	87	12.56
3500 hrs	11.72	1.5	75.06	52.7	90	11.57
4000 hrs	12.98	0.9	73.14	44.5	79	12.67

ID	dE*	Gloss	DSC	CA	Hardness	Lightness
1K Alkyd	0	51.2	0	69.6	11	0
500 hrs	3.9	5.3	14.02	55	29	3.88
1000 hrs	5.29	3.1	15.54	47.8	33	5.25
1500 hrs	6.68	3.3	18.11	53.8	34	6.64
2000 hrs	7.62	2.5	23.76	46.2	39	7.59
2500 hrs	8.43	2.5	25.68	47.6	58	8.41
3000 hrs	9.52	2.1	22.59	36.5	64	9.51
3500 hrs	9.96	2.5	21.07	43.5	73	9.95
4000 hrs	11.26	2.3	19.62	51.2	77	11.25

ID	dE*	Gloss	DSC	CA	Hardness	Lightness
1K LSA Alkyd	0	49.3	5.8	79	11	0
500 hrs	4.93	2.7	16.54	49.9	42	4.92
1000 hrs	7.38	2.2	14.91	41.3	36	7.29
1500 hrs	9.08	2	23.44	44.4	49	8.83
2000 hrs	11.23	2	28.78	34.1	42	10.76
2500 hrs	11.88	1.9	30.78	30.3	57	11.28
3000 hrs	13.95	1.8	25.66	33.4	68	13.15
3500 hrs	14.87	2.1	24.05	41.9	80	13.61
4000 hrs	16.21	2.1	22.21	48.1	74	14.79

ID	dE*	Gloss	DSC	CA	Hardness	Lightness
2K Poly	0	67.3	55.26	92.7	110	0
500 hrs	3.73	32.2	81.63	72.5	104	3.7
1000 hrs	5.52	25.4	80.1	60.6	94	5.46
1500 hrs	7.27	5.6	83.14	43.7	103	7.12
2000 hrs	8.49	3	83.55	48.8	104	8.19
2500 hrs	9.59	2.8	87.77	32.6	98	9.06
3000 hrs	10.46	2.1	87.44	31.5	104	9.77
3500 hrs	11.24	1.4	87.95	38.3	98	10.14
4000 hrs	12.44	1.5	87.42	31.1	98	11.18

QUV-A test data:

ID	dE*	Gloss	DSC	CA	Hardness	Lightness
1K Poly		64.4	53.86	81.9	101	0
500 hrs	0.15	44.1	77.19	75.7	105	0.11
1000 hrs	0.36	39.6	76.97	68.9	110	0.35
1500 hrs	0.64	31.5	77.43	74.6	100	0.59
2000 hrs	1.11	30.7	76.46	60.5	99	0.92
2500 hrs	1.37	21.6	77.61	62.2	100	1.29
3000 hrs	1.76	19.2	76.59	58.2	107	1.72
3500 hrs	2.35	17.9	78.36	63.7	105	2.29
4000 hrs	2.9	14.7	76.56	68.5	93	2.85

ID	dE*	Gloss	DSC	CA	Hardness	Lightness
2K Poly		34.6	51.02	78.9	65	0
500 hrs	1.19	35.5	50.06	71.3	82	0.2
1000 hrs	1.01	17.3	48.51	69.3	82	0.53
1500 hrs	0.99	17.8	51.68	63.3	71	0.68
2000 hrs	1.22	17.9	46.03	64.6	73	1
2500 hrs	1.31	16.8	47.97	51.7	84	0.99
3000 hrs	1.46	19.1	42.81	66.5	94	0.99
3500 hrs	2.14	15.5	46.16	67.1	94	1.85
4000 hrs	2.39	17.8	44.53	60.4	92	2.06

ID	dE*	Gloss	DSC	CA	Hardness	Lightness
2K Epoxy		6.2	60.08	96.2	69	0
500 hrs	8.77	4.3	51.91	56.4	87	8.48
1000 hrs	11.9	2	70.1	61.1	87	11.82
1500 hrs	9.24	1.7	74.66	61.5	87	8.91
2000 hrs	12.31	1.8	74.28	50.3	86	12.16
2500 hrs	11.99	1.8	74.24	49.7	89	11.92
3000 hrs	10.42	1.7	76.72	48.7	90	10.29
3500 hrs	12.78	1.7	76.11	46.1	88	12.65
4000 hrs	12.65	1.5	75.19	55.1	87	12.49

ID	dE*	Gloss	DSC	CA	Hardness	Lightness
1K Alkyd		51.2	0	69.6	11	0
500 hrs	1.7	11.7	13.67	71.5	36	1.61
1000 hrs	2.53	8.5	14.49	69.9	35	2.44
1500 hrs	3.02	5.6	19.99	79.3	40	2.9
2000 hrs	4.33	3.5	19.78	53.2	51	4.22
2500 hrs	3.88	3.7	20.41	54	53	3.74
3000 hrs	5.05	3.2	23.46	60.4	68	4.95
3500 hrs	6.49	2.5	23.53	62	73	6.4
4000 hrs	7.31	2.2	23.1	64.9	69	7.24

ID	dE*	Gloss	DSC	CA	Hardness	Lightness
1K LSA Alkyd		49.3	5.8	79	11	0
500 hrs	1.93	7.6	15.05	68.5	38	1.9

1000 hrs	2.82	5.1	17.21	80.8	35	2.8
1500 hrs	3.68	3.3	26.06	72.5	44	3.67
2000 hrs	5.17	2.4	23.05	42.1	49	5.15
2500 hrs	5.26	2.1	24.03	59.3	56	5.24
3000 hrs	6.81	2.2	25.06	68.3	69	6.71
3500 hrs	8.29	2	30.65	41	71	8.18
4000 hrs	9.37	1.9	28.55	44.5	72	9.15

ID	dE*	Gloss	DSC	CA	Hardness	Lightness
2K Poly		67.3	55.26	92.7	110	0
500 hrs	0.2	50.8	79.26	74.4	114	0.09
1000 hrs	2.32	46.4	80.14	84.1	124	2.28
1500 hrs	3.52	43.8	79.68	75.7	110	3.48
2000 hrs	6.21	35.1	81.74	74.3	109	6.18
2500 hrs	4.88	38.1	78.71	76.3	115	4.83
3000 hrs	6.06	32.9	83.31	86.2	110	6.01
3500 hrs	7.66	31	84.08	81.2	104	7.6
4000 hrs	8.28	29	85.82	73.5	103	8.2

Key West test data:

ID	dE*	Gloss	DSC	CA	Hardness	Lightness
1K Poly	0	64.4	53.86	81.9	101	0
30 days	0.07	60.2	61.97	86.8	106	-0.03
60 days	0.26	50	68.10	81.4	104	-0.16
90 days	0.29	48.8	74.03	70	107	-0.03
180 days	1.31	35.9	74.79	66.1	109	1.08
270 days	1.36		76.29	61.9	111	0.93
360 days	1.91	32.7	75.09	64.3	95	1.58
540 days	2.53	23.9	72.30		104	2.3
720 days	2.74	22.3	68.25	46.3	105	2.54

ID	dE*	Gloss	DSC	CA	Hardness	Lightness
2K Poly	0	34.6	51.02	78.9	65	0
30 days	1.35	41.9	50.27	84.1	81	-0.88
60 days	0.48	40.7	49.86	79	81	-0.02
90 days	0.52	40.1	44.21	69.4	86	-0.1
180 days	1.02	33.8	51.71	60.4	92	0.36
270 days	1.26		50.91	55.5	91	0.38
360 days	1.72	31.1	52.78	66.8	79	0.77
540 days	2.99	20.5	55.11		88	1.56
720 days	4.18	21.5	55.25	40.7	84	1.98

ID	dE*	Gloss	DSC	CA	Hardness	Lightness
2K Epoxy	0	6.2	60.08	96.2	69	0
30 days	1.53	5.8	49.35	68.6	65	-0.5

60 days	2.73	5.5	55.36	65.5	67	-0.72
90 days	4.13	2.2	51.73	44.8	66	3.34
180 days	7.07	1.4	58.64	41.3	82	6.77
270 days	6.35		52.06	47.5	89	6.04
360 days	6.19	1.2	55.96	24.2	76	5.53
540 days	5.24	1.3	66.40		80	4.79
720 days	6.73	1	65.30	39	76	6.38

ID	dE*	Gloss	DSC	CA	Hardness	Lightness
Alkyd	0	51.2	-0.03	69.6	11	0
30 days	1.07	12.6	6.35	80	23	1.06
60 days	1.63	8.9	5.78	75.5	19	1.61
90 days	1.62	8.8	6.05	65.2	20	1.58
180 days	2.35	5.6	18.73	57.2	32	2.33
270 days	3		16.84	58.8	52	2.94
360 days	4.18	3.7	19.36	69	37	4.13
540 days	6.31	3.2	21.70		52	6.28
720 days	10.52	3.2	24.11	39.6	45	10.5

ID	dE*	Gloss	DSC	CA	Hardness	Lightness
Alkyd	0	49.3	5.80	79	11	0
30 days	0.75	11.6	7.85	77.3	22	0.72
60 days	1.35	9.2	12.16	79.6	20	1.32
90 days	1.89	7.7	11.42	67	19	1.87
180 days	3.08	5.4	19.15	56.3	32	2.97
270 days	3.65		14.91	54.4	48	3.47
360 days	4.77	3.3	19.19	42.5	38	4.54
540 days	7.09	2.2	19.78		46	6.67
720 days	9.79	1.3	25.38	44.5	41	9.02

ID	dE*	Gloss	DSC	CA	Hardness	Lightness
2K Poly	0	67.3	55.26	92.7	110	0
30 days	0.37	56.8	64.47	90.6	123	-0.14
60 days	0.42	56.1	70.69	93.7	127	-0.3
90 days	0.38	49.4	74.53	79.5	127	0.06
180 days	0.59	49.5	77.73	67.3	120	0.36
270 days	0.6		77.23	64.7	121	-0.02
360 days	0.86	45	78.54	57.1	104	0.46
540 days	1.42	43.2	78.88		126	0.9
720 days	1.88	38.9	81.02	34.7	74	1

Shipboard test data:

ID	dE*	Gloss	DSC	CA	Hardness	Lightness
1K Poly	0	64.4	53.86	81.9	101	0
180 days	0.61	59.8	62.58	82.1	112	-0.57
360 days	0.9	38.9	71.14		93	0.26

ID	dE*	Gloss	DSC	CA	Hardness	Lightness
2K Poly	0	34.6	51.02	78.9	65	0
180 days	0.76	38.4	55.91	70.6	91	-0.49
360 days	1.03	28.5	55.12		88	0.21

ID	dE*	Gloss	DSC	CA	Hardness	Lightness
2K Epoxy	0	6.2	60.08	96.2	69	0
180 days	1.35	4.9	52.73	61.3	77	-0.51
360 days	4	2.5	58.32		84	3.11

ID	dE*	Gloss	DSC	CA	Hardness	Lightness
1K Alkyd	0	51.2	-0.03	69.6	11	0
180 days	0.58	19.4	5.78	69.1	30	0.57
360 days	2.43	8.7	18.15		46	2.41

ID	dE*	Gloss	DSC	CA	Hardness	Lightness
1K LSA Alkyd	0	49.3	5.80	79	11	0
180 days	0.34	14.3	11.44	68.4	49	0.14
360 days	2.17	6.1	21.11		74	1.71

ID	dE*	Gloss	DSC	CA	Hardness	Lightness
2K Poly	0	67.3	55.26	92.7	110	0
180 days	0.53	52.9	64.59	76	124	-0.23
360 days	1.38	37.4	75.31		96	-0.62