NASA Technology Evaluation for Environmental Risk Mitigation
Kennedy Space Center, FL 32899

Gas Dynamic Spray Technology Demonstration Project Management

Final Joint Test Report
June 30, 2011

NASA Contract: NNH09CF09B
Task Order No. NNH11AA25D

ITB, Inc.
7333 Paragon Road, Suite 250
Dayton, Ohio 45459

National Aeronautics and Space Administration (NASA)
Technology Evaluation for Environmental Risk Mitigation Principal Center (TEERM)

Final

Joint Test Report

For

Gas Dynamic Spray Technology Demonstration

NASA.NNH09CF09B.JTR.NNH11AA25D.PL.06.30.11.F

June 30, 2011

Contract No. NNH09CF09B
Task Order No. NNH11AA25D

Prepared by
ITB, Inc.
Dayton, OH 45459

Submitted by
NASA Technology Evaluation for Environmental Risk Mitigation Principal Center

PREFACE

This report was prepared by ITB, Inc., through the National Aeronautics and Space Administration (NASA) Technology Evaluation for Environmental Risk Mitigation Principal Center (TEERM) under Contract Number NNH09CF09B, Task Order No. NNH11AA25D. The structure, format, and depth of technical content of the report were determined by NASA TEERM, Air Force Space Command, Government contractors, and other Government technical representatives in response to the specific needs of this project.

We wish to acknowledge the invaluable contributions provided by all the organizations involved in the creation of this document. Special thanks go to the L3 Corrosion Control Group working out of Patrick Air Force Base, FL, and the NASA Corrosion Technology Laboratory located at Kennedy Space Center, FL.

TABLE OF CONTENTS

Page

LIST OF FIGURES

Page

LIST OF TABLES

Page

1. INTRODUCTION

Headquarters National Aeronautics and Space Administration (NASA) chartered the Technology Evaluation for Environmental Risk Mitigation Principal Center (TEERM) to coordinate agency activities affecting pollution prevention issues identified during system and component acquisition and sustainment processes. The primary objectives of TEERM are to:

- Reduce or eliminate the use of hazardous materials (HazMats) or hazardous processes at manufacturing, maintenance, and sustainment locations.
- Avoid duplication of effort in actions required to reduce or eliminate HazMats through joint center cooperation and technology sharing.

Air Force Space Command (AFSPC) and NASA have similar missions, facilities, and structures located in similar harsh environments. Both are responsible for a number of facilities/structures with metallic structural and non-structural components in highly and moderately corrosive environments. Regardless of the corrosivity of the environment, all metals require periodic maintenance activity to guard against the insidious effects of corrosion and thus ensure that structures meet or exceed design or performance life.

The standard practice for protecting metallic substrates in atmospheric environments is the use of an applied coating system. Current coating systems used across AFSPC and NASA contain volatile organic compounds (VOCs) and hazardous air pollutants (HAPs). These coatings are subject to environmental regulations at the Federal and State levels that limit their usage. In addition, these coatings often cannot withstand the high temperatures and exhaust that may be experienced by AFSPC and NASA structures.

In response to these concerns, AFSPC and NASA have approved the use of thermal spray coatings (TSCs). Thermal spray coatings are extremely durable and environmentally friendly coating alternatives, but utilize large cumbersome equipment for application that make the coatings difficult and time consuming to repair. Other concerns include difficulties coating complex geometries and the cost of equipment, training, and materials.

Gas Dynamic Spray (GDS) technology (also known as Cold Spray) was evaluated as a smaller, more maneuverable repair method as well as for areas where thermal spray techniques are not as effective. The technology can result in reduced maintenance and thus reduced hazardous materials/wastes associated with current processes. Thermal spray and GDS coatings also have no VOCs and are environmentally preferable coatings.

To achieve a condition suitable for the application of a coating system, including GDS coatings, the substrate must undergo some type of surface preparation and/or depainting operation to ensure adhesion of the new coating system. The GDS unit selected for demonstration had a powder feeding system that can be used for surface preparation or coating application. The surface preparation feature was also examined.

The primary objective of this effort was to demonstrate GDS technology as a repair method for TSCs. The aim was that successful completion of this project would result in approval of GDS technology as a repair method for TSCs at AFSPC and NASA installations to improve corrosion protection at critical systems, facilitate easier maintenance activity, extend maintenance cycles, eliminate flight hardware contamination, and reduce the amount of hazardous waste generated.

This project was a continuation of various AFSPC and NASA studies including:

- Coatings Pollution Prevention Opportunity Assessment.
- AFSPC Protective Coating Evaluation.
- The Testing and Demonstration of Metal Wire Arc Spray Materials on Rocket Launch Facilities.
- 18-Month Climate Exposure, Hypergolic Fuel and High Temperature Service Testing, and Field Demonstration Test Plan Cape Canaveral Air Force Station, FL.
- Depainting Pollution Prevention Opportunity Assessment.
- Low Emission Surface Preparation/Depainting Technologies for Structural Steel.
- Alternatives to Isocyanate Urethanes for Structural Steel.
- Low VOC Coatings and Depainting Technologies Field Testing Phase 2.

This project will help AFSPC and NASA meet the tenets of agency and federal directives, such as Presidential Executive Order 13148, *Greening the Government through Leadership in Environmental Management*. The reduction or elimination of hazardous materials will also reduce the amount of hazardous waste and the associated disposal fees and fugitive emissions. This project will also better prepare the Air Force and NASA to comply with federal, state and local regulations. Finally, by working together on this project, both AFSPC and NASA will benefit through the merging of data and knowledge from current pollution prevention projects.

The Joint Test Protocol (JTP) defined the test coupon matrix and performance requirements for validating the GDS technology as a repair method for TSCs. This Joint Test Report (JTR) details the results of the testing conducted in accordance with the JTP.

2. MATERIALS AND METHODS

2.1 Overview

AFSPC and NASA have approved the use of TSCs, extremely durable and environmentally friendly coating alternatives, but they are time consuming to repair. The GDS technology would allow for surface preparation and coating application in a single portable self-contained unit. Due to funding, the project was divided into multiple phases; Phase 1 testing results are covered by this JTR.

The JTP, which was followed, included lab testing by the NASA Corrosion Technology Laboratory. The idea of this testing was to coat panels of the selected substrates with each of the coatings (both TSC and GDS). Flat undamaged panels served as baseline data. Some of the flat panels were damaged and then repaired with the alternative coatings to determine how effective the alternatives are at providing corrosion protection. Composite coupons, flat panels in which a U-shaped channel is welded on, were used to simulate corners and edges that are difficult to coat using TSC. The GDS coatings were applied to these areas to determine whether they provide additional corrosion protection.

2.2 Materials

In order to meet the objectives of the project, the selected coatings were applied to a variety of alloys to simulate potential applications.

2.2.1 Coupon Matrix

The coupon matrix was developed based on information provided by the technical stakeholders and encompassed a wide range of possible applications. The substrates were selected because they were deemed to be the most likely encountered in which this technology may be used. The coatings were selected by stakeholders because it is believed that they would provide the best corrosion protection for the selected alloys.

Three (3) substrates of interest were identified:

- A36 Carbon Steel
- 6061-T6 Aluminum alloy
- 5052-H32 Aluminum alloy

Five (5) Base/Repair Coating materials of interest were identified:

- Zinc (Zn) TSC
- Aluminum-Magnesium (Al-Mg) TSC
- Zn GDS coating
- Zinc-Aluminum (Zn-Al) GDS coating
- Aluminum (Al) GDS coating

Topcoated coupons and non-topcoated coupons were also desired to determine whether a topcoat supplements corrosion protection in addition to providing aesthetic appeal. The topcoat was selected based on performance potential and lack of environmental concerns such as volatile organic compound and hazardous material content.

Table 1 identifies the coupon matrix that was developed based on information provided by the technical stakeholders and includes the substrates and coatings identified as being of interest.

Table 1 Coupon Matrix

Substrate	***Base Coat***	***Coupon***	***Repair Coat***	***Topcoat***
A36 Carbon Steel	Zn TSC *or* Al-Mg TSC *or* Zn GDS *or* Zn-Al GDS *or* Al GDS	Undamaged	Not Applicable	Yes
				No
		Damaged	Zn GDS	Yes
				No
			Zn-Al GDS	Yes
				No
			Al GDS	Yes
				No
			None	Yes
				No
		Composite	Zn GDS	Yes
				No
			Zn-Al GDS	Yes
				No
			Al GDS	Yes
				No
			None	Yes
				No
6061-T6 Aluminum	Zn TSC *or* Al-Mg TSC *or* Zn GDS *or* Zn-Al GDS *or* Al GDS	Undamaged	Not Applicable	Yes
				No
		Damaged	Zn GDS	Yes
				No
			Zn-Al GDS	Yes
				No
			Al GDS	Yes
				No
			None	Yes
				No
5052-H32 Aluminum	Zn TSC *or* Al-Mg TSC *or* Zn GDS *or* Zn-Al GDS *or* Al GDS	Undamaged	Not Applicable	Yes
				No
		Damaged	Zn GDS	Yes
				No
			Zn-Al GDS	Yes
				No
			Al GDS	Yes
				No
			None	Yes
				No

This JTR covers testing conducted only during Phase 1 which included those coatings identified as being of most interest to technical stakeholders. Future phases will address the remainder of the coupon matrix to be completed at a later date. Table 2 identifies those coupons selected for Phase 1 of this effort.

Table 2 Test Phase 1 Coupon Matrix

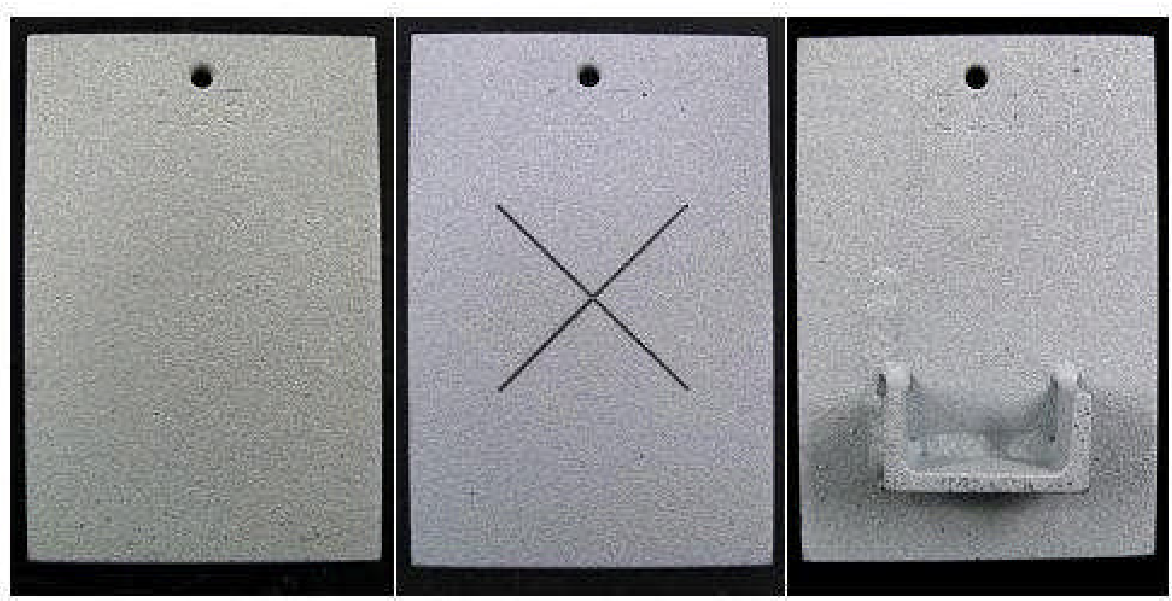
Substrate	***Base Coat***	***Coupon***	***Repair Coat***	***Topcoat***
A36 Carbon Steel	Zn TSC	Undamaged	NA	Yes
				No
		Damaged	Zn GDS	Yes
				No
			None	Yes
				No
		Composite	Zn GDS	Yes
				No
			None	Yes
				No
	Zn GDS	Undamaged	NA	Yes
				No

2.2.2 Coupon Materials

KTA-Tator 4 inch x 6 inch x 3/16 inch (4" x 6" x 3/16") flat and composite coupons, fabricated from ASTM A 36, "Standard Specification for Carbon Structural Steel", hot rolled carbon steel, were used for each coating system. The composite panels have a 1" channel welded on the front face. The composite test panels incorporate common surface irregularities such as welds, crevices, and sharp edges. All panels were abrasive blasted to a white metal (per SSPC-SP-5/NACE-No. 1, "White Metal Blast Cleaning") to remove any mill scale and weld slag. The anchor profile created by the abrasive blasting was approximately 3.5 mils (1 mil = 0.001 of an inch) as measured by the Test-X replica tape method.

The following coupons (Figure 1) were used:

- Flat panel, undamaged—to provide baseline data
- Flat panel, damaged— to simulate damaged/repaired coatings
- Composite panel—to simulate corners and edges



Flat Undamaged Flat Damaged Composite (Steel only)

Figure 1 Typical Flat and Composite Test Panels

2.2.3 Coating Materials

Table 1 details the coatings used for this project. The TSC coating material supplied for this study was 100% zinc wire from The Platt Brothers & Company. The GDS powder material was 100% zinc from Centerline Ltd., and the topcoat material was Carbothane 133MC from Carboline. The topcoat was selected based on performance potential and reduced environmental concerns such as volatile organic compound and hazardous material content.

Table 3 Coatings

Coating	***Type***	***Manufacturer***	***PN***	***Finish***	***Lot***	***Size***
Zn TSC	Wire	Platt	302	Bright	7-17-08 F6	3.2 mm (1/8”)
Zn GDS	Powder	Centerline	440-00316	n/a	n/a	325 mesh
Carbothane	Liquid	Carboline	133MC	White	7H8209L	n/a

2.2.4 Equipment

The TSC equipment used for the coating application was a Thermion Bridgemaster powered using a Miller Invision 456 MIG welder (Figure 2). The gas dynamic spray zinc powder was applied using a portable Centerline SST Cold Gas-Dynamic Spray machine, Model Number SSM-P3800-001 (Figure 3).

Figure 2 Thermion Bridgemaster TSC Equipment

Figure 3 Centerline SST Cold GDS Machine

2.2.5 Test Panel Preparation

In preparation for the atmospheric field exposure testing, six (6) sets of eight (8) panels were coated. A matrix of flat and composite carbon steel panels were coated with either Zn TSC, Zn GDS, or a combination of both. Half of the panels were topcoated.

The L3 Corrosion Control Group working out of Patrick Air Force Base (PAFB), FL, provided their services for the TSC (Figure 4) and GDS (Figure 5) applications. Representatives from the NASA Corrosion Technology Laboratory located at Kennedy Space Center (KSC) were present to observe and record the application process.

Figure 4 Zinc TSC Application

Figure 5 Zinc GDS Application

The application started on 07/20/2009 and finished on 07/27/2009. The environmental conditions were monitored during the application and were found to be acceptable each day for the application process (Table 4).

Table 4 Environmental Conditions During Coating Application

Date	***Time***	***Relative Humidity***	***Air Temperature***	***Dew Point***	***Surface Temperature***
7/20/09	1000	72%	83 °F	73 °F	85 °F
7/20/09	1100	47%	96 °F	73 °F	90 °F
7/20/09	1200	61%	89 °F	75 °F	92 °F
7/21/09	0900	81%	82 °F	75 °F	80 °F
7/21/09	1000	73%	84 °F	74 °F	87 °F
7/21/09	1100	53%	94 °F	75 °F	110 °F
7/21/09	1200	45%	96 °F	72 °F	115 °F
7/21/09	1300	42%	100 °F	72 °F	120 °F
7/27/09	0900	86%	83 °F	76 °F	81 °F
7/27/09	1000	61%	91 °F	76 °F	90 °F

°F = degrees Fahrenheit

Scribed Panels

The flat panels were intentionally damaged by using a carbide tipped scribe tool to gouge a double 1/16" (0.16 centimeter) wide by 3" (7.6 centimeter) cut in the center of the face of the panel forming an "X" shape (Figure 6). The depth of the cut during the scribe process was inspected to make sure that the coatings were cleanly cut and the metallic substrate was exposed.

Figure 6 Typical Scribed Panels

2.2.6 Testing Location and Configurations

Once the final preparations were completed, the test panels were mounted on test racks and transported to the KSC Beach Corrosion Test Site. The test racks and stands utilized for this project have been used for previous corrosion projects and were designed according to ASTM G 50, "Standard Practice for Conducting Atmospheric Corrosion Tests on Metals".

The distance of the test stands from the mean high tide line is approximately 100 feet (30 meters). The site is located approximately 1.5 miles south of Launch Complex 39A directly on the Atlantic Ocean (Figure 7). The site provides an aggressive and very corrosive high salt, high humidity, high ultra-violet light Florida seacoast environmental exposure for test articles.

Figure 7 KSC Beach Corrosion Test Site

The coupon test racks form a matrix of five (5) rows (numbered 1-5) and five (5) columns (lettered A-E). A total of 48 test panels were placed on two (2) test racks on 08/20/2009 for a total of 18 months with photographs taken every six (6) months. Figures 8 and 9 document the location and respective coatings of each test panel.

	A	B	C	D	E
5	**3** Zn TSC + GDS / 133MC	**6** Zn TSC + GDS / 133MC	**7** Zn TSC + GDS / 133MC	**16** Zn TSC + GDS / 133MC	**14** Zn TSC
4	**4** Zn TSC + GDS	**5** Zn TSC + GDS	**8** Zn TSC + GDS	**9** Zn TSC + GDS	**15** Zn TSC
3	**1** Zn TSC / 133MC	**2** Zn TSC / 133MC	**12** Zn TSC / 133MC	**129** Zn TSC / 133MC	**16** Zn TSC
2	**121** Zn TSC	**127** Zn TSC	**128** Zn TSC	**130** Zn TSC	**123** Zn TSC
1	**17** Zn TSC / 133MC	**122** Zn TSC / 133MC	**125** Zn TSC / 133MC	**126** Zn TSC / 133MC	EMPTY

Figure 8 Test Panel Configurations for Test Rack 1

	A	B	C	D	E
5	**192** Zn GDS / 133MC	**198** Zn GDS / 133MC	**342** Zn GDS / 133MC	**352** Zn GDS / 133MC	**237** Zn TSC
4	**182** Zn GDS	**185** Zn GDS	**186** Zn GDS	**235** Zn GDS	**311** Zn TSC
3	**194** Zn TSC + GDS / 133MC	**203** Zn TSC + GDS / 133MC	**286** Zn TSC + GDS / 133MC	**343** Zn TSC + GDS / 133MC	**345** Zn TSC
2	**314** Zn TSC + GDS	**318** Zn TSC + GDS	**333** Zn TSC + GDS	**336** Zn TSC + GDS	**374** Zn TSC
1	**264** Zn TSC / 133MC	**275** Zn TSC / 133MC	**341** Zn TSC / 133MC	**40** Zn TSC / 133MC	EMPTY

Figure 9 Test Panel Configurations for Test Rack 2

2.3. Engineering and Testing Requirements

A joint group consisting of technical representatives from AFSPC and NASA reached technical consensus on engineering, performance, and testing requirements for the GDS technology. The joint group defined critical tests with procedures, methodologies, and acceptance criteria to qualify alternatives against these technical requirements.

Table 5 lists the testing requirements used to evaluate the performance of the repair coatings. The table includes acceptance criteria and reference specifications, if any, used to conduct the tests. All generated data was recorded by the project engineer and includes photographic documentation.

For initial acceptance to the NASA-STD-5008A Qualified Products List (QPL), the primer only (untopcoated) panels must achieve an average rating (from multiple test coupons) of nine (9) or better in accordance with both ASTM D 610 and ASTM D 1654 for a period of 18 months. The topcoated panels must achieve an average rating (from multiple test coupons) of eight (8) or better in accordance with both ASTM D 610 and ASTM D 1654 for a period of 18 months. The panels must also continue to provide acceptable protection and performance for a period of five (5) years to remain on the QPL.

Table 5 Engineering and Testing Requirements

Test	***JTR Section***	***Acceptance Criteria***	***Test Method References***
Coating Application	3.1	Smooth coat with acceptable appearance and Dry Film Thickness (DFT)	SSPC-CS 23.00/ AWS C2.23M/ NACE No. 12; SSPC-PA-2
18-Month Marine Environment Exposure	3.2		NASA-STD-5008A
Degree of Rusting	3.2.1	Attain a numerical rating of not less than nine (9) for primer only and 8 for topcoated systems.	ASTM D 610
Degree of Blistering	3.2.2	Attain a numerical rating of not less than 9F. This applies to topcoated coupons only.	ASTM D 714
Scribe Ratings	3.2.3	Attain a numerical rating of not less than nine (9) for primer only and eight (8) for topcoated systems.	ASTM D 1654
Gloss Measurements	3.2.4	High gloss minimum of 85 Gloss Units at 60° angle and retaining 80% gloss over 18 months. This applies to topcoated coupons only.	ASTM D 523
Color Measurements	3.2.5	Less than three (3) delta E color change units over 18 months. This applies to topcoated coupons only.	ASTM D 2244
Heat Adhesion	3.2.6	Dry-temperature resistance to 400°C (750°F) for 24 hours for untopcoated systems.	ASTM D 4541

3. TEST RESULTS

3.1 Coating Application

This test is conducted to determine whether GDS coatings are difficult to properly apply under normal maintenance operation conditions. The engineering evaluation was substantiated by written descriptions. Dry Film Thickness (DFT) measurements were recorded for the TSCs, GDS coatings, and topcoats.

The Zn TSC easily achieved a 10+ mils coating thickness by applying at least three alternate criss-cross patterns with each pass applying three-four (3-4) mils of coating thickness. The Zn GDS coating thickness was achieved by at least eight (8) multiple criss-cross patterns adding one-two (1-2) mils per pass. The spray pattern (~0.5” wide) and amount of overlapping passes took on average five (5) times as long to coat compared to the TSC operation.

The DFT measurements were performed in accordance with SSPC-CS 23.00/AWS C2.23M/NACE No. 12, “Specification for the Application of Thermal Spray Coatings (Metallizing) of Aluminum, Zinc, and Their Alloys and Composites for the Corrosion Protection of Steel,” using a SSPC-PA-2, “Measurement of Dry Coating Thickness with Magnetic Gages”, Type 2 Fixed Probe Gauge.

Five (5) spot measurements were made in the locations shown below (Figure 10) for each panel and averaged for a single indicator of coating thickness. Long term performance characteristics were compared with film thickness at the end of the test program.

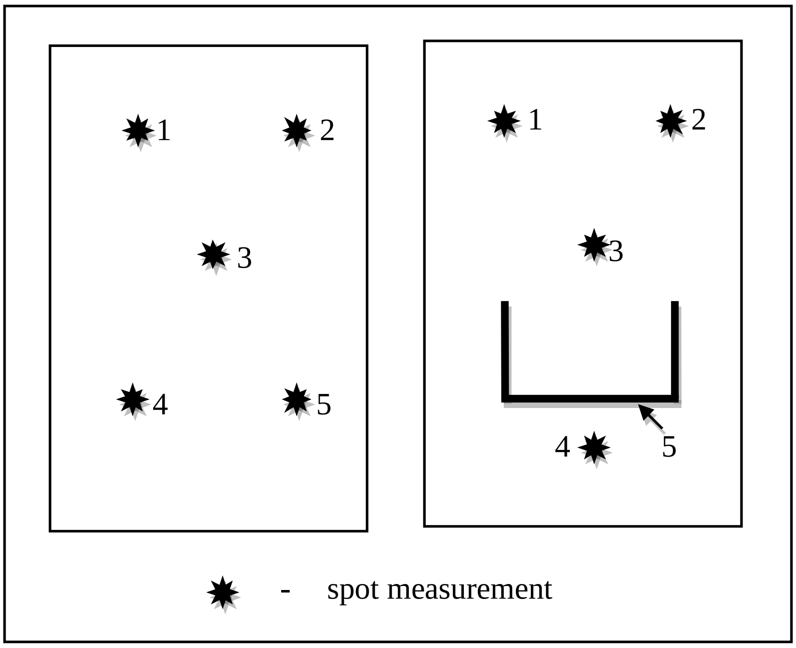


Figure 10 Panel DFT Measurement Locations

Four (4) panels from each set or condition were brought to the KSC Corrosion Coatings Laboratory to be topcoated. Carboline Carbothane 133MC was applied in two (2) coats. The first coat was applied as a thin seal or mist coat (~2-3 mils) and allowed to dry for 24 hours before the final coat (~3-5 mils). The DFT for the topcoat ranged from 5.9 mils to 11.3 mils, averaging 7.9 mils. The highest DFTs were noticed on the Zn GDS coated panels. This could be due to a smoother, less porous coating than what was witnessed on the Zn TSC panels.

Composite panel DFT measurements are given in Table 6 and flat panel DFT measurements are given in Table 7. Panel numbers given in the tables correspond to the panel numbers given in the test panel configurations shown in Figures 8 and 9.

Table 6 Composite Panel Dry Film Thickness Measurements

Panel	*Coating*	*Primer DFT*	*Topcoat DFT*	*Average Panel DFT*
237	Zn TSC	17.1	N/A	17.1
345	Zn TSC	28.0	N/A	28.0
374	Zn TSC	13.1	N/A	13.1
311	Zn TSC	12.6	N/A	12.6
341	Zn TSC + 133MC	21.5	6.9	28.4
275	Zn TSC + 133MC	17.8	7.2	25.0
264	Zn TSC + 133MC	13.0	7.8	20.8
401	Zn TSC + 133MC	18.2	7.3	25.5
318	Zn TSC + GDS*	19.8	N/A	19.8
336	Zn TSC + GDS*	15.5	N/A	15.5
314	Zn TSC + GDS*	24.0	N/A	24.0
333	Zn TSC + GDS*	22.0	N/A	22.0
194	Zn TSC + GDS* + 133MC	14.8	9.0	23.8
343	Zn TSC + GDS* + 133MC	13.1	7.8	20.9
286	Zn TSC + GDS* + 133MC	12.6	7.1	19.7
203	Zn TSC + GDS* + 133MC	14.0	8.3	22.3
12	Zn GDS	12.0	N/A	12.0
186	Zn GDS	13.5	N/A	13.5
235	Zn GDS	9.7	N/A	9.7
185	Zn GDS	10.6	N/A	10.6
192	Zn GDS + 133MC	7.7	10.0	17.7
342	Zn GDS + 133MC	6.5	11.3	17.8
352	Zn GDS + 133MC	5.6	11.0	16.6
198	Zn GDS + 133MC	6.7	11.1	17.8

* GDS applied to the C-channel area

N/A = Not Applicable

Table 7 Flat Panel Dry Film Thickness Measurements

Panel	***Coating***	***Primer DFT***	***Topcoat DFT***	***Average Panel DFT***
14	Zn TSC	20.1	N/A	20.1
15	Zn TSC	19.0	N/A	19.0
16	Zn TSC	16.2	N/A	16.2
123	Zn TSC	16.8	N/A	16.8
17	Zn TSC + 133MC	13.2	7.9	21.1
122	Zn TSC + 133MC	17.4	6.3	23.7
125	Zn TSC + 133MC	19.9	5.9	25.8
126	Zn TSC + 133MC	16.5	6.6	23.1
130	Zn TSC - scribed	14.3	N/A	14.3
121	Zn TSC - scribed	22.0	N/A	22.0
128	Zn TSC - scribed	17.0	N/A	17.0
127	Zn TSC - scribed	18.3	N/A	18.3
1	Zn TSC (scribed) + 133MC	19.0	8.4	27.4
2	Zn TSC (scribed) + 133MC	15.9	8.3	24.2
12	Zn TSC (scribed) + 133MC	14.6	7.1	21.7
129	Zn TSC (scribed) + 133MC	13.5	7.0	20.5
8	Zn TSC (scribed) + GDS*	16.1	N/A	16.1
5	Zn TSC (scribed) + GDS*	24.0	N/A	24.0
4	Zn TSC (scribed) + GDS*	24.5	N/A	24.5
9	Zn TSC (scribed) + GDS*	16.0	N/A	16.0
6	Zn TSC + GDS* + 133MC	11.9	7.2	19.1
10	Zn TSC + GDS* + 133MC	18.5	7.1	25.6
3	Zn TSC + GDS* + 133MC	18.0	7.4	25.4
7	Zn TSC + GDS* + 133MC	13.8	7.4	21.2

* GDS applied to the scribed area

N/A = Not Applicable

3.2 18-Months Marine Environment Exposure

The purpose of this test was to evaluate the corrosion resistance and surface appearance of the repair coating and performance after exposure to a marine environment for 18 months. This test was conducted to provide critical detailed evaluation of coating appearance and integrity by the actual exposure of the coatings to UV radiation, as well as different cycles of salt spray exposure.

Some test panels were subjected to heat adhesion testing. After 18 months, the test panels placed at the KSC Beach Corrosion Test Site were visually inspected and rated for rusting, blistering, reduction of gloss, and color change. Table 8 shows the Task Schedule.

Table 8 Task Schedule

Interval (month)	*Date*	*Task*
0	08/20/2009	Install and Photo
6	02/20/2010	Photo
12	08/20/2010	Photo
18	02/20/2011	Photo and Evaluation

Coating evaluators photographed the test coupons at installation and at six (6)-months, 12-months, and 18-months. Figures 11-14 show Test Rack 1 at six (6)-months, 12-months, and 18-months, respectively. Figures 15-18 show Test Rack 2 at six (6)-months, 12-months, and 18-months, respectively.

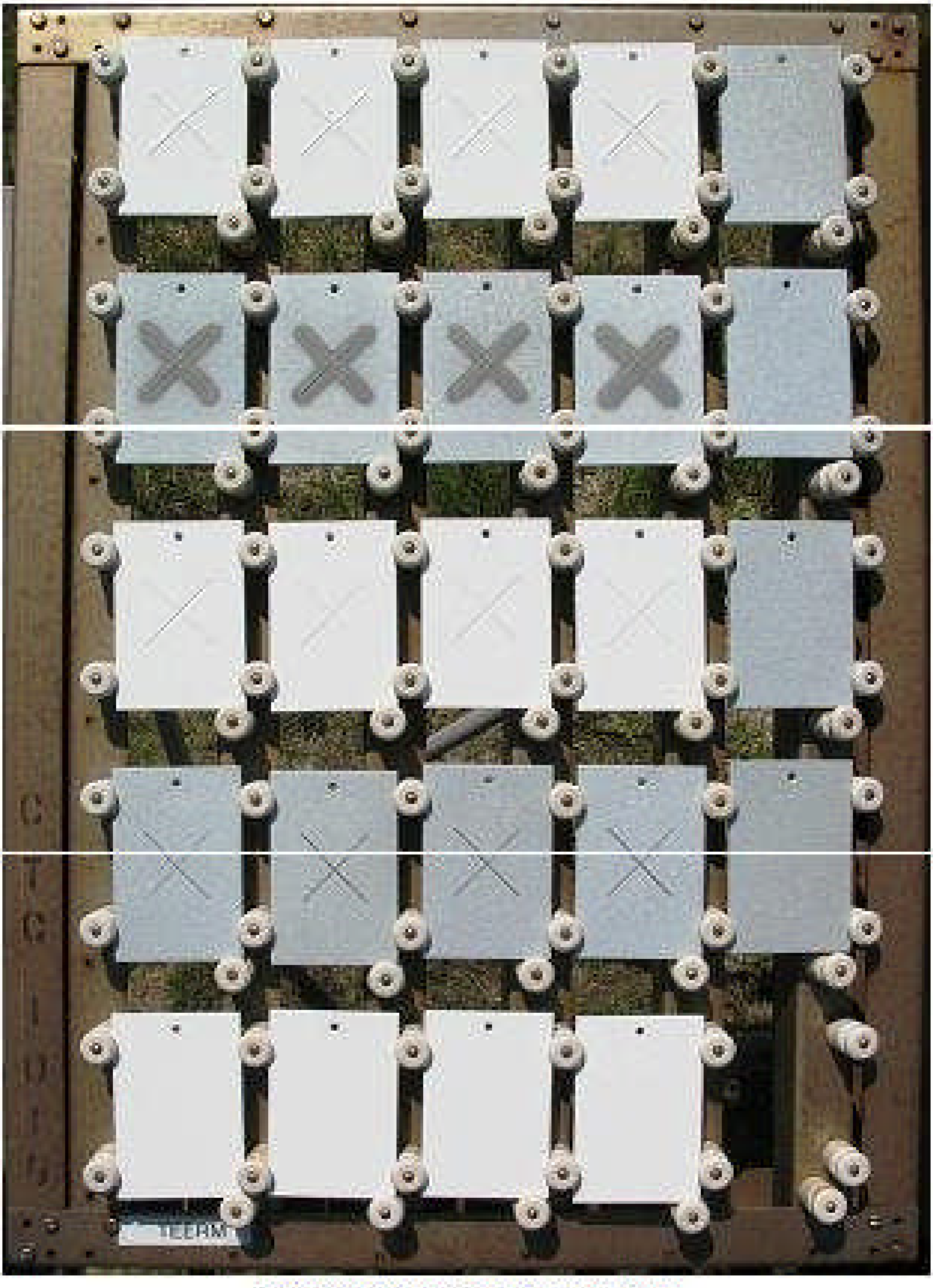


Figure 11 Test Rack 1 Initial Condition

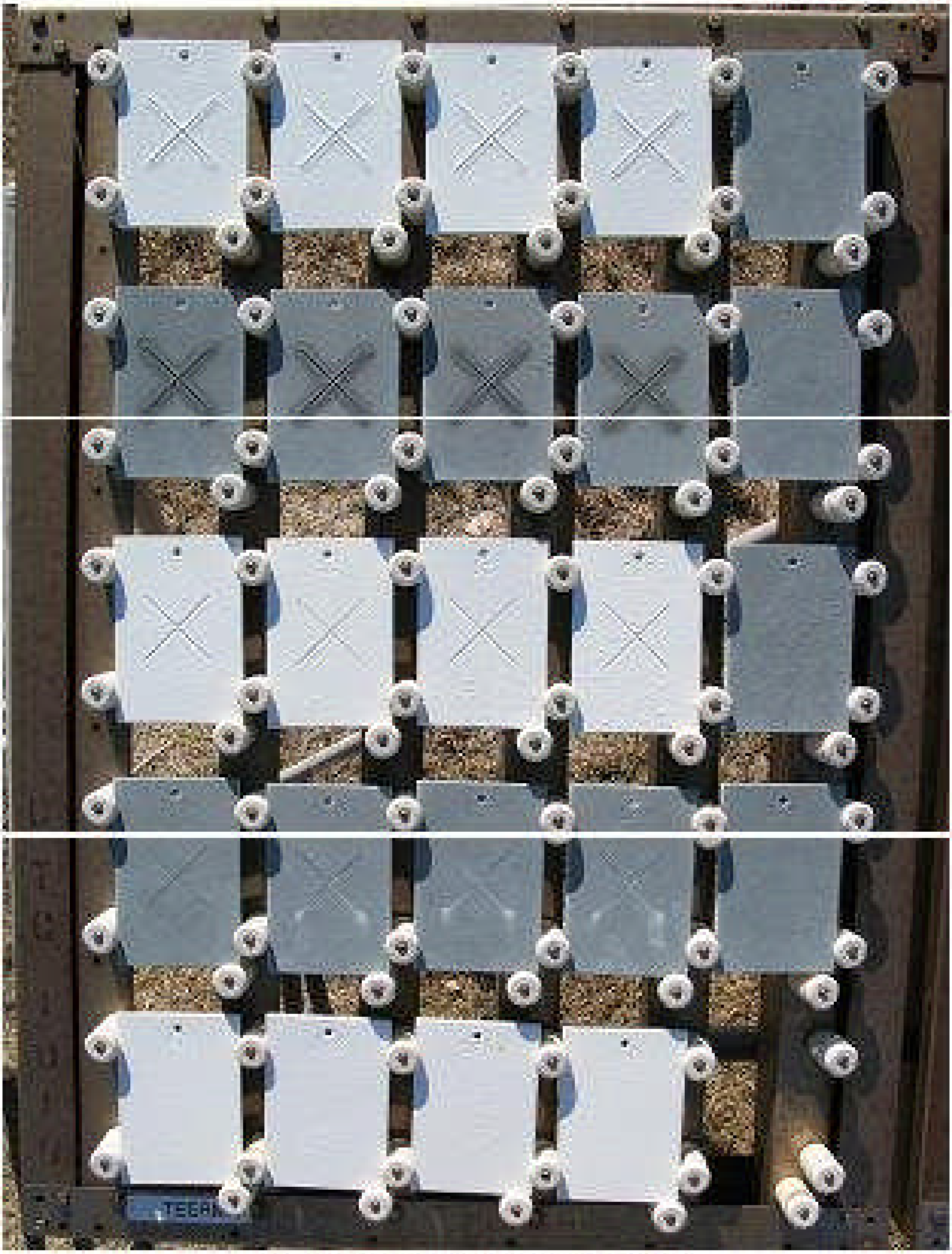


Figure 12 Test Rack 1 after 6 Months

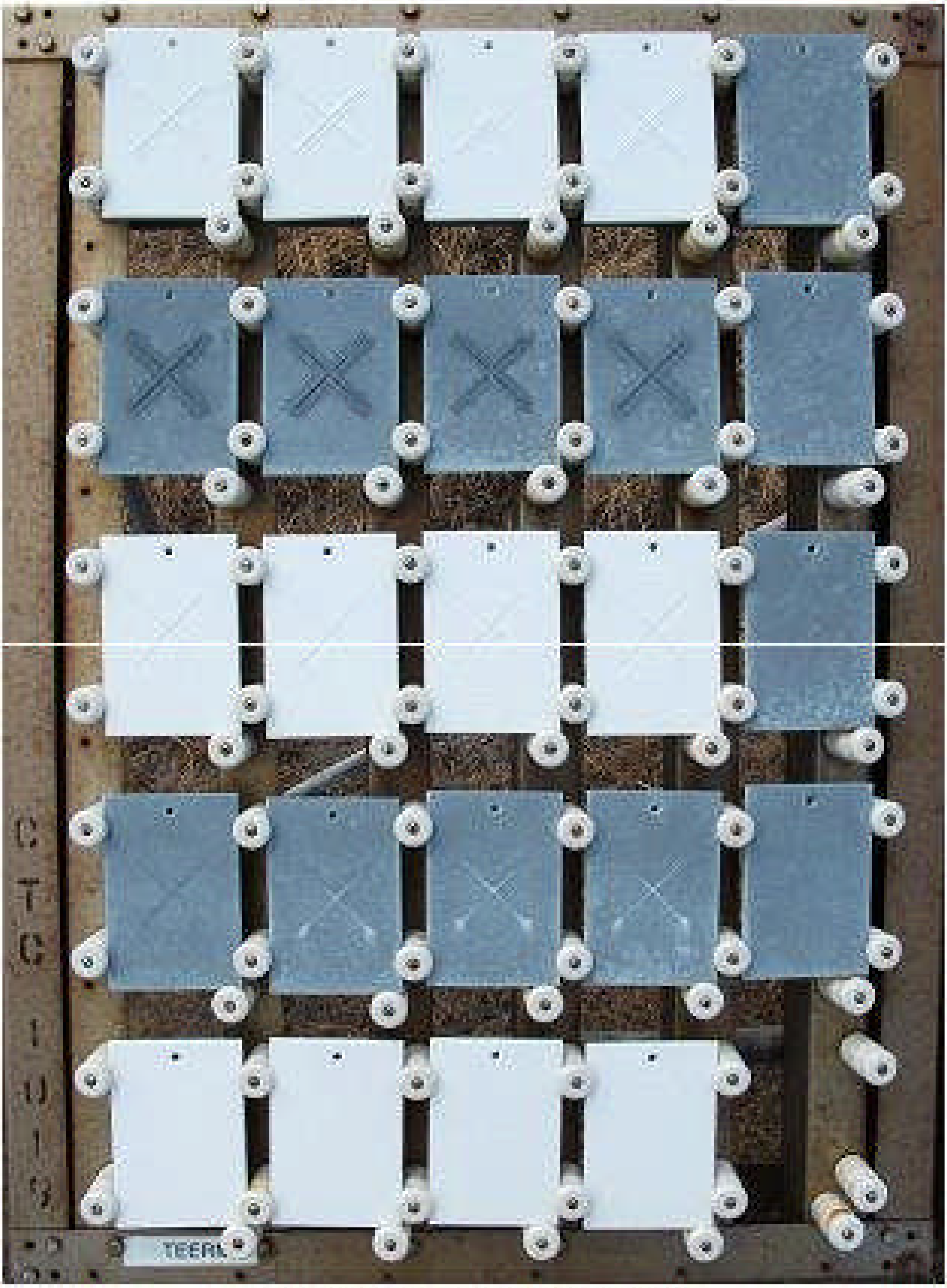


Figure 13 Test Rack 1 after 12 Months

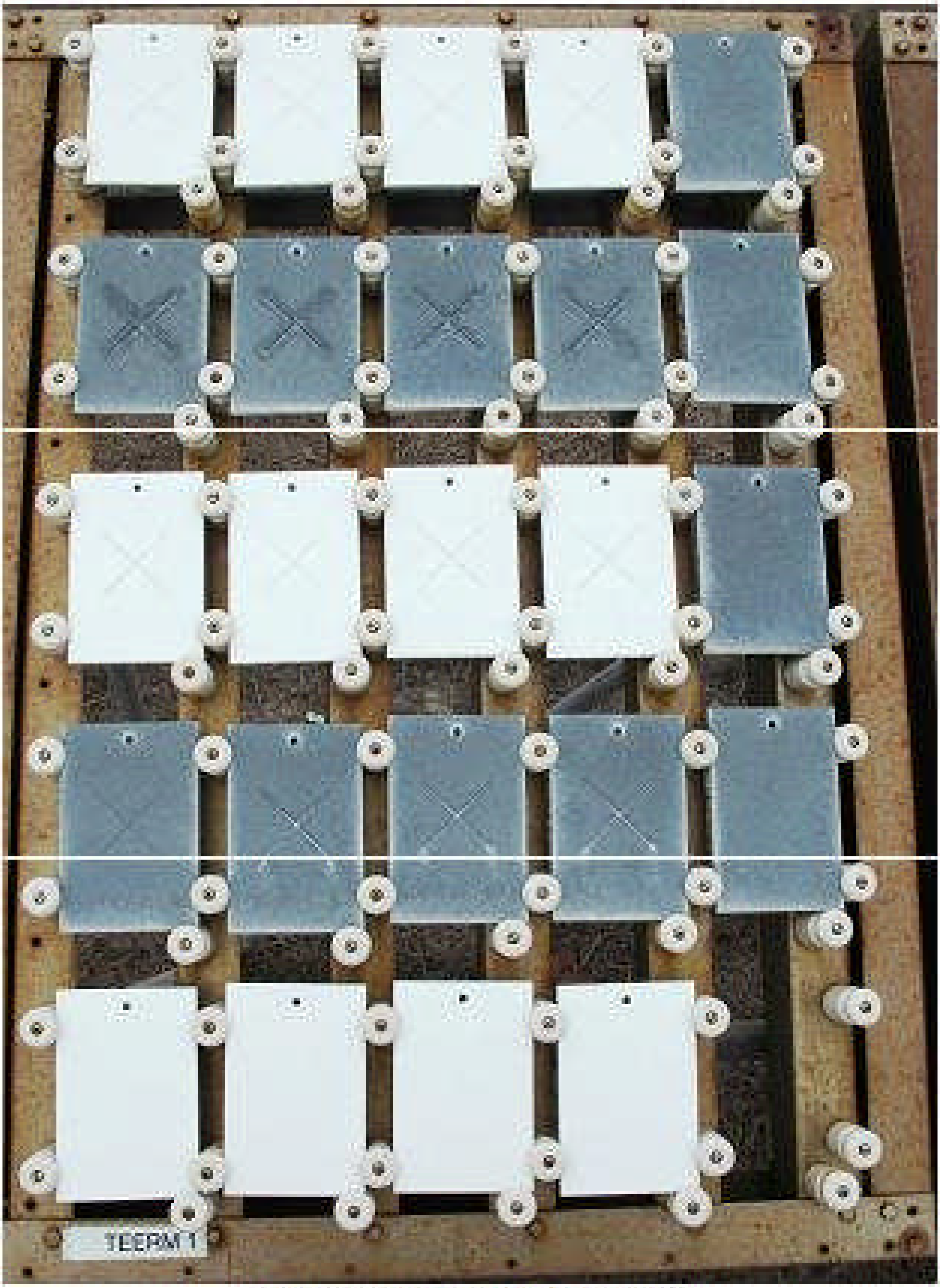


Figure 14 Test Rack 1 after 18 Months

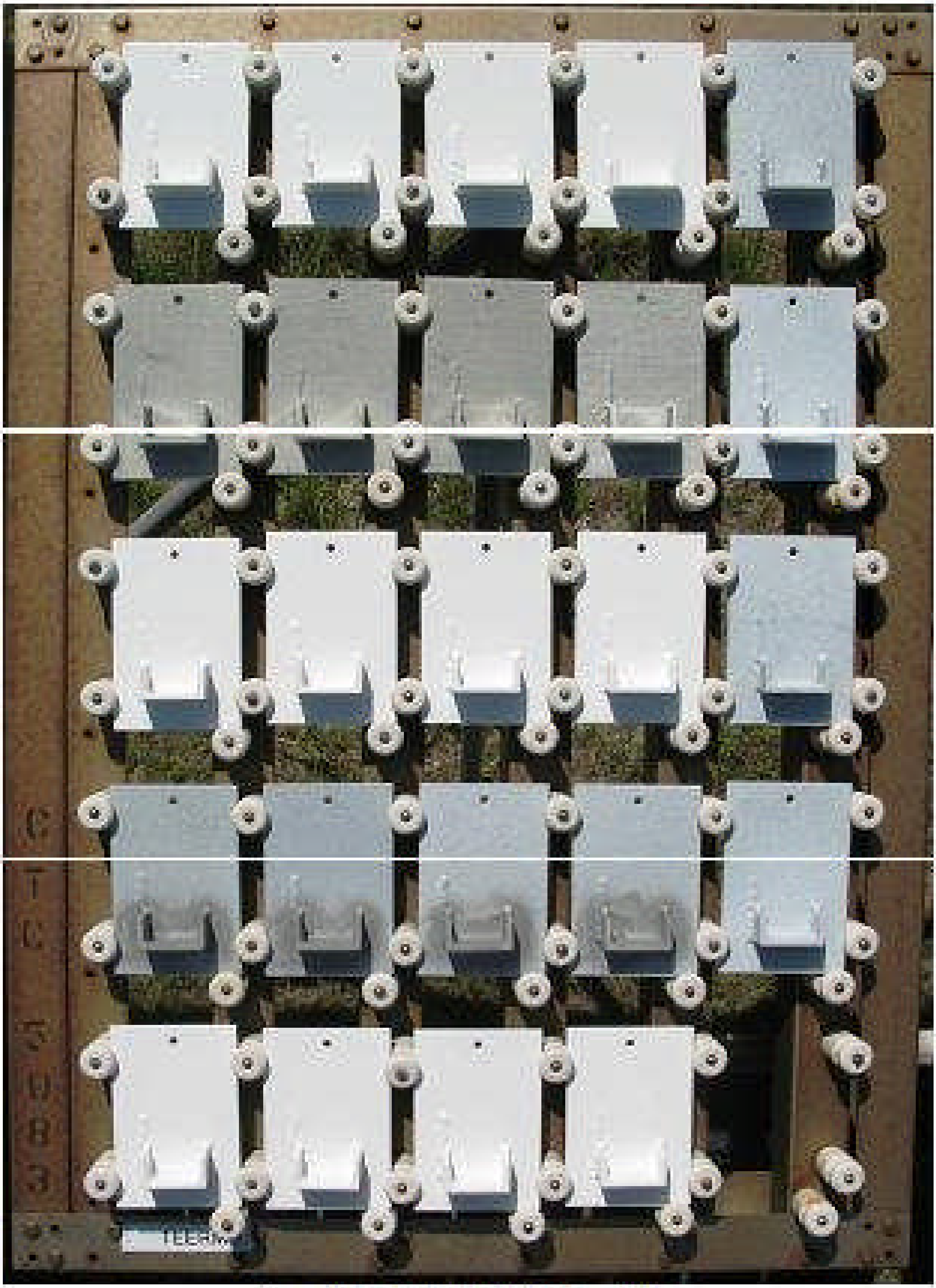


Figure 15 Test Rack 2 Initial Condition

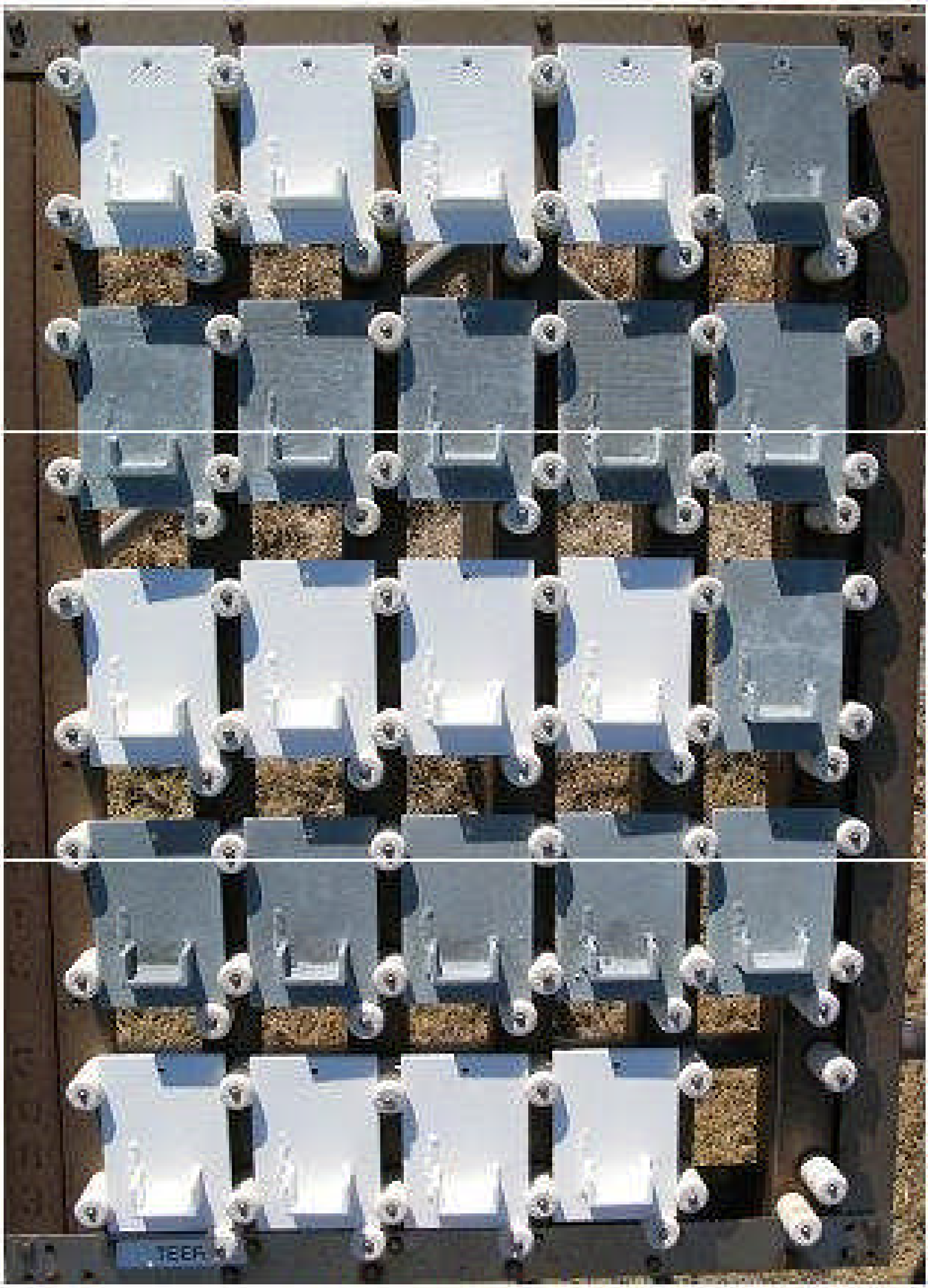


Figure 16 Test Rack 2 after 6 Months

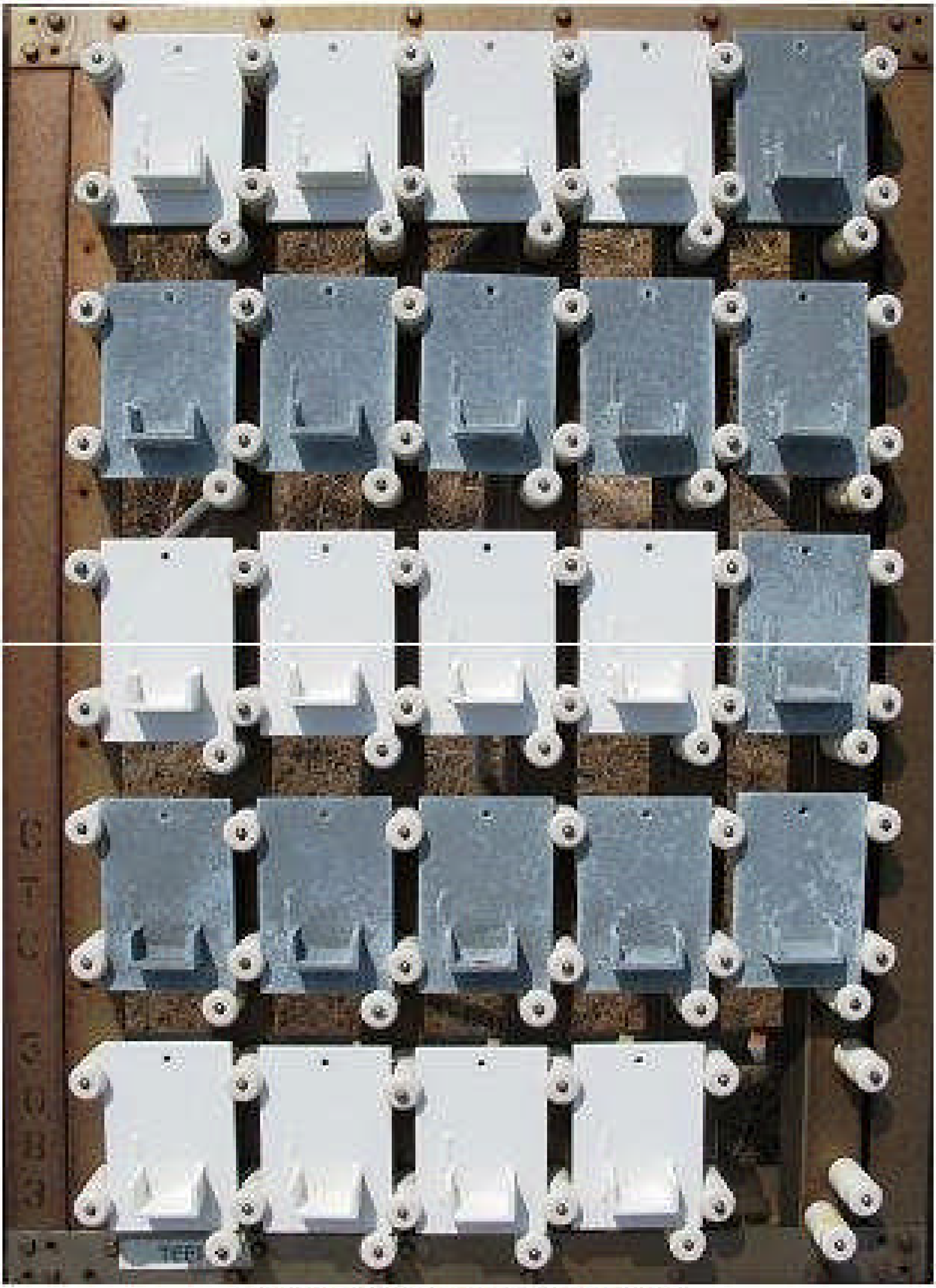


Figure 17 Test Rack 2 after 12 Months

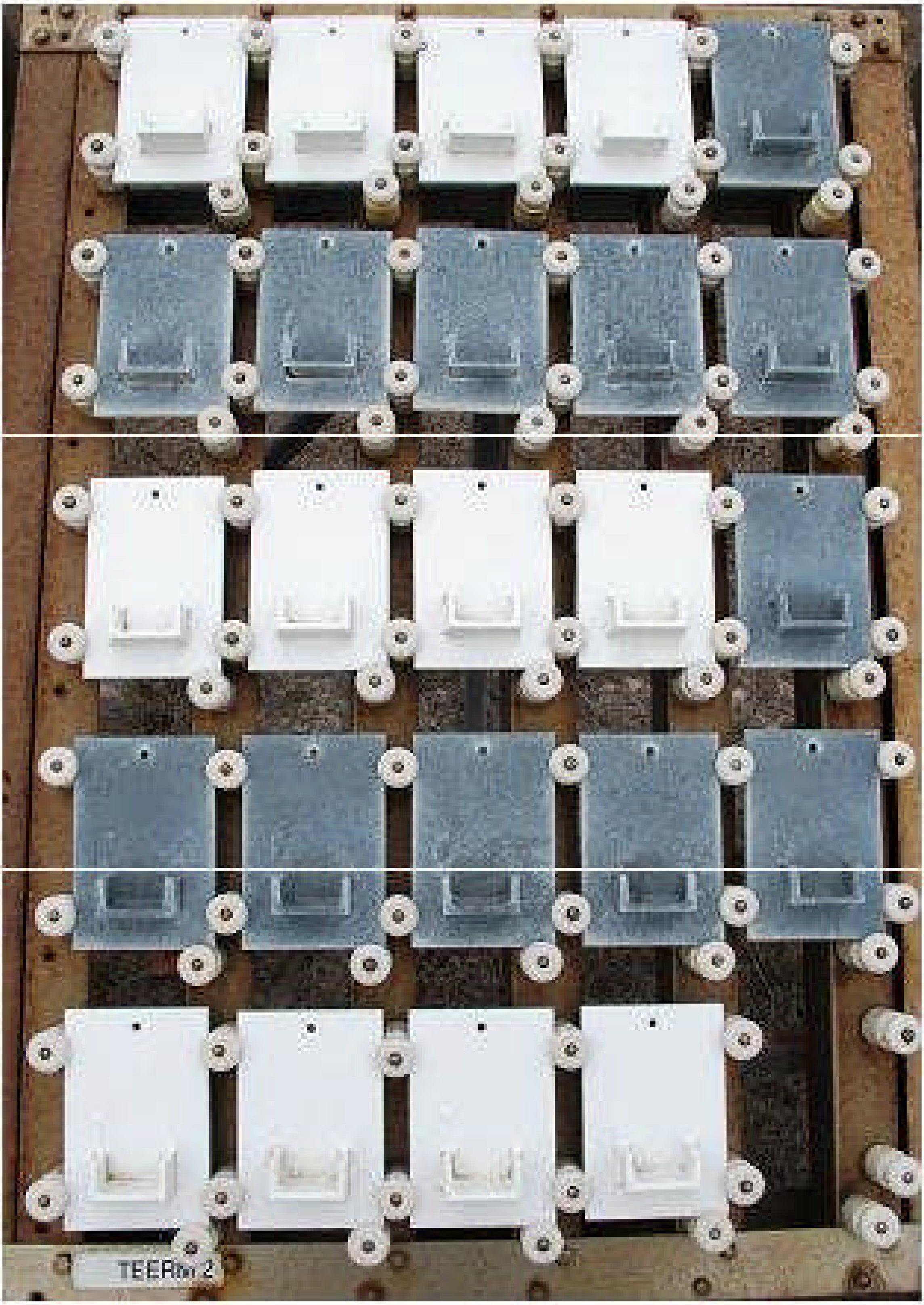


Figure 18 Test Rack 2 after 18 Months

3.2.1 Degree of Rusting

Rusting on the test coupon was rated per ASTM D 610, "Standard Test Method for Evaluating Degree of Rusting on Painted Steel Surfaces", using the numerical grade scale in ASTM D 610 (as shown in Table 9), where 0 indicates 100% surface rusting and 10 indicates less than 0.01% surface rusting.

Table 9 ASTM D 610 Rust Ratings Scale

Rating	*Description*
10	No rusting or less than 0.01% of surface rusted.
9	Minute rusting, less than 0.03% of surface rusted.
8	Few isolated rust spots, less than 0.1% of surface rusted.
7	Less than 0.3% of surface rusted.
6	Extensive rust spots, but less than 1% of surface rusted.
5	Rusting to the extent of 3% of surface rusted.
4	Rusting to the extent of 10% of surface rusted.
3	Approximately 1/6 of the surface rusted.
2	Approximately 1/3 of the surface rusted.
1	Approximately 1/2 of surface rusted.
0	Approximately 100% of surface rusted.

The composite panels used for coating testing have approximately 32 square inches of exposed area. This calculates to 0.0096 square inches for a rating of "9", 0.032 square inches for a rating of "8", 0.096 square inches for a rating of "7", and so on according to ASTM D 610.

Results for the degree of rusting are given in Table 10. Typically, all rating values presented are an average of four panels, which were prepared and exposed at the same time. The final rating value of each coating system is an average of four ratings, and is listed in accordance with the ASTM method of evaluation. Where the panel ratings differed from panel to panel, a simple arithmetic mean is reported. In cases where the rating for a single panel showed extraneous degradation in comparison to the other three, the rating was not included in the average due to the possibility of application or preparation defects.

Appendix A shows the test panels up close for pictorial evidence for the given ratings.

Table 10 Rust Ratings after 18 Months per ASTM D 610

System	Panel Type	SSPC-VIS 2 "G" Ratings				
		Panel 1	Panel 2	Panel 3	Panel 4	Avg.
Zn TSC	Flat	10	10	10	10	10.0
Zn TSC + 133 MC	Flat	10	10	10	10	10.0
Zn TSC	Composite	9	9	10	10	9.5
Zn TSC + 133 MC	Composite	10	10	10	9	9.8
Zn TSC + GDS*	Composite	10	9	8	9	9.0
Zn TSC + GDS* + 133 MC	Composite	10	10	10	10	10.0
Zn GDS	Composite	9	9	9	8	8.8
Zn GDS + 133 MC	Composite	10	10	10	10	10.0

* GDS applied to the C-channel area

3.2.2 Degree of Blistering

Topcoated coupons were rated on Blistering per ASTM D 714, "Standard Test Method for Evaluating Degree of Blistering of Paints"; using the reference standards in section 3. The surface of each coated area was examined for coating defects. ASTM D 714 provides photographic reference standards which are used to compare the size and frequency of blisters observed on the test panels. The blister sizes range from 0 to 10, in which 10 represents no blistering and sizes 8, 6, 4, and 2 represent progressively larger sizes. The frequency of blisters is reported as Few, Medium, Medium Dense, or Dense.

After 18 months of exposure, however, the test panels exhibited no blistering and all rated a 10-none per ASTM D 714.

3.2.3 Scribe Ratings

A set of undamaged topcoated test coupons were scribed prior to exposure and rated per ASTM D 1654, "Standard Test Method for Evaluation of Painted or Coated Specimens Subjected to Corrosive Environments". ASTM D 1654 ratings follow a scale similar to ASTM D 610, except the ratings are based on the mean creepage from the scribe (Table 11). The surface of each coated area was examined for coating defects with the unaided eye and with 10X magnification.

Table 11 ASTM D 1654 Rating Scale
Representative Mean Creepage from Scribe

Millimeters	*Approximate Inches*	*Rating*
0	0	10
Over 0.0-0.5	0- 1/64	9
Over 0.5-1.0	1/64- 1/32	8
Over 1.0-2.0	1/32- 1/16	7
Over 2.0-3.0	1/16- 1/8	6
Over 3.0-5.0	1/8- 3/16	5
Over 5.0-7.0	3/16- 1/4	4
Over 7.0-10.0	1/4- 3/8	3
Over 10.0-13.0	3/8- 1/2	2
Over 13.0-16.0	1/2- 5/8	1
Over 16.0	5/8-more	0

Results for the scribe failure ratings are given in Table 12. Typically, all rating values presented are an average of four panels, which were prepared and exposed at the same time. The final rating value of each coating system is an average of four ratings, and is listed in accordance with the ASTM method of evaluation. Where the panel ratings differed from panel to panel, a simple arithmetic mean is reported. In cases where the rating for a single panel showed extraneous degradation in comparison to the other three, the rating was not included in the average due to the possibility of application or preparation defects.

Appendix A shows the test panels up close for pictorial evidence for the given ratings.

Table 12 Scribe Ratings after 18 Months per ASTM D 1654

System	Panel Type	SSPC-VIS 2 "G" Ratings				
		Panel 1	Panel 2	Panel 3	Panel 4	Avg.
Zn TSC	Flat	10	10	10	10	10.0
Zn TSC + 133 MC	Flat	10	10	9	9	9.5
Zn TSC + GDS*	Flat	10	10	10	10	10.0
Zn TSC + GDS* + 133 MC	Flat	10	10	10	10	10.0

3.2.4 Gloss Measurements

Gloss measurements were conducted on each topcoated coupon per ASTM D 523, "Standard Test Method for Specular Gloss", to document the specular gloss of the original finish of the test areas. Gloss measurements were taken at installation and 18 months to determine gloss retention.

Gloss measurements were performed on the unexposed surfaces using a calibrated BYK Gardner Tri-Gloss portable gloss meter at the 60° angle. The 60° angle was used for the systems because most of the values were between 10 to 70 Gloss Units.

The values presented are an average of four panels, which were prepared and exposed at the same time. The final rating value of each coating system is an average of four ratings, and a simple arithmetic mean is reported. The initial and 18-month data, along with the final gloss retention data, are presented in the Table 13.

Table 13 Gloss Retention Results per ASTM D 523

Panels	Primer	Panel Type	Initial	18-Month	Retention
17, 122, 125, 126	Zn TSC	Flat	19.8	17.3	98%
192, 198, 342, 352	Zn GDS	Composite	29.2	21.3	92%
264, 275, 341, 40	Zn TSC	Composite	23.1	17.8	95%

The GDS primer had a smoother finish and therefore a slightly higher gloss. Both systems, however, maintained over 90% of gloss after 18 months exposure.

3.2.5 Color Measurements

Color measurements shall be conducted on each topcoated coupon per ASTM D 2244, “Test Method for Calculation of Color Differences from Instrumentally Measured Color Coordinates”, to document the color of the original finish of the test areas. Measurements shall also be taken at six (6) months, 12 months, and 18 months to determine color change. All color values shall be recorded by the coatings inspector.

Color measurements were recorded at ambient temperatures on a ColorTec-PCM handheld portable color meter using the CIE L*a*b* format, D-65 illuminant, and a 10° observer. Briefly, a color’s “lightness” (L*) runs from light (white) to dark (black). A more reddish color will give a positive a* value and conversely, a more greenish color will give a negative a* value. As with the a* values, the more bluish color will give a positive b* value, and a more yellowish color will give a negative b* value.

A single number indicator of overall color change (delta E) was calculated by taking the square root of the sum of the squares of the lightness and color difference according to Equation 1.

$$\Delta E = \sqrt{(L_i - L_f)^2 + (a_i - a_f)^2 + (b_i - b_f)^2} \qquad \text{(Eq. 1)}$$

where:

L_i = initial Lightness value

L_f = final Lightness value

a_i = initial Red/Green value

a_f = final Red/Green value

b_i = initial Blue/Yellow value

b_f = final Blue/Yellow value

The results of the color retention test are shown in Table 14. As a general rule, a delta E value of 1 would be discernable by the human eye in a side by side comparison. However, in less than ideal lighting, a delta E value of 2 or 3 can still be considered the same color.

The smoother GDS coating maintained its color better with a delta E of 2.9, while the TSC coated panels averaged a delta E of 4.3.

Table 14 Color Retention Results per ASTM D 2244

Panels	Primer	Panel Type	Initial			18-Month			Delta E
			L	a	b	L	a	b	
17, 122, 125, 126	Zn TSC	Flat	94.49	-0.68	2.69	95.14	-2.64	7.55	5.3
192, 198, 342, 352	Zn GDS	Composite	94.74	-0.71	2.81	95.61	-1.29	5.52	2.9
264, 275, 341, 40	Zn TSC	Composite	94.64	-0.7	2.8	95.58	-1.84	6.85	4.3

3.2.6 Heat Adhesion

As a part of the 18-month Marine Environment test, NASA-STD-5008A requires zinc primer coatings have a temperature resistance of 750° F (400° C) for use on launch structures and ground support equipment subject to the elevated temperatures associated with rocket exhaust. Although coatings are exposed to much higher temperatures for shorter times, this test is designed to ensure that organic zinc materials are not used on the launch pads. Alternative coatings tested under this effort were tested to the requirement.

The requirement is satisfied by exposing the coated panels in a high temperature oven to a temperature of 750° F for 24 hours. Any visual deterioration, such as destruction or burning of the coating, would indicate failure of the product. Pre-heat and post-heat tensile adhesion tests in accordance with ASTM D 4541, “Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers”, are performed to see if there were any signs of degradation due to the heat. Loss of adhesion after heating also constitutes a failure due to temperature effects on the film.

Each of the TSC is first tested for tensile adhesion, using ASTM D 4541, and then exposed to the heat cycle. The coating film is then re-tested for tensile adhesion to check for adhesion loss or film deterioration caused by heating. Since the TSC’s in this study are considered replacements for the zinc primers they were tested according to this requirement.

Dollies were prepared and bonded to each of the TSC and GDS panels, allowed to dry for 24 hours, and then pulled using a PATTI pneumatic adhesion tester. Once complete, the panels were placed in an oven at the above specified temperature and time and the adhesion test process was repeated once the samples cooled to room temperature.

Figure 19 shows the pre-heat and post-heat results for the Zn TSC panels. Figure 20 shows the pre-heat and post-heat panels for the Zn TSC panels.

Figure 19 Pre-heat and Post-heat Zn TSC Panels

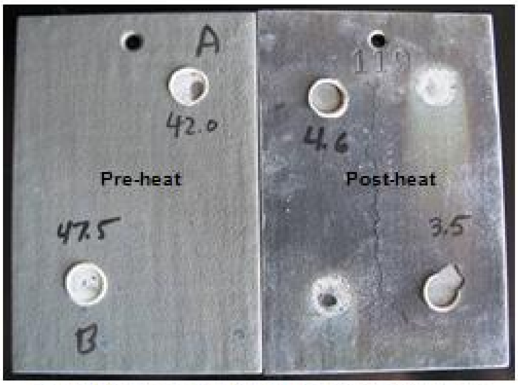


Figure 20 Pre-heat and Post-heat Zn GDS Panels

Results of the heat adhesion testing are given in Table 15. As applied, the GDS adhesion values (2625 psi) initially averaged over three (3) times the adhesive strength of the TSC (780 psi). Both the GDS and TSC meet the minimum adhesion criteria of 500 psi found in SSPC-CS 23.00/AWS C2.23M/NACE No. 12.

The post-heat TSC showed a 42% increase in tensile adhesion after heating, but the GDS lost 88% of its adhesive strength and failed to meet the minimum adhesion value stated in SSPC-CS 23.00/AWS C2.23M/NACE No. 12.

Table 15 Heat Adhesion Results

Coating	***Avg DFT (mils)***	***Pre-heat PSI***	***Avg Pre-heat PSI***	***Failure Mode***	***Post-heat PSI***	***Avg Post-heat PSI***	***Failure Mode***
Zn TSC	10-12	740	780	Cohesive	1111	1111	Cohesive
Zn TSC	10-12	860		Cohesive	1029		Cohesive

Zn TSC	10-12	781		Cohesive	1358		Cohesive
Zn TSC	10-12	739		Cohesive	946		Cohesive
Zn GDS	8-10	2512	2625	Cohesive	492	310	zinc split
Zn GDS	8-10	2018		Cohesive	294		zinc split
Zn GDS	8-10	3131		Cohesive	336		zinc split
Zn GDS	8-10	2840		Cohesive	117		zinc split

The manufacturer of the GDS unit (CenterLine) was contacted to discuss why the dramatic drop in adhesion may have occurred. It is believed that there was a weak Zn particle/particle boundary (due to a lack of diffusion bonding). This allowed oxygen to find open diffusion paths during the heating phase and led to oxidation within the layers of the coating. The manufacturer is conducting tests to determine whether varying parameters produce better results.

4. SUMMARY

For initial acceptance to the NASA-STD-5008 Qualified Products List (QPL), the primer only (untopcoated) panels must achieve an average rating (from multiple test coupons) of nine (9) or better in accordance with ASTM D 610 and ASTM D 1654 for a period of 18 months. The topcoated panels must achieve an average rating (from multiple test coupons) of eight (8) or better in accordance with ASTM D 610 and ASTM D 1654 for a period of 18 months. The panels must also continue to provide acceptable protection and performance for a period of five (5) years to remain on the QPL.

All of the coatings in test performed adequately, scoring an average score above 9.0, except the Zn GDS composite panels, which scored an average of 8.8. This set of test panels was the only one that had failures on each panel. All of the failures were in and around the “C” channel. This area is the most difficult area to coat and needs the most attention when coating operations are performed. The coating may show improved performance if the coating applicator spends additional time and effort to ensure an even and smooth coating on those more difficult areas.

The Zn GDS repair of the flat scribed panels (rating of 10) showed a slight improvement in performance over the Zn TSC scribed panel (rating of 9.5). Application of a topcoat improved the performance of both sets of composite panels.

The GDS coating requires many more layers than TSC to obtain the same coating thickness. These multiple passes may have led to the drop in adhesion after heating. GDS coatings are less porous that TSC, however, and may not need as thick a coating for similar performance. The reduction in passes may also address the heat adhesion issues. Additional testing to determine minimum GDS coating thickness while optimizing performance is recommended.

5. REFERENCE DOCUMENTS

American Society for Testing and Materials
2008 *Standard Specification for Carbon Structural Steel.* Document Identification ASTM A 36.

American Society for Testing and Materials
2008 *Standard Test Method for Specular Gloss.* Document Identification ASTM D 523.

American Society for Testing and Materials
2008 *Standard Test Method for Evaluating Degree of Rusting on Painted Steel Surfaces.* Document Identification ASTM D 610.

American Society for Testing and Materials
2009 *Standard Test Method for Evaluating Degree of Blistering of Paints.* Document Identification ASTM D 714.

American Society for Testing and Materials
2008 *Standard Test Method for Evaluation of Painted or Coated Specimens Subjected to Corrosive Environments.* Document Identification ASTM D 1654.

American Society for Testing and Materials
2009 *Test Method for Calculation of Color Differences from Instrumentally Measured Color Coordinates.* Document Identification ASTM D 2244.

American Society for Testing and Materials
2009 *Standard Test Method for Pull-off Strength of Coatings Using Portable Adhesion Testers.* Document Identification ASTM D 4541.

American Society for Testing and Materials
2003 *Standard Practice for Conducting Atmospheric Corrosion Tests on Metals.* Document Identification ASTM G 50.

CenterLine (Windsor) Ltd.
2005 *Portable Supersonic Spray Machine User's Manual*. Document # SST-PBS-PM-P-1.0-0605.

NACE (National Association of Corrosion Engineers)
2002 *Field Measurement of Surface Profile of Abrasive Blast-Cleaned Steel Surfaces Using a Replica Tape*. Document Identification NACE-STD-RP0287.

NASA (National Aeronautics and Space Administration)

2004 *Protective Coating of Carbon Steel, Stainless Steel, and Aluminum on Launch Structures, Facilities, and Ground Support Equipment*. Document Identification NASA-STD-5008A.

SSPC (The Society for Protective Coatings)
2004 *Measurement of Dry Coating Thickness with Magnetic Gages*. Document Identification SSPC-PA-2.

SSPC/AWS (American Welding Society)/NACE
2003 *Specification for the Application of Thermal Spray Coatings (Metallizing) of Aluminum, Zinc, and Their Alloys and Composites for the Corrosion Protection of Steel*. Document Identification SSPC-CS 23.00/AWS C2.23M/NACE No. 12.

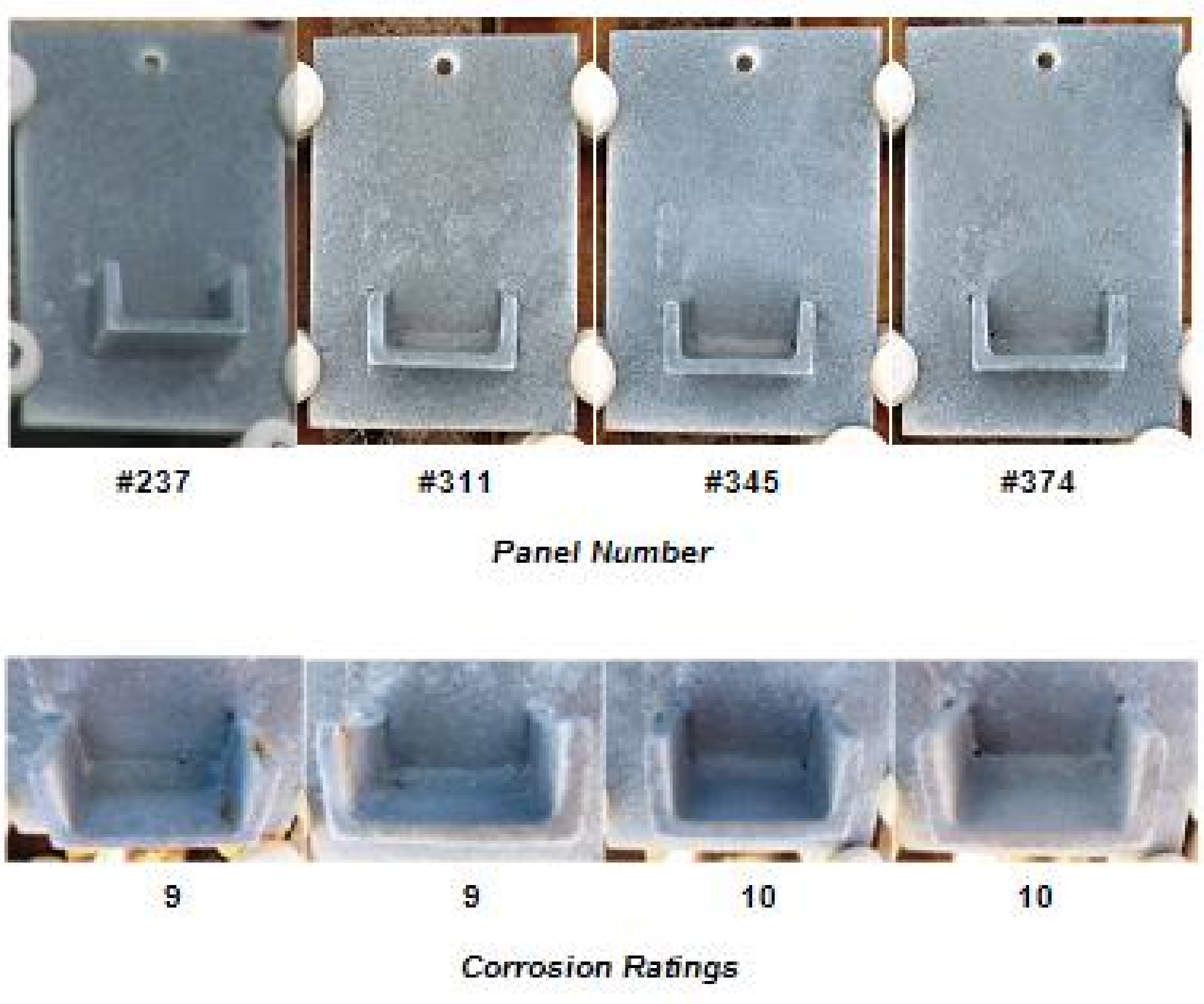
SSPC/NACE
2000 *White Metal Blast Cleaning*. Document Identification SSPC-SP-5/NACE-No. 1.

SSPC/NACE
2000 *Near-White Blast Cleaning*. Document Identification SSPC-SP-10/NACE-No. 2.

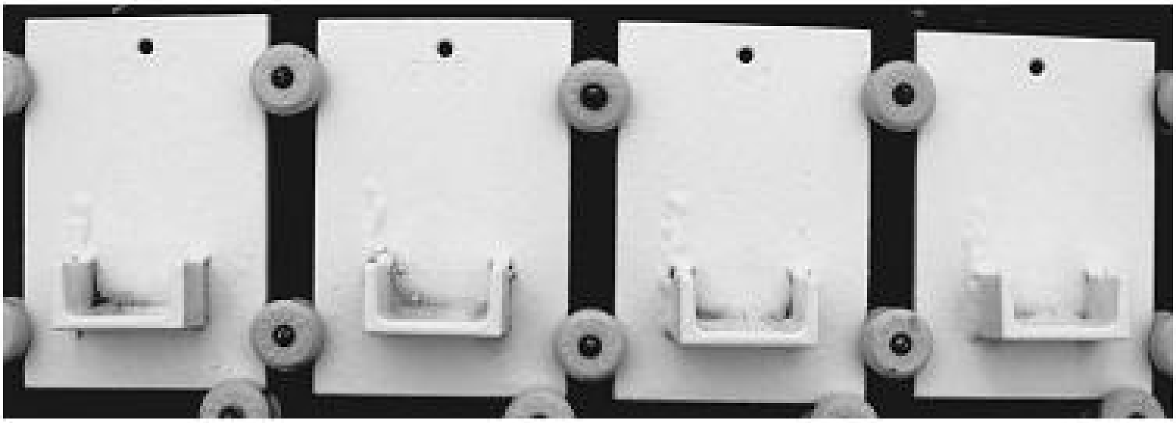
APPENDIX A

Pictorial Evidence of Corrosion Ratings

Zinc TSC

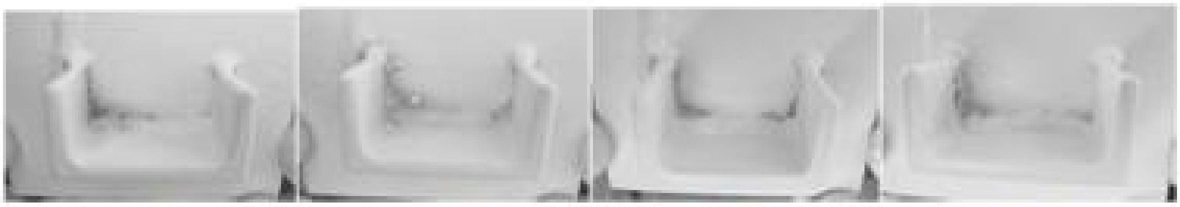


Zinc TSC + 133MC



#264 #275 #341 #40

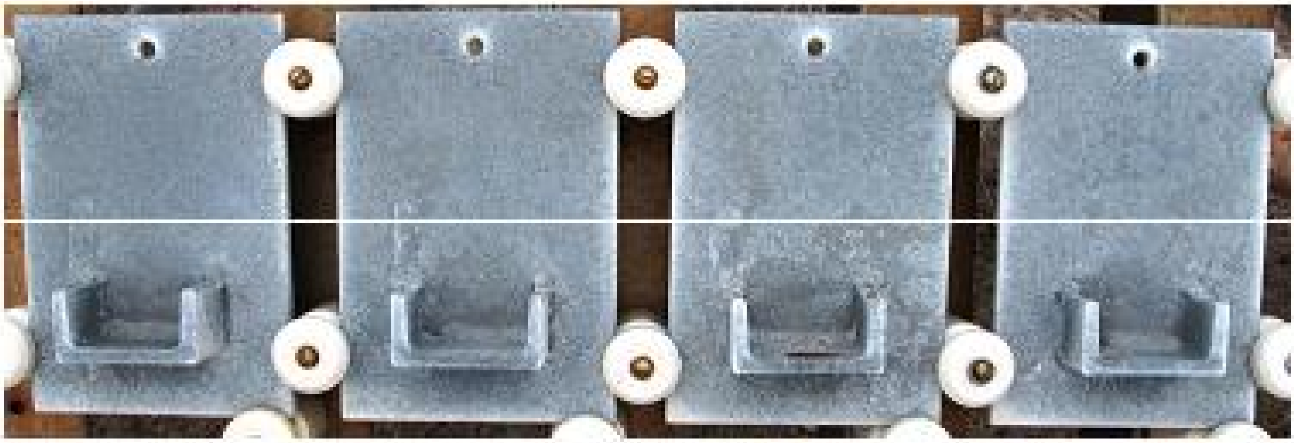
Panel Number



10 10 10 10

Corrosion Ratings

Zinc TSC + GDS



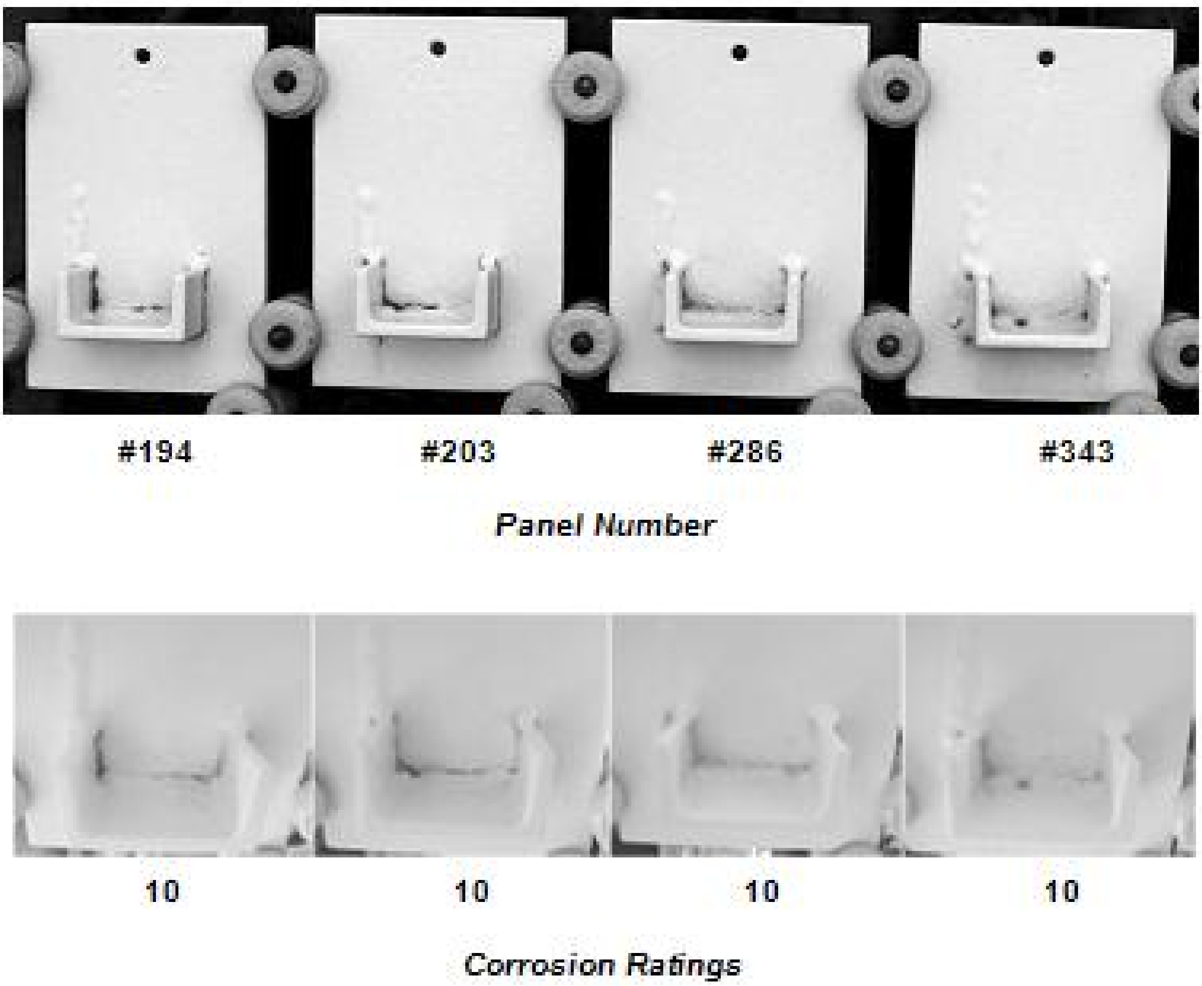
#314 #318 #333 #336

Panel Number

10 9 8 9

Corrosion Ratings

Zinc TSC + GDS + 133MC



Zinc GDS

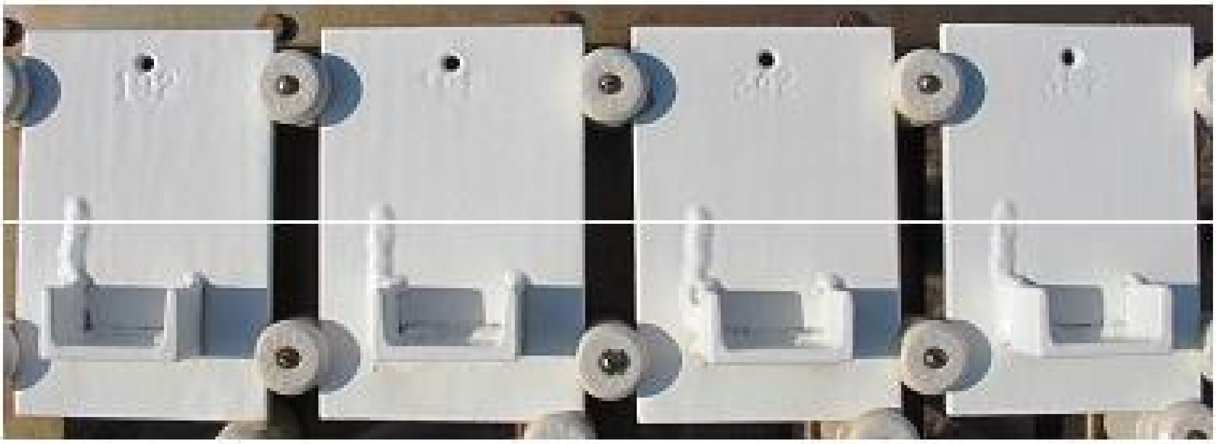
#182 #185 #186 #235

Panel Number

9 8 9 9

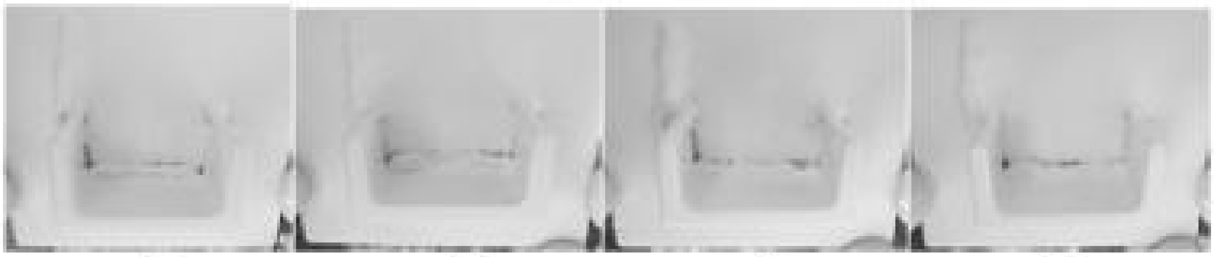
Corrosion Ratings

Zinc GDS + 133MC



#192 #198 #342 #352

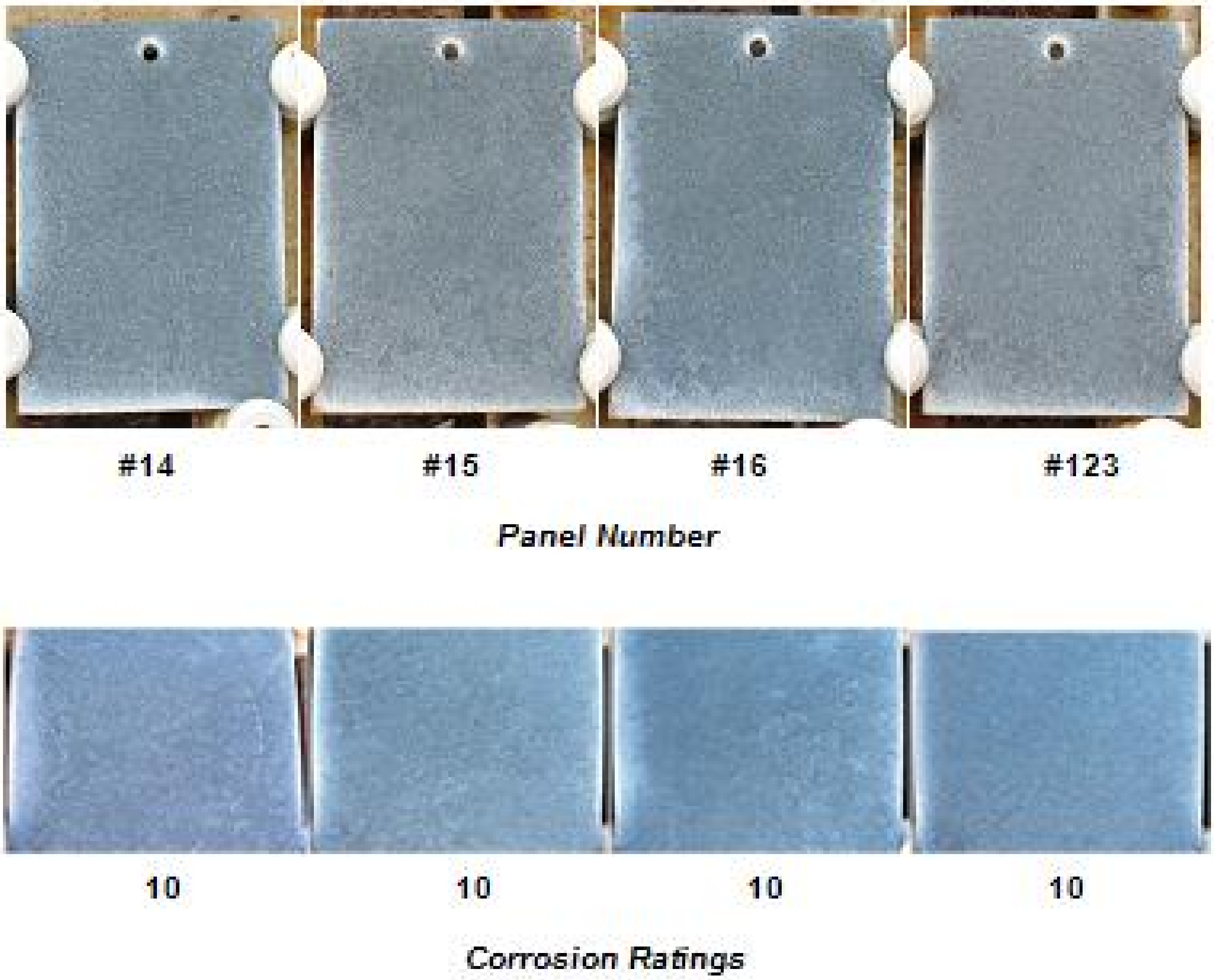
Panel Number



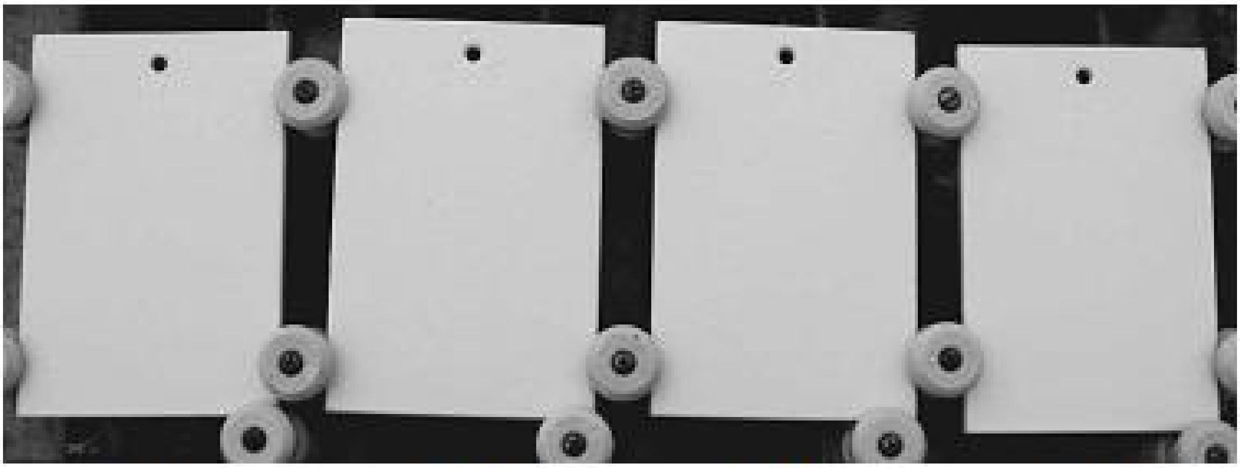
10 10 10 10

Corrosion Ratings

Zinc TSC

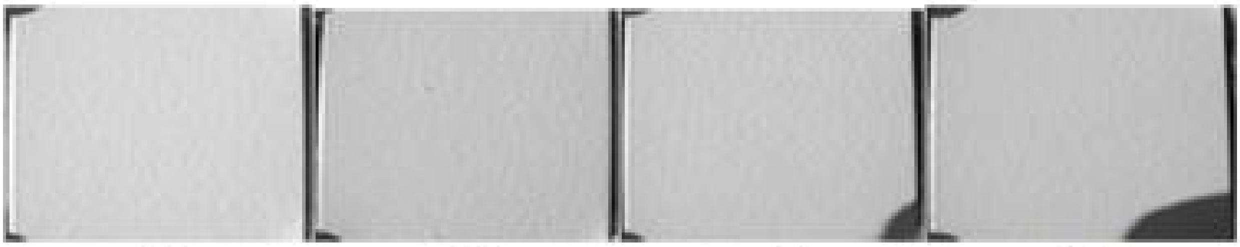


Zinc TSC + 133MC



#17 #122 #125 #126

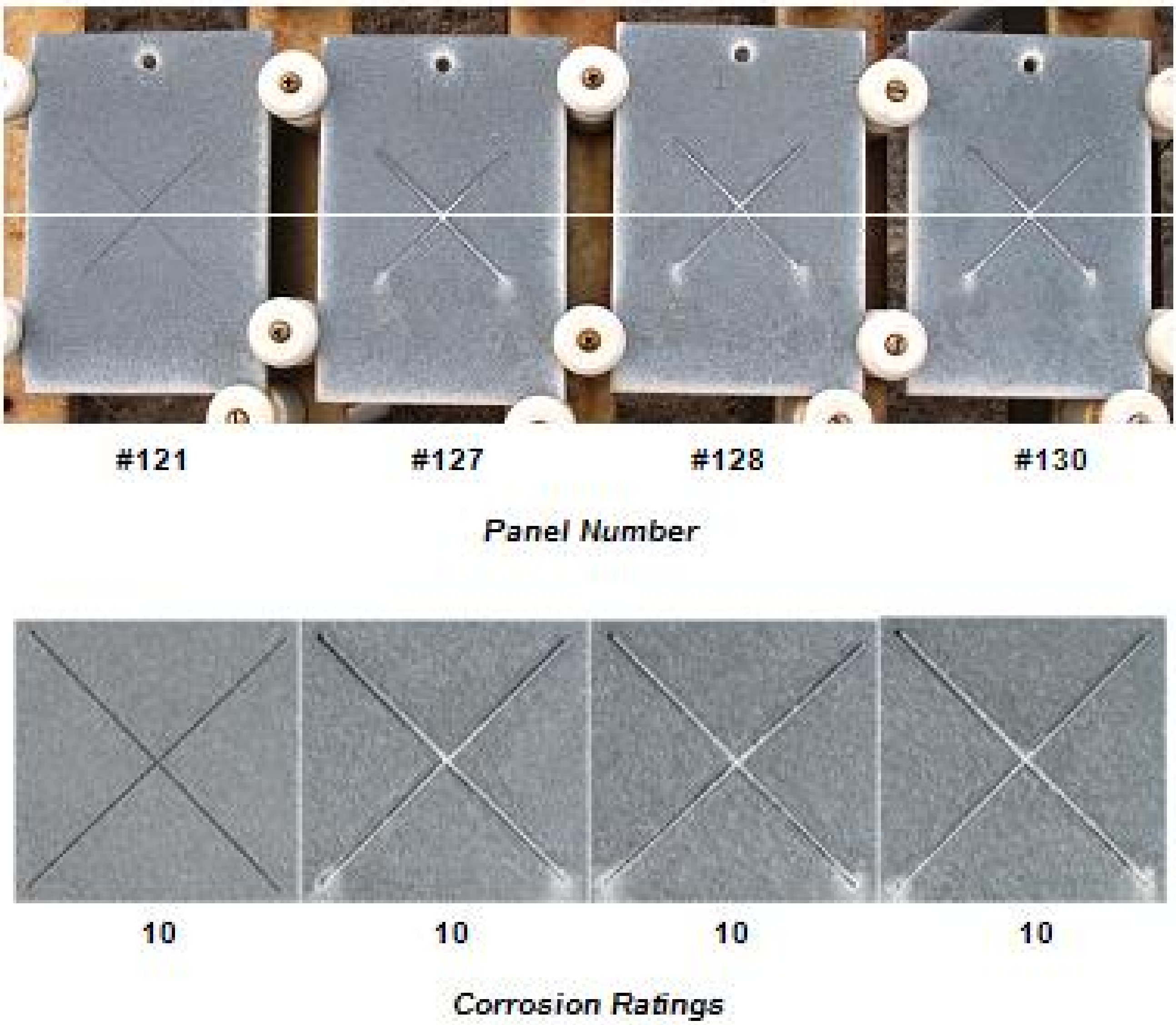
Panel Number



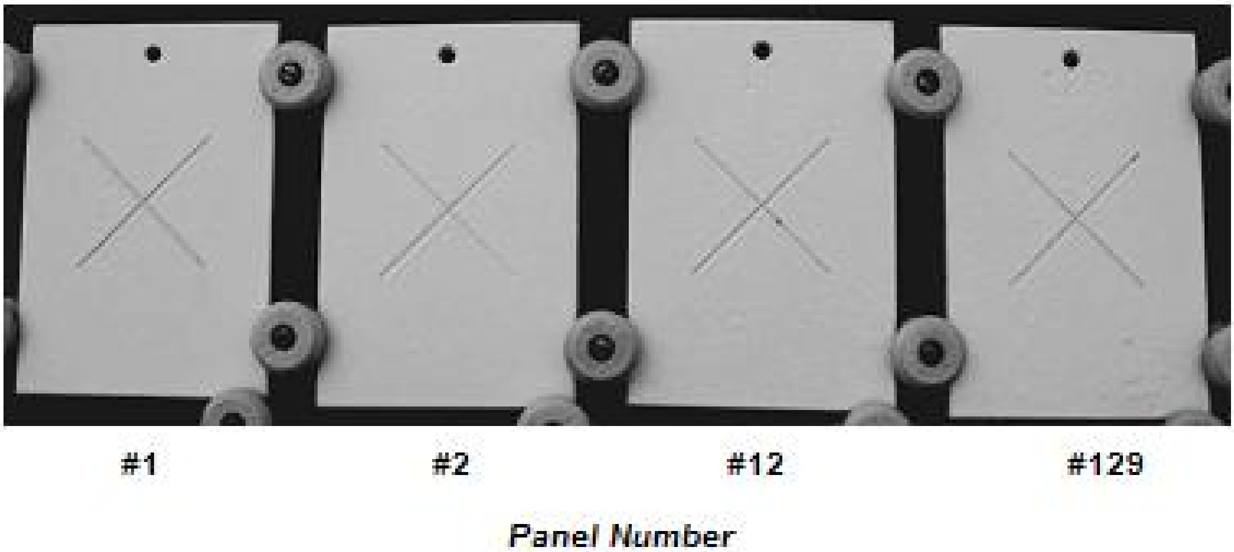
10 10 10 10

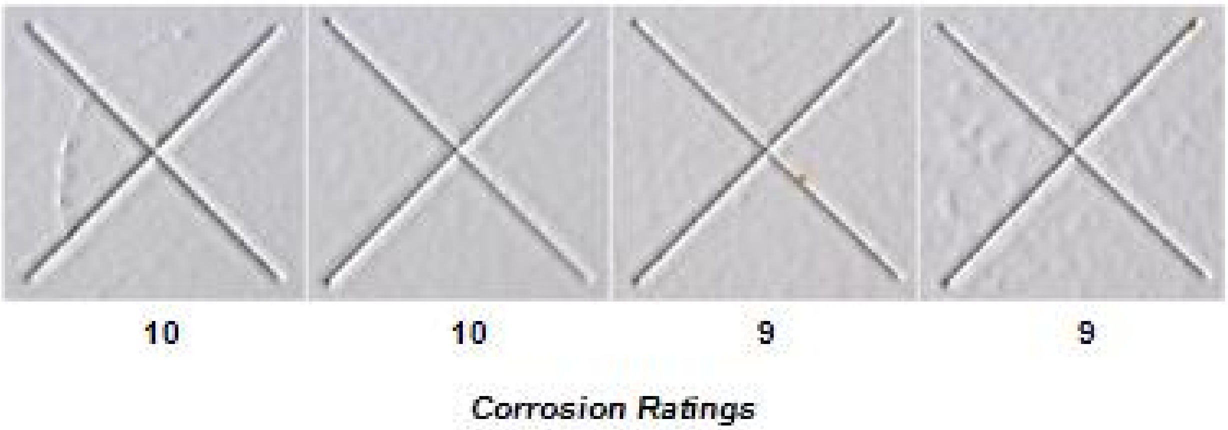
Corrosion Ratings

Zinc TSC

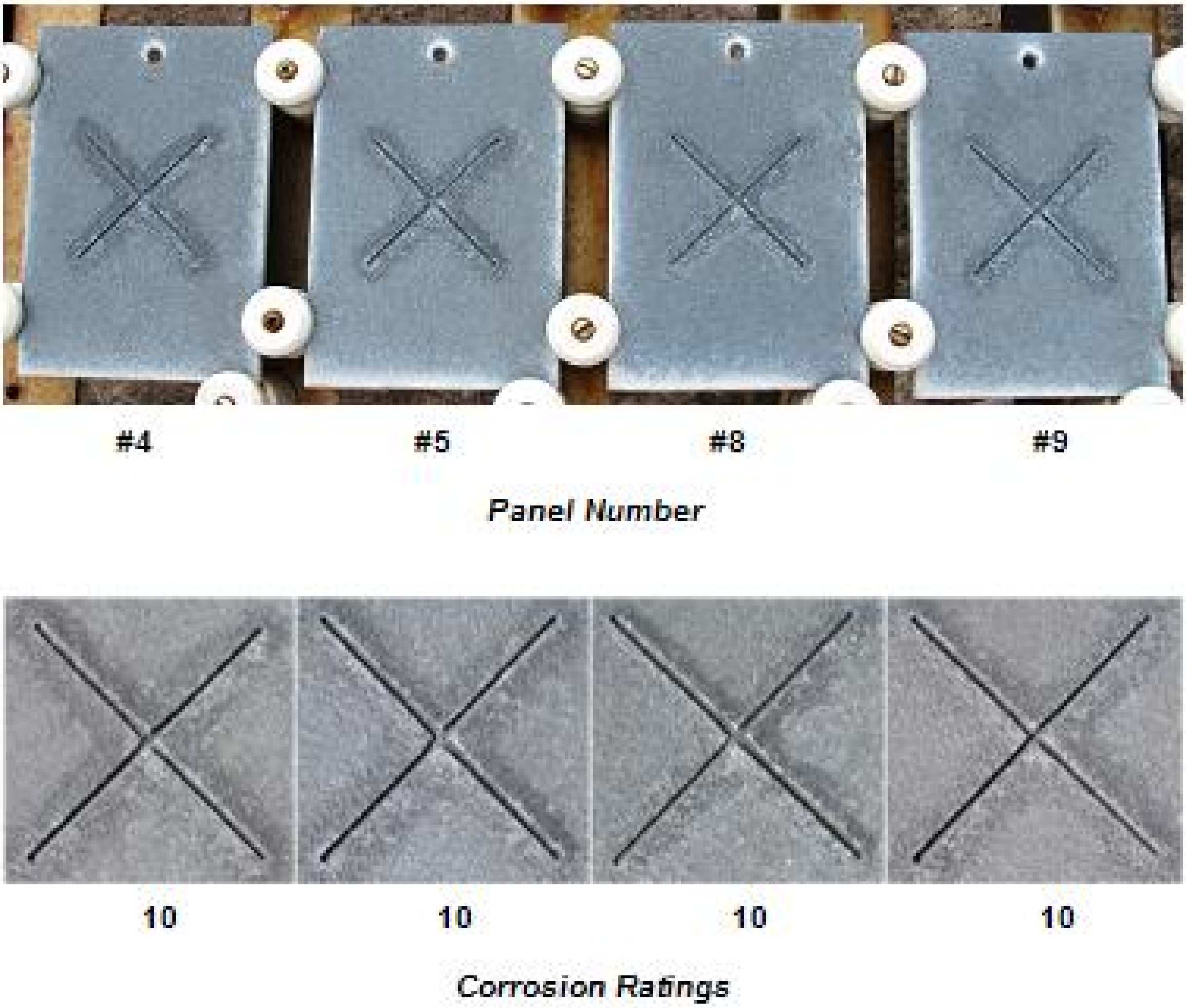


Zinc TSC + 133MC





Zinc TSC + GDS



Zinc TSC + GDS + 133MC