MATERIALS & PROCESSES LAB

Hex-Chrome Free Sealant Project Phase II with Beachfront Test Vehicle Addendum

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MPLR – 101562A
January 13, 2015

Hex-Chrome Free Sealant Project Phase II with Beachfront Test Vehicle Addendum

T.R. # 101562
Lockheed Martin Corporate Project

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Hex-Chrome Free Sealant Project Phase II with Beachfront Test Vehicle Addendum

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AIA/NAS NAS1102	"Screw, Machine, Flat 100 Degrees Head, Full Thread, Offset Cruciform," January 31, 2013.
MS35690F	"Nut, Plain, Hexagon, UNC-2B and UNF-2B," June 6, 2005.
ASTM G85 Annex 4	"Standard Practice for Modified Salt Spray (Fog) Testing," May 1, 2011.
MIL-PRF-23377K	"Primer, Coatings: Epoxy, High Solids," June 7, 2012.
MIL-PRF-81733D	"Sealing and Coating Compound, Corrosion Inhibitive," May 15, 1998.
MIL-PRF-85285E	"Coating: Polyurethane, Aircraft and Support Equipment," January 12, 2012.
MIL-PRF-85582E	"Primer Coatings: Epoxy, Waterborne," October 16, 2012.

1. LIST OF ABBREVIATIONS

ANOVA	Analysis of Variance
DFARS	Defense Federal Acquisition Regulation Supplement
DOE	Design of Experiments
HC	Hexavalent Chromium (Containing)
HCF	Hexavalent Chromium Free
HS	High Solids
MIL	Military Specification
NASA	National Aeronautics and Space Administration
NAVAIR	Naval Air Systems Command
RO	Reverse Osmosis
RT	Room Temperature
TBD	To Be Determined
TURI	Toxic Use Reduction Institute
TV	Test Vehicle

2. ABSTRACT

A single test vehicle design was used to compare the corrosion inhibition of six sealants:

- PS-870 – a polysulfide sealant which contains hexavalent chromium corrosion inhibitors.
- AC-735 – a polysulfide sealant which contains zinc phosphate corrosion inhibitors.
- PR-1775 – a polysulfide sealant which contains phosphite salt corrosion inhibitors.
- RW-6040-71 - a polythioether sealant which contains phosphite salt corrosion inhibitors.
- CS 55000N CI - a polysulfide sealant which contains molybdate corrosion inhibitors.
- PR-1440 - a polysulfide sealant which contains no corrosion inhibitors.

The test vehicles comprised of three plates of 7075-T6 aluminum alloy. All three plates were conversion coated with Iridite 14-2. Two of the plates were closely butted together leaving a 0.25" gap and fastened on top of the third plate. Sealant was used to protect the butt-joint, faying surfaces, fasteners by wet installation, and some of the fastener heads and nuts. A primer and topcoat system was sprayed over the fastened and sealed test vehicles. To initiate damage that would allow moisture to attack the sealant, each test vehicle was scribed in certain areas and was also subjected to mechanical stresses under -65ºF. After damage had been initiated, the test vehicles were exposed to SO_2 salt fog (ASTM G85 Annex 4) for 1008 hours to determine

corrosion resistance. After completion of SO_2 salt fog exposure, destructive inspections of the test vehicles revealed:

- PR-1775, AC-735, RW-6040-71, CS 5500N CI, and PS-870 had similar corrosion resistance characteristics, with PR-1775 performing the best of the HCF sealants.

- On the external surfaces, PR-1775, AC-735, RW-6040-71, and PS-870 performed similarly. The blistering of the primer and top coat on the substrate caused a considerable amount of corrosion to the coupon exteriors that in some cases extended into areas of interest. This blistering may have been caused by surface preparation issues, but further testing is recommended to confirm this result.

- A considerable amount of corrosion occurred from the presence of a leak path, allowing moisture to attack the substrate. These leak paths include the scribes made during coupon prep and cracks in the sealant and primer/topcoat as testing was performed.

- Destructive inspection of the test vehicles revealed that the fasteners overcoated with sealant provided more resistance to corrosion than the fasteners that were not protected with sealant.

3. BACKGROUND

Polysulfide sealants containing hexavalent chromium compounds are currently being used in a variety of applications in aerospace manufacturing. Some applications involve the filling of gaps and recesses to prevent water intrusion and collection. These sealants are used on both ferrous and aluminum assemblies and are often over coated with a variety of coating systems. Hexavalent chromium free sealants are desired because hexavalent chromium containing materials are prohibited under the DFARS Part 223.73 and OSHA 29 CFR 1910.1026. This test plan was developed to provide an evaluation of the corrosion resistance of hexavalent-chromium-free sealants and to compare their performance to a hexavalent-chromium-containing sealant.

4. OBJECTIVE

The objective of this test program is to evaluate alternatives to hexavalent chromium containing sealants used in aerospace vehicle fabrication in the aerospace/defense industry.

5. MATERIALS

5.1 Sealants

The six sealants used in the experiment were supplied by Raytheon – Tuscon Az.

- PS-870 – a polysulfide sealant which contains hexavalent chromium corrosion inhibitors.

- AC-735 – a polysulfide sealant which contains zinc phosphate corrosion inhibitors.
- PR-1775 – a polysulfide sealant which contains phosphite salt corrosion inhibitors.
- RW-6040-71 – a polythioether sealant which contains phosphite salt corrosion inhibitors.
- CS 55000N CI – a polysulfide sealant which contains molybdate corrosion inhibitors.
- PR-1440 – a polysulfide sealant which contains no corrosion inhibitors.

5.2 Support Materials

- Iridite 14-2 (performed at Northrop Grumman-Baltimore, Md) – a conversion coating containing hexavalent chromium corrosion inhibitors.
- Water Reducible High Performance Epoxy Primer Not Containing Hexavalent Chromium: 44GN098 (performed at Raytheon-Tuscon, AZ)
  Vendor: Deft Inc.
  Vendor part number: 44GN098 1GK base and catalyst
  Spec: MIL-PRF-85582, Type 1, Class N
- PPG topcoat : CA8211/F37886 Base, CA8200B M&D Activator (performed at Raytheon-Tuscon, AZ)
  Vendor: PRC DeSoto of PPG Aerospace
  Vendor Part Number: 8211F37886MPY22K
  Spec: MIL-PRF-85285 Type 1

6. TEST VEHICLE PREPARATION

6.1 Testing Schedule

The test schedule was developed by a collaborative effort from engineers and scientists at Raytheon, Northrop Grumman, the Toxics Use Reduction Institute (TURI), NAVAIR, NASA, Bombardier, and Lockheed Martin. Some of the participants performed some part of the fabrication or testing of the test vehicles as indicated by Table 6.1.1.

TABLE 6.1.1. TEST PLAN MAJOR TASKS AND DESIGNATIONS

Task	Responsible	Location	Target Dates
Develop Phase II test plan and Design of Experiments (DOE)	All participants	Conference Calls	June – July 2013
Procure aluminum plates for test vehicles (TV)	Toxics Use Reduction Institute (TURI)	Lowell, Massachusetts	July 2013
Procure fasteners for test vehicles	Bombardier	St. Laurent, Quebec	July – August, 2013
Develop test vehicle mechanical drawings	Raytheon	Tucson, Arizona	July 2013
Drill holes in test vehicles	NASA	Kennedy Space Center, Florida	July 9 – July 22, 2013
Obtain necessary sealant samples	Raytheon & Lockheed Martin	Tucson, Arizona	July 10 – August 14, 2013
Apply hex chrome conversion coating on TVs	Northrop Grumman	Baltimore, Maryland	July 22 – July 30, 2013
Apply sealant to fasteners and test vehicles	Raytheon	Tucson, Arizona	August 14 – September 4, 2013
Apply primer, topcoat, and scribes to TVs and photo documentation	Raytheon	Tucson, Arizona	August 14 – September 4, 2013
Conduct test vehicle mechanical and thermal preconditioning	NAVAIR	Patuxent River, Maryland	September 6 - September 20, 2013
Conduct salt fog testing for aluminum test vehicles, non-destructive inspection, and photo documentation	Lockheed Martin	Fort Worth, Texas	September 23 – November 4, 2013
Conduct beachfront corrosion test for aluminum test vehicles, and photo documentation	NASA	Kennedy Space Center, Florida	September 2013 – September 2014
Determine sealant removal evaluation process	All participants	Conference Calls	August – October 2013
Obtain sealant removal materials and conduct prescreening of sealant removal materials	TURI,University of Massachusetts	Lowell, Massachusetts	September - October, 2013
Sealant Removal/Test Vehicle dismantling, and photo documentation	University of Massachusetts	Lowell, Massachusetts	November 5 – November 19, 2013
Conduct test vehicle inspection after dismantling (destructive inspection), and photo documentation	Lockheed Martin	Fort Worth, Texas	November 20 – December 4, 2013
Conduct corrosion ranking analysis	Lockheed Martin	Fort Worth, Texas	November 20 – December 4, 2013
Conduct statistical analysis (DOE, ANOVA, etc.) for corrosion testing results using Minitab software	TURI	Lowell, Massachusetts	December 2013
Write a technical paper to document the research results of this corrosion testing research and to acknowledge contributors to the research effort	TURI	Lowell, Massachusetts	January 2014

6.2 Test Vehicle Design

A single test vehicle was created to test the six sealants. The final test vehicle design is illustrated in Figures 6.2.1 through Figure 6.2.4.

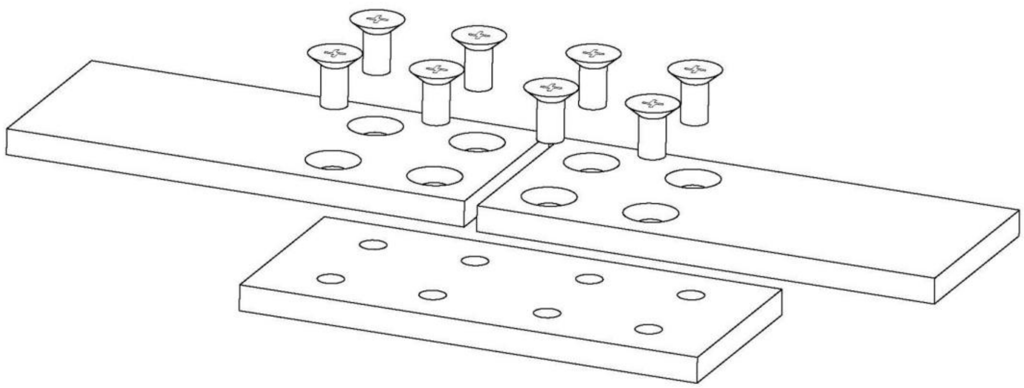


FIGURE 6.2.1 EXPLODED VIEW OF TEST VEHICLE

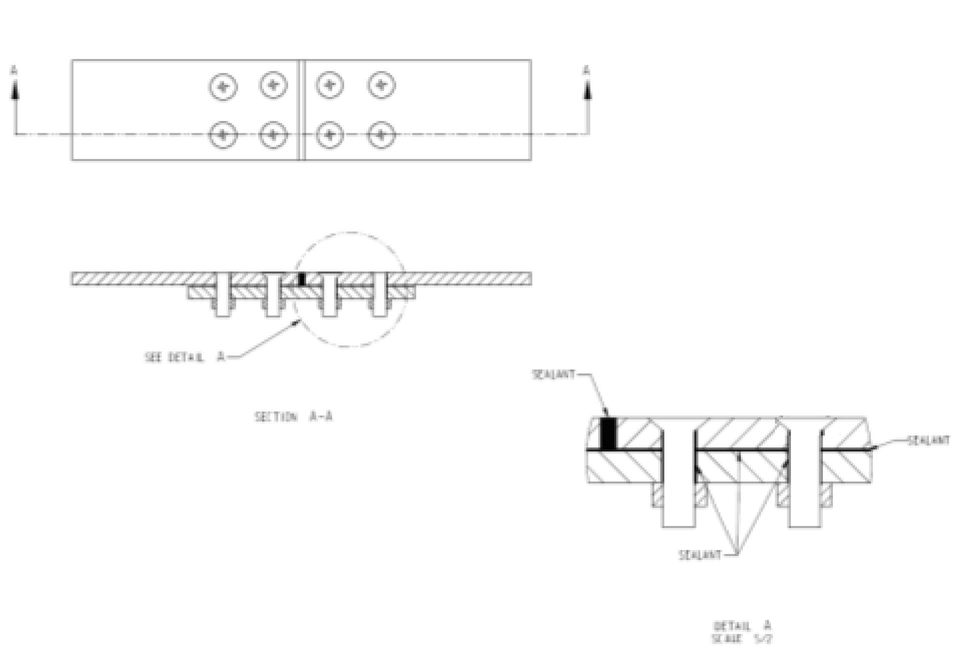


FIGURE 6.2.2 TOP VIEW AND SLICED SIDE VIEW OF TEST VEHICLE

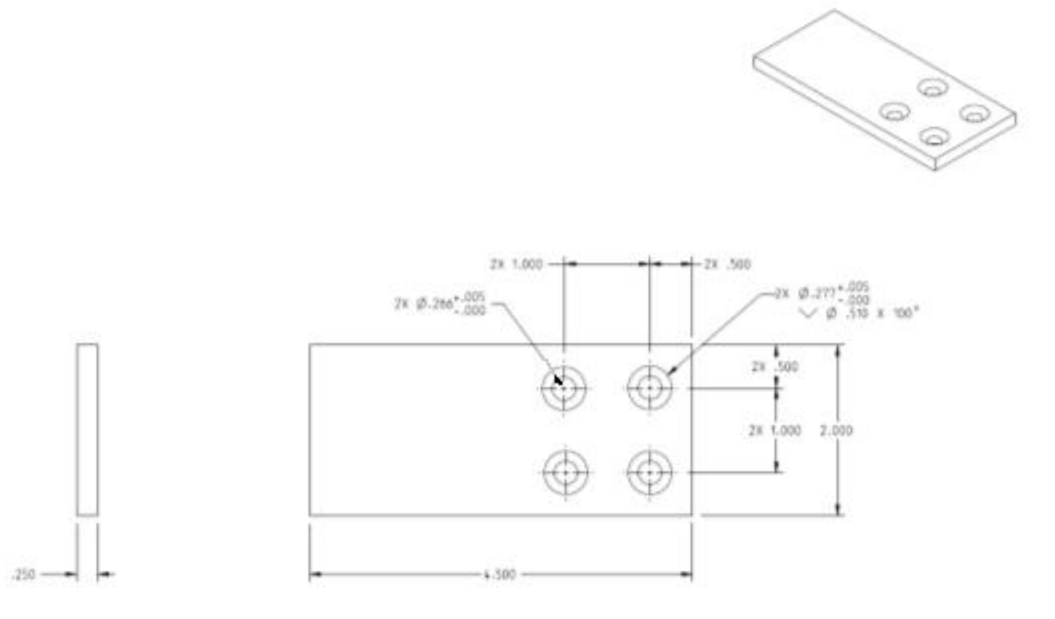


FIGURE 6.2.3 DIAGRAM OF IDENTICAL TOP PANEL OF TEST VEHICLE

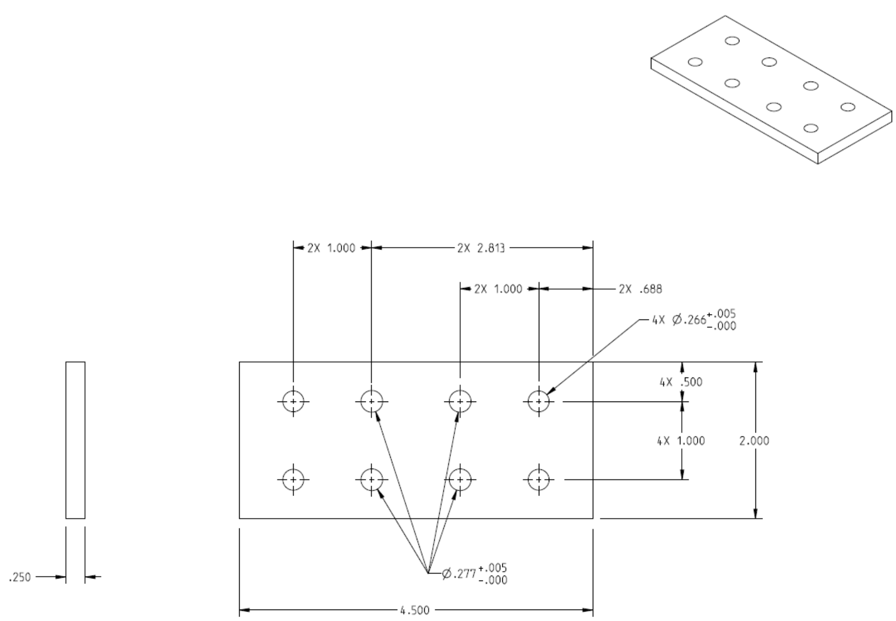


FIGURE 6.2.4 DIAGRAM OF BOTTOM PANEL OF TEST VEHICLE

As illustrated in Figure 6.2.1 and Figure 6.2.4, each test vehicle consisted of three metal plates with a series of matching holes through which threaded fasteners were inserted and held in place by nuts. These test vehicles comprised of three 0.25" thick 7075-T6 aluminum alloy plates. The 7075 aluminum alloy was chosen because it is considered to be a challenging aluminum alloy to pass corrosion testing. The aluminum plates were 2.0" wide by 4.5" long.

Each test vehicle had eight fasteners made of stainless steel (A286). The stainless steel material was chosen because it is commonly used by participating companies and presented galvanic mismatch with the aluminum plates. Based upon a mechanical analysis conducted by Northrop Grumman, it was determined that ¼" A286 bolts would provide an adequate margin of safety so that a load of 5,000 lb_f could be applied to the test vehicles without bending the plates or shearing the bolts. The fasteners and nuts conformed to specification NAS1102E4-14 (100 degree flat head) and MS35690-430 (plain hex nut), respectively.

6.3 Test Matrix

The design of experiments followed the test plan detailed in Tables 6.3.1.

TABLE 6.3.1 TEST VEHICLE MATRIX

Number	Alloy	Sealant	Conversion Coating	Secondary Finish	Corrosion Test
1	7075	PPG PS-870	Iridite 14-2	HCF Primer & Topcoat	$S0_2$ 1,008 hrs
2	7075	PPG PS-870	Iridite 14-2	HCF Primer & Topcoat	$S0_2$ 1,008 hrs
3	7075	PPG PS-870	Iridite 14-2	HCF Primer & Topcoat	$S0_2$ 1,008 hrs
4	7075	PPG PS-870	Iridite 14-2	HCF Primer & Topcoat	$S0_2$ 1,008 hrs
5	7075	PPG PS-870	Iridite 14-2	HCF Primer & Topcoat	Beachfront
6	7075	3M AC-735	Iridite 14-2	HCF Primer & Topcoat	$S0_2$ 1,008 hrs
7	7075	3M AC-735	Iridite 14-2	HCF Primer & Topcoat	$S0_2$ 1,008 hrs
8	7075	3M AC-735	Iridite 14-2	HCF Primer & Topcoat	$S0_2$ 1,008 hrs
9	7075	3M AC-735	Iridite 14-2	HCF Primer & Topcoat	$S0_2$ 1,008 hrs
10	7075	3M AC-735	Iridite 14-2	HCF Primer & Topcoat	Beachfront
11	7075	PPG PR-1775	Iridite 14-2	HCF Primer & Topcoat	$S0_2$ 1,008 hrs
12	7075	PPG PR-1775	Iridite 14-2	HCF Primer & Topcoat	$S0_2$ 1,008 hrs
13	7075	PPG PR-1775	Iridite 14-2	HCF Primer & Topcoat	$S0_2$ 1,008 hrs
14	7075	PPG PR-1775	Iridite 14-2	HCF Primer & Topcoat	$S0_2$ 1,008 hrs
15	7075	PPG PR-1775	Iridite 14-2	HCF Primer & Topcoat	Beachfront
16	7075	Spare (PPG PS-870)	Iridite 14-2	HCF Primer & Topcoat	Spare

TABLE 6.3.1 TEST VEHICLE MATRIX (CONTINUED)

Number	Alloy	Sealant	Conversion Coating	Secondary Finish	Corrosion Test
17	7075	PPG RW-6040-71	Iridite 14-2	HCF Primer & Topcoat	$S0_2$ 1,008 hrs
18	7075	Spare (PPG PS-870)	Iridite 14-2	HCF Primer & Topcoat	Spare
19	7075	PPG RW-6040-71	Iridite 14-2	HCF Primer & Topcoat	$S0_2$ 1,008 hrs
20	7075	PPG RW-6040-71	Iridite 14-2	HCF Primer & Topcoat	$S0_2$ 1,008 hrs
21	7075	PPG RW-6040-71	Iridite 14-2	HCF Primer & Topcoat	$S0_2$ 1,008 hrs
22	7075	PPG RW-6040-71	Iridite 14-2	HCF Primer & Topcoat	Beachfront
23	7075	FM CS 5500N CI	Iridite 14-2	HCF Primer & Topcoat	$S0_2$ 1,008 hrs
24	7075	FM CS 5500N CI	Iridite 14-2	HCF Primer & Topcoat	$S0_2$ 1,008 hrs
25	7075	FM CS 5500N CI	Iridite 14-2	HCF Primer & Topcoat	$S0_2$ 1,008 hrs
26	7075	FM CS 5500N CI	Iridite 14-2	HCF Primer & Topcoat	$S0_2$ 1,008 hrs
27	7075	FM CS 5500N CI	Iridite 14-2	HCF Primer & Topcoat	Beachfront
28	7075	PPG PR-1440	Iridite 14-2	HCF Primer & Topcoat	$S0_2$ 1,008 hrs
29	7075	PPG PR-1440	Iridite 14-2	HCF Primer & Topcoat	$S0_2$ 1,008 hrs
30	7075	PPG PR-1440	Iridite 14-2	HCF Primer & Topcoat	$S0_2$ 1,008 hrs
31	7075	PPG PR-1440	Iridite 14-2	HCF Primer & Topcoat	$S0_2$ 1,008 hrs
32	7075	PPG PR-1440	Iridite 14-2	HCF Primer & Topcoat	Beachfront

Six test vehicles underwent beach front testing instead of salt fog testing. The NASA beach front laboratory is used to conduct real-time corrosion experiments. They provide remote monitoring of surrounding weather conditions including wind speed and direction, and rainfall.

6.4 Test Vehicle Fabrication

The test vehicles were fabricated in the following order:

1. 7075 aluminum alloy plates were procured and machined by the Toxics Use Reduction Institute (TURI), and holes were drilled and tapped according to Figures 6.1.1 through 6.1.4.

2. Bare aluminum plates were sent to Northrop Grumman to be conversion coated with Iridite 14-2. The conversion coating process is described in Tables 6.4.1.

TABLE 6.4.1 CONVERSION COATING PROCESS

Operation	Tank contents	Concentration	Temperature (°F)	Time
Non-Etch Cleaner	Oakite Aluminum Cleaner NST	8 oz/gal	120 - 140	3 - 5 minutes
Cold Water Rinse	RO Water		RT	30 sec -1 minute
Etch Cleaner as required	Oakite 33	4 - 6 oz/gal	125 - 145	25 - 35 seconds
Cold Water Rinse	RO Water		RT	30 sec -1 minute
Deoxidizer as required	Oakite Deoxidizer LNC	15 - 20 % by Vol.	RT	2 - 5 minutes
Cold Water Rinse	RO Water		RT	30 sec -1 minute
Descaler as required	Nitric Acid Mixed with Actane 70	68 % Nitric Acid and 1 - 2 oz/gal ammonium bifluoride	RT	
Cold Water Rinse	RO Water		RT	
Cold Water Rinse	RO Water		RT	
Iridite	Iridite 14-2	1.4 - 1.8 oz/gal	70 - 90	50 - 70 seconds
Cold Water Rinse	RO Water		RT	30 sec - 1 minute
Warm Water Rinse	RO Water		120	
Air Dry				

3. Conversion coated panels were packaged and mailed to Raytheon to be assembled.

4. For the butt joint scribe, the top side of the bottom plate was scribed with an "X" using a Erichsen Scratch Stylus. See Figure 6.4.1.

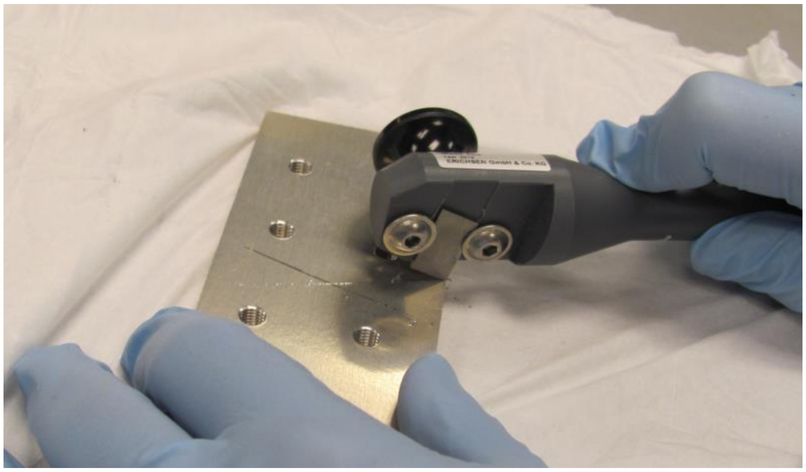


FIGURE 6.4.1 X-SCRIBE ON TOP OF BASE PLATE FOR BUTT JOINT

5. For the faying surface, approximately 0.005" of sealing compound was applied to one side of each panel by spatula. Two 0.005" wires were laid across the sealing compound to control the bond line. The surfaces were mated together. See Figure 6.4.2.

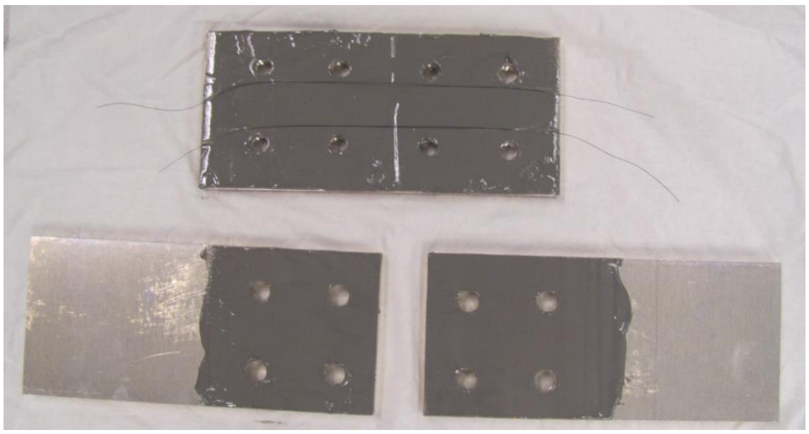


FIGURE 6.4.2 APPLICATION OF SEALANT ON TOP SIDE OF BASE PLATE (ON TOP OF X-SCRIBE) AND BOTTOM SIDE OF TOP PLATES AND ADDITION OF TWO WIRES (5 MIL DIAMETER) TO BASE PLATE

6. The fasteners were coated by finger with the sealing compound and were inserted into the freshly mated panels. Nuts were installed and torqued to 40 in-lb_f. See Figures 6.4.3 through 6.4.5.

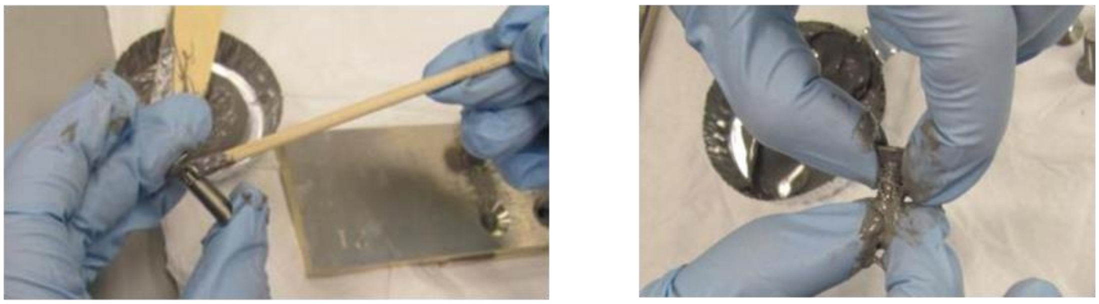


FIGURE 6.4.3 SEALANT BRUSHED ON TO FASTENERS

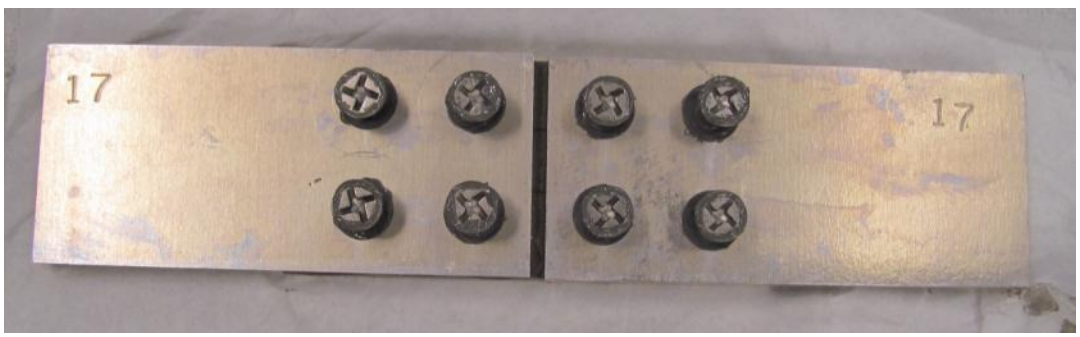


FIGURE 6.4.4 FASTENERS INSERTED INTO FRESHLY MATED PANELS

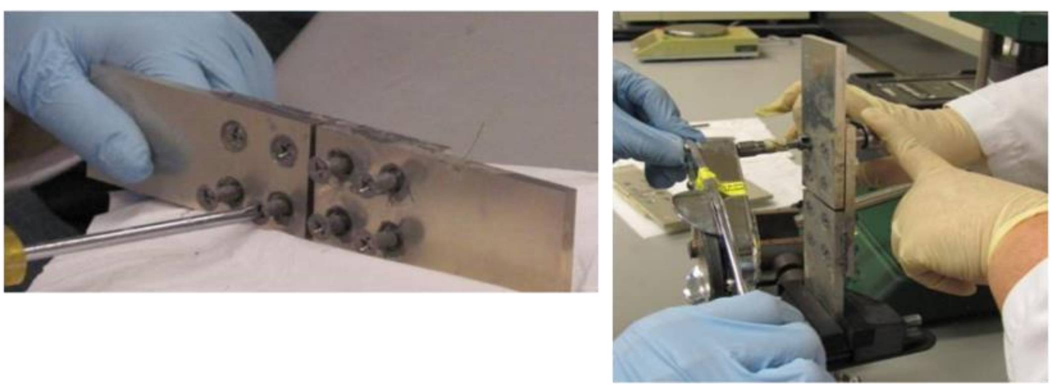


FIGURE 6.4.5 FASTENERS TORQUED TO 40 IN·LB_F (SQUEEZE OUT ALMOST COMPLETELY FILLED BUTT GAP

7. For the butt joint, sealing compound was applied to the butt joint to completely fill the gap using a Q-tip stick. See Figure 6.4.6.

FIGURE 6.4.6 SEALANT APPLICATION TO THE BUTT JOINT AND EXCESS REMOVAL

8. Excess sealant was wiped from the entire test vehicle prior to proceeding.

9. For the fastener heads, six of the fastener head were completely covered over and around on each plate, as well as the corresponding nuts. See Figure 6.4.7.

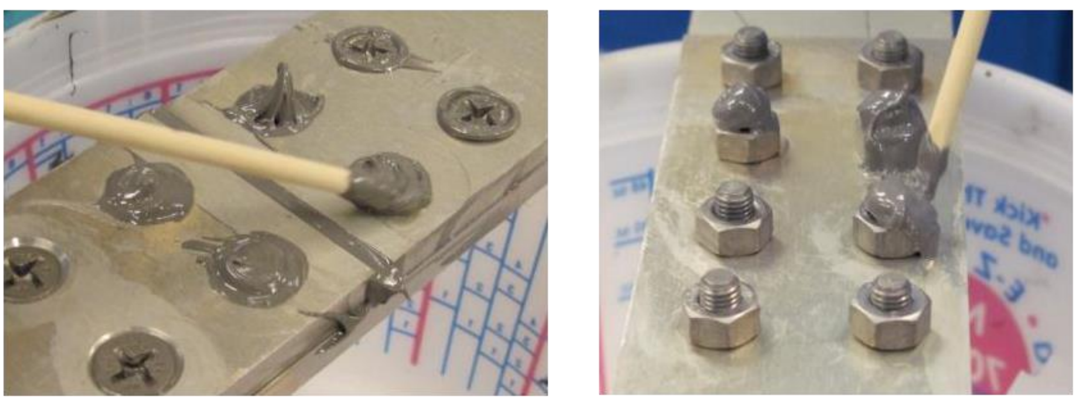


FIGURE 6.4.7 SEALANT APPLIED OVER FASTENER HEADS

10. The assembly was cured at room temperature for 48 hours.

11. The specific primer and topcoat were applied to the test vehicles according to the design of experiments and per manufacturer instructions.

12. To portray a worst-case scenario, damage including scribing of plate surface and fasteners was initiated. Scribes were generated by an Erichsen Scratch Stylus acc. to

Sikkens Model 463 with a 1 mm wide carbon tip. A scribe through the primer and topcoat at edge of test vehicle in four locations was made. In addition, scribes were applied to three fastener heads and the three corresponding nuts on each test vehicle. The other five fastener heads and five nuts on each test vehicle did not get scribed. The scribed areas are portrayed in Figure 6.4.8. Dark marks denote sealant overcoated areas, and lines indicate a scribe.

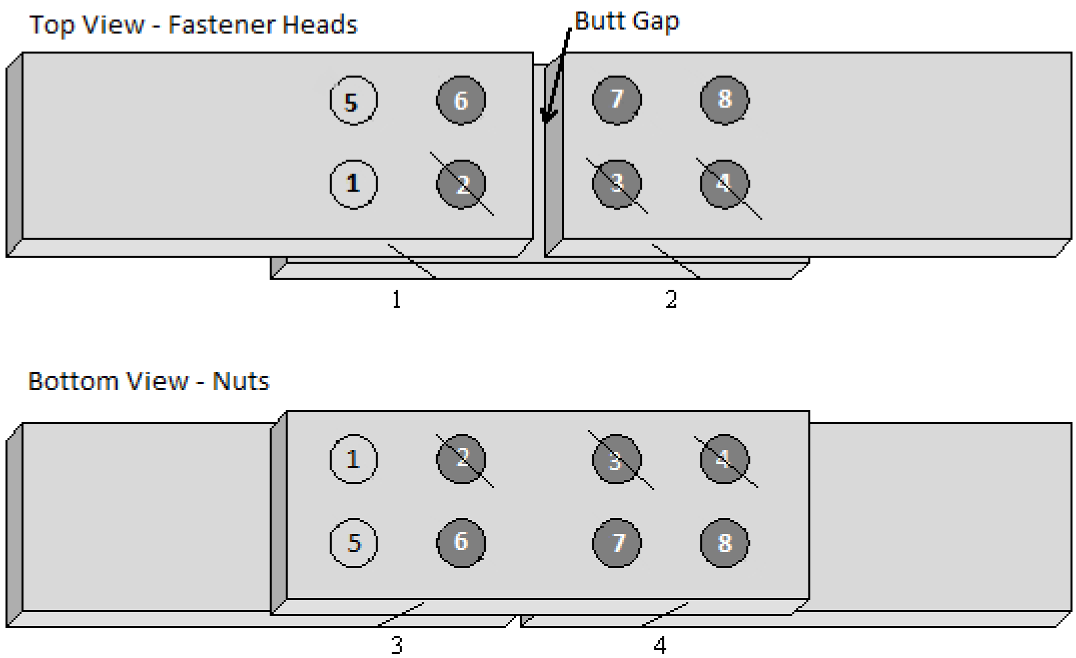


FIGURE 6.4.8 SCRIBED AREAS OF THE TEST VEHICLE

7. TEST VEHICLE TESTING

7.1 Cyclic Loading

After fabrication, all test vehicles were sent to NAVAIR in Patuxent River, MD to mechanically stress the sealant joints at -65ºF. The cyclic loading was performed according to MIL-PRF-81733D Section 4.8.9.3.1 for Class 1 materials. The test vehicles were conditioned at -65 °F for thirty minutes. The test vehicles were cyclically loaded between 0 and 5,000 lb_f for 250 cycles at the same temperature of -65 °F. The intent of this testing was to simulate several stress applications including: fighter aircraft, cargo aircraft, missiles, ground equipment, and maritime/naval equipment.

After mechanical and thermal preconditioning, the test vehicles were packaged and mailed to Lockheed Martin Aeronautics in Fort Worth, TX for exposure to SO_2 (sulfur dioxide) salt fog according to ASTM G85 A4 for 1008 hours (6 weeks).

7.2 Beach Front Corrosion Testing

Six test vehicles underwent beach front testing instead of SO_2 salt fog testing. The NASA beach front laboratory is used to conduct real-time corrosion experiments. They provide remote monitoring of surrounding weather conditions including wind speed and direction, and rainfall. After one year in the lab, these test vehicles will be returned to Lockheed Martin for analysis. Results will be added to this report as an addendum.

7.3 SO_2 Salt Fog Corrosion Testing

Upon receiving the test vehicles at Lockheed Martin Aeronautics, Fort Worth, tape was applied to the ends of the coupons to cover clamp marks caused by the mechanical cycling to prevent corrosion in those areas before being introduced to the salt fog chamber. The test vehicles were oriented so that the bottom (nut) side was facing the humidifying tower. The salt fog chamber was operated in accordance with ASTM G85 Annex 4, consisting of a continuous six hour cycle in which a 5% NaCl solution (aq) was constantly sprayed into the chamber for all six hours at a collection rate of 1-2 ml/hr. After the first 5 hours of the cycle, SO_2 gas was introduced into the chamber for 1 hour to complete the cycle. The pH of the salt fog was kept in the range of 2.5 - 3.2 and was controlled by adjusting the flow rate of SO_2 gas. The chamber was kept at 95 +/- 3 °F and the temperature in the air saturator tower was kept at 117 +/- 2 °F.

7.4 Non-Destructive Inspection

Non-destructive inspections examined the outer appearance of the test vehicles and were performed on all of the test vehicles at the 336, 678, and 1008 hour intervals of exposure to the salt fog.

Each test vehicle was divided into areas of interest. At each area of interest, the test vehicle was examined and given a numerical value according to the level of corrosion for each area of interest. Table 7.4.1 describes the rating point system and Table 7.4.2 and Figure 7.4.1 illustrate the areas of interest for non-destructive inspection.

TABLE 7.4.1 RATING SYSTEM FOR NON-DESTRUCTIVE INSPECTION OF TEST VEHICLES

Rating	Test Vehicle Observations
5	No observable changes.
4.5	Darkening of scribe line.
4	Slight salt build-up of scribe. No evidence of corrosion.
3.5	Slight evidence of substrate pitting or very small amount of corrosion product limited to the scribe.
3	Slight evidence of substrate pitting or very small amount of corrosion product extending beyond scribe.
2	Evidence of substrate pitting or some corrosion product.
1	Extensive substrate pitting or excessive corrosion product.

TABLE 7.4.2 AREAS OF INTEREST FOR NON-DESTRUCTIVE OBSERVATION OF TEST VEHICLES

Top View - Fastener Heads	
Number	Description
1	Recessed Head No Sealant
2	Scribed Recessed Head w/Sealant
3	Scribed Recessed Head w/Sealant
4	Scribed Recessed Head w/Sealant
5	Recessed Head No Sealant
6	Non-Scribed Recessed Head w/ Sealant
7	Non-Scribed Recessed Head w/ Sealant
8	Non-Scribed Recessed Head w/ Sealant
NA	Butt Joint
Bottom View - Nuts	
Number	Description
1	Recessed Head No Sealant
2	Scribed Recessed Head w/Sealant
3	Scribed Recessed Head w/Sealant
4	Scribed Recessed Head w/Sealant
5	Recessed Head No Sealant
6	Non-Scribed Recessed Head w/ Sealant
7	Non-Scribed Recessed Head w/ Sealant
8	Non-Scribed Recessed Head w/ Sealant
Sides	
Number	Description
1	Scribed Side Location Common to Fasteners 1 & 2
2	Scribed Side Location Common to Fasteners 3 & 4
3	Scribed Side Location Common to Fasteners 5 & 6
4	Scribed Side Location Common to Fasteners 7 & 8

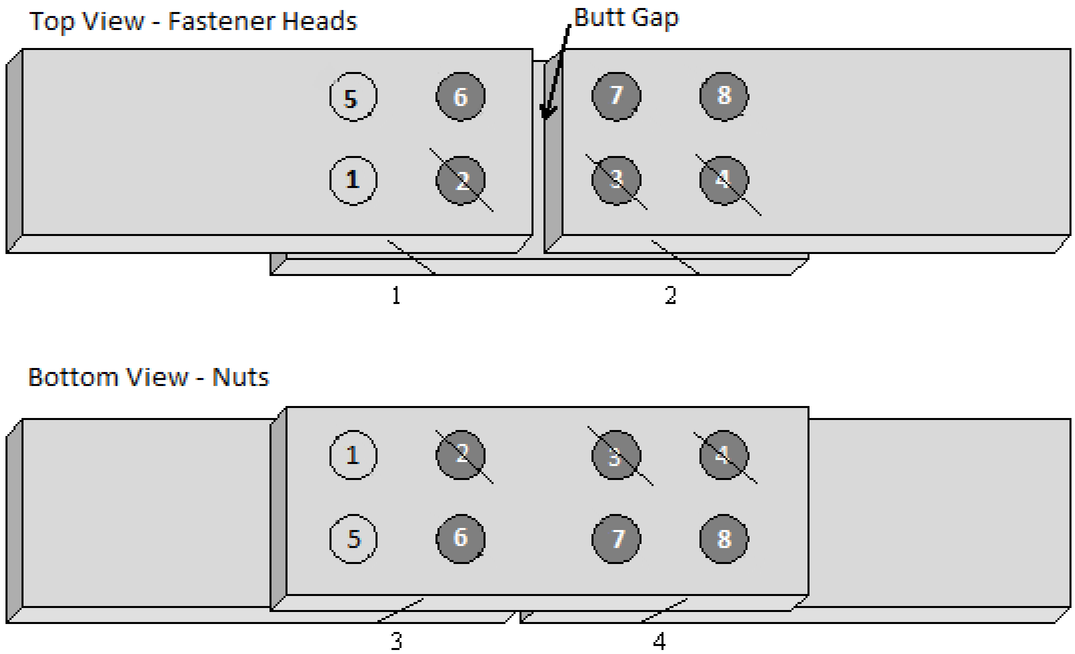


FIGURE 7.4.1 AREAS OF INTEREST FOR NON-DESTRUCTIVE OBSERVATION OF TEST VEHICLES

7.5 Sealant Removal Process

After the test vehicles completed 1008 hours of SO_2 salt fog exposure, the test vehicles were deconstructed so that the interiors could be examined. Deconstruction involved removing the fasteners, separating the plates of the test vehicles, and stripping the sealant away to examine the inner surfaces that were protected by sealant. For the stripping of the sealants, TURI tested a variety of products in an attempt to find an ideal candidate. Results of this experiment will be in another report.

7.6 Destructive Inspections

After deconstruction, the test vehicle parts were returned to Lockheed Martin for destructive inspection. The now exposed inner surfaces were divided into areas of interest, and a rating for the amount of corrosion in each area of interest was recorded. The ratings ranged from 0 – 100 percent area corroded; 0 representing no corrosion and 100 representing corrosion of the entire area of interest. Table 7.6.1 describes the three areas of interest and which parts of each area that will be examined. Figure 7.6.1 shows the location of each individual area to be inspected on a diagram of a deconstructed test vehicle.

Additionally, the exterior surfaces were examined to determine the impact of the overcoat of sealant. Areas used to quantify that data are ring around the fastener hole area and exterior corrosion.

TABLE 7.6.1 AREAS OF INTEREST FOR DESTRUCTIVE OBSERVATION OF TEST VEHICLES

Fastener Holes	
Number	Description
1	Fastener Hole (Barrel Area)
2	Fastener Hole (Barrel Area)
3	Fastener Hole (Barrel Area)
4	Fastener Hole (Barrel Area)
5	Fastener Hole (Barrel Area)
6	Fastener Hole (Barrel Area)
7	Fastener Hole (Barrel Area)
8	Fastener Hole (Barrel Area)
Countersink Areas	
Number	Description
1	Countersink Fastener Hole (countersink area)
2	Countersink Fastener Hole (countersink area)
3	Countersink Fastener Hole (countersink area)
4	Countersink Fastener Hole (countersink area)
5	Countersink Fastener Hole (countersink area)
6	Countersink Fastener Hole (countersink area)
7	Countersink Fastener Hole (countersink area)
8	Countersink Fastener Hole (countersink area)
Butt Joint and Faying Surfaces	
Butt Joint (X-Scribe)	
Butt Joint (Sides) (2)	
Faying Surface	

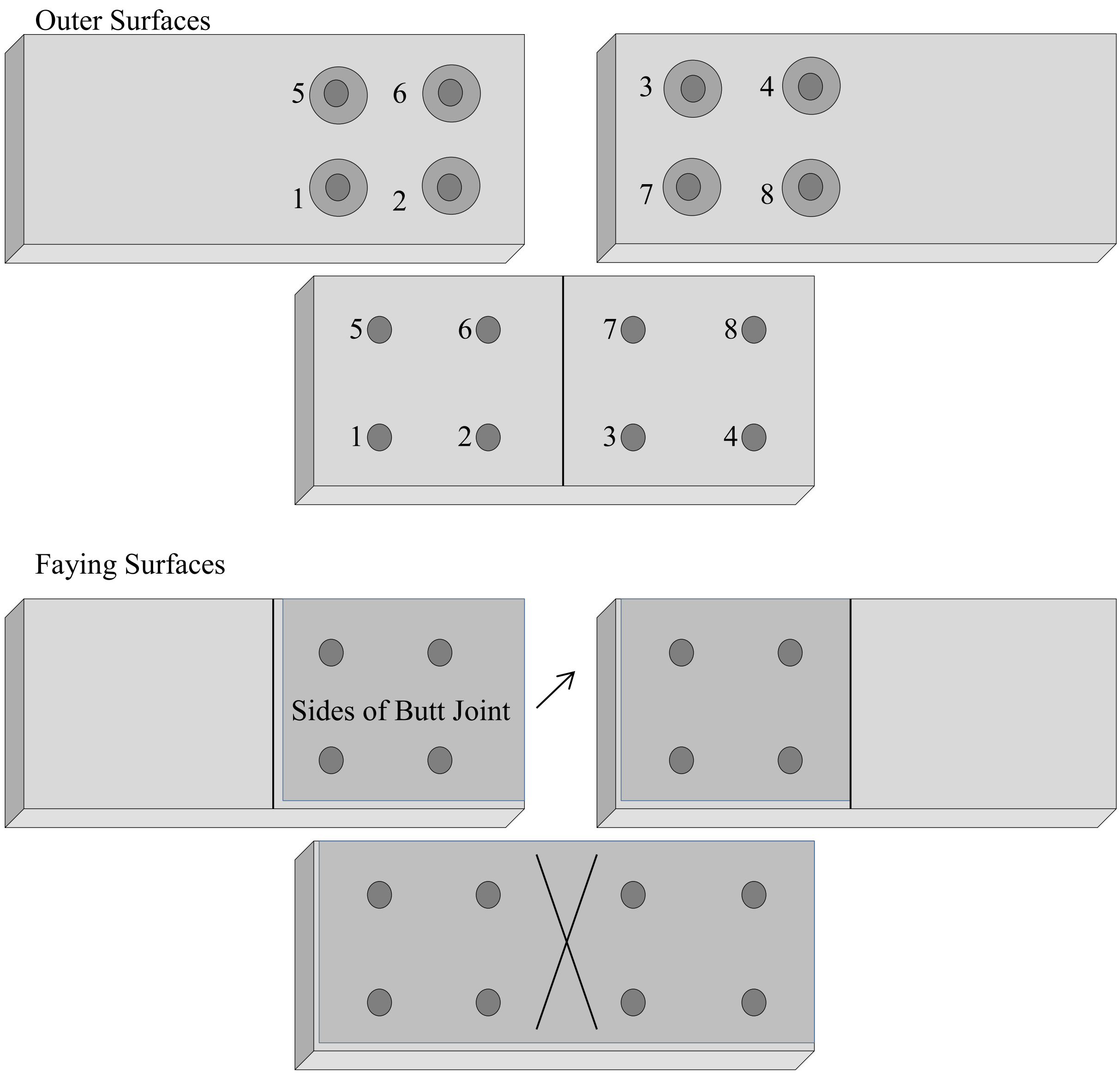


FIGURE 7.6.1 AREAS OF INTEREST FOR DESTRUCTIVE OBSERVATION OF TEST VEHICLES

8. RESULTS

The results provided in this report only include the salt fog testing performed at Lockheed Martin Aeronautics in Fort Worth, TX. The results of the beachfront test vehicle will be added to the end of this report as an addendum at a later date once the exposure is completed.

8.1 Non-Destructive Inspection Results

Non-destructive inspection of the test vehicles provided valuable information regarding the outside appearance of the test vehicles. Due to the corrosive environment of the SO_2 salt fog, many instances of lifting, peeling, discoloration, rust, and blisters were observed for the secondary finishes on the test vehicles. These observations were noted, and pictures were taken to document the corrosion. The following Figures create a representative illustration of what each specific group of the test vehicles looked like around the fasteners through the SO_2 exposure to demonstrate what was observed for non-destructive inspections.

Countersink side | Nut Side

0 hrs

336 hrs

672 hrs

1008 hrs

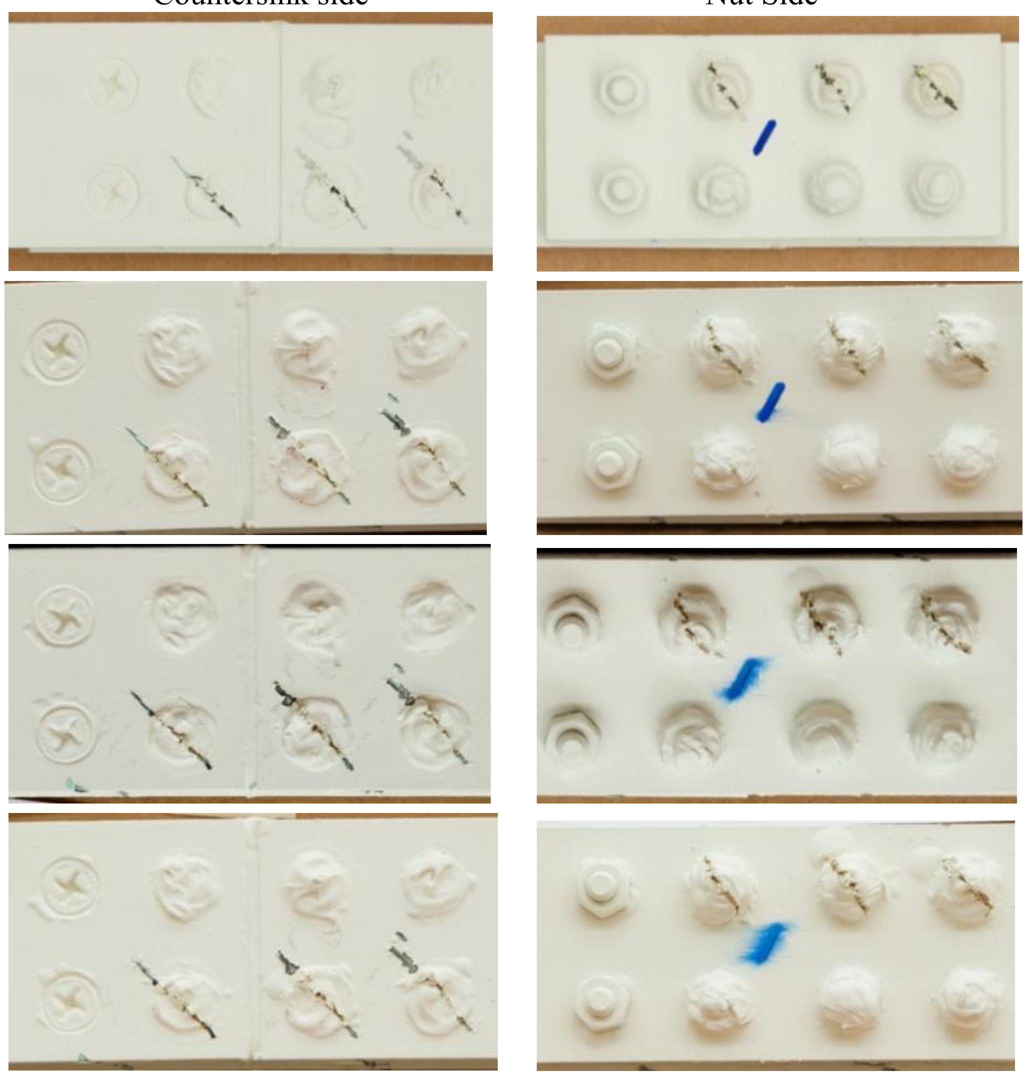


FIGURE 8.1.1 TEST VEHICLE WITH PPG PS-870 SEALANT THROUGH 1008 HOURS ACIDIC SALT FOG EXPOSURE

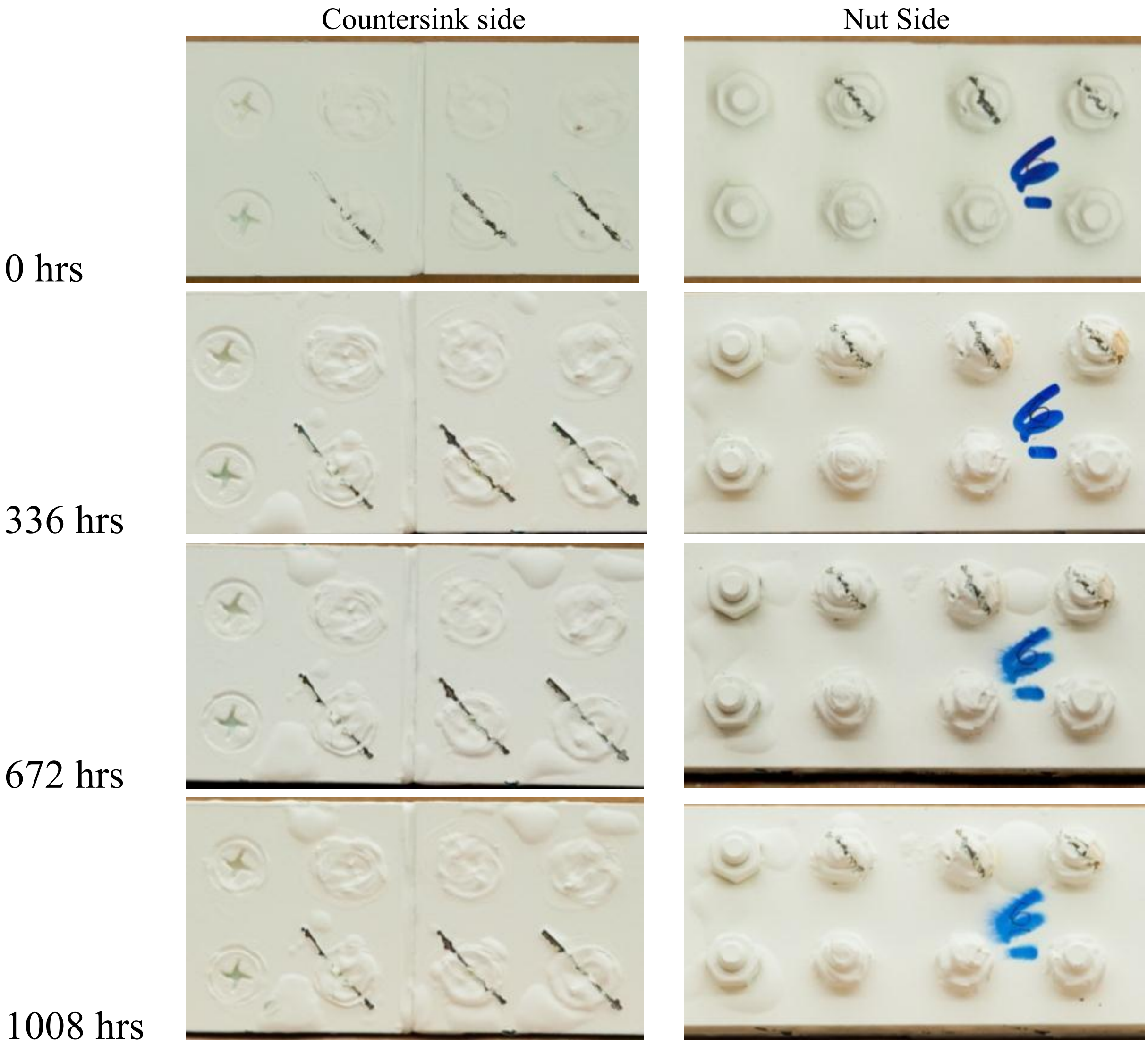


FIGURE 8.1.2 TEST VEHICLE WITH 3M AC-735 SEALANT THROUGH 1008 HOURS ACIDIC SALT FOG EXPOSURE

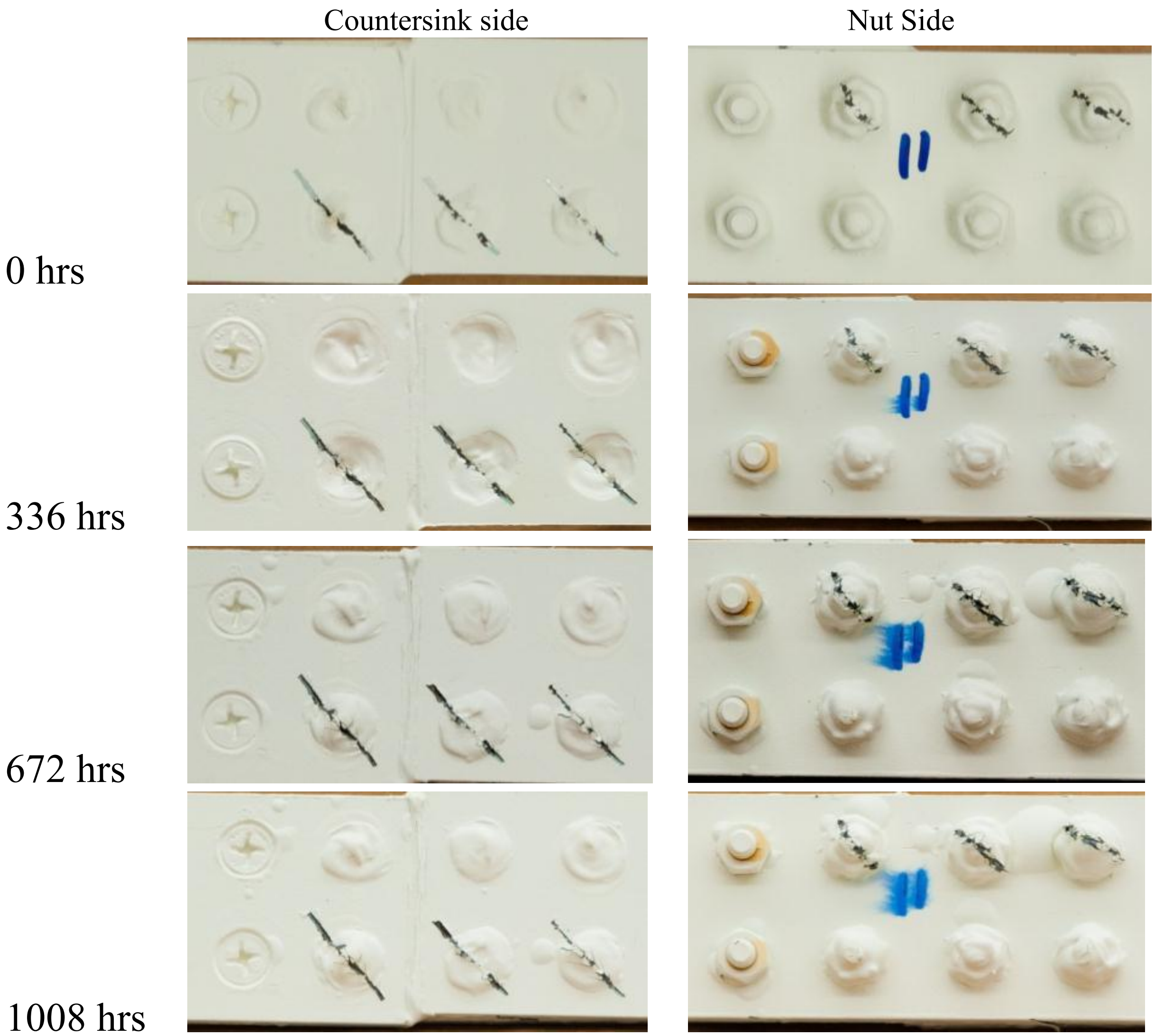


FIGURE 8.1.3 TEST VEHICLE WITH PPG PR-1775 SEALANT THROUGH 1008 HOURS ACIDIC SALT FOG EXPOSURE

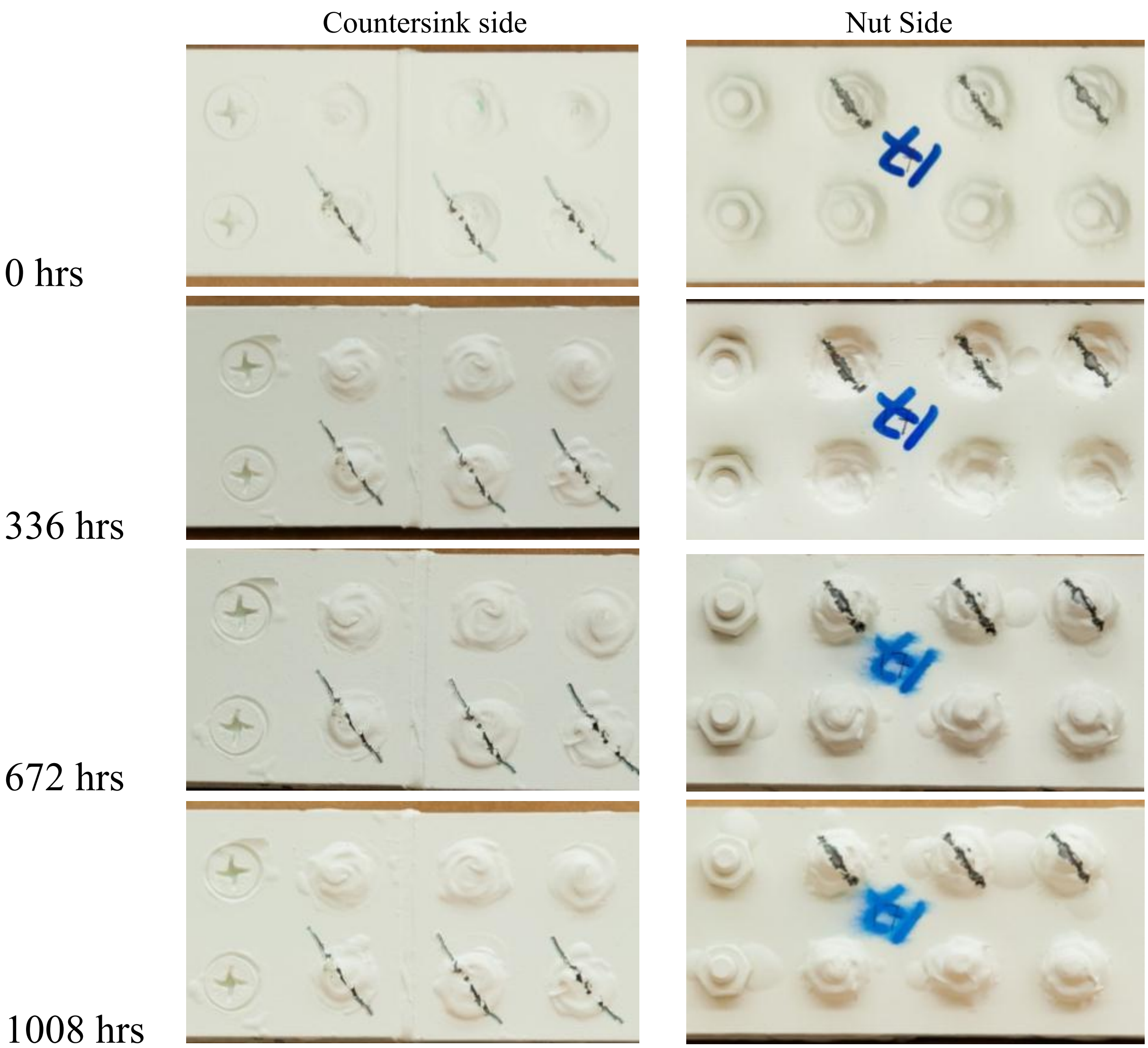


FIGURE 8.1.4 TEST VEHICLE WITH PPG RW-6040-71 SEALANT THROUGH 1008 HOURS ACIDIC SALT FOG EXPOSURE

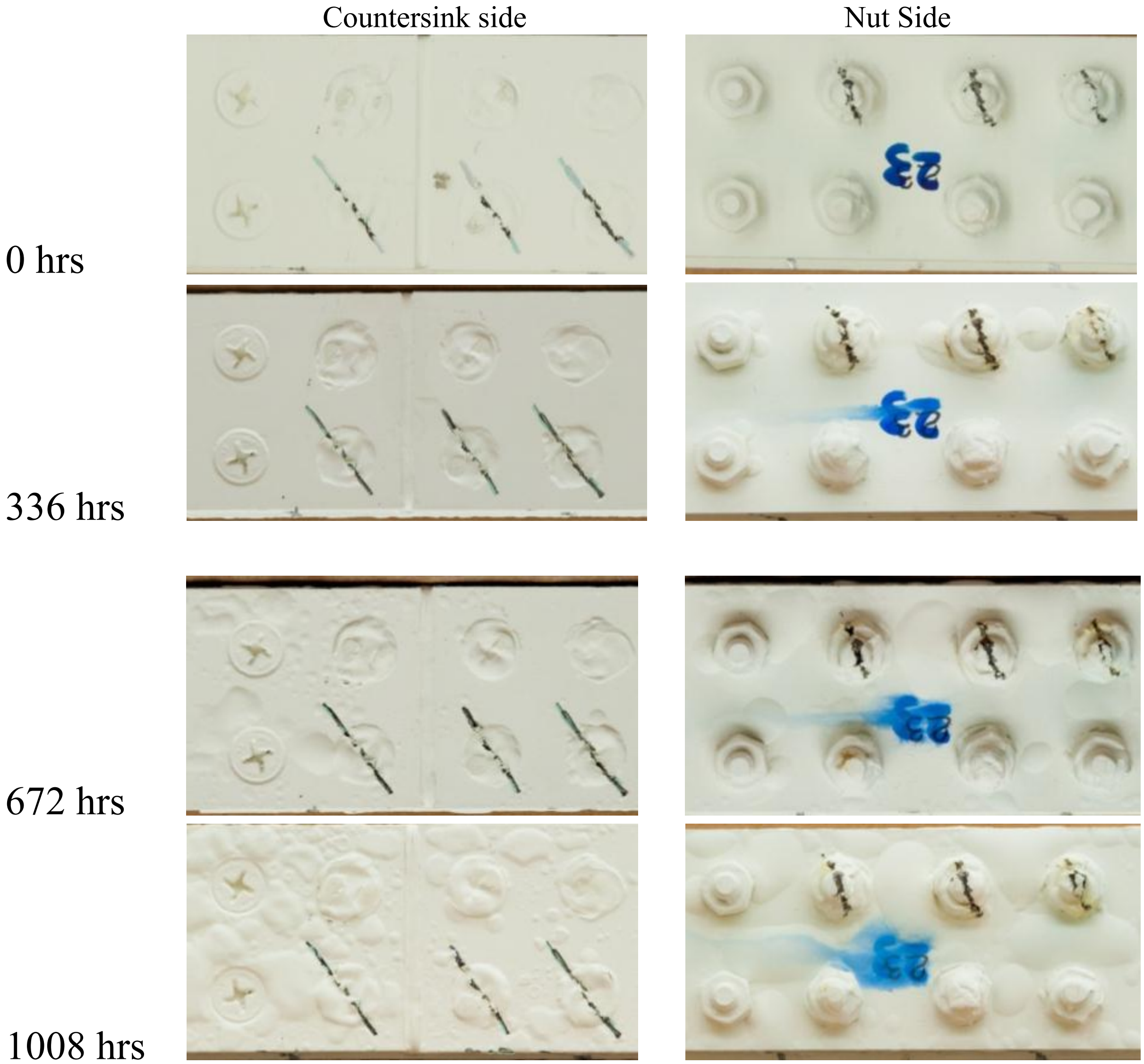


FIGURE 8.1.5 TEST VEHICLE WITH FM CS 5500N CI SEALANT THROUGH 1008 HOURS ACIDIC SALT FOG EXPOSURE

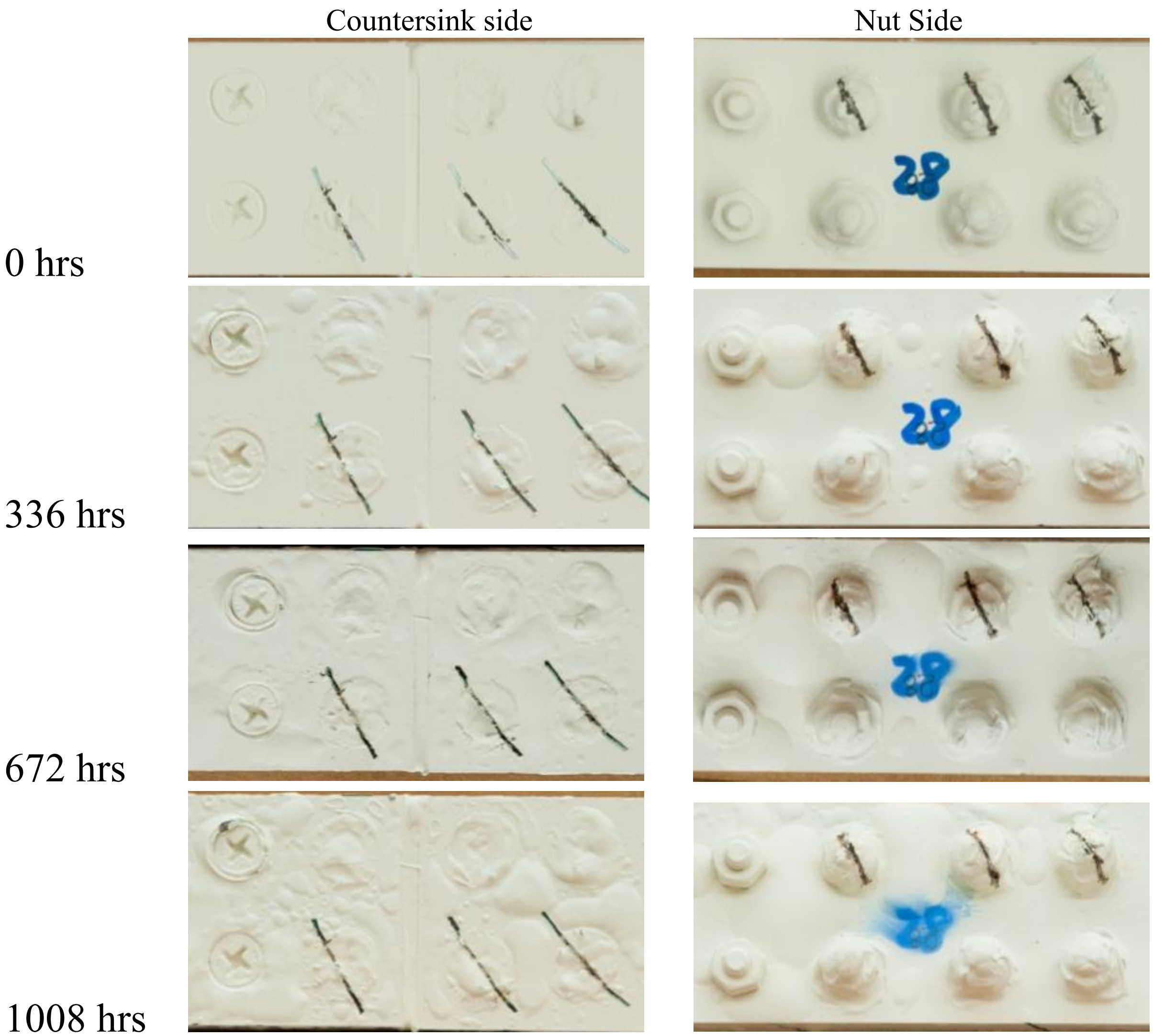


FIGURE 8.1.6 TEST VEHICLE WITH PPG PR-1440 SEALANT THROUGH 1008 HOURS ACIDIC SALT FOG EXPOSURE

Tables 8.1.1 through 8.1.3 present the non-destructive ratings of the test vehicles from 336 hours to 1008 hours of exposure to the SO_2 salt fog. It should be noted that because fay surfaces could not be examined, some of the lower value ratings do not reflect sealant performance, just damage noted on the surface.

TABLE 8.1.1 NON-DESTRUCTIVE INSPECTION RATINGS AT 336 HOURS OF EXPOSURE TO SO_2 SALT FOG

Test Vehicle	1	2	3	4	6	7	9	10	11	12	13	14	17	19	20	21	23	24	25	26	28	29	30	31
Exposure Time	336	336	336	336	336	336	336	336	336	336	336	336	336	336	336	336	336	336	336	336	336	336	336	336
Fastener 1 Top	5	5	5	5	5	5	5	5	5	5	5	5	5	5	4	5	5	5	5	5	5	5	5	5
Fastener 2 Top	5	3.5	4.5	3.5	4	4	4.5	4.5	5	5	3.5	3.5	4.5	5	4.5	4.5	4.5	3.5	3.5	4.5	3.5	3.5	3.5	3.5
Fastener 3 Top	5	3.5	5	3.5	4	4	4	4.5	5	5	3.5	3.5	3.5	5	4.5	4.5	4.5	4.5	5	3.5	3.5	3.5	3.5	4.5
Fastener 4 Top	4.5	5	3.5	3.5	3.5	4	3.5	4.5	5	5	3.5	5	4.5	5	4.5	3.5	4.5	4.5	4.5	4.5	3.5	4.5	3	3.5
Fastener 5 Top	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Fastener 6 Top	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	4.5	5	5	5	5	5	5	5	5
Fastener 7 Top	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	4.5	5	5	5	5	5	5	5	5
Fastener 8 Top	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Fastener 1 Bottom	5	5	5	5	3	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Fastener 2 Bottom	5	3.5	3.5	5	3.5	4.5	4	3.5	5	5	3.5	3	5	5	5	5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3
Fastener 3 Bottom	5	3.5	3.5	5	3	4.5	5	3.5	3.5	5	5	3	5	3.5	5	5	3.5	3	3.5	3.5	3.5	3.5	3	3
Fastener 4 Bottom	5	5	3.5	5	3.5	3.5	4	3.5	3.5	5	3.5	3	5	5	5	5	3.5	3.5	3.5	3.5	3.5	3.5	3	3
Fastener 5 Bottom	5	5	5	5	5	5	5	5	4	5	5	5	5	5	5	5	4.5	5	4.5	4.5	5	5	5	5
Fastener 6 Bottom	5	5	5	4.5	3.5	5	5	5	5	5	5	5	5	5	5	5	5	4.5	5	5	5	5	5	5
Fastener 7 Bottom	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Fastener 8 Bottom	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	4.5	5	5	5	5	5	5
Scribe Side 1	4.5	4.5	4.5	5	4.5	4.5	5	4.5	4.5	5	5	5	4	4.5	4.5	5	4.5	4.5	5	5	5	4	4.5	4.5
Scribe Side 2	4.5	5	4.5	4.5	4.5	4	5	5	4.5	4	5	5	4	4.5	4.5	4.5	4.5	4.5	5	5	5	4	4.5	4
Unscribe Side 1	4	4	4	4	4.5	4.5	5	4.5	4	4.5	4.5	4.5	4	4.5	4.5	5	5	5	4	4.5	5	4.5	4	5
Unsribe Side 2	4.5	4	4.5	4	4.5	4.5	5	4.5	4.5	4.5	5	4.5	4	4.5	4.5	5	4	4.5	4.5	4.5	4.5	5	5	4.5
Butt Joint	5	4.5	5	5	5	5	5	5	5	4.5	5	4.5	5	5	5	4	5	5	4.5	5	5	5	5	5
	PPG PS-870				3M AC-735				PPG PR-1775				PPG RW-6040-71				FM CS 5500 CI				PPG PR-1440			
Overall Appearance	102	96	96	97.5	91	97	100	97.5	98.5	102.5	97	94.5	98.5	101.5	100.5	100	96.5	95	96	96.5	95.5	94.5	92.5	93.5
Sum per Sealant	391.5				385.5				392.5				400.5				384				376			

Cracking
Rust
Blistering
Flaking/Peeling
Rust & Cracking
Rust & Blistering
Rust & Flaking/Peeling
Blistering & Flaking/Peeling
Blistering & Cracking
Blistering & Cracking & Rust
Chip & Cracking
Color Change
Color Change and Cracking
Salt Deposit
Rust & Flaking & Salt Deposit
Blistering & Flaking & Salt Deposit

TABLE 8.1.2 NON-DESTRUCTIVE INSPECTION RATINGS AT 672 HOURS OF EXPOSURE TO SO_2 SALT FOG

Test Vehicle	1	2	3	4	6	7	9	10	11	12	13	14	17	19	20	21	23	24	25	26	28	29	30	31
Exposure Time	672	672	672	672	672	672	672	672	672	672	672	672	672	672	672	672	672	672	672	672	672	672	672	672
Fastener 1 Top	5	5	5	5	5	4.5	5	5	5	5	5	5	5	5	3.5	3.5	3.5	3.5	5	3	5	3.5	3	3
Fastener 2 Top	4.5	4.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3	3.5	5	3.5	3.5	3	3.5	3	3.5	3	3.5	3	3	3.5
Fastener 3 Top	3.5	4.5	5	3.5	3.5	3	3.5	3.5	3.5	3.5	3.5	3.5	5	3.5	3.5	3	3.5	3.5	3.5	3.5	3.5	3	3.5	3.5
Fastener 4 Top	4.5	4.5	3.5	3.5	3.5	3	3.5	3.5	3.5	3.5	3.5	3.5	5	0	3.5	3	3.5	3.5	3	3.5	3	3.5	3.5	3
Fastener 5 Top	5	5	5	5	5	3	5	5	4.5	5	5	5	5	5	3.5	3.5	3.5	3.5	5	3.5	5	3.5	3.5	3.5
Fastener 6 Top	5	5	4.5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	3.5	5	5
Fastener 7 Top	4.5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	3.5	5	5	5	5
Fastener 8 Top	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	3.5	5	3.5	5	5	5
Fastener 1 Bottom	5	3.5	4	5	4	3	3	5	3.5	5	3	3	3.5	3.5	3.5	3.5	3	3.5	3.5	3.5	3.5	3.5	3.5	3.5
Fastener 2 Bottom	3.5	5	3.5	3.5	3.5	3.5	3.5	3.5	5	3	3.5	3	3	3.5	3	3.5	3	3.5	3	3.5	3	3.5	3.5	3
Fastener 3 Bottom	3.5	3.5	3.5	3.5	3.5	3.5	3	3.5	5	3	3.5	3	3	3.5	3	3.5	3	3.5	3	3.5	3	3	3.5	2
Fastener 4 Bottom	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	4	3	3.5	3	3	3.5	3	3.5	3	3.5	3	3.5	3	3	3.5	2
Fastener 5 Bottom	5	5	5	5	3	3	5	5	3.5	4	4.5	3	3.5	3.5	3.5	5	3	3.5	3	3.5	3.5	3.5	3.5	3.5
Fastener 6 Bottom	5	5	5	5	5	5	5	5	5	4.5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Fastener 7 Bottom	5	5	5	5	5	5	5	5	5	5	5	5	3.5	5	5	5	5	5	5	5	5	5	5	5
Fastener 8 Bottom	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Scribe Side 1	4.5	5	4.5	4.5	4	4.5	4.5	5	4.5	5	4.5	5	4.5	5	3.5	4.5	4.5	4.5	5	4.5	3.5	3.5	4.5	4
Scribe Side 2	4.5	5	4.5	4.5	4.5	4.5	4	4.5	4.5	4	4.5	5	4.5	5	3.5	4	4.5	4.5	5	4.5	3.5	5	3.5	4.5
Unscribe Side 1	4.5	4	4.5	4	4.5	3	4	4	4	4.5	4.5	4.5	4	4.5	5	4.5	4	4.5	4.5	5	4.5	4.5	4.5	4.5
Unscribe Side 2	4.5	4	4.5	4	4.5	4.5	4	4.5	4	4.5	4	4.5	5	4.5	5	4	4	4.5	4.5	4.5	4.5	4	4	4.5
Butt Joint	5	4.5	4.5	4.5	5	3.5	4.5	4.5	5	5	5	3	5	4.5	5	3.5	4	5	5	4	3.5	4	4.5	3.5
	PPG PS-870				3M AC-735				PPG PR-1775				PPG RW-6040-71				FM CS 5500 CI				PPG PR-1440			
Overall Appearance	95.5	96.5	93.5	92.5	90.5	83.5	89.5	93.5	93	91	90.5	87.5	92.5	88	85.5	85.5	83.5	87.5	88	85	84	82.5	85	81.5
Sum per Sealant	378				357				362				351.5				344				333			

Cracking
Rust
Blistering
Flaking/Peeling
Rust & Cracking
Rust & Blistering
Rust & Flaking/Peeling
Blistering & Flaking/Peeling
Blistering & Cracking
Blistering & Cracking & Rust
Chip & Cracking
Color Change
Color Change and Cracking
Salt Deposit
Rust & Flaking & Salt Deposit
Blistering & Flaking & Salt Deposit

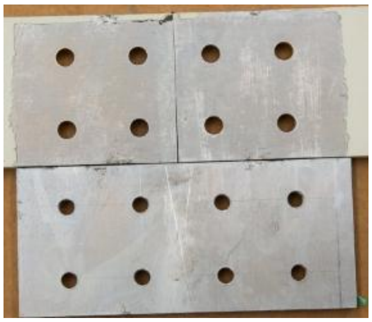
TABLE 8.1.3 NON-DESTRUCTIVE INSPECTION RATINGS AT 1008 HOURS OF EXPOSURE TO SO_2 SALT FOG

Test Vehicle	1	2	3	4	6	7	9	10	11	12	13	14	17	19	20	21	23	24	25	26	28	29	30	31
Exposure Time	1008	1008	1008	1008	1008	1008	1008	1008	1008	1008	1008	1008	1008	1008	1008	1008	1008	1008	1008	1008	1008	1008	1008	1008
Fastener 1 Top	3.5	5	5	5	3.5	5	5	5	5	3.5	5	5	5	5	5	3.5	3.5	3	3.5	3.5	3.5	3.5	2	3.5
Fastener 2 Top	3.5	3	3.5	3.5	3.5	3.5	3	3.5	3	3	2	3	3.5	3.5	3	2	2	2	3.5	3	3	2	2	3
Fastener 3 Top	3	3.5	3	3	3.5	3.5	3	3.5	3.5	3	3	2	3.5	3	3.5	3	2	3	3	3	3	3	2	3
Fastener 4 Top	3.5	3.5	3.5	3	3.5	3.5	3	3.5	3	3	3	2	3.5	3.5	3.5	2	2	3	3	3	3	3	3	3
Fastener 5 Top	3.5	5	5	5	5	3.5	5	5	5	5	5	5	5	3.5	5	3.5	3.5	5	3.5	3.5	1	3.5	3	2
Fastener 6 Top	5	5	5	5	4	5	5	5	5	5	5	5	5	5	5	5	3	3.5	3.5	5	5	3	5	5
Fastener 7 Top	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	3.5	5	5	5	5	5	5	5
Fastener 8 Top	5	5	5	5	4	5	5	5	5	5	3.5	5	5	5	5	5	5	3.5	3.5	5	5	3.5	5	5
Fastener 1 Bottom	3.5	3.5	3.5	3.5	3	3.5	3.5	5	3.5	3.5	2	3.5	3.5	3.5	3.5	3.5	3	3.5	3.5	3.5	3.5	3.5	3.5	3.5
Fastener 2 Bottom	3.5	3	3.5	3.5	3	3	3.5	3.5	3	3	3	3	3.5	3	3.5	3.5	3	3	3	3.5	3	1	2	3
Fastener 3 Bottom	3.5	3	3	3	3	3	3.5	2	3	3	3	3	3.5	3	3.5	3.5	3	3	2	3.5	3.5	3	2	2
Fastener 4 Bottom	3.5	3.5	3.5	3.5	3	2	3.5	2	3	3.5	3	3	3	3	3	3.5	3	3	2	3.5	3.5	3	2	2
Fastener 5 Bottom	3.5	5	3.5	5	2	3.5	3.5	3.5	2	3.5	3.5	3.5	3.5	3.5	3.5	5	3	3.5	2	3.5	3.5	3.5	3.5	3.5
Fastener 6 Bottom	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	3.5	5	3	5	5	5	5	5
Fastener 7 Bottom	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	3.5	5	5	5	5	5	5	5
Fastener 8 Bottom	5	5	5	5	5	5	5	5	5	5	5	3.5	5	5	5	5	3.5	5	5	5	5	5	5	5
Scribe Side 1	4.5	4.5	4.5	3.5	4	4.5	4.5	2	4.5	4.5	4.5	4.5	4.5	4.5	3.5	4.5	4	4	3.5	3.5	4	3.5	3.5	3.5
Scribe Side 2	4.5	4	4.5	3.5	4.5	4.5	4.5	4.5	3.5	3.5	3.5	4.5	4.5	4.5	3.5	3.5	3.5	4	3.5	3	4	3.5	3.5	4
Unscribe Side 1	4.5	4.5	4.5	4	4.5	4	4	3.5	4	4.5	3.5	3.5	3.5	3.5	4.5	4	4	3.5	3.5	3.5	3.5	3.5	4	3.5
Unscribe Side 2	4	4.5	4.5	4	4.5	4	3.5	3.5	2	4.5	3.5	4	4	3.5	3.5	3.5	3.5	3.5	3.5	3	3.5	3.5	3	3.5
Butt Joint	4.5	3.5	5	5	3.5	4.5	3.5	3.5	3	3.5	3.5	3.5	4.5	4	5	3.5	3.5	3	2.5	3	4	3	3	3
	PPG PS-870				3M AC-735				PPG PR-1775				PPG RW-6040-71				FM CS 5500 CI				PPG PR-1440			
Overall Appearance	64.5	68	67	68	61	64	66.5	66.5	64	64	61	61.5	67.5	64.5	67	63	50	59	54	63.5	60.5	55.5	55	58.5
Sum per Sealant	267.5				258				250.5				262				226.5				229.5			

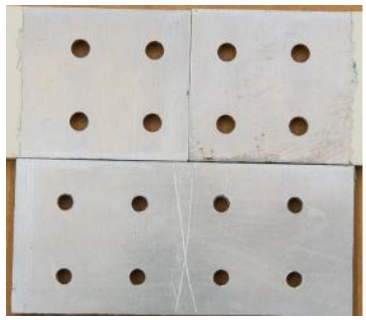
Cracking
Rust
Blistering
Flaking/Peeling
Rust & Cracking
Rust & Blistering
Rust & Flaking/Peeling
Blistering & Flaking/Peeling
Blistering & Cracking
Blistering & Cracking & Rust
Chip & Cracking
Color Change
Color Change and Cracking
Salt Deposit
Rust & Flaking & Salt Deposit
Blistering & Flaking & Salt Deposit

8.2 Destructive Inspection Results

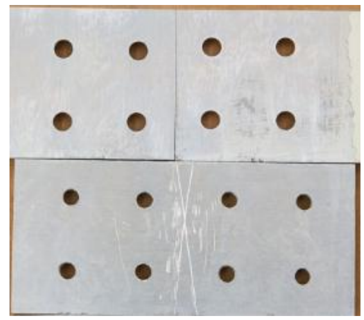
The following Figures show the faying surfaces, butt joints, and countersink holes of the interim test vehicles after being deconstructed. Table 8.2.1 presents the results of the destructive inspections of the test vehicles.



PPG PS-870



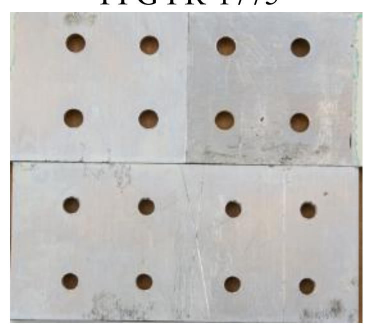
3M AC-735



PPG PR-1775

PPG RW-6040-71

FM CS 5500N CI



PPG PR-1440

FIGURE 8.2.1 FAYING SURFACES OF TEST VEHICLES AFTER DESTRUCTION


PPG PS-870


3M AC-735


PPG PR-1775


PPG RW-6040-71

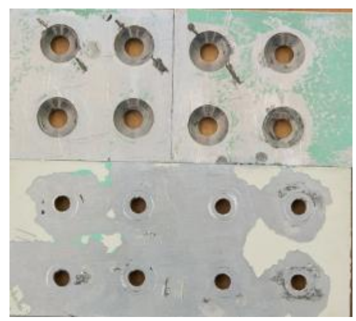

FM CS 5500N CI

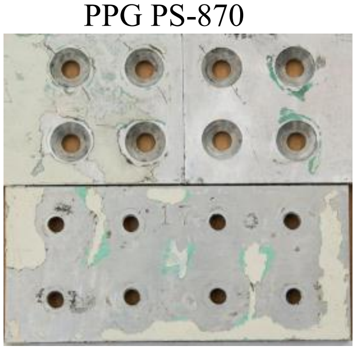

PPG PR-1440

FIGURE 8.2.2 BUTT JOINTS OF TEST VEHICLES AFTER DESTRUCTION


PPG PS-870


3M AC-735


PPG PR-1775


PPG RW-6040-71


FM CS 5500N CI


PPG PR-1440

FIGURE 8.2.3 COUNTERSINK HOLES AND BARREL HOLES OF TEST VEHICLES AFTER DESTRUCTION

TABLE 8.2.1 DESTRUCTIVE INSPECTION RESULTS

Sealant	PPG PS-870				3M AC-735				PPG PR-1775				PPG RW-6040-71				FM CS 5500 CI				PPG PR-1440			
Test Vehicle	1	2	3	4	6	7	9	10	11	12	13	14	17	19	20	21	23	24	25	26	28	29	30	31
Fastener Countersink 1	6	2	20	10	8	3	42	20	2	1	2	9	1	13	90	4	0	65	2	45	5	58	12	1
Fastener Countersink 2	3	3	2	4	25	30	8	0	2	20	85	17	16	100	65	5	55	25	1	27	7	17	7	8
Fastener Countersink 3	80	6	8	5	80	50	20	0	6	15	30	23	10	7	4	5	38	1	22	1	9	70	4	11
Fastener Countersink 4	2	38	75	65	40	50	12	80	4	17	13	55	70	40	33	5	55	19	18	0	42	39	14	14
Fastener Countersink 5	2	3	0	2	10	8	3	90	35	2	3	19	8	2	6	3	0	25	6	15	78	90	16	4
Fastener Countersink 6	1	2	0	1	2	0	1	0	0	1	0	0	0	0	0	1	0	30	0	7	0	2	1	2
Fastener Countersink 7	0	1	0	0	0	0	0	0	0	1	0	1	1	0	0	0	30	14	0	18	1	0	3	1
Fastener Countersink 8	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	13	16	3	2	0	20	4	0
Fastener 1 Hole Area	1	0	0	0	0	0	0	0	0	0	0	0	0	0	30	0	0	0	0	0	0	0	0	0
Fastener 2 Hole Area	0	0	0	0	0	0	0	0	0	0	0	0	0	20	30	0	0	0	0	0	0	0	0	0
Fastener 3 Hole Area	0	0	0	0	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0	0	0
Fastener 4 Hole Area	0	0	0	15	0	0	0	0	0	0	0	0	0	3	30	0	0	0	0	0	0	0	0	0
Fastener 5 Hole Area	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	30	0	0	0
Fastener 6 Hole Area	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fastener 7 Hole Area	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fastener 8 Hole Area	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Butt Joint Side 1 1-5	12	10	5	2	1	8	15	25	2	0	0	7	2	0	0	0	8	20	8	2	14	12	21	16
Butt Joint Side 2 3-7	5	17	9	9	3	1	35	7	3	2	3	9	7	55	0	0	8	23	1	3	9	15	11	21
Faying Surface 1 8	7	2	1	1	0	0	1	3	3	2	1	7	9	1	4	1	2	1	6	3	12	4	1	9
Faying Surface 2 1-5	2	2	4	6	1	1	1	0	1	2	2	1	1	0	0	0	6	1	1	1	8	1	1	2
Faying Surface 3 3-7	4	1	1	1	1	1	1	2	0	3	3	4	0	1	12	2	1	4	5	6	5	4	2	7
Butt Scribe	5	0	0	0	0	0	0	0	7	1	0	0	0	1	0	1	0	0	0	2	0	0	1	9
Overall Corrosion	131	87	125	121	171	152	139	227	65	67	152	152	126	243	304	27	216	244	73	132	220	332	98	105
Average Overall Corrosion	116				172.25				109				175				166.25				188.75			
Faying Surfaces/Butt Joint/Butt Scribe	35	32	20	19	6	11	53	37	16	10	9	28	19	58	16	4	25	49	21	17	48	36	37	64
Average Faying Surfaces/Butt Joint/Butt Scribe	26.5				26.75				15.75				24.25				28				46.25			
Countersink Corrosion/Fastener Areas	96	55	105	102	165	141	86	190	49	57	143	124	107	185	288	23	191	195	52	115	172	296	61	41
Average Countersink Corrosion/Fastener Areas	89.5				145.5				93.25				150.75				138.25				142.5			
Butt Joint Total	17	27	14	11	4	9	50	32	5	2	3	16	9	55	0	0	16	43	9	5	23	27	32	37
Butt Joint Total Average	17.25				23.75				6.5				16				18.25				29.75			
Faying Surfaces/Butt Scribe Total	18	5	6	8	2	2	3	5	11	8	6	12	10	3	16	4	9	6	12	12	25	9	5	27
Faying Surfaces/Butt Scribe Total Average	9.25				3				9.25				8.25				9.75				16.5			
Exterior Corrosion % 1-5	1	2	6	3	14	6	4	1	2	11	2	3	2	5	13	18	86	45	90	73	95	77	58	90
Exterior Corrosion % 3-7	3	6	2	4	17	5	7	1	1	17	3	0	1	2	16	20	28	33	78	68	89	69	31	78
Exterior Corrosion % 8	4	11	5	6	9	5	9	4	4	5	6	7	5	6	17	3	12	7	9	5	4	4	5	8
Exterior Side Corrosion % 1-4	44	39	25	15	54	62	28	17	28	24	40	14	26	16	34	23	17	20	43	28	46	63	38	45
Exterior Side Corrosion % 5-8	38	21	59	19	38	53	32	19	19	58	31	4	36	52	45	14	29	28	21	30	27	29	32	55
Total Exterior Corrosion	90	79	97	47	132	131	80	42	54	115	82	28	70	81	125	78	172	133	241	204	261	242	164	276
Average Exterior Corrosion Per Sealant	78.25				96.25				69.75				88.5				187.5				235.75			
Average Exterior Surface Corrosion	2.66667	6.33333	4.33333	4.33333	13.3333	5.33333	6.66667	2	2.33333	11	3.66667	3.33333	2.66667	4.33333	15.3333	13.6667	42	28.3333	59	48.6667	62.6667	50	31.3333	58.6667
Average Exterior Surface Corrosion Per Sealant	4.416666667				6.833333333				5.083333333				9				44.5				50.66666667			
Average Side Corrosion	41	30	42	17	46	57.5	30	18	23.5	41	35.5	9	31	34	39.5	18.5	23	24	32	29	36.5	46	35	50
Average Side Corrosion Per Sealant	32.5				37.875				27.25				30.75				27				41.875			

After rating each area, it was necessary to determine how to best analyze the data to determine sealant performance. Therefore, three categories were used to analyze the ratings of the test vehicles: Butt Joints and Faying Surfaces, Countersink Areas, and Ring around Fastener Hole Areas. Table 8.2.2 presents the data analysis of the destructive inspection results of test vehicles that completed 1008 hours of SO_2 salt fog exposure. Additional data was collected on the amount of corrosion seen on external surfaces to examine why certain test vehicles performed worse than others.

TABLE 8.2.2 DATA ANALYSIS OF DESTRUCTIVE INSPECTION RESULTS AFTER 1008 HOURS OF EXPOSURE TO SO_2 SALT FOG

Surface Area	PS-870	AC-735	PR-1775	RW-6040-71	CS 5500N CI	PR-1440
Faying Surface Area	2.7%	1.1%	2.6%	3.0%	3.1%	5.2%
Butt Joint Area	6.2%	7.9%	2.8%	5.5%	6.3%	10.8%
Countersink area (Holes with Sealant Overcoat and No Scribes)	0.2%	0.1%	0.1%	0.1%	4.3%	1.1%
Countersink area (Holes with Sealant Overcoat and Scribes)	10.2%	12.8%	9.8%	15.9%	8.5%	7.8%
Countersink area (Holes with No Sealant Overcoat and No Scribes)	2.3%	8.9%	3.5%	8.5%	7.7%	15.1%
Ring around fastener hole areas with Sealant Overcoat and No Scribes	0.1%	0%	0%	0.3%	2.6%	3.4%
Ring around fastener hole areas with Sealant Overcoat and Scribes	2.4%	3.5%	5.4%	5.6%	5.4%	14%
Ring around fastener hole areas with No Sealant Overcoat and No Scribes	9.6%	2.5%	5.4%	9.2%	39%	33%
External Corrosion	12.7%	15.7%	11.5%	15.1%	35.4%	43.1%

9. DISCUSSIONS

9.1. Non-Destructive Inspection

When examining sealant performance, the non-destructive observations proved difficult because the sealant-to-metal interface could not be observed (i.e. how well the sealant was protecting the area it was sealing off from exposure), therefore all corrosion data from the nondestructive inspection is speculative.

One aspect of corrosion that could be observed, as seen in Figures 8.1.1 through 8.1.6, is the test vehicles' blistering through the exposure process, causing what is believed to be corrosion beneath the primer/topcoat. The control test vehicle, as well as the AC-735, PR-1775, and RW-6040-71, all blistered at roughly the same rate through the exposure. The FM CS5500N CI and PR-1440, however, blistered at an accelerated rate.

Using the rating scale as described in Table 7.3.1.1 and the data from Tables 8.1.1 through 8.1.3, PS-870, AC-735, PR-1775, and RW-6040-71 had only minor drop offs of about 30 rating points across all four test vehicles combined from the 0 to 336 hour mark, and again from the 336 to 672 hour mark, before a significant drop of about 100 rating points at 1008 hours. The FM CS5500N CI and PR-1440 both had a 45 rating point drop off from 0 to 336 and another 45 from 336 to 672 hours for all four test vehicles combined before a roughly 120 rating point reduction as the test vehicles approached the 1008 hour mark.

From both the mechanical stress and SO_2 salt fog exposure, several leak paths, which caused corrosion within the butt joint and countersink areas, were formed, as seen through cracking and blistering of the primer/topcoat. After the 1008 hour inspection, several cracks were observed through the sealant in the butt joint of many of the coupons. The cracks around the countersink areas were a result of the scribes through the sealant overcoat, and possibly due to the blistering phenomenon issue. The fastener heads that were scribed and overcoated with sealant showed corrosion due to the existing presence of such leak paths. Fasteners that were overcoated with sealant and not scribed appeared to have less damage, although some blisters appeared around the fasteners.

9.2. Destructive Inspection

To determine which sealant had the most corrosion resistance, an analysis of the destructive inspection results was performed and described in Section 8.2 of this report. The ratings provided in the inspection were summed up into three categories: Butt Joints, Faying Surfaces, and Butt Scribe; Countersinks and Fastener Areas; and Ring Around Fastener Hole Areas. Each category provided different information about sealant performance. Because of the large amount of surface area that each sealant had to protect for the Butt Joints and Faying Surface category, it was regarded as the best indicator of sealant performance.

For the butt joint area, PR-1775 performed the best out of all the sealants corroding on an average of only 2.8% area within each test vehicles butt joint. The PS-870, RW-6040-71, and CS5500N CI corroded an average of around 6% total area on each butt joint, and AC-735 corroded on average 7.9% in each butt joint. The negative control, PR-1440, performed the worst by allowing 10.8% area corrosion on each test vehicle. Some of this corrosion came from cracking in the butt joint, both on the top of the joint and from the sides, while some came from blisters on the surface.

Despite the cracks and corrosion to the butt joint sides, the faying surfaces experienced minimal total area of corrosion. Within the faying surface, AC-735 preformed the best at 1.1% total area corrosion, while the other sealants, excluding the negative control, performed about the same at around 3% total area corrosion. PR-1440 had corrosion on an average of 5.2% of each faying surface. The corrosion on the faying surfaces came from the initiated damage done by the scribes on the sides of the test vehicles.

In the Countersink and Fastener Hole Areas a few trends immerged during the destructive inspection. The fastener heads overcoated with sealant and not scribed provided sufficient corrosion resistance for a majority of the sealants, with only 0.1% area corrosion. FM CS5500N CI and PR 1440 were less protected because of the primer/topcoat blistering phenomenon.

The fasteners overcoated with sealant and scribed demonstrated that PR-1775, CS5500N CI, and PR-1440 were as good as PS-870 at preventing moisture from attacking the countersink areas when damage was initiated, with corrosion occurring on 10% of the countersink and barrel areas. The AC-735 and RW-6040-71 did not provide as much corrosion resistance with roughly 13% corrosion.

For the fasteners that relied purely on wet installation for corrosion protection, PS-870 performed the best at 2.3% total area corrosion, with PR-1775 performing closest at 3.5% countersink area corrosion. The CS 5500N CI, AC 735, and RW-6040-71 each had about 8.5% of the countersink areas corroded, and PR-1440 had 15.1% area corrosion.

The areas around the fastener heads were examined at in an attempt to determine why some of the countersinks corroded so much more than the others. The sealant overcoats without scribes performed well for the PS-870, AC-735, PR-1775, and RW6040-71, allowing virtually no corrosion. The CS 5500N CI and PR-1440 had about 3% of the area around each fastener head corroded due to the blistering phenomenon on the test vehicle surfaces.

However, some fastener heads, despite being overcoated, had moisture seep through the sealant and corrode the substrate due to the presence of the scribes. In this case, the AC-

735, which had 3.5% corrosion around the countersink came the closest to PS-870, which had 2.4% of the total area of interest corroded. The PR-1775, RW-6040-71, and CS 5500N CI had corroded 5.5% of the area around the countersink areas. PR-1440 had 14% of the area around each countersink area corrode.

The fasteners that were not overcoated with sealant were used to examine the benefits of overcoating as a method of corrosion prevention for the fasteners. Without an overcoat present, AC-735 performed the best with only 2.5% of the substrate area around the fasteners corroded. The next best performing sealant was PR-1775, corroding on 5.4% of the substrate area. PS-870 and RW-6040-71 both allowed 9.5% corrosion around the fasteners. CS 5500N CI and PR-1440, without the protection of the sealant overcoat coupled with the blistering on the exterior surfaces of the test vehicles, saw about 35% of the substrate area around the fasteners corrode.

Upon stripping the panels during destructive inspection, it was noted that several of the test vehicles had corrosion along several of their external surfaces away from the fastener heads and nuts. These areas of corrosion are consistent with the blistered areas observed during non-destructive evaluations. Some of this corrosion caused leak paths, which allowed moisture to penetrate the coating and attack the substrate. This corrosion was overwhelming present on the PPG PR-1440 and FM CS5500N CI test vehicles on the two top plates, which were about 40% corroded, while the other four sealants were about 12% corroded. Most of the bottom plates had a relatively similar amount of corrosion, despite those surfaces directly facing the salt spray chamber humidifying tower. The blistering phenomenon of the test vehicles is believed to be the cause of this corrosion.

According to Table 8.2.2, AC-735, CS 5500N CI, PR-1775, and RW-6040 provided the same corrosion prevention as the baseline sealant PS-870 in the faying surface and butt joint areas. In the countersink areas and ring around the fastener areas, AC-735, PR-1775, and RW-6040 provided the same corrosion prevention as the baseline sealant PS-870. Further testing should be done to determine the root cause of the blistering phenomenon, which affected the results of the CS 5500N CI and PR-1440.

10. CONCLUSIONS

When looking at the faying surfaces of the test vehicles, PR-1775, AC-735, RW-6040-71, CS 5500N CI, and PS-870 had similar corrosion resistance characteristics with PR-1775 performing the best of the HCF sealants.

On the external surfaces, PR-1775, AC-735, RW-6040-71, and PS-870 performed similarly. A blistering phenomenon caused CS 5500N CI and PR-1440 to perform worst. Further testing to repeat the test vehicles with CS 500N CI and PR-1440 to confirm the blistering phenomenon is recommended.

A considerable amount of corrosion occurred from the presence of a leak path, allowing moisture to attack the substrate. These leak paths include the scribes made during coupon prep and cracks in the sealant and primer/topcoat as testing was performed.

Destructive inspection of the test vehicles revealed that the fasteners overcoated with sealant provided more resistance to corrosion than the fasteners that were not protected with sealant.

Addendum A: Beachfront Exposure Corrosion Test

Beachfront Results

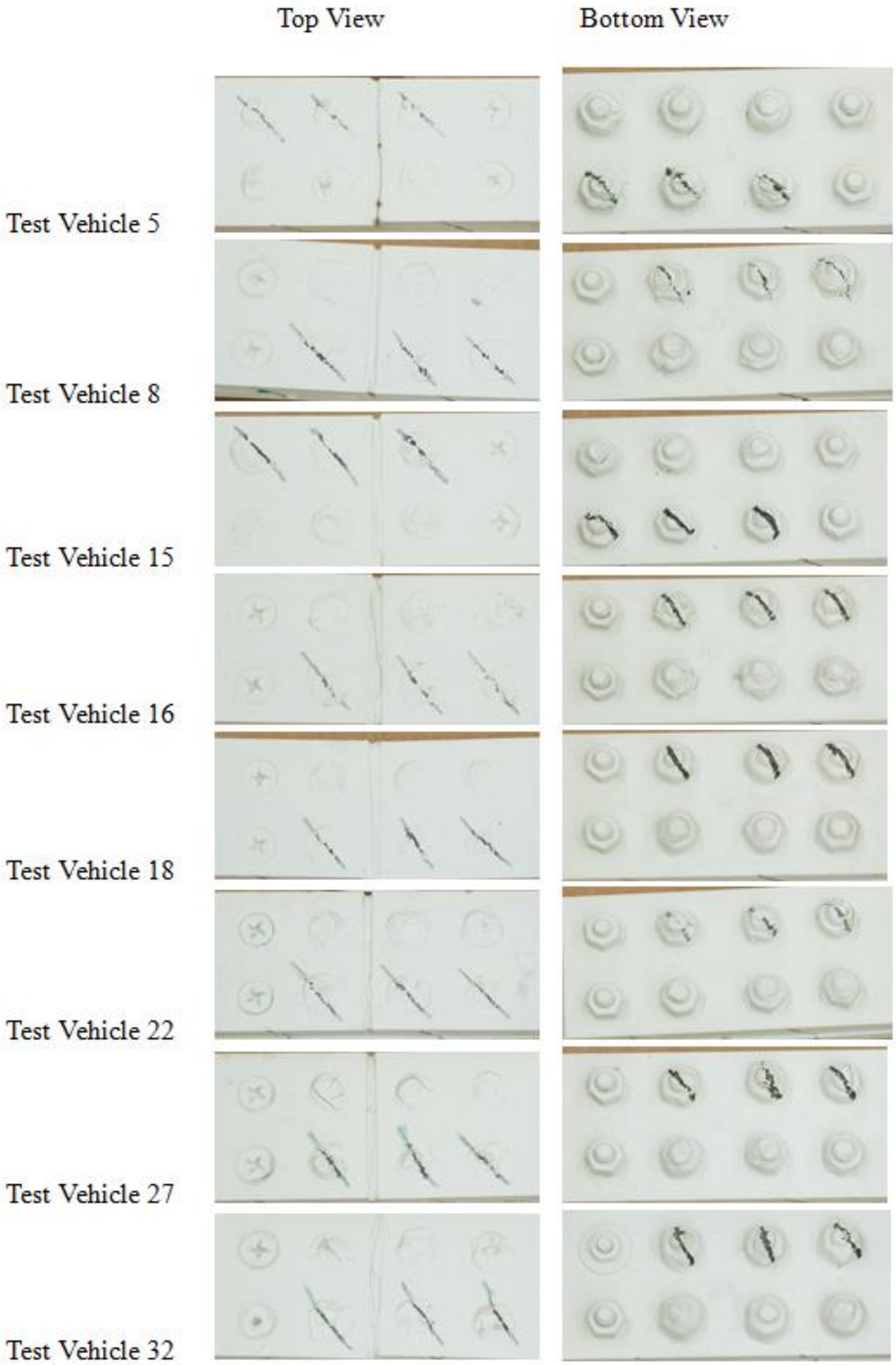
The test vehicles exposed to a beach environment were manufactured at the same time and manner as those in MPLR-101562 Section 6.4. Table A1 shows the conversion coating and external coating combinations used for these test vehicles. The test vehicles discussed here were exposed to a beach environment at the NASA – Beachside Atmospheric Test Facility at Kennedy Space Center, Florida for one year.

TABLE A1.TEST VEHICLE DESIGN COMBINATIONS

Test Vehicle Number	Alloy	Sealant	Conversion Coating	Primer/Topcoat	Exposure
5	7075	PS-870	Iridite 14-2	HCF Primer and Topcoat	Beachfront
8	7075	AC-735	Iridite 14-2	HCF Primer and Topcoat	Beachfront
15	7075	PR-1775	Iridite 14-2	HCF Primer and Topcoat	Beachfront
16	7075	PS-870	Iridite 14-2	HCF Primer and Topcoat	Beachfront
18	7075	PR-1440	Iridite 14-2	HCF Primer and Topcoat	Beachfront
22	7075	RW-6040	Iridite 14-2	HCF Primer and Topcoat	Beachfront
27	7075	CS 5500	Iridite 14-2	HCF Primer and Topcoat	Beachfront
32	7075	PR-1440	Iridite 14-2	HCF Primer and Topcoat	Beachfront

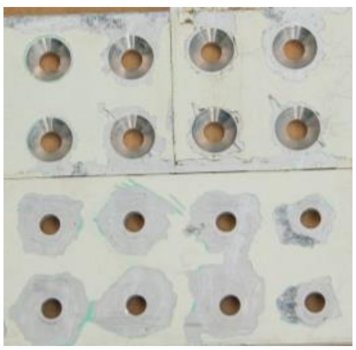
The nondestructive evaluation of the test vehicles were done similar to MPLR-101562 Paragraph 7.4, by providing exterior surface corrosion observations. The beachfront exposure, since it is not as harsh of an environment as the SO_2 salt fog exposure, damaged the test vehicles much less on the external surfaces. The only location corrosion could be seen during the nondestructive evaluation was the areas around the fasteners that were not overcoated with sealant. Figure A1 shows the top and bottom areas of the test vehicles before they were broken apart.

FIGURE A1. NONDESTRUCTIVE VIEWS

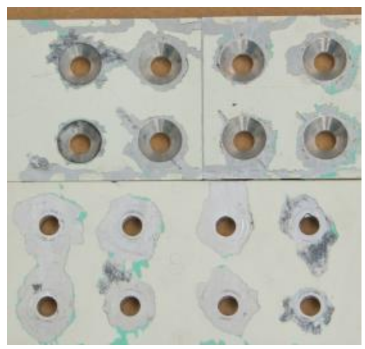


The test vehicles subjected to beachfront corrosion exposure were disassembled using a pneumatic press and hammer after their arrival at Lockheed Martin. The sealant inside the test vehicle pieces were stripped from the substrate using toluene. Figures A2 through A4 show views of the test vehicles after disassembly. Table A1 shows the % area of corrosion results of the destructive inspection for each area of interest, using the process described in Section 7.6.

FIGURE A2. DECONSTRUCTED COUNTERSINKS AND NUT AREAS

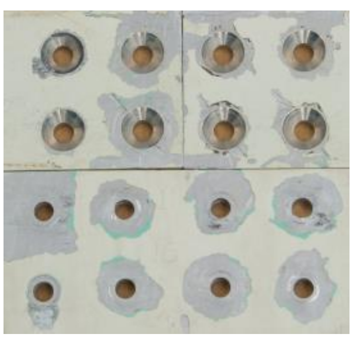


Test Vehicle 5

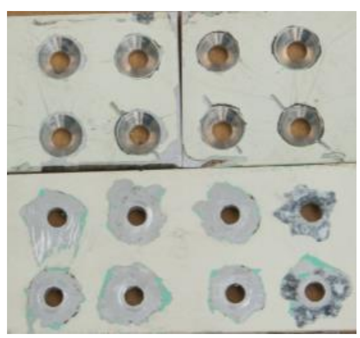


Test Vehicle 8

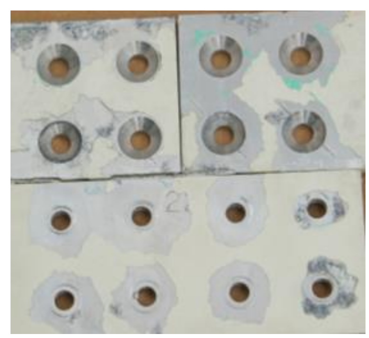
Test Vehicle 15



Test Vehicle 16

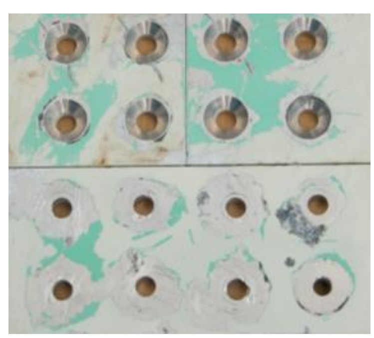


Test Vehicle 18



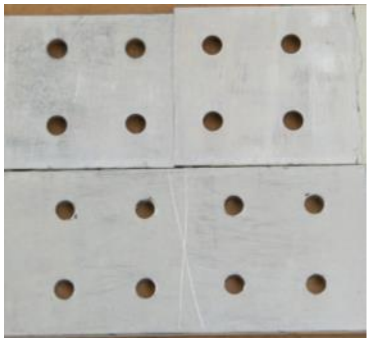
Test Vehicle 22

Test Vehicle 27

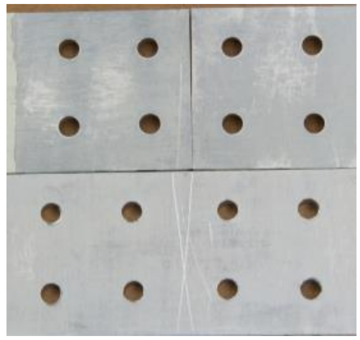


Test Vehicle 32

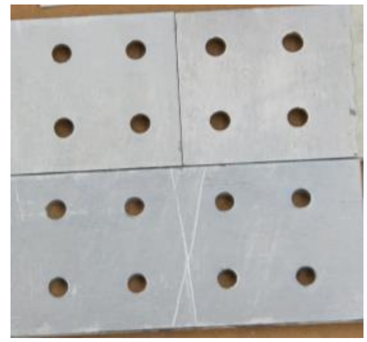
FIGURE A3. DECONSTRUCTED FAYING SURFACE AREAS



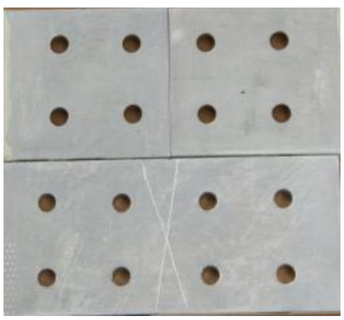
Test Vehicle 5



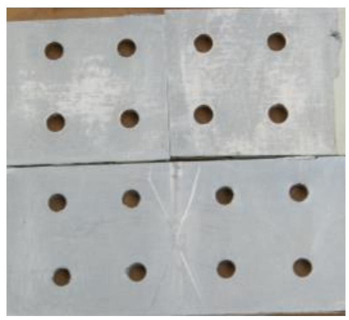
Test Vehicle 8



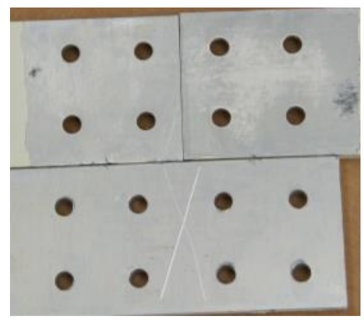
Test Vehicle 15



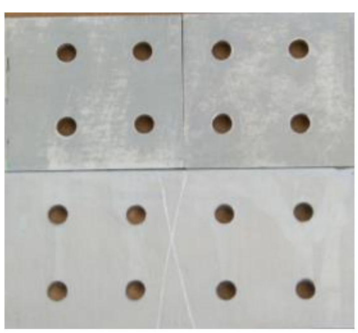
Test Vehicle 16



Test Vehicle 18



Test Vehicle 22



Test Vehicle 27

Test Vehicle 32

FIGURE A4. DECONSTRUCTED BUTT JOINT AREAS

Test Vehicle 5

Test Vehicle 8

Test Vehicle 15

Test Vehicle 16

Test Vehicle 18

Test Vehicle 22

Test Vehicle 27

Test Vehicle 32

TABLE A2. DESTRUCTIVE INSPECTION RESULTS

Test Vehicle #	5	8	15	16	18	22	27	32
Surface Area	PS-870	AC-735	PR-1775	PS-870	PR-1440	RW-6040	CS 5500	PR-1440
Total % Faying Surface Corrosion	0.3%	0.0%	0.7%	0.0%	0.2%	2.4%	0.0%	0.2%
Total % Butt Joint Corrosion	1.1%	0.0%	4.6%	2.7%	0.0%	4.6%	0.0%	1.5%
Total % Butt Joint Corrosion Excluding Scribe	1.5%	0.0%	6.0%	3.5%	0.0%	6.0%	0.0%	2.0%
Average % Countersink Corrosion	1.3%	4.0%	4.3%	2.1%	1.4%	3.8%	1.3%	2.3%
Total % Corrosion on Overcoated Countersinks	2.0%	1.0%	0.0%	0.0%	0.3%	0.0%	1.0%	0.3%
Total % Corrosion on Nonovercoated Countersinks	2.0%	13.5%	14.5%	8.5%	2.5%	14.0%	3.0%	8.5%
Total % Corrosion Overcoated & Scribed Countersinks	0.0%	0.7%	1.7%	0.0%	1.7%	0.7%	0.3%	0.0%
Total % Areas of Interest Corroded	0.5%	0.9%	1.8%	0.6%	0.5%	2.9%	0.3%	0.8%

The ring areas around the fastener holes v were not documented because only a few of these areas corroded during the exposure with a bulk of the corrosion taking place around the fastener heads that were not overcoated with sealant. The other value not documented was overall external corrosion because, when compared to the SO_2 exposed test vehicles, there was much less corrosion.

The faying surfaces were very well protected, with a large majority of the corrosion migrating in through the side scribes. There were, however, a few exceptions. One exception is the PR-1775, which had moisture leak through the butt joint sides. The other exception was the RW-6040, which had moisture migrate into the faying surfaces from the edges of the bottom plate. The AC-735, CS 5500N CI, and one of the two PS-870 test vehicles had no corrosion on the faying surfaces. The other PS-870, both PR-1440, and the PR-1775 had less than 1% total area of corrosion.

Corrosion within the butt joint was caused by cracks formed along the butt joint by the cyclic loading as described in MPLR-101562 Section 7.1. During this process, the topcoat and primer cracked in several locations along the butt joint top and sides, creating a path for moisture to migrate into the faying surfaces of the test vehicle.

All of the sealants performed comparably with the exception of the PR-1775 and the RW-6040 sealants. While there were cracks within the butt joint for all of the test vehicles, there is no way of knowing how the cracks propagated beneath the surface. Upon completing the destructive analysis, it was revealed that the cracks formed within these two test vehicles formed in such a way that they caused more corrosion by growing along the sealant/substrate interface.

When overcoated but not scribed, the countersink hole areas were one of the least corroded area of interest on the entire test vehicle. All but one of the PS-870 test vehicles had 1% or less corrosion across all three overcoated fasteners. The PS-870 test vehicle that had the most corrosion only had 2% of its total overcoated countersink area corroded.

The fastener heads and nuts that were overcoated and scribed also performed very well. The PS-870, CS 5500N CI, and one of the PR-1440 had only minimal corrosion in the countersink areas. The AC-735 and PR-2870 also performed well, corroding on less than 1% of the total overcoated and scribed countersink area. The test vehicles with PR-1775 and the other PR-1440 corroded on 1.7% of the total countersink area.

Fastener heads and nuts that were not overcoated had the most corrosion in and around the countersink areas. When no overcoat is present, moisture can attack the countersink much quicker, resulting in much more corroded countersinks. Only one of the PS-870, one of the PR-1440, and the CS 5500N CI corroded on less than 5% of the countersink areas. The remaining PS-870 and PR-1440 test vehicles had 8.5% corrosion in the countersink areas. The AC-735, PR-1775, and RW-6040 sealants performed the worst, with corrosion in 14% of the countersink areas. It is also worth noting that all the external corrosion and corrosion within the ring area around the fastener holes were all around fasteners that had not been overcoated.

From the Phase II beachfront exposure, the AC-735 and CS 5500N CI sealants performed the best of the nonchromated sealants, corroding on 0.5% of the total test vehicle areas of interest. The next best performer was the PR-1775, which corroded on 2% of the total test vehicle areas of interest. RW-6040 performed the worst of the nonchromated sealants, with corrosion on 3% of the total areas