National Aeronautics and Space Administration (NASA)

Gas Dynamic Spray Technology Demonstration

AFSPC Corrosion Prevention Advisory Board Meeting
June 2011

NASA Technology Evaluation for Environmental Risk Mitigation Principal Center (TEERM)

Pattie Lewis Burford, ITB
Kennedy Space Center

http://www.nasa.gov

National Aeronautics and Space Administration (NASA)

Project Goals

Validate Gas Dynamic Spray as a means of repairing Thermal Spray Coatings

- Zinc primer systems are currently used across NASA and AFSPC for corrosion protection of steel.
- AFSPC and NASA have approved the use of Thermal Spray Coatings (TSCs) as an environmentally preferable alternative.
- TSCs are approved in NASA-STD-5008 and AFSPC and KSC is currently looking for additional applications in which TSC can be used.
- Gas Dynamic Spray (GDS, also known as Cold Spray) is being evaluated as a means of repairing TSCs and for areas such as corners and edges where TSCs do not work as well.
- Other applications could include spot repair/maintenance of steel on structures, facilities, and ground support equipment.

2

National Aeronautics and Space Administration (NASA)

Description

Stakeholders:

- Kennedy Space Center (KSC), Cape Canaveral Air Force Station (CCAFS), Patrick Air Force Base (PAFB), and Air Force Space Command (AFSPC)

Project Set-up:

- 18-Month Marine Exposure at KSC Beach Corrosion Test Site

★ Also tested at CCAFS SLC 17A as part of Launch Coatings Ph 2 Project

National Aeronautics and Space Administration (NASA)

Project Justification

- Eliminates risk associated with environmental, safety, and health concerns associated with volatile organic compounds (VOCs), hazardous air pollutants (HAPs), isocyanates, and other hazardous materials.
- Reduced material obsolescence risks.
- Low temperature spray reduces oxidation, vaporization, and residual stresses associated with traditional thermal spray or welding processes.
- Sprayed material is machinable and corrosion-resistant.
- Finished materials have high densities and high electrical and thermal conductivities.
- Material can build up to as much as one inch.
- Findings applicable to both NASA and AFSPC

4

National Aeronautics and Space Administration (NASA)

Technical Analysis

- **Current (baseline) Coating Process**
  - ***Identified in NASA-STD-5008***
    - Inorganic zinc primer
    - Intermediate coating
    - Isocyanate-containing polyurethane topcoat
  - ***Strengths***
    - Excellent corrosion protection
    - Excellent gloss and color retention
  - ***Weaknesses***
    - Contains isocyanates, high VOC content, HAPs, and other hazardous materials
    - Material obsolescence risks

5

National Aeronautics and Space Administration (NASA)

Technical Analysis

- **Alternative Coating Systems**
  - ***TSCs***
    - **Strengths**
      - Zero VOCs
      - Zero HAPs
      - Zero isocyanates
      - Excellent corrosion and heat resistance
      - Can last up to 20 years
    - **Weaknesses**
      - Bulky, hard to maneuver equipment
      - Ineffective in corners and on edges
      - Expensive equipment and coating materials

6

National Aeronautics and Space Administration (NASA)

Technical Analysis

- **Alternative Coating Systems**
  - ***GDS Coatings***
    - **Strengths**
      - Zero VOCs, HAPs, and isocyanates
      - Able to be used on edges and in corners
      - Equipment smaller and more portable than TSC equipment
      - Equipment can also perform surface preparation
    - **Weaknesses**
      - Costs of equipment and materials
      - Speed of coating application

7

National Aeronautics and Space Administration (NASA)

Approach

Substrates and Coatings of Interest

- ***Substrates:***
  - A36 Carbon Steel
  - 6061-T6 Aluminum alloy
  - 5052-H32 Aluminum alloy
- ***Base/Repair Coatings:***
  - Zinc (Zn) TSC
  - Aluminum-Magnesium (Al-Mg) TSC
  - Zn GDS coating
  - Zinc-Aluminum (Zn-Al) GDS coating
  - Aluminum (Al) GDS coating
- ***Liquid Topcoat***
  - Carboline Carbothane 133MC

8

National Aeronautics and Space Administration (NASA)

Approach

The following test panels were decided upon:

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

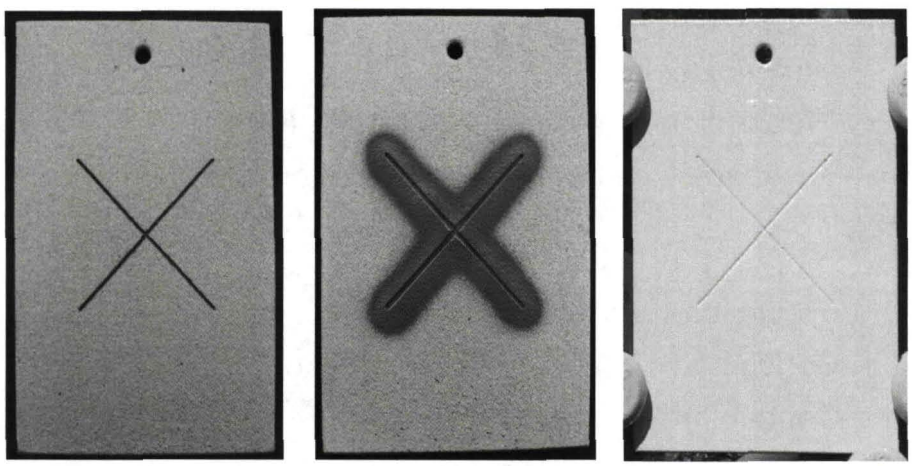
Flat Undamaged | Flat Damaged | Composite (Steel only)

9

National Aeronautics and Space Administration (NASA)

Approach

- Scribed Panels



Scribed | Scribed-GDS Repaired | Scribed-Topcoated

10

National Aeronautics and Space Administration (NASA)

Approach

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

11

National Aeronautics and Space Administration (NASA)

Progress

- Equipment purchased and delivered.
- Final Joint Test Plan completed and approved by stakeholders.
- Preparation for testing completed (Jul 09).
- Test panels places at KSC Corrosion Test Site (Aug 09).
- Conducted Heat Adhesion Testing and 6-month evaluation (Feb 10).
- Conducted 12-month evaluation (Aug 10).
- Conducted 18-month evaluation (Feb 11).
- Draft test report distributed to stakeholders (Jun 11)12

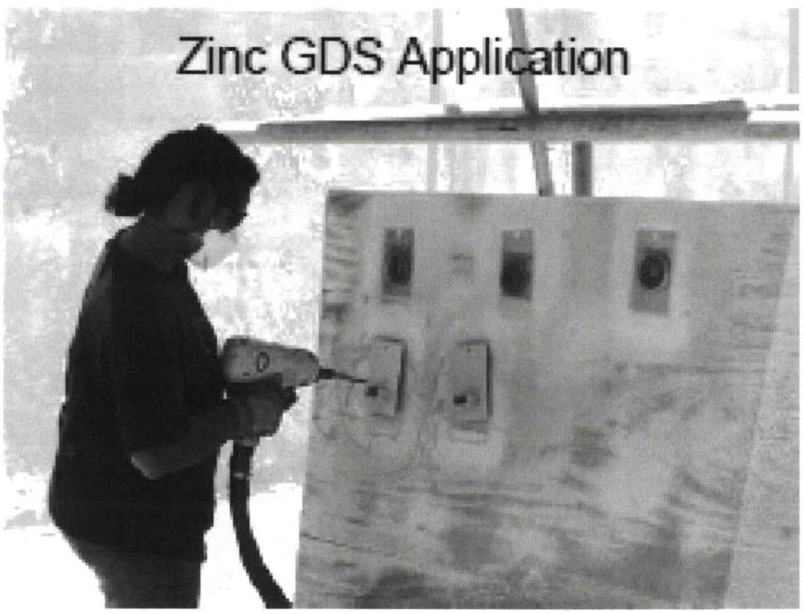
National Aeronautics and Space Administration (NASA)

Zinc TSC Application

13

National Aeronautics and Space Administration (NASA)

Zinc GDS Application



14

National Aeronautics and Space Administration (NASA)

DFT Measurements for Flat Panels

Panel	Coating	Primer DFT	Topcoat DFT	Avg 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

15

National Aeronautics and Space Administration (NASA)

DFT Measurements for Composite Panels

Panel	Coating	Primer DFT	Topcoat DFT	Avg 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

16

National Aeronautics and Space Administration (NASA)

Test Rack 1 Layout

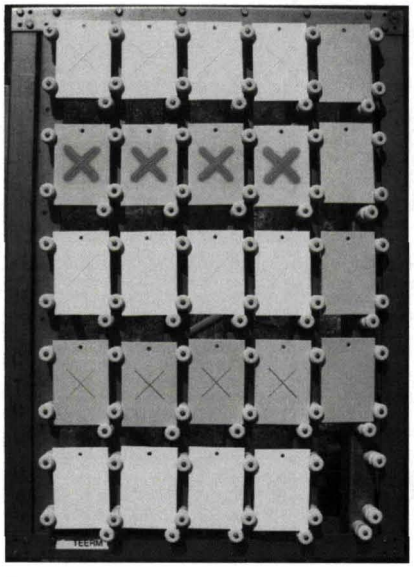
Zn TSC + GDS +133MC	Zn TSC + GDS +133MC	Zn TSC + GDS +133MC	Zn TSC + GDS +133MC	Zn TSC
Zn TSC + GDS	Zn TSC + GDS	Zn TSC + GDS	Zn TSC + GDS	Zn TSC
Zn TSC +133MC	Zn TSC +133MC	Zn TSC +133MC	Zn TSC +133MC	Zn TSC
Zn TSC	Zn TSC	Zn TSC	Zn TSC	Zn TSC
Zn TSC +133MC	Zn TSC +133MC	Zn TSC +133MC	Zn TSC +133MC	Empty

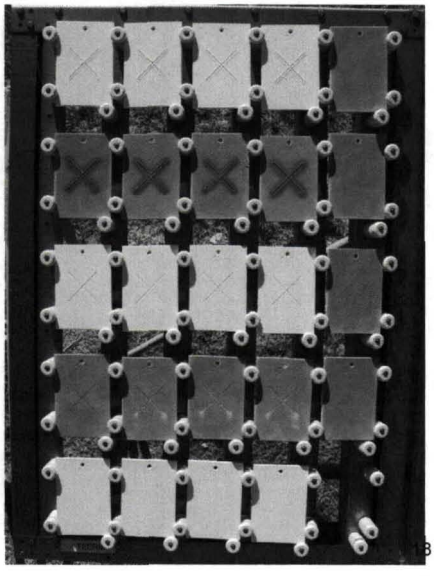
17

National Aeronautics and Space Administration (NASA)

Test Rack 1 Photos

Initial (Aug 09)





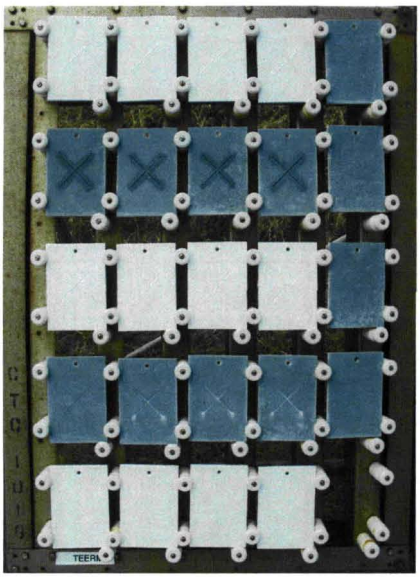
Six-Months (Feb 10)

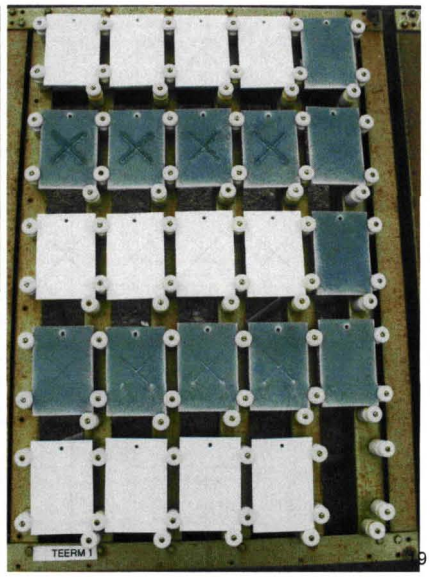
18

National Aeronautics and Space Administration (NASA)

Test Rack 1 Photos

12-Months (Aug 10)





18-Months (Feb 11)

19

National Aeronautics and Space Administration (NASA)

Test Rack 2 Layout

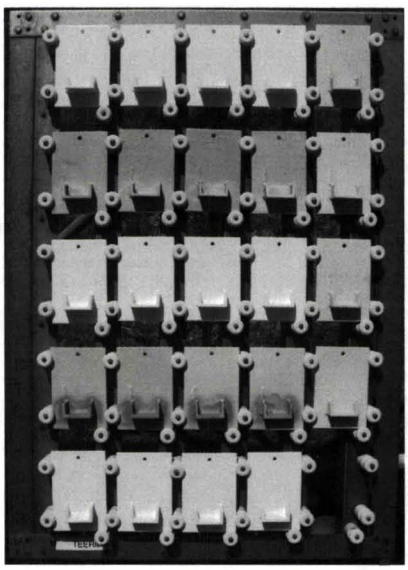
Zn GDS +133MC	Zn GDS +133MC	Zn GDS +133MC	Zn GDS +133MC	Zn TSC
Zn GDS	Zn GDS	Zn GDS	Zn GDS	Zn TSC
Zn TSC + GDS +133MC	Zn TSC + GDS +133MC	Zn TSC + GDS +133MC	Zn TSC + GDS +133MC	Zn TSC
Zn TSC + GDS	Zn TSC + GDS	Zn TSC + GDS	Zn TSC + GDS	Zn TSC
Zn TSC +133MC	Zn TSC +133MC	Zn TSC +133MC	Zn TSC +133MC	Empty

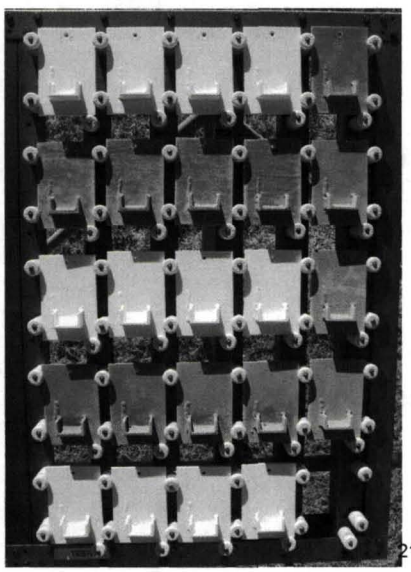
20

National Aeronautics and Space Administration (NASA)

Test Rack 2 Photos

Initial (Aug 09)





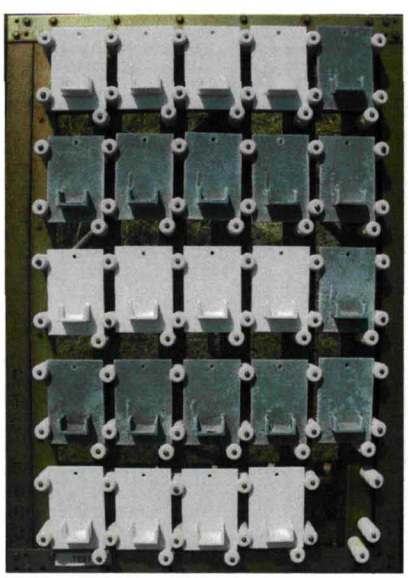
Six-Months (Feb 10)

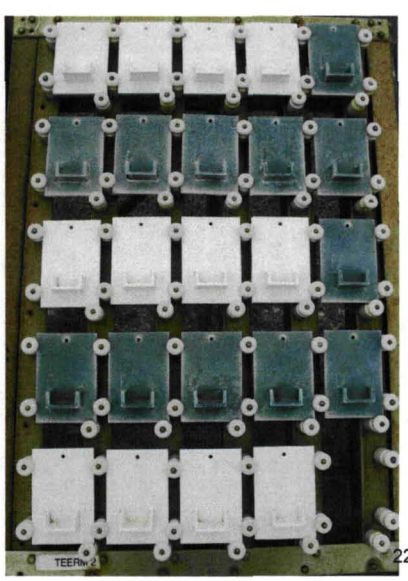
21

National Aeronautics and Space Administration (NASA)

Test Rack 2 Photos

12-Months (Aug 10)





18-Months (Feb 11)

22

National Aeronautics and Space Administration (NASA)

Degree of Rusting

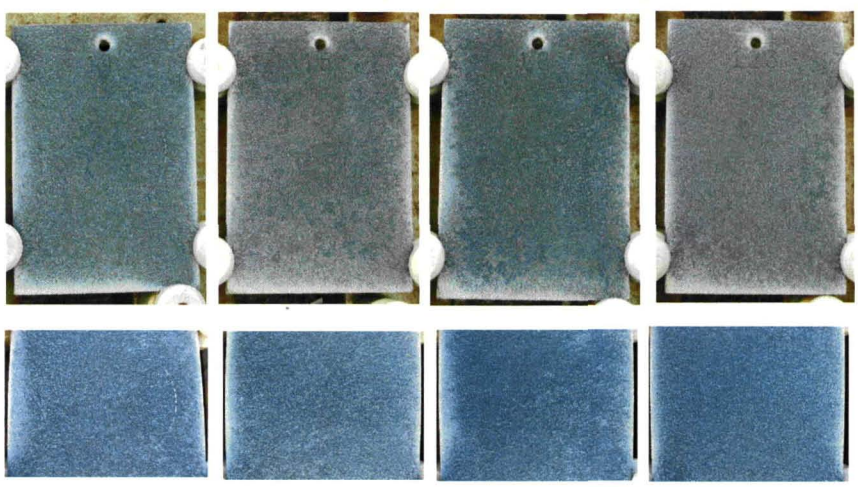
Rust Ratings after 18 Months per ASTM D 610

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

23

National Aeronautics and Space Administration (NASA)

Zn TSC

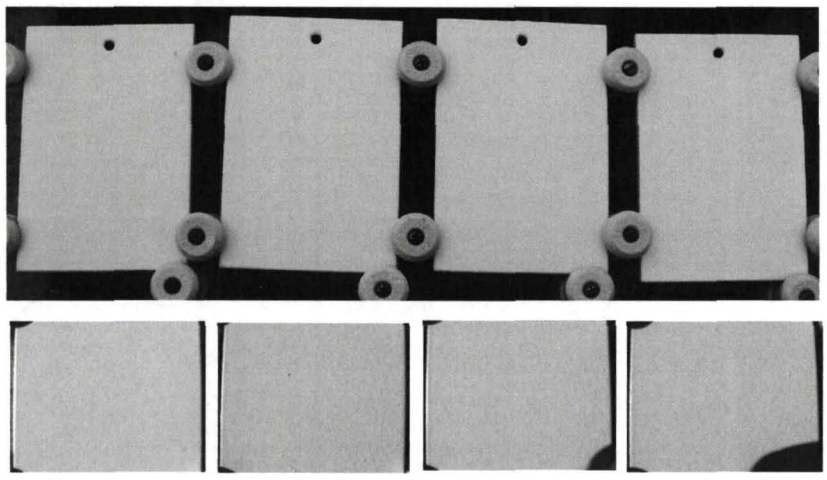


10 10 10 10

24

National Aeronautics and Space Administration (NASA)

Zn TSC + 133MC

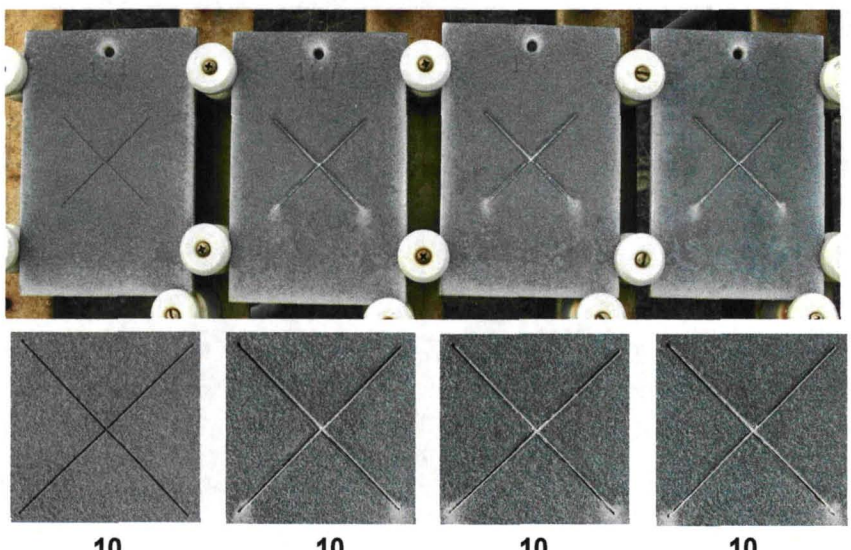


10 10 10 10

25

National Aeronautics and Space Administration (NASA)

Zn TSC

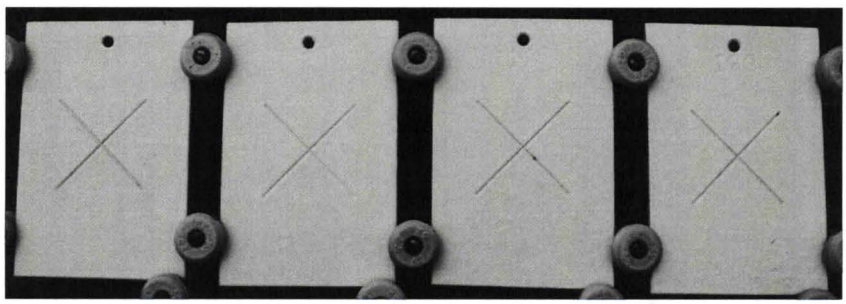


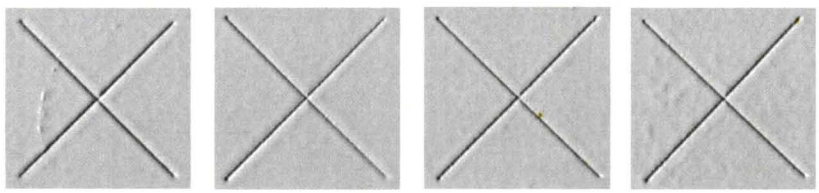
10 10 10 10

26

National Aeronautics and Space Administration (NASA)

Zn TSC



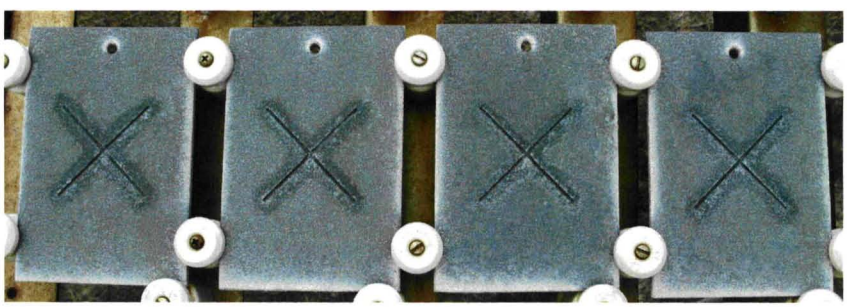


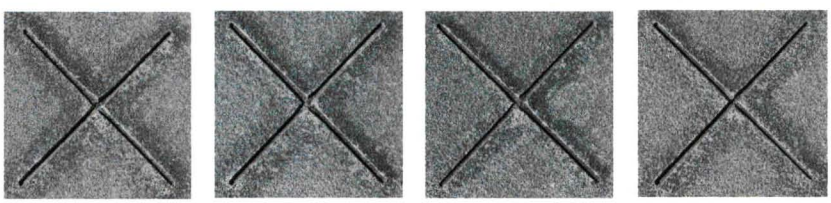
10 10 10 10

27

National Aeronautics and Space Administration (NASA)

Zn TSC + Zn GDS



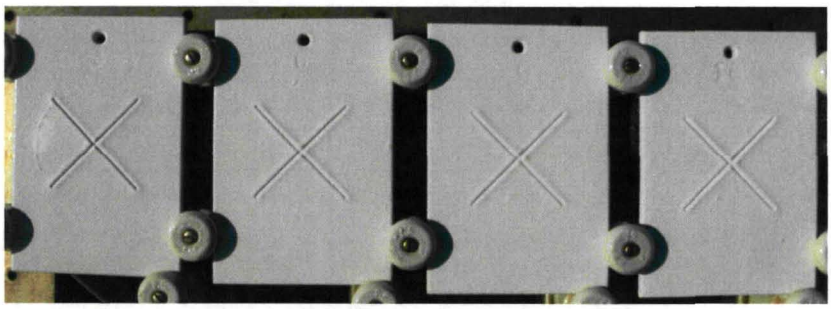


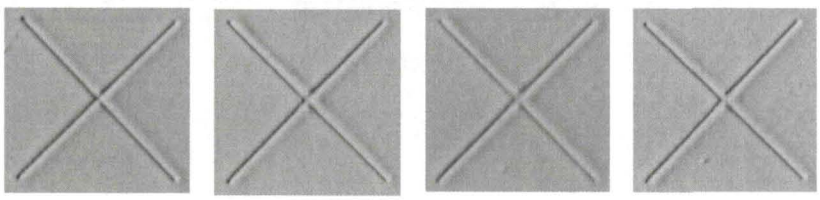
10 10 10 10

28

National Aeronautics and Space Administration (NASA)

Zn TSC + Zn GDS + 133MC



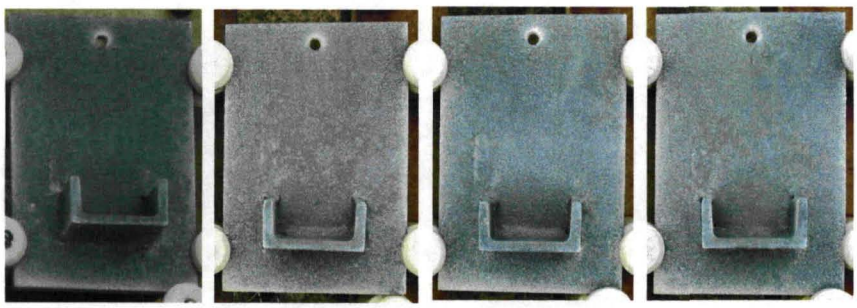


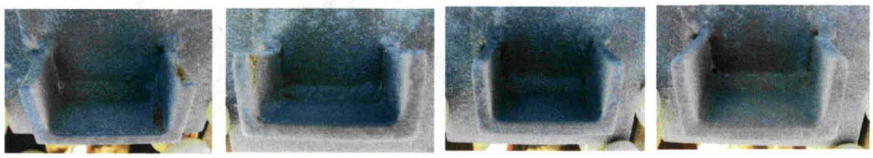
10 10 10 10

29

National Aeronautics and Space Administration (NASA)

Zn TSC



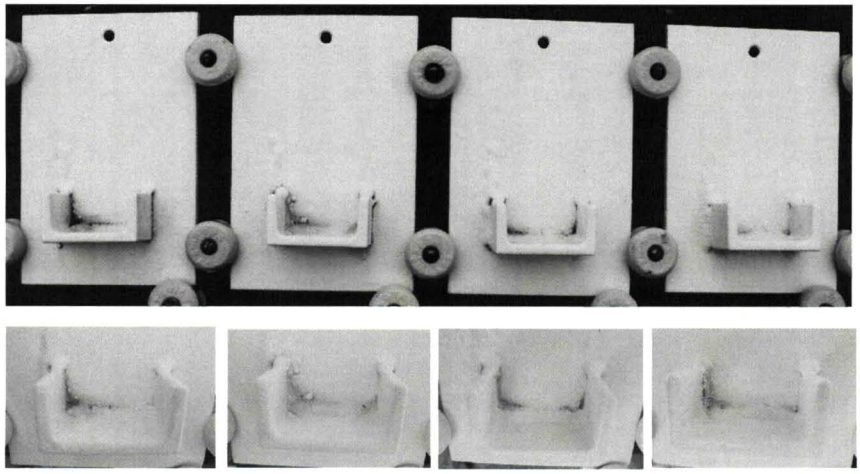


9 9 10 10

30

National Aeronautics and Space Administration (NASA)

Zn TSC + 133MC

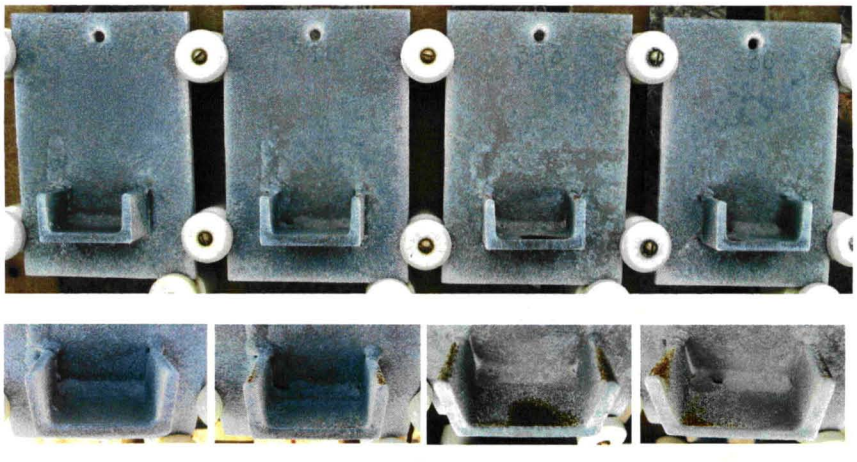


10 10 10 10

31

National Aeronautics and Space Administration (NASA)

Zn TSC + Zn GDS

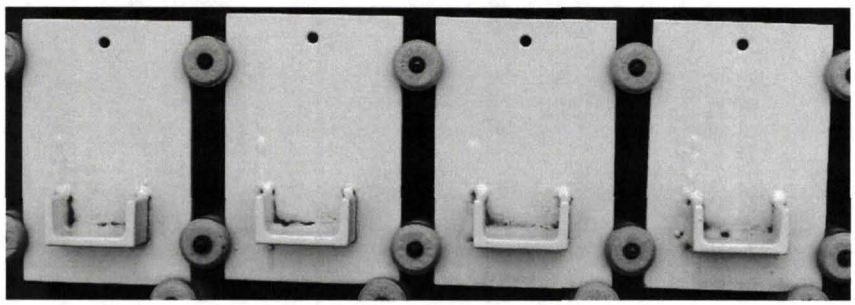


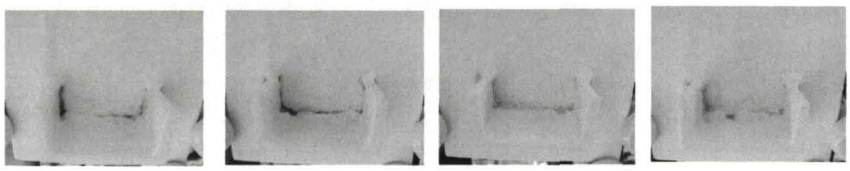
10 9 8 9

32

National Aeronautics and Space Administration (NASA)

Zn TSC + Zn GDS + 133MC



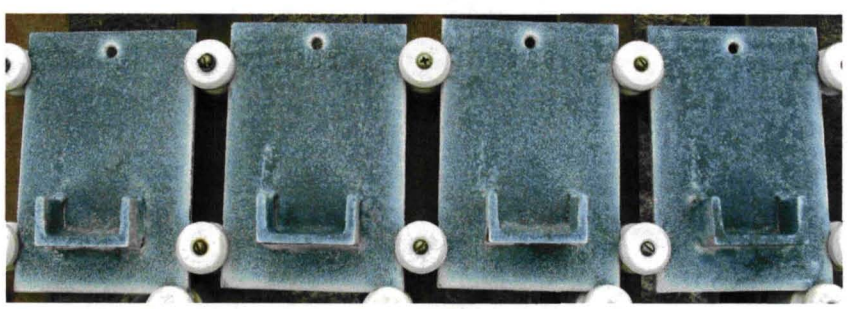


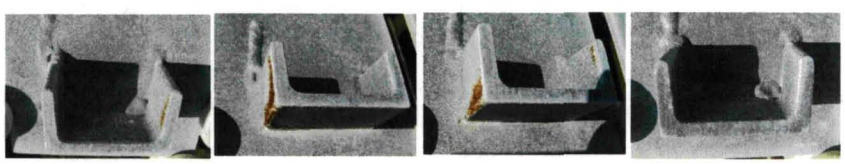
10 10 10 10

33

National Aeronautics and Space Administration (NASA)

Zn GDS



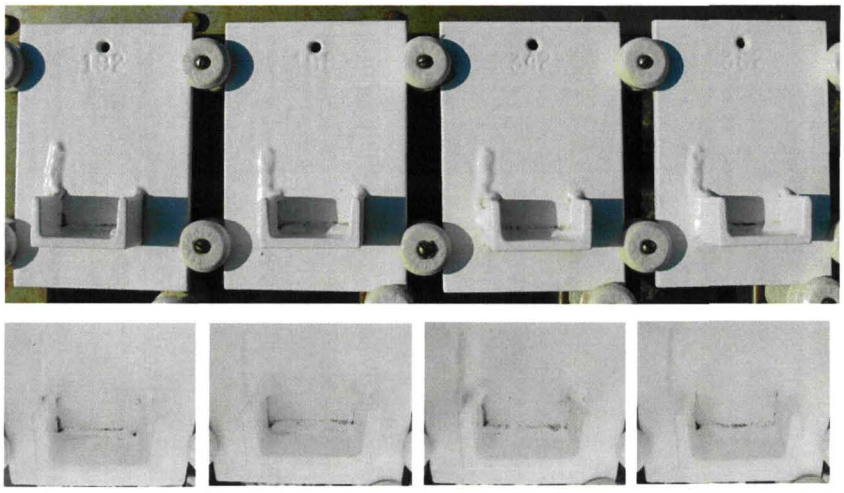


9 8 9 9

34

National Aeronautics and Space Administration (NASA)

Zn GDS + 133MC



10 10 10 10

35

National Aeronautics and Space Administration (NASA)

Scribe Ratings

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

Blister Ratings

- Blister ratings per ASTM D 714.
- After 18 months, no panels exhibited blistering and all rated a 10-None.

36

National Aeronautics and Space Administration (NASA)

Gloss Measurements

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

37

National Aeronautics and Space Administration (NASA)

Color Measurements

Color Retention Results per ASTM D 2244

			Initial			*18-Month*			
Panels	*Primer*	*Panel Type*	*L*	*a*	*b*	*L*	*a*	*b*	*Delta E*
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	Comp	94.74	-0.71	2.81	95.61	-1.29	5.52	2.9
264, 275, 341, 40	Zn TSC	Comp	94.64	-0.7	2.8	95.58	-1.84	6.85	4.3

As a general rule, a delta E value of one (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 two (2) or three (3) can still be considered the same color.

38

National Aeronautics and Space Administration (NASA)

Adhesion Testing

- NASA-STD-5008 requires zinc primer coatings have a temperature resistance of 400°C (750°F).
- Tested by exposing panels in an oven to a temperature of 400°C for 24 hours.
- Any visual deterioration, such as destruction or burning of the coating, would establish failure of the product.
- Loss of adhesion (per ASTM D 4541) also constitutes a failure due to temperature effects on the film.
- Comparisons are made pre- and post-heat exposure.
- Since TSC are considered replacements for zinc primers, they were tested to this requirement.
- GDS was also tested.

39

National Aeronautics and Space Administration (NASA)

Adhesion Testing Results

- As applied, the Zn GDS adhesion values (2625 psi) initially averaged over three (3) times the adhesive strength of the Zn TSC (780 psi).
  - Both the Zn GDS and Zn TSC meet the minimum adhesion criteria of 500 psi found in SSPC-CS 23.00.
- The post-heat Zn TSC showed a 42% increase in tensile adhesion after heating.
- The Zn GDS, however, lost 88% of its adhesive strength and failed to meet the minimum adhesion values stated in SSPC-CS 23.00.

40

National Aeronautics and Space Administration (NASA)

Adhesion Testing Results Table

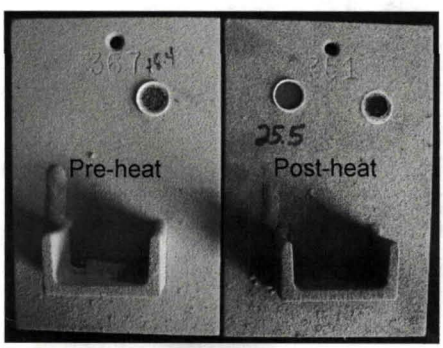
Coating	avg dft	pre-heat psi	avg pre-heat psi	Failure Mode	post-heat* psi	avg post-heat psi	Failure Mode
Zn TSC	10-12 mils	740	780	cohesive	1111	1111	cohesive
Zn TSC	10-12 mils	860		cohesive	1029		cohesive
Zn TSC	10-12 mils	781		cohesive	1358		cohesive
Zn TSC	10-12 mils	739		cohesive	946		cohesive
Zn GDS	8-10 mils	2512	2625	cohesive	492	310	zinc split
Zn GDS	8-10 mils	2018		cohesive	294		zinc split
Zn GDS	8-10 mils	3131		cohesive	336		zinc split
Zn GDS	8-10 mils	2840		cohesive	117		zinc split

* heated to 750F for 24 hours and cooled to room temperature before re-testing

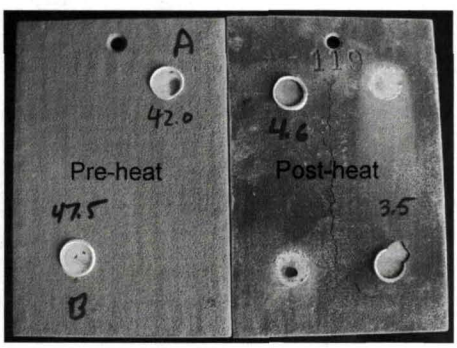
41

National Aeronautics and Space Administration (NASA)

Adhesion Testing Results



Zn TSC Panels



Zn GDS Panels

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.

42