HCAT/JCAT Program Review Meeting

San Diego, CA
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PERFORMANCE ASSESSMENT OF TWO DIFFERENT AVIATION CARC COATING SYSTEMS ON STEEL WHEN CADMIUM PLATING IS ELIMINATED

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Report Documentation Page

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Outline

- Introduction
- Experimental Procedure
- Results
- Conclusions

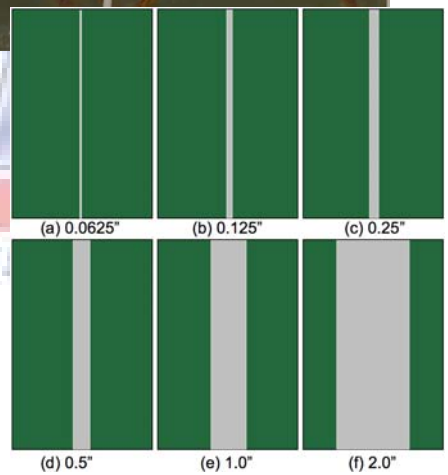
Introduction/Background

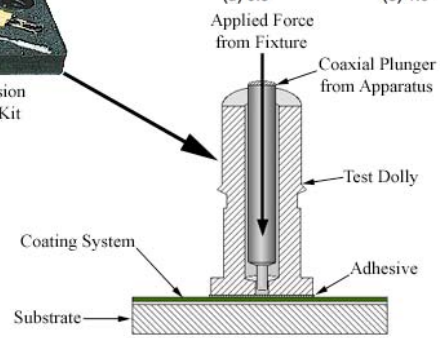
- AMCOM G4 (Logistics), Environmental Division funded project to AMRDEC Aviation Engineering and subtasked to ARL WMRD.

- New Cr^{+6} free primers introduced
  - *Hentzen*
  - *Deft*
- Qualify under MIL-PRF-23377
- Hentzen formulation used for this study
- Can electroplated Cd or Cr^{+6} primers be reduced?

Experimental Procedure

- General Corrosion
- Crevice Corrosion
- Throwing Power
- Coating Adhesion
- Hydrogen Embrittlement

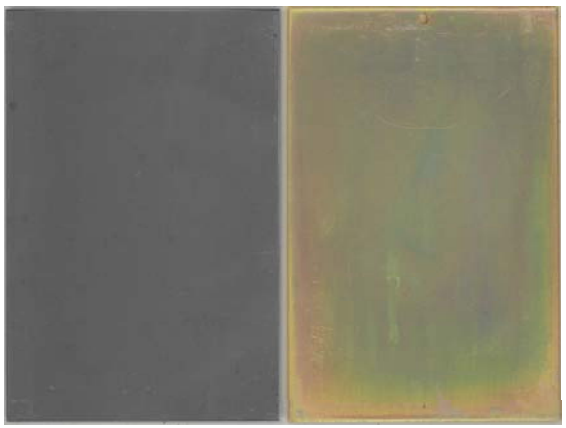




Coating Configurations

Designation	Plating	Primer	Topcoat
1	Cadmium	MIL-PRF-23377, Class C	MIL-DTL-64159
2	None	MIL-PRF-23377, Class C	MIL-DTL-64159
3	Cadmium	MIL-PRF-23377, Class N	MIL-DTL-64159
4	None	MIL-PRF-23377, Class N	MIL-DTL-64159

- Same for all testing methods except throwing power
- Cd plating in accordance with SAE AMS QQ-P-416, Type II, Class II
- 1 week cure @25C followed by 1 additional week @65C
- Throwing power also evaluated with primers only
- All exposed under GM 9540P



General Corrosion

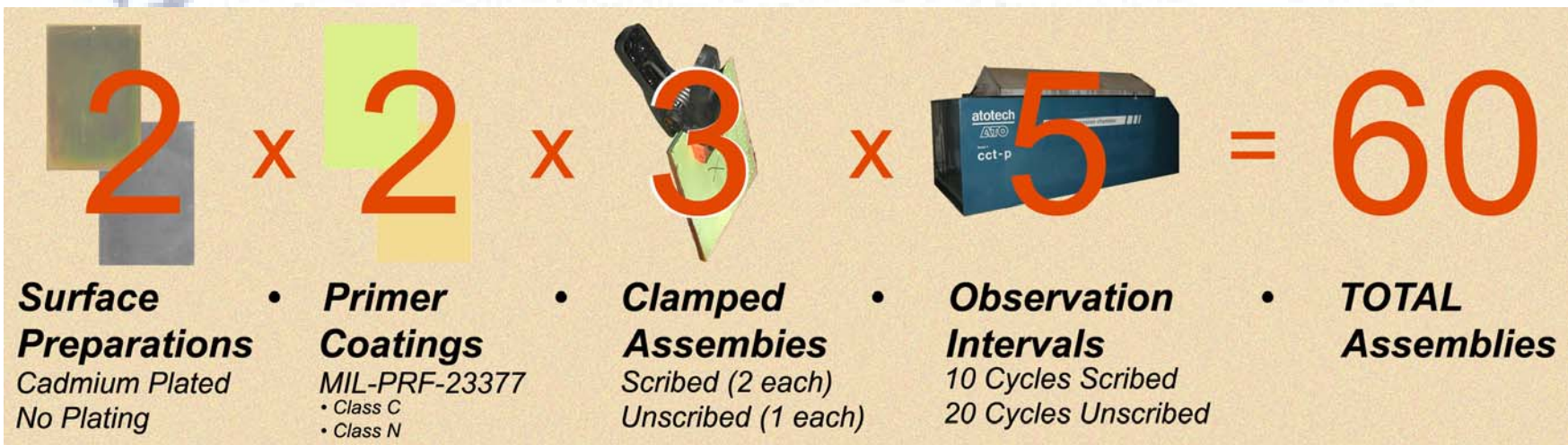
- 4” X 6” AISI 4130 Steel Panels
  - Scribed (2 replicates for each coating system)
  - Unscribed (1 panel for each coating system)
- GM 9540P
  - 80 cycles for scribed and unscribed conditions

Designation	Plating	Surface Profile	Primer	Topcoat
1G	Cadmium	Mill Finish	MIL-PRF-23377, Class C	MIL-DTL-64159
2G	None	Mill Finish	MIL-PRF-23377, Class C	MIL-DTL-64159
3G	Cadmium	Mill Finish	MIL-PRF-23377, Class N	MIL-DTL-64159
4G	None	Mill Finish	MIL-PRF-23377, Class N	MIL-DTL-64159

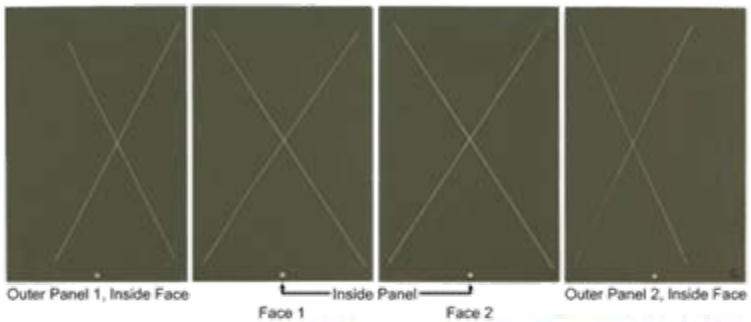
Crevice Corrosion

Panel #	Condition	Replicates per Removal Interval	GM 9540P Cycles per Removal Interval	Surface	Plating	Primer	Topcoat
1C	Scribed	2	10	Mill Finish	Cadmium	MIL-PRF-23377, Class C	MIL-DTL-64159
1C	Unscribed	1	20	Mill Finish	Cadmium	MIL-PRF-23377, Class C	MIL-DTL-64159
2C	Scribed	2	10	Mill Finish	None	MIL-PRF-23377, Class C	MIL-DTL-64159
2C	Unscribed	1	20	Mill Finish	None	MIL-PRF-23377, Class C	MIL-DTL-64159
3C	Scribed	2	10	Mill Finish	Cadmium	MIL-PRF-23377, Class N	MIL-DTL-64159
3C	Unscribed	1	20	Mill Finish	Cadmium	MIL-PRF-23377, Class N	MIL-DTL-64159
4C	Scribed	2	10	Mill Finish	None	MIL-PRF-23377, Class N	MIL-DTL-64159
4C	Unscribed	1	20	Mill Finish	None	MIL-PRF-23377, Class N	MIL-DTL-64159

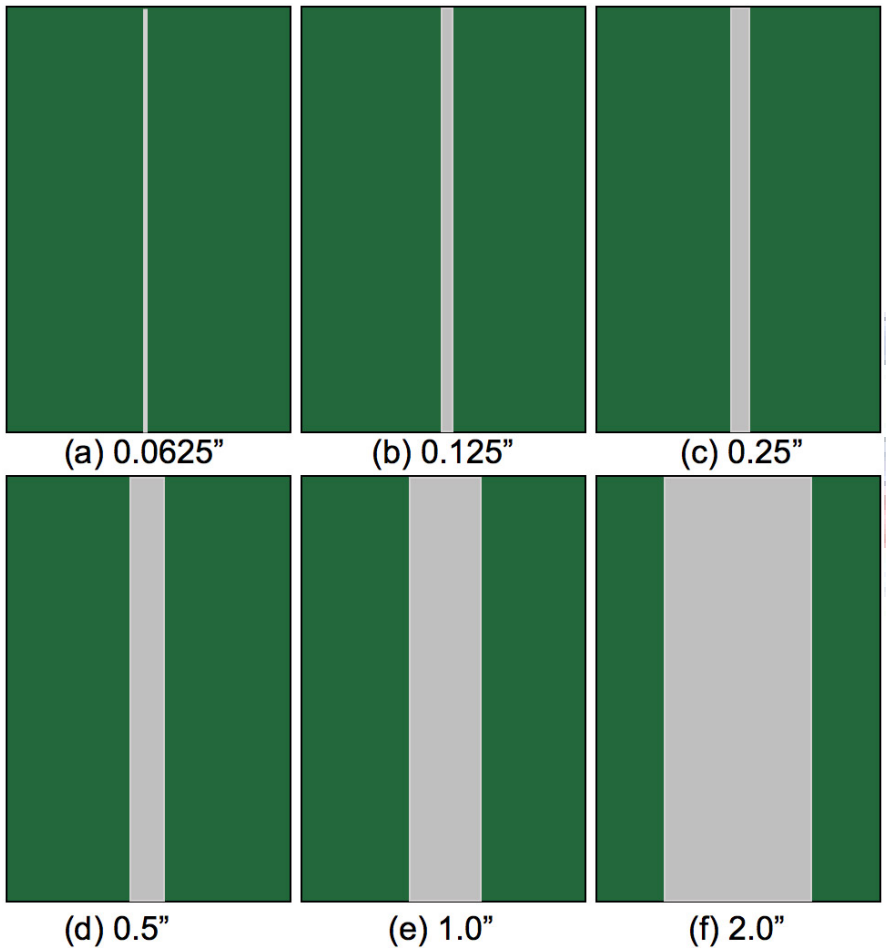
- Topcoated sides faced inwards
- Scribed panels “X” scribes were offset



Crevice Corrosion *(cont.)*



Throwing Power



- Coating Systems 1 - 4
- Minus topcoat (primer only)
- Masked with tape
- Sprayed at widths a - f
- Ran to failure in GM 9540P
- Failure = Appearance of Rust

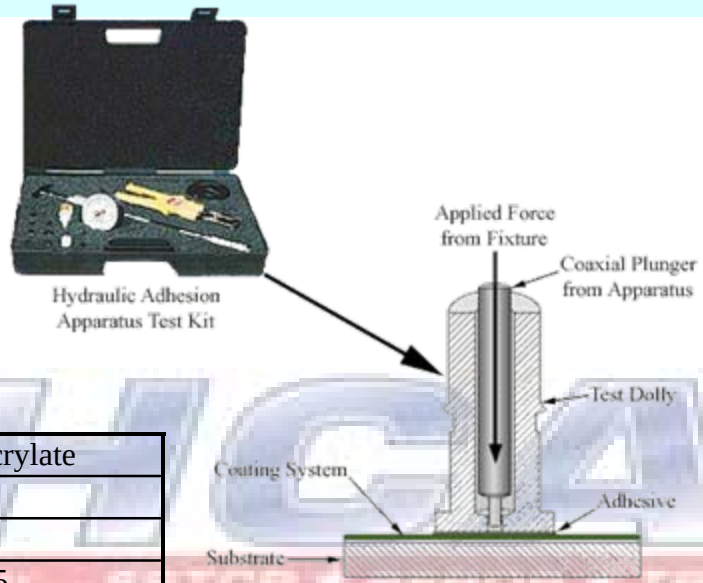
Coating Adhesion

- Varied after blast dwell times
- Panels blasted to SSPC-10
- Prior to coating, panels left in air or N_2 packaged for set dwell interval

Panel Designation	Plating System	Surface Profile	Post Blast Dwell Time (min)	Primer Coating	Topcoat Coating
1	Cadmium	Mill with Plating	N/A	MIL-PRF-23377C	MIL-DTL-64159
2A	None	Abrasive Blasted	15	MIL-PRF-23377C	MIL-DTL-64159
2AS	None	Abrasive Blasted	15	MIL-PRF-23377C	MIL-DTL-64159
2B	None	Abrasive Blasted	30	MIL-PRF-23377C	MIL-DTL-64159
2BS	None	Abrasive Blasted	30	MIL-PRF-23377C	MIL-DTL-64159
2C	None	Abrasive Blasted	60	MIL-PRF-23377C	MIL-DTL-64159
2CS	None	Abrasive Blasted	60	MIL-PRF-23377C	MIL-DTL-64159
2D	None	Abrasive Blasted	120	MIL-PRF-23377C	MIL-DTL-64159
2DS	None	Abrasive Blasted	120	MIL-PRF-23377C	MIL-DTL-64159
2E	None	Abrasive Blasted	240	MIL-PRF-23377C	MIL-DTL-64159
2ES	None	Abrasive Blasted	240	MIL-PRF-23377C	MIL-DTL-64159
2M	None	Mill Finish	N/A	MIL-PRF-23377C	MIL-DTL-64159
3	Cadmium	Mill with Plating	N/A	MIL-PRF-23377N	MIL-DTL-64159
4A	None	Abrasive Blasted	15	MIL-PRF-23377N	MIL-DTL-64159
4AS	None	Abrasive Blasted	15	MIL-PRF-23377N	MIL-DTL-64159
4B	None	Abrasive Blasted	30	MIL-PRF-23377N	MIL-DTL-64159
4BS	None	Abrasive Blasted	30	MIL-PRF-23377N	MIL-DTL-64159
4C	None	Abrasive Blasted	60	MIL-PRF-23377N	MIL-DTL-64159
4CS	None	Abrasive Blasted	60	MIL-PRF-23377N	MIL-DTL-64159
4D	None	Abrasive Blasted	120	MIL-PRF-23377N	MIL-DTL-64159
4DS	None	Abrasive Blasted	120	MIL-PRF-23377N	MIL-DTL-64159
4E	None	Abrasive Blasted	240	MIL-PRF-23377N	MIL-DTL-64159
4ES	None	Abrasive Blasted	240	MIL-PRF-23377N	MIL-DTL-64159
4M	None	Mill Finish	N/A	MIL-PRF-23377N	MIL-DTL-64159

Packaging Aids Corporation Series 88 Tabletop Vacuum Impulse Sealer with N_2 Backfill

Coating Adhesion *(cont.)*



Adhesive Type	Cyanoacrylate
Cure time (hours)	24
Temperature (C)	40
Percent Relative Humidity	~65
Substrate Material	AISI 4130 Steel
Substrate Thickness (in)	0.12
Substrate Surface	Cadmium Plated SSPC-10 Blasted Mill Finish
Pretreatment Types	Chromate Rinse (Cd)
Primer Types	MIL-PRF-23377, Class C MIL-PRF-23377, Class N
Topcoat	MIL-DTL-64149
Coating Thickness (mils)	4 (maximum)

Pull-off Lab Conditions *(ASTM-D-4541)*

Hydrogen Embrittlement

- Type 1d C-rings
- AISI 4340 @HRC 52
- Sensitivity performed in accordance with ASTM-F-519
- C-rings passed 75% load in air for unplated and dull Cd
- C-ring test load set at 40% UTS after sub 200 hour failures in air at:
  - 65%
  - 50%

  for SAE AMS QQ-P-416, Type II, Class II plated C-rings
- Coating Systems 1 - 4
  - Damaged coating over notch
  - Undamaged coating over notch
- Run to fracture under GM 9540P

Results

General Corrosion

Panel #	Initial Scribe	10 Cycles	20 Cycles	30 Cycles	40 Cycles	50 Cycles	60 Cycles	70 Cycles	80 Cycles
1G	8	8	8	8*	8	7	5	4	2
1G	8	8	8	8	6	6	6	6	6*
1G	8	8	8	8	8*	6	3	2	0
1G	8	8	8	8	8*	5	3	3	0
1G	8	8	8	8	8	8*	8	4	3
2G	8	6*	5	4	3	2	1	0	
2G	9	6*	4	2	1	1	0		
2G	8	7*	5	4	2	0			
2G	8	7*	5	4	3	0			
2G	7	6*	5	3	2	0			
3G	9	8	8	8*	7	4	3	0	
3G	8	8	8	8	8	8	8*	8	8
3G	9	8*	6	4	3	3	1	0	
3G	9	9	9*	9	9	9	5	2	2
3G	8	8	8	8*	8	5	4	3	0
4G	9	6*	5	3	3	1	1	0	
4G	9	6*	4	2	1	0			
4G	9	6*	3	2	0				
4G	9	7*	4	3	2	1	1	0	
4G	8	6*	5	4	3	1	0		

Rating of Failure at Scribe (Procedure A)		
Representative Mean Creepage From Scribe (Millimeters)	(Inches)	Rating Number
Over 0	0	10
Over 0 to 0.5	0 to 1/64	9
Over 0.5 to 1.0	1/64 to 1/32	8
Over 1.0 to 2.0	1/32 to 1/16	7
Over 2.0 to 3.0	1/16 to 1/8	6
Over 3.0 to 5.0	1/8 to 3/16	5
Over 5.0 to 7.0	3/16 to 1/4	4
Over 7.0 to 1 0.0	1/4 to 3/8	3
Over 10.0 to 13.0	3/8 to 1/2	2
Over 13.0 to 16.0	1/2 to 5/8	1
Over 16.0 to more	5/8 to more	0

*Denotes first observed red rust

- Corrosion damage on scribed panels only
- Unscribed panels were undamaged - even after 80 cycles
- Major variations depending on coating system for scribed panels
- Coating system 1 had superior performance
- Coating system 3 performed excellent
- Comparable Performance for systems 2 and 4 but much worse than systems 1 and 3
- Cadmium plating was obviously the key

Results

General Corrosion

Coating System 1 @80 cycles

Coating System 2 @50 cycles

Coating System 3 @80 cycles

Coating System 4 @50 cycles

Coating System 1 @80 cycles

Coating System 2 @80 cycles

Coating System 3 @80 cycles

Coating System 4 @80 cycles

Results

Crevice Corrosion - Scribed

Panel #	10 Cycles				20 Cycles				30 Cycles				40 Cycles				50 Cycles			
	Outer 1	Center 1	Center 2	Outer 2	Outer 1	Center 1	Center 2	Outer 2	Outer 1	Center 1	Center 2	Outer 2	Outer 1	Center 1	Center 2	Outer 2	Outer 1	Center 1	Center 2	Outer 2
1C	8	8	8	8	**8***	**8***	8	8	8	8	9*	8*	8*	8*	8*	**8***	7	9	8	8
1C	8	8	8	8	8	9	8*	8	8	8*	8*	8	8*	8*	8*	**8***	8*	8*	8*	8*
2C	5*	5*	5*	6*	4*	**5***	4*	4*	4*	2*	4*	5*	3*	1*	3*	4*	3*	**2***	2*	3*
2C	7*	6*	5*	6*	4*	**4***	4*	5*	4*	4*	3*	3*	3*	**3***	4*	4*	3*	2*	3*	4*
3C	9*	8	9*	9	**9***	**8***	9*	9*	6*	9*	9*	9*	**9***	9*	9*	8*	9*	9*	9*	7*
3C	8*	8*	8*	7*	9*	9*	**9***	**9***	9*	9	9*	**8***	7*	9*	9*	9*	7*	6*	8*	9
4C	5*	6*	5*	4*	3*	3*	5*	3*	3*	3*	3*	3*	3*	**2***	**3***	3*	5*	2*	4*	2*
4C	4*	5*	6*	5*	4*	**4***	4*	5*	3*	3*	4*	5*	**3***	**3***	3*	2*	1*	2*	3*	1*

Rating of Failure at Scribe (Procedure A)		
Representative Mean Creepage From Scribe		Rating
(Millimeters)	(Inches)	Number
Over 0	0	10
Over 0 to 0.5	0 to 1/64	9
Over 0.5 to 1.0	1/64 to 1/32	8
Over 1.0 to 2.0	1/32 to 1/16	7
Over 2.0 to 3.0	1/16 to 1/8	6
Over 3.0 to 5.0	1/8 to 3/16	5
Over 5.0 to 7.0	3/16 to 1/4	4
Over 7.0 to 1 0.0	1/4 to 3/8	3
Over 10.0 to 13.0	3/8 to 1/2	2
Over 13.0 to 16.0	1/2 to 5/8	1
Over 16.0 to more	5/8 to more	0

- Coatings systems 1 and 3 performed best
- Comparable Performance for systems 2 and 4 but much worse than systems 1 and 3

*Denotes red rust
Cross-hatched for blisters away from scribe area

Results

Crevice Corrosion - Scribed

Coating System 1 @10 cycles

Coating System 2 @10 cycles

Coating System 1 @50 cycles

Coating System 3 @10 cycles

Coating System 4 @10 cycles

Coating System 3 @50 cycles

- Coatings systems 1 and 3 better @50 cycles than coating systems 2 and 4 @10 cycles
- Cd plating again superior
- Chromated primer gives slight performance edge

Results

Crevice Corrosion - Unscribed

Panel #	20 Cycles				40 Cycles				60 Cycles				80 Cycles				100 Cycles			
	Outer 1	Center 1	Center 2	Outer 2	Outer 1	Center 1	Center 2	Outer 2	Outer 1	Center 1	Center 2	Outer 2	Outer 1	Center 1	Center 2	Outer 2	Outer 1	Center 1	Center 2	Outer 2
1C	10	10	10	9*	10	10	10	10	10	10	10	5	10	8	9	9	9	10	7	4
2C	3*	9*	9*	1	2*	4*	1*	1*	1	10	10	2	0*	4	5	2	2	6	7	1
3C	10	10	10	10	10	10	10	10	9	10	10	10	7	10	10	9	10	10	10	10
4C	9*	10	8*	10	1*	10	10	9*	2*	9	3*	8	8	5	3	1	4	10	8	3

*Denotes red rust observed
ASTM-D-1654B (rating for blisters)

Coating System 1 @60 cycles

Coating System 2 @60 cycles

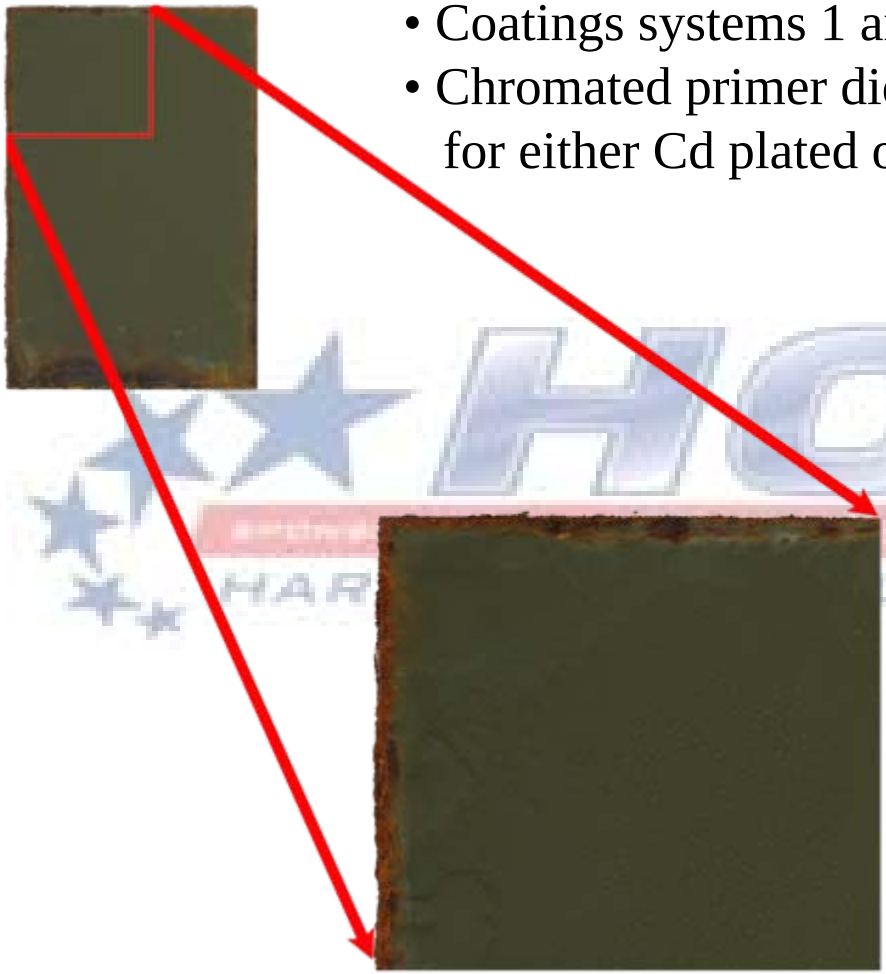
Coating System 3 @60 cycles

Coating System 4 @60 cycles

Results

Crevice Corrosion - Unscribed

- Coatings systems 1 and 3 performed best and were comparable
- Chromated primer did not seem to enhance corrosion resistance for either Cd plated or unplated conditions



40 Cycle GM 9540P Exposure Unscribed Crevice Corrosion
with Coating Blistering at 3X Mag. (relative) for Coating System 2.

Results

Throwing Power GM 9540P Cycles to Red Rust Failure

Primer Coat Only

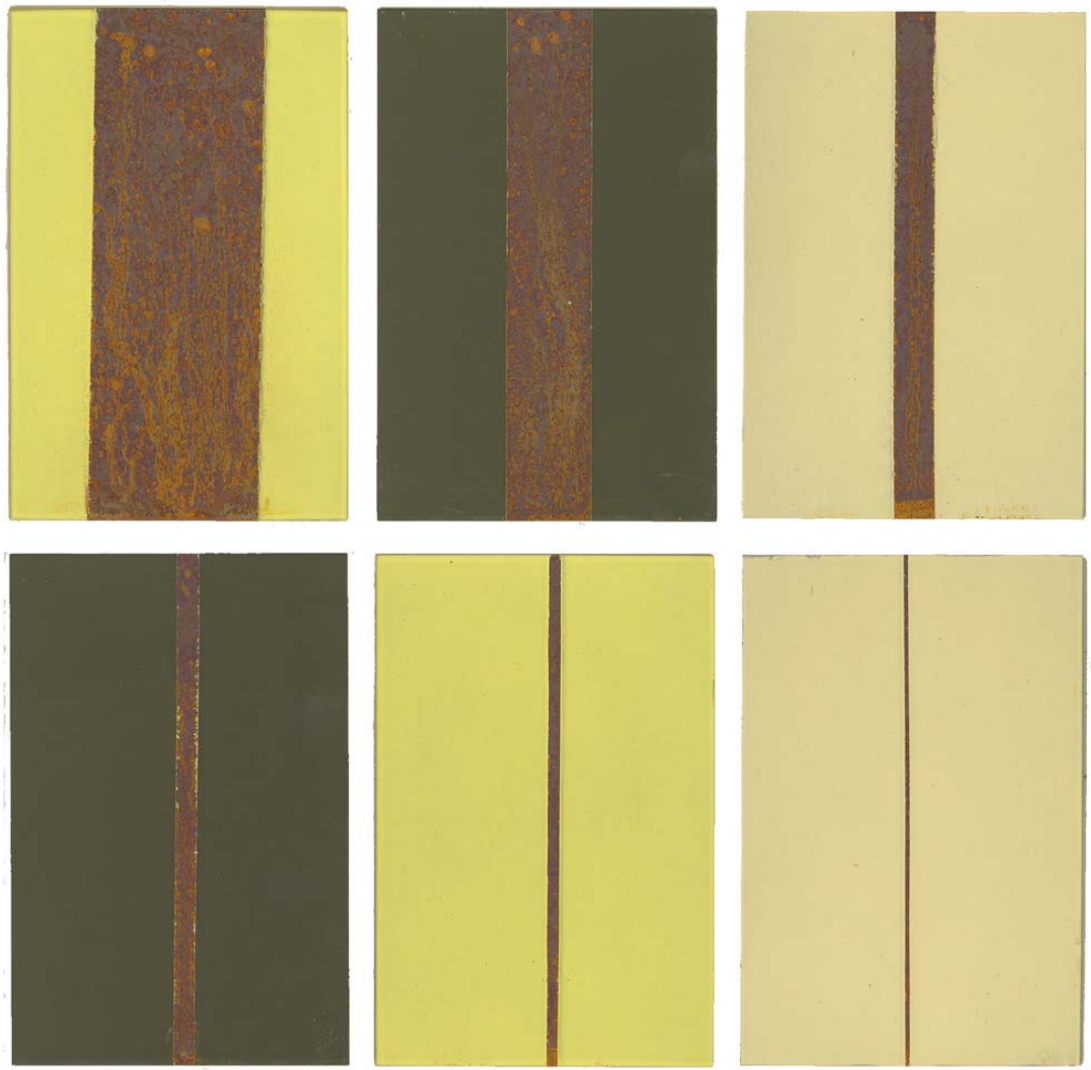
Masked Area Width (in)	Coating System 1 GM 9540P Cycles Without Topcoat					Coating System 2 GM 9540P Cycles Without Topcoat					Coating System 3 GM 9540P Cycles Without Topcoat					Coating System 4 GM 9540P Cycles Without Topcoat				
0.0625	29	32	91	120	120	1	1	1	1	1	18	48	48	63	91	1	1	1	1	1
0.125	37	120	120	120	120	1	1	1	1	1	120	120	120	120	120	1	1	1	1	1
0.25	21	32	103	120	120	1	1	1	1	1	8	24	67	120	120	1	1	1	1	1
0.5	29	44	53	59	120	1	1	1	1	1	23	32	44	61	74	1	1	1	1	1
1.0	8	8	44	59	120	1	1	1	1	1	8	8	8	14	79	1	1	1	1	1
2.0	33	71	120	120	120	1	1	1	1	1	8	8	23	44	59	1	1	1	1	1

Full Coating System

Masked Area Width (in)	Coating System 1 GM 9540P Cycles					Coating System 2 GM 9540P Cycles					Coating System 3 GM 9540P Cycles					Coating System 4 GM 9540P Cycles				
0.0625	37	101	120	120	120	1	1	1	1	1	8	18	24	120	120	1	1	1	1	1
0.125	44	48	100	120	120	1	1	1	1	1	120	120	120	120	120	1	1	1	1	1
0.25	29	48	100	120	120	1	1	1	1	1	8	18	56	97	120	1	1	1	1	1
0.5	18	44	101	120	120	1	1	1	1	1	44	44	56	97	107	1	1	1	1	1
1.0	8	8	18	23	44	1	1	1	1	1	21	44	56	105	120	1	1	1	1	1
2.0	8	8	8	29	120	1	1	1	1	1	29	44	53	56	120	1	1	1	1	1

Results

Throwing Power



- Complete corrosion of masked regions prior to completion of (1) GM 9540P cycle
- No difference when chromated vs. nonchromated
- No difference when topcoated vs. primer coating only

Results

Throwing Power

Typical progression of cadmium plating breakdown

Initial

White Cadmium Corrosion Products and Blotching,

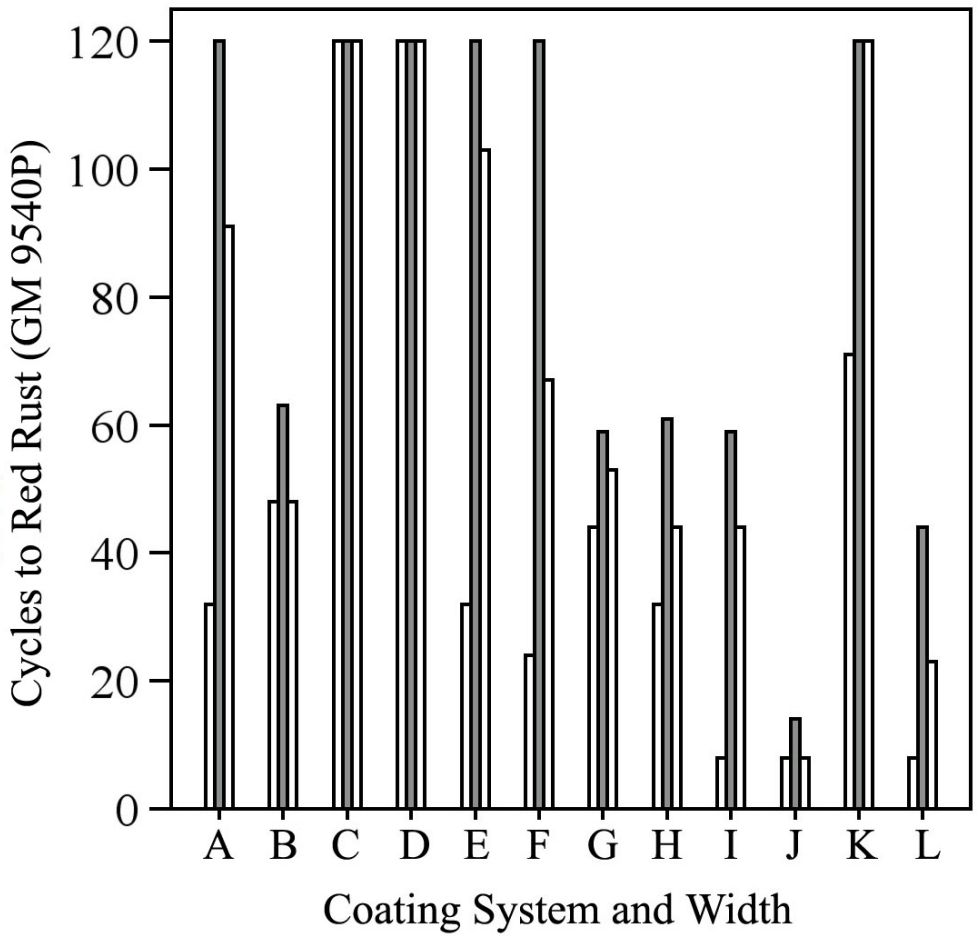
Dark Gray to Black Blotches of Oxidized Cadmium

Exposed Areas of Gray Unrusted Steel or Chromate Depleted Cadmium Plating

Final Rusting of Steel Substrate

Results

Throwing Power

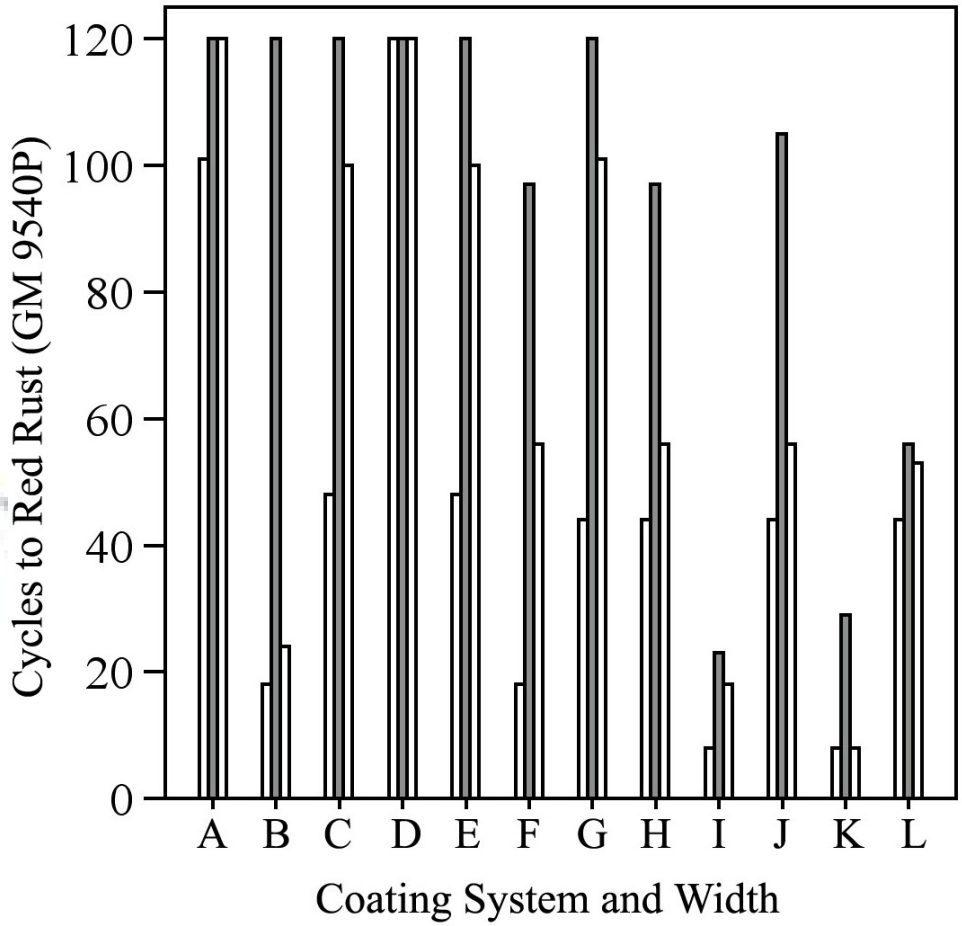


A - Coating 1, No Topcoat @0.0625”
B - Coating 3, No Topcoat @0.0625”
C - Coating 1, No Topcoat @0.125”
D - Coating 3, No Topcoat @0.125”
E - Coating 1, No Topcoat @0.250”
F - Coating 3, No Topcoat @0.250”
G - Coating 1, No Topcoat @0.5”
H - Coating 3, No Topcoat @0.5”
I - Coating 1, No Topcoat @1.0”
J - Coating 3, No Topcoat @1.0”
K - Coating 1, No Topcoat @2.0”
L - Coating 3, No Topcoat @2.0”

- Class C primer was equal or better than Class N primer when omitting topcoat

Results

Throwing Power

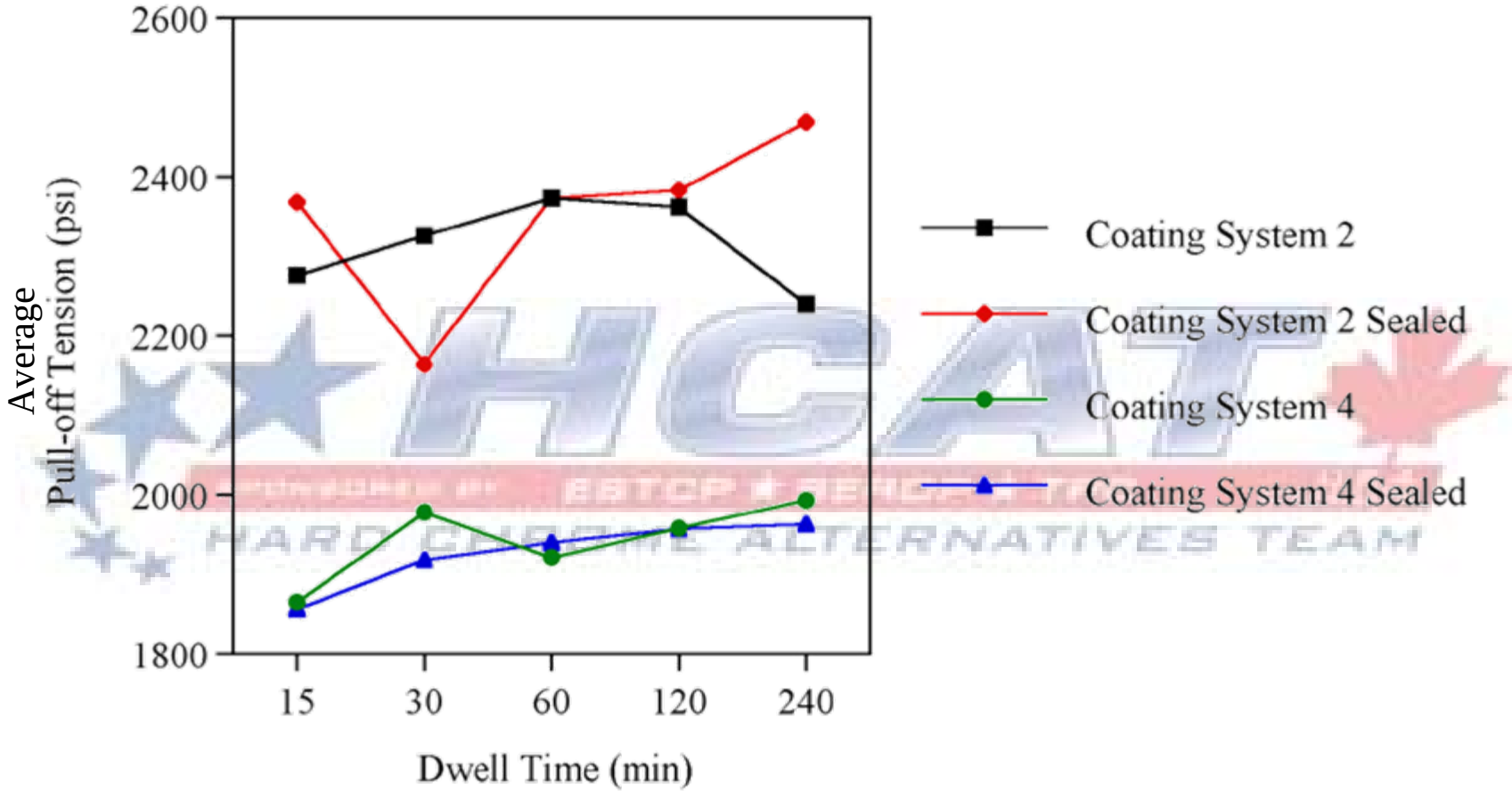


A - Coating 1 @0.0625”
B - Coating 3 @0.0625”
C - Coating 1 @0.125”
D - Coating 3 @0.125”
E - Coating 1 @0.250”
F - Coating 3 @0.250”
G - Coating 1 @0.5”
H - Coating 3 @0.5”
I - Coating 1 @1.0”
J - Coating 3 @1.0”
K - Coating 1 @2.0”
L - Coating 3 @2.0”

- No apparent Class C primer advantages vs. Class N primer with topcoat

Results

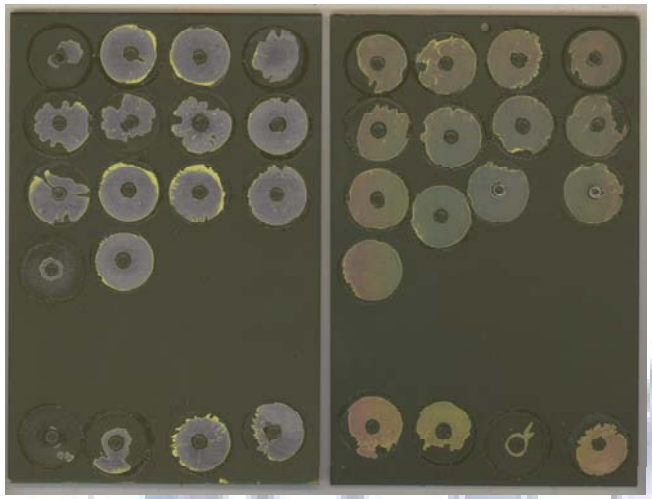
Adhesion



1 (no dwell)		3 (no dwell)		2M (no dwell)		4M (no dwell)	
Average	1594.77	Average	1849.39	Average	1783.18	Average	1829.38
STD DEV	462.45	STD DEV	183.33	STD DEV	421.30	STD DEV	128.80
Geometric Mean	1531.80	Geometric Mean	1839.41	Geometric Mean	1734.78	Geometric Mean	1824.94
Median	1475	Median	1860	Median	1705	Median	1810
95% Confidence	136.64	95% Confidence	51.33	95% Confidence	124.48	95% Confidence	36.44
MAX	2530	MAX	2300	MAX	2550	MAX	2090
MIN	900	MIN	1100	MIN	950	MIN	1600

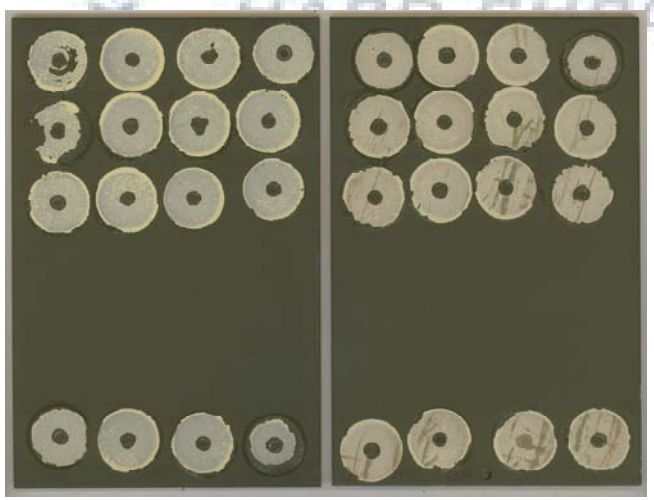
Results

Adhesion



Mill finish 4130 Cd Plating

Class C



Mill finish 4130 Cd Plating

Class N

- More uniform pull-off tensions for Class N primer
- Class N had better adhesion on smooth surface profiles than Class C
  (cohesive for Class N vs. adhesive for Class C)
- Class C had higher adhesion pull-off tensions on abrasive blasted surface profiles than Class N
- Dwell times and N_2 packaging had no measurable effect at the dwell times examined

Results

Hydrogen Embrittlement

Type 1d Specimens - Cd Plated - Notched Rods - Sensitivity and Test Load Calibration					
Specimen Number	**Beginning Width (in)**	**Loaded Width (in)**	**Percent of UTS**	**Displacement @Load (in)**	**Hours Until Failure**
Bright Cd1	1.962	1.863	75	0.099	< 1
Bright Cd2	1.962	1.863	75	0.099	< 1
Bright Cd3	1.962	1.863	75	0.099	< 1
Dull Cd1	1.962	1.863	75	0.099	> 200
Dull Cd2	1.962	1.863	75	0.099	> 200
Dull Cd3	1.963	1.864	75	0.099	> 200
Plain 1	1.966	1.867	75	0.099	Did Not Fail
Plain 2	1.968	1.869	75	0.099	Did Not Fail
Plain 3	1.968	1.869	75	0.099	Did Not Fail
SAE AMS QQ-P-416 #1	1.968	1.882	65	0.086	< 6
SAE AMS QQ-P-416 #2	1.970	1.884	65	0.086	< 6
SAE AMS QQ-P-416 #3	1.971	1.885	65	0.086	< 6
SAE AMS QQ-P-416 #4	1.964	1.898	50	0.066	< 24
SAE AMS QQ-P-416 #5	**1.970**	**1.917**	**40**	**0.053**	**> 200***

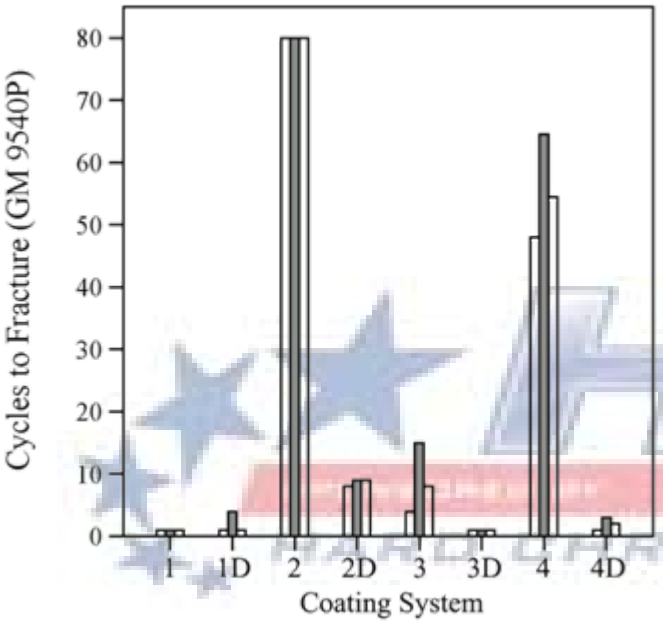
** Used as basis for loading of C-ring test matrix*

- Pre-existing hydrogen from defective bath or failure to hydrogen relief bake within the 4 hour window on Cd plated C-rings

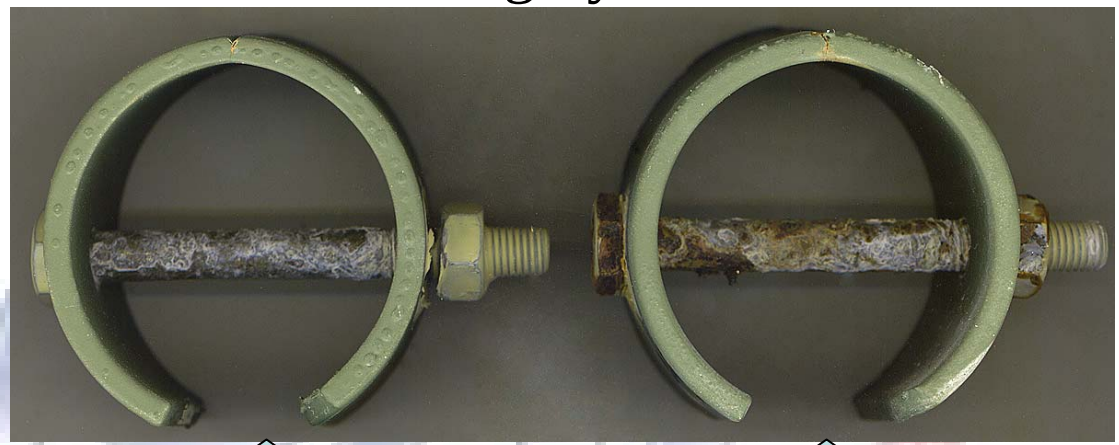
Designation	Coating System Description	GM 9540P Cyles to Fracture (Replicates 1-5)				
1	Cd Plating with MIL-PRF-23377C	1	1	15	1	1
1D	Cd Plating with MIL-PRF-23377C Damaged	1	4	6	1	1
2	Unplated with MIL-PRF-23377C	80	80	80	80	80
2D	Unplated with MIL-PRF-23377C Damaged	7	9	48	9	8
3	Cd Plating with MIL-PRF-23377N	4	15	26	8	4
3D	Cd Plating with MIL-PRF-23377N Damaged	1	1	5	1	1
4	Unplated with MIL-PRF-23377N	4	54	71	64	48
4D	Unplated with MIL-PRF-23377N Damaged	1	3	3	2	1

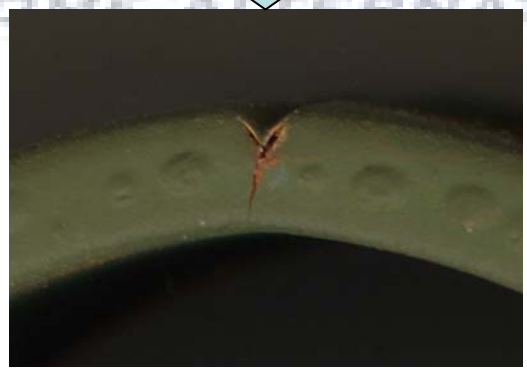
Results

Hydrogen Embrittlement



Coating System 4





4 Cycles (7X)

48 Cycles (7X)

Conclusions

- Electroplated cadmium cannot be eliminated without detrimentally affecting corrosion resistance.

- Substitution of the MIL-PRF-23377 Class C chromated primer with MIL-PRF-23377 Class N qualified non-chromate primers may be possible when cadmium plating is retained as was observed in general and crevice corrosion conditions.

- Throwing power is overwhelmingly a function of a sacrificial coating such as cadmium as evidenced by all 120 panels without cadmium failing before the end of the first corrosion cycle. No differences or trends could be established for any of the 120 panels without cadmium plating, whether or not a chromate or nonchromate primer was used.

Conclusions

- The presence of topcoat hindered the corrosion performance of chromate-inhibited epoxy primer by effectively severing the source of Cr^{+6} during the evaluation of throwing power. Therefore, chromate-inhibited epoxy primer may be beneficial for the throwing power effectiveness of a sacrificial cadmium coating but only when exposed without a topcoat, or perhaps in certain situations where large portions of the topcoat is significantly damaged or degraded.

- For smooth profiled surfaces, non-chromated MIL-PRF-23377 Class N has better adhesion than chromated MIL-PRF-23377 Class C.

- Non-chromated MIL-PRF-23377 Class N has better flexibility vs. chromated MIL-PRF-23377 Class C.

- To maximize coating adhesion of MIL-PRF-23377 Class C to steels in low risk applications where cadmium plating is not used, abrasive blasting is recommended.

Conclusions

- Direct to metal applications of MIL-PRF-23377 primers to abrasive blasted steel surfaces within 4 hours of the blast step are feasible in depot situations when relative humidity is below 50% and the environment is maintained free of particulate debris.