

Status of the UV Cure Powder Coating Demonstration Project



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Outline

- Project Team
- UV Cure Technology
- UV Curable Powder Overview
- UV Cure Powder Coating
Demonstration/Validation



Project Team

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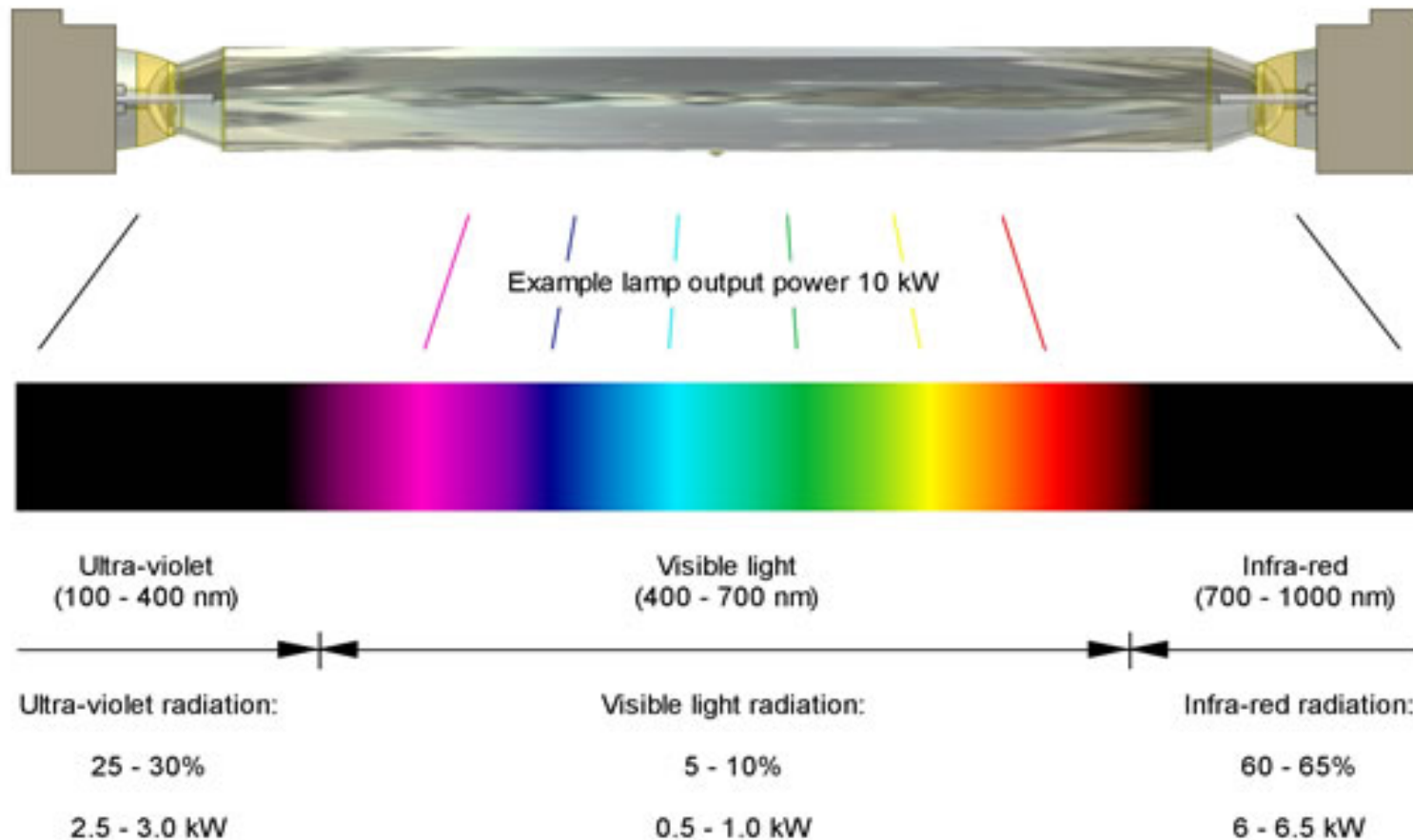
UV Cure Technology

UV Cure Technology

- Requires a source of UV light



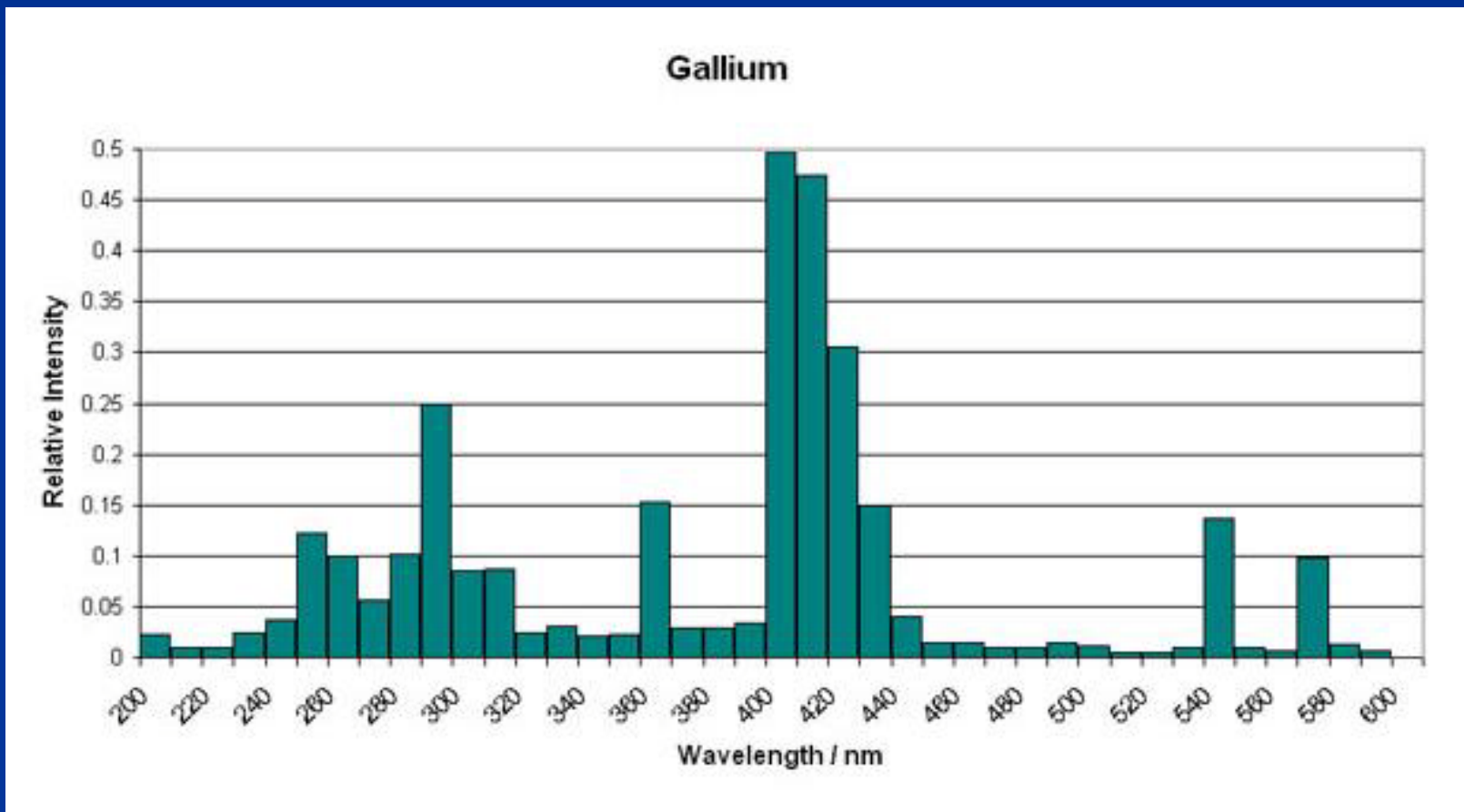
UV Cure Technology



Typical medium pressure mercury discharge lamp power distribution.

UV-Cure Technology

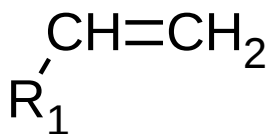
- We use a Gallium doped lamp:



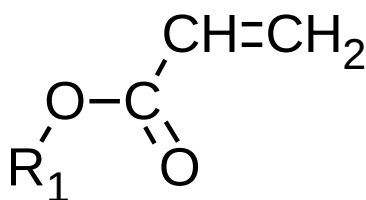
UV Cure Technology

■ Chemistry of UV-cure coatings

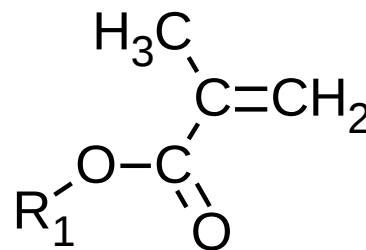
- Can be virtually any polymer matrix used for organic coatings
- The common denominator is the presence of a UV light reactive species on/in the polymer matrix
- Commonly vinyl, acrylate or methacrylate groups



Vinyl



Acrylates

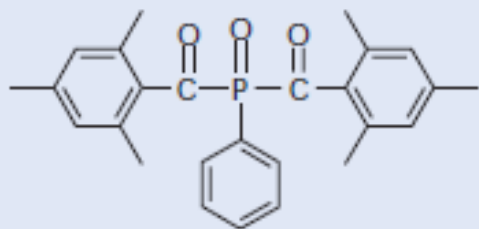


Methacrylates

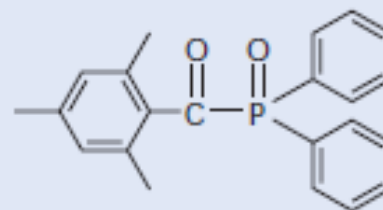
UV Cure Technology

- UV Cure formulations require:
 - Light reactive polymer resins
 - Additives such as pigments and flow agents
 - Photoinitiators

IRGACURE 819 and IRGACURE 819 DW



DAROCUR TPO



UV Cure Technology

- UV-cure powder coatings
 - Typically, the most common UV curable powders are:
 - Polyurethanes
 - Polyesters
 - Epoxies
 - Hybrids and mixtures of the above
 - For the UVCPC project, we use a special composition of light activated polyurethanes and polyesters

UV Curable Powder Overview

UV-Curable Powder Overview

- Previous ways of thinking about powder
 - Coating cure temperatures – typically above 220°C
 - Prohibitive for use on tempered metals (Al, Mg, Ti)
 - Prohibitive to use on composites
 - Powder coatings were designed as barrier protection

UV-Curable Powder Overview

- Modern powder coatings can be formulated to have:
 - Lower melt & flow temperatures ($< 110^{\circ}\text{C}$)
 - UV or EB cure functionality can be added
 - Various advanced non-chrome corrosion inhibitors



UV-Curable Powder Overview

- Advantages of UV-cure powder coating:
 - Elimination of volatile organics (VOC)
 - Elimination of hazardous air pollutants (HAP)
 - Reduction/elimination of hazardous waste
 - Transfer efficiencies as high as 95% (w/reclaim)
 - Decrease in thermal exposure.
 - Large bulky parts that cannot fit into existing ovens can be coated and cured.
 - UV-cure powder requires less energy because the energy is focused to a specific part only as long as needed.

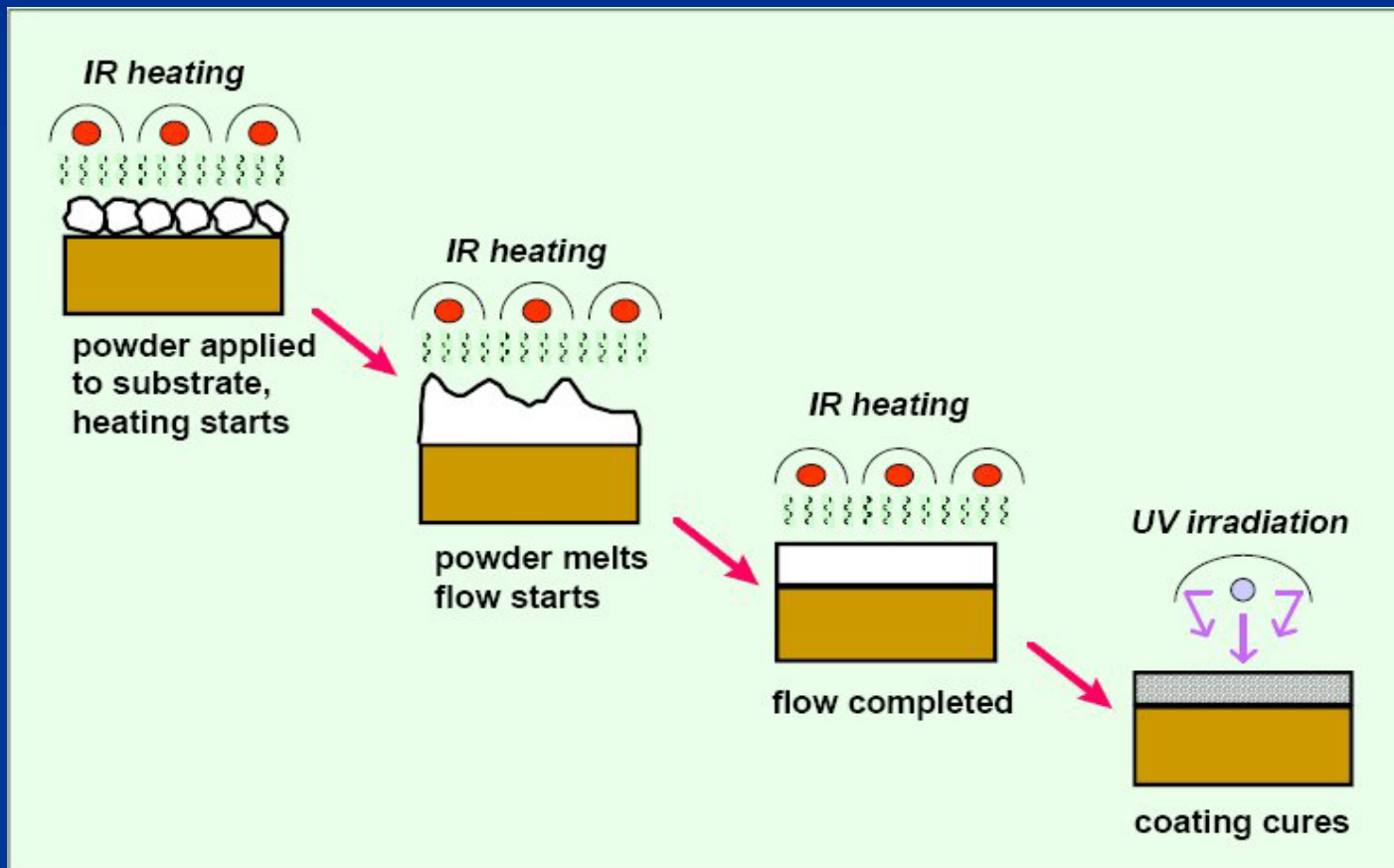
UV Curable Powder Overview



- Powder is applied using electrostatic powder gun
- Applied powder is cured with IR and UV lights mounted on robotic curing system

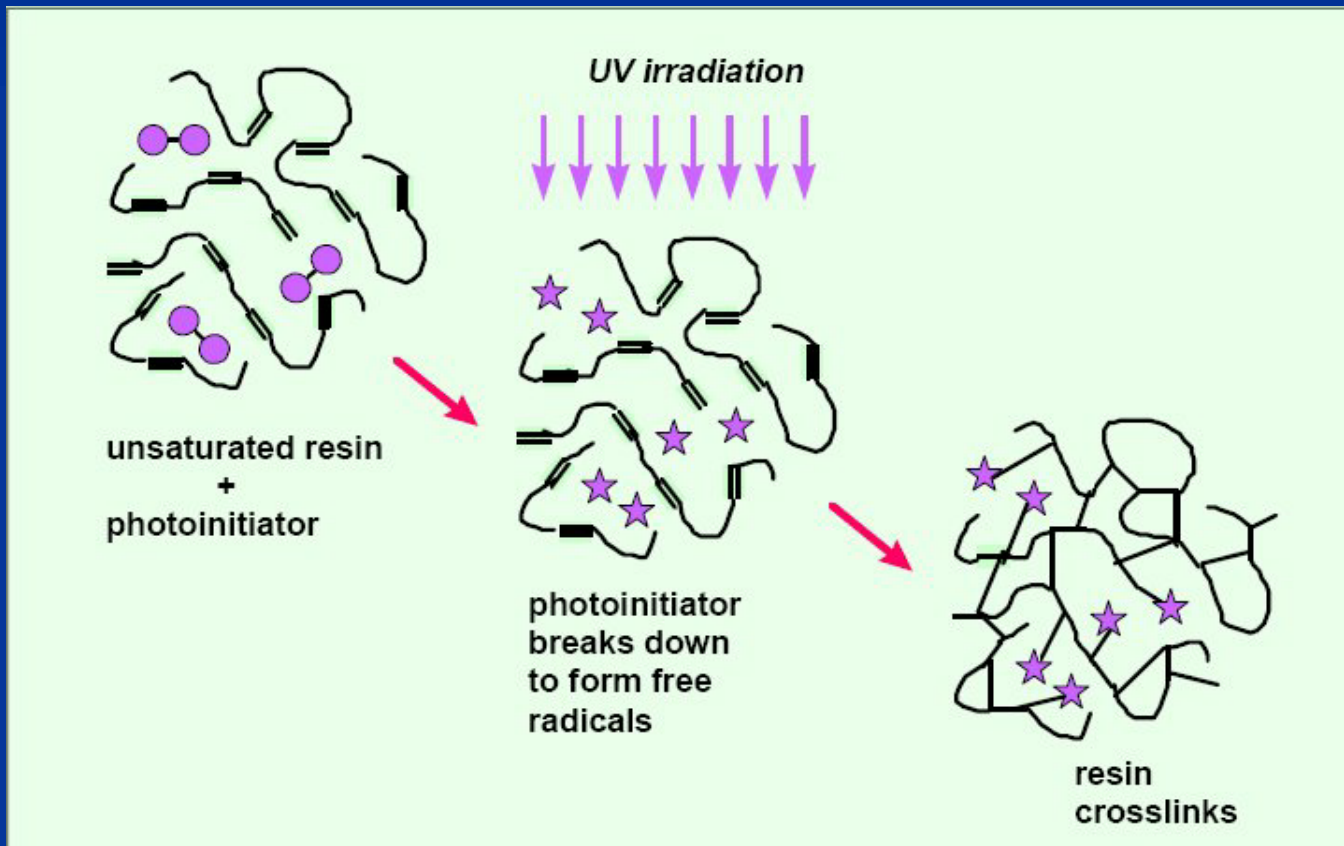
UV Curable Powder Overview

- The UV cure powder process:



UV Curable Powder Overview

- Crosslinking occurs during UV irradiation:



UV Cure Powder Coating Demonstration/Validation

UVCPC Dem/Val

■ Timeline

- Project based on Commercial Off The Shelf (COTS) UV cured powder coatings
- Project started in 2008
- Initially had two powder vendors
- One dropped because of constant merger issues
- Initial validation testing completed in 2010
 - Results questionable due to adhesion issues
 - A number of tests rerun as a result
- Adhesion study completed in 2010
 - Found one of the reasons for poor adhesion

UVCPC Dem/Val

■ Timeline (Cont.)

- Adhesion study completed in 2010 (Cont.)
 - Low copper alloys (6000, 3000 series) not a problem
 - High copper alloys scavenge free radicals at surface
 - Determined that certain surface treatments are effective:
 - Anodized
 - Alodine 1600
 - Zinc Phosphate
 - Epoxy wash primers
- Building 2801 modification completed end 2010
- Robot installation occurred in 2011

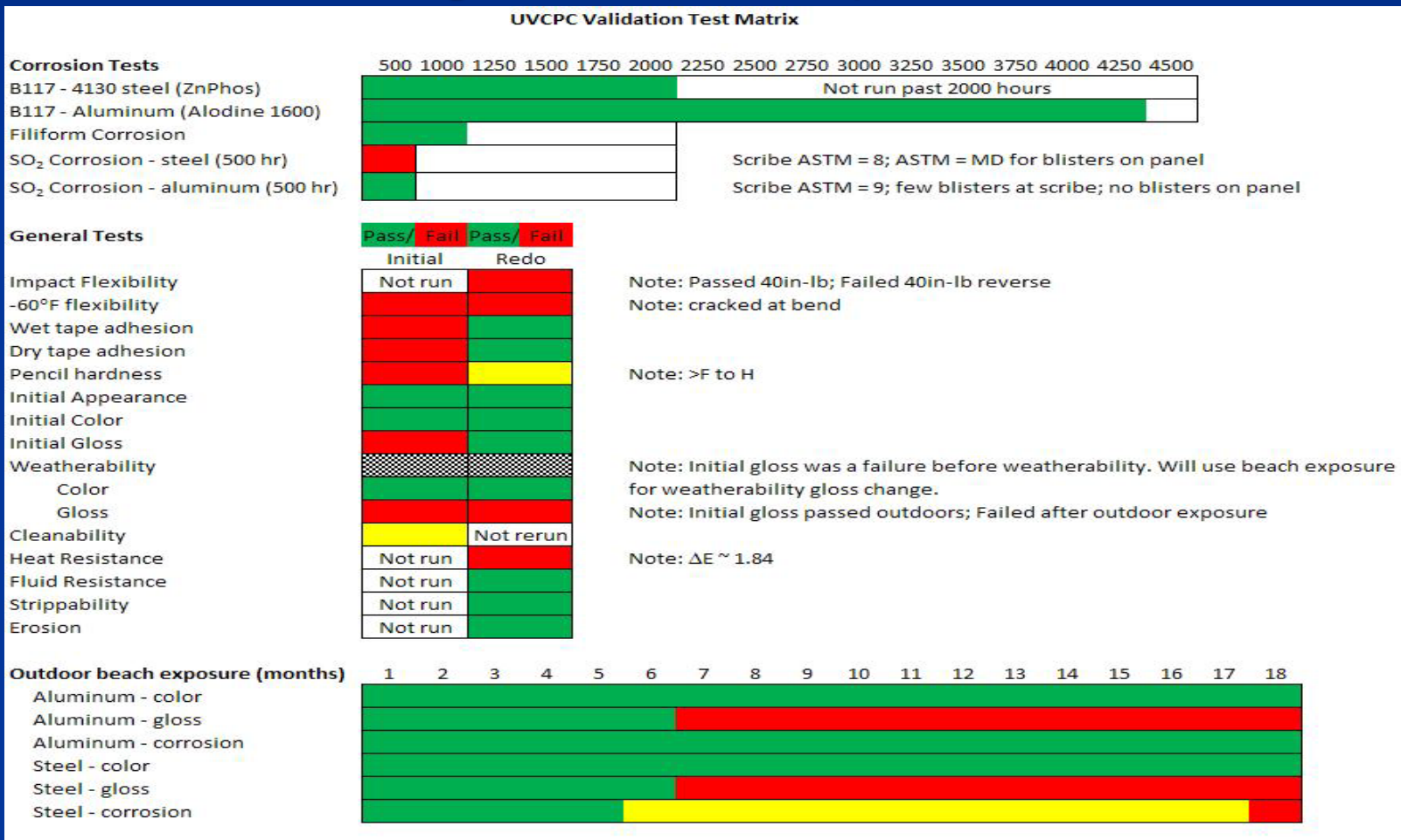
UVCPC Dem/Val

■ Timeline (Cont.)

- First light and testing in early 2012
 - Discovery that kinetics also play major role in adhesion
- First parts coated with UVCPC
 - Ammo can
 - Aircraft jack hydraulic reservoirs
 - USAF aircraft wheels

UVCPC Dem/Val

■ Validation Testing Results (Summary) of COTS UVCPC



UVCPC Dem/Val

■ General test results

■ Color (FED-STD-595C)

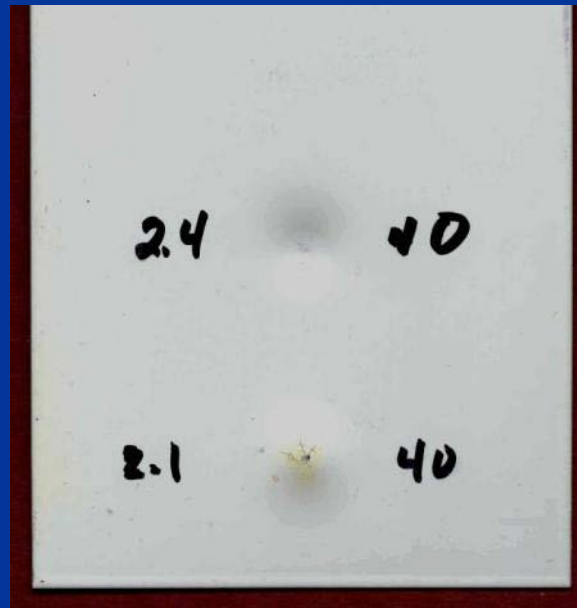
Coating	L*	a*	b*	ΔL^*	Δa^*	Δb^*	ΔE^*
FED-STD-595C 17925 Reference Chip	96.06	-1.95	3.10				
PCRG High Gloss White	95.82	-1.96	2.66	-0.24	-0.01	-0.45	0.5
FED-STD-595C 26173 Reference Chip	55.05	-1.24	-3.66				
PCRG Semigloss Initial	55.13	-1.24	-3.98	0.08	0.00	0.32	0.2

■ Gloss (FED-STD-595C)

Sample ID	20°	60°	85°
PCRG High Gloss White	55.1	84.4	95.6
PCRG Semi Gloss Initial	8.8	45.8	78.1

UVCPC Dem/Val

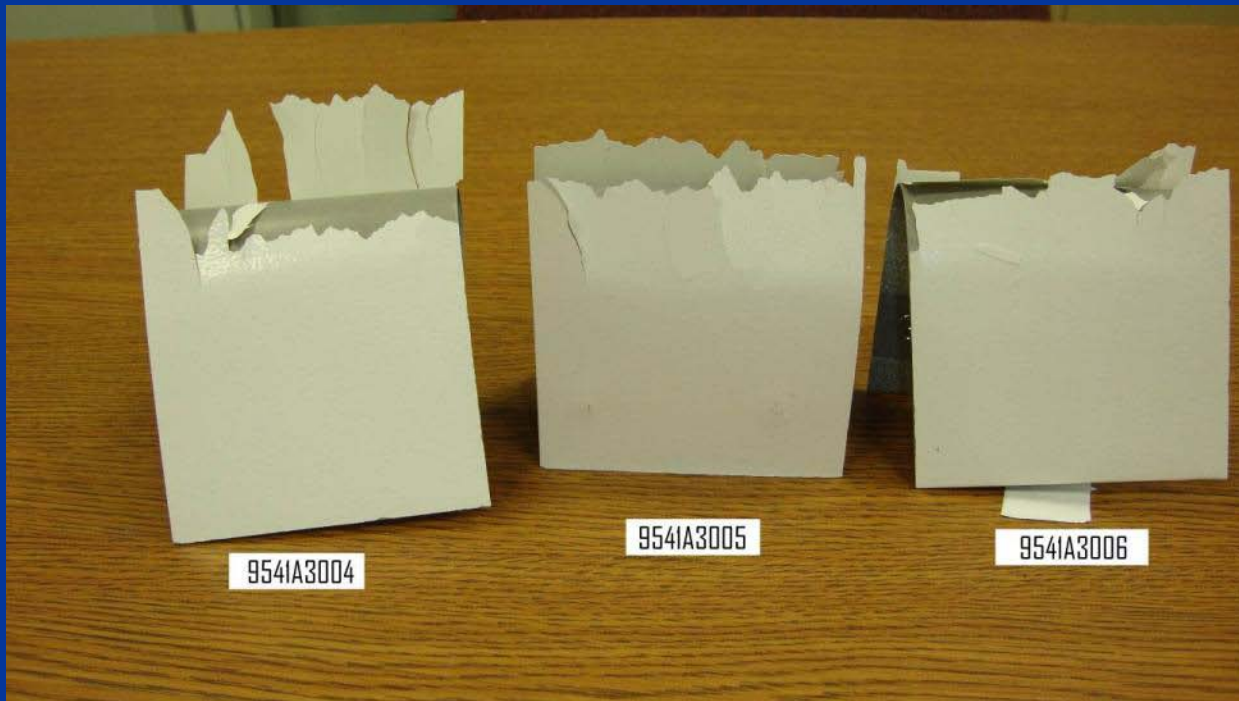
- General test results
 - Pencil Hardness (ASTM D3363)
 - Marginal, falls between F and H pencil
 - Impact Flexibility (MIL-PRF-85285D)
 - Passed 40 in-lb forward, Failed 40 in-lb reverse



UVCPC Dem/Val

■ General test results

- Low temperature (-60°F) flexibility initial (MIL-PRF-85285D)



UVCPC Dem/Val

- General test results
 - Low temperature (-60°F) flexibility rerun



UVCPC Dem/Val

■ General test results

- Dry/Wet tape adhesion (ASTM D3359, FED-STD-141D)
 - Initial results were failures due to adhesion issue
- Dry adhesion was rerun on various pretreatments
 - Because adhesion seemed to change with time, a month of testing run
 - Summary of the dry tape adhesion results is shown on next slide

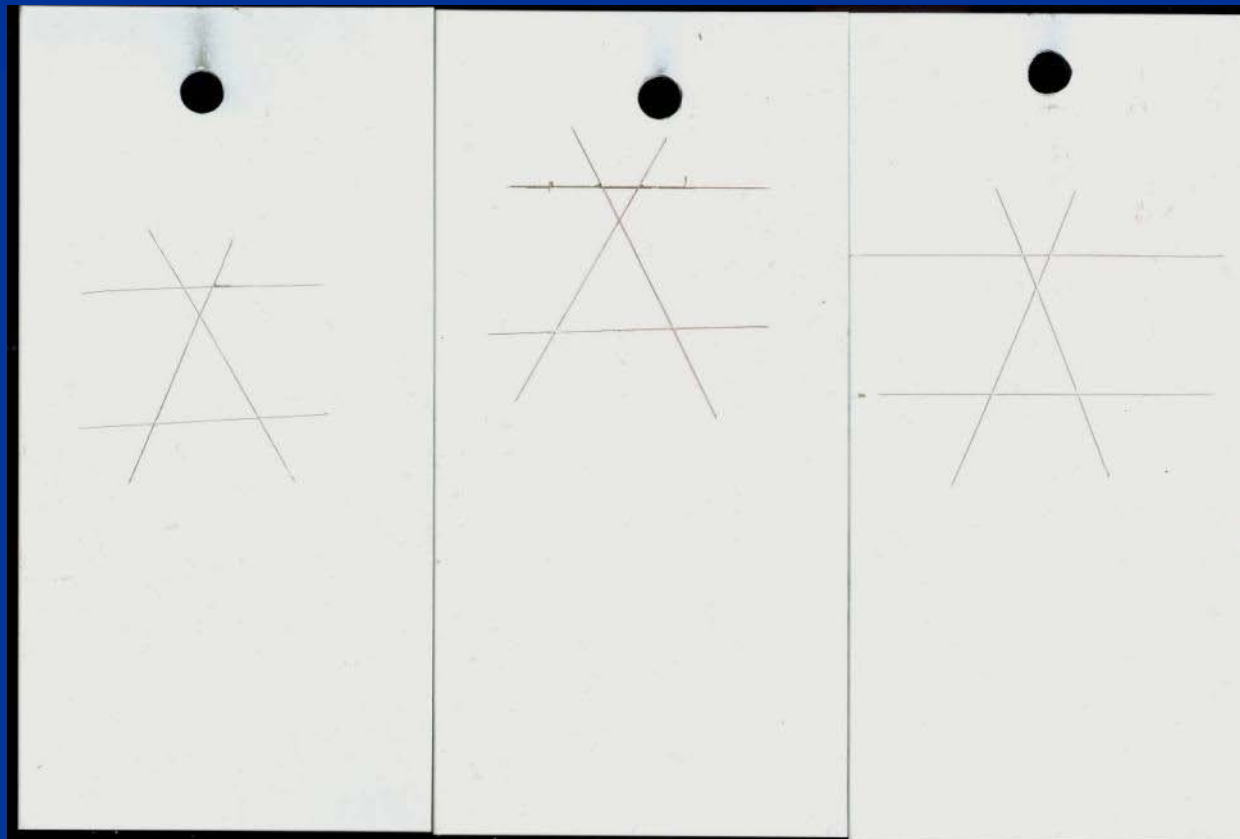
UVCPC Dem/Val

■ General test results

	Film Thickness	Cross Hatch Adhesion							
		1/5/2011	1/7/2011	1/10/2011	1/12/2011	1/14/2011	1/17/2011	1/19/2011	2/3/2011
Alodine 1200S									
45 sec	1.3 - 1.4	4B	4B	4B	4B	4B	2B	2B	N/A
90 sec	1.5 - 1.8	4B	3B	3B	3B	3B	3B	2B	N/A
3 min	1.7 - 2.2	4B	2B	2B	0B	0B	0B	0B	N/A
Alodine 1600									
1 min	1.7 - 2.1	5B	5B	5B	5B	5B	5B	5B	4-5B
3 min	1.5 - 1.7	5B	5B	5B	5B	5B	4-5B	4-5B	4-5B
5 min	1.4 - 1.7	5B	5B	5B	5B	5B	4-5B	4-5B	4-5B
20 sec	1.6 - 2.0	5B	5B	4-5B	4-5B	4-5B	4-5B	4-5B	4-5B
Alodine 5200									
1 min	1.3 - 1.5	5B	5B	5B	5B	5B	5B	5B	N/A
2 min	1.5 - 1.8	5B	5B	5B	5B	5B	5B	5B	N/A
4 min	1.5 - 2.0	4B	4B	4B	5B	4-5B	5B	5B	N/A
Alodine 5900									
5 min	1.3 - 1.4	4B	4B	3B	3B	2B	0B	0B	N/A
10 min	1.2 - 1.5	4B	3B	3B	2B	2B	0B	0B	N/A
Alodine 8800									
Heavy	1.6 - 1.7	5B	5B	5B	5B	5B	5B	5B	N/A
Light	1.5 - 1.7	5B	5B	5B	5B	5B	5B	5B	N/A
Control	1.5 - 1.9	0B	0B	0B	0B	0B	0B	0B	N/A
Carpenter B/700									
								5B	33 days
S-W Wash Primer	Test	Initial + 2 week							
2024-T3	Dry	5B + no change							
2024-T3	Wet	5B + no change							
4130 steel	Dry	5B + no change							
4130 steel	Wet	5B + no change							

UVCPC Dem/Val

- General test results
 - Wet tape adhesion



UVCPC Dem/Val

■ General test results

- Fluid resistance (MIL-PRF-85285D)
- Initial fluid resistance test halted as soon as adhesion issue discovered
- Follow on fluid resistance test rerun passed



UVCPC Dem/Val

■ General test results

- Weatherometer (MIL-PRF-85285D, ASTM G155)
 - 500 hour test
 - $\Delta E^* = 0.97$ (Pass)
 - Gloss loss ≈ 63.7 units (Fail)
- Heat Resistance (MIL-PRF-85285D)
 - $\Delta E^* = 1.84$ (Marginal)
- Cleanability (MIL-PRF-85285D)
 - Efficiency = 67% (Marginal)
- Strippability (MIL-PRF-85285D)
 - 100% removed in < 4 hours (Pass)

UVCPC Dem/Val

■ Corrosion resistance tests

■ Neutral salt fog (MIL-PRF-23377J, ASTM B117)

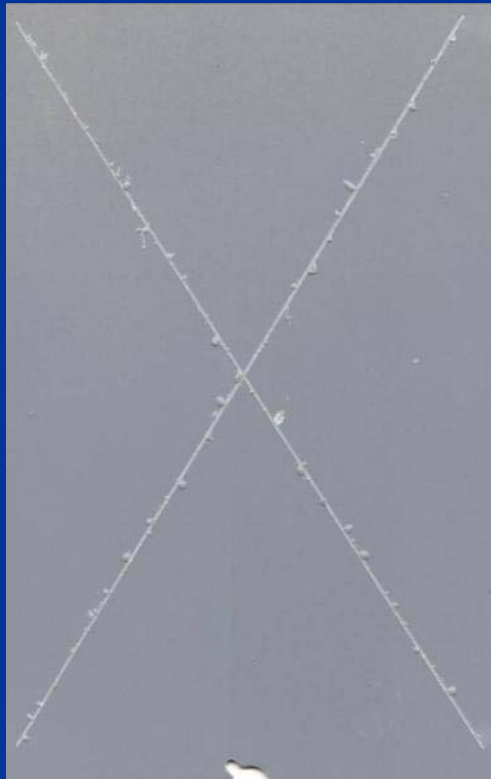
- UVCPC over Zn Phosphate 4130 steel, 2000 hrs (Pass)

- UVCPC over Alodine 1600, 2024-T3 Al, 4430 hrs (Pass)



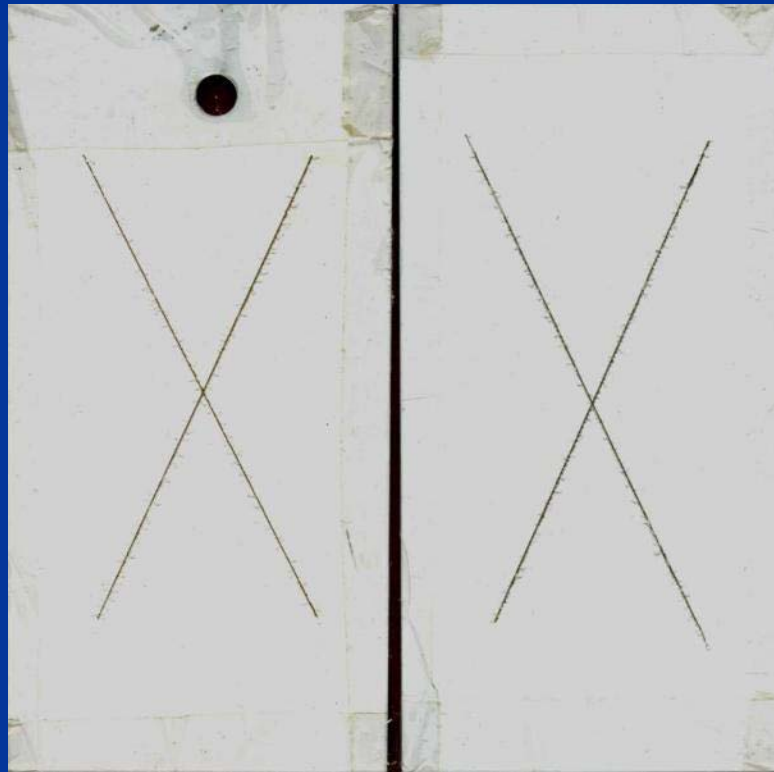
UVCPC Dem/Val

- Corrosion resistance tests
 - SO₂ corrosion resistance (ASTM G85, Annex 4)
 - UVCPC over Aluminum (Pass)
 - UVCPC over cold rolled steel (Fail)



UVCPC Dem/Val

- Corrosion resistance tests
 - Filiform corrosion resistance (MIL-PRF-23377J, ASTM D2803)
 - 1000 hour test (Pass)



UVCPC Dem/Val

- Erosion/Abrasion tests
 - Falling sand erosion testing (ASTM D968)
 - Within 1σ of the legacy coating

Falling Sand Evaluation (UVCPC)

Sample #	Liters (V)	Mean thickness (t)	A Factor $A=V/t$
2	144	2.32	62.1
3	162	2.8	57.9
4	144	2.53	56.9
5	133	2.53	52.6
6	144	2.58	55.8
8	143	2.49	57.4
Mean			57.0
Std Dev			3.09

UVCPC Dem/Val

- Long term outdoor exposure (ASTM D1014)
 - Three parameters evaluated
 - Color drift
 - Gloss drift
 - Overall corrosion
 - Semi-gloss gray UVCPC used
 - Results:
 - Color drift maximum $\Delta E^* = 0.82$ (Pass)
 - Gloss drift 36.6 gloss units (Fail)
 - Corrosion overall:
 - Aluminum still passing after 18 months (~12900 hours exposure)
 - Cold rolled steel failed after 7 months (~5000 hours exposure)

UVCPC Dem/Val

- Long term outdoor exposure
 - Color drift

Coating	L*	a*	b*	ΔL^*	Δa^*	Δb^*	ΔE^*
FED-STD-595C 26173 Reference Chip	55.05	-1.24	-3.66				
PCRG Semigloss Initial	55.13	-1.24	-3.98	0.08	0.00	0.32	0.2
PCRG 7-month color	55.40	-1.18	-4.16	0.35	-0.06	0.50	0.32
PCRG 12-month color	55.77	-1.16	-4.11	0.72	-0.08	0.45	0.75
PCRG 18-month color	55.82	-1.21	-4.17	0.76	-0.07	0.31	0.82

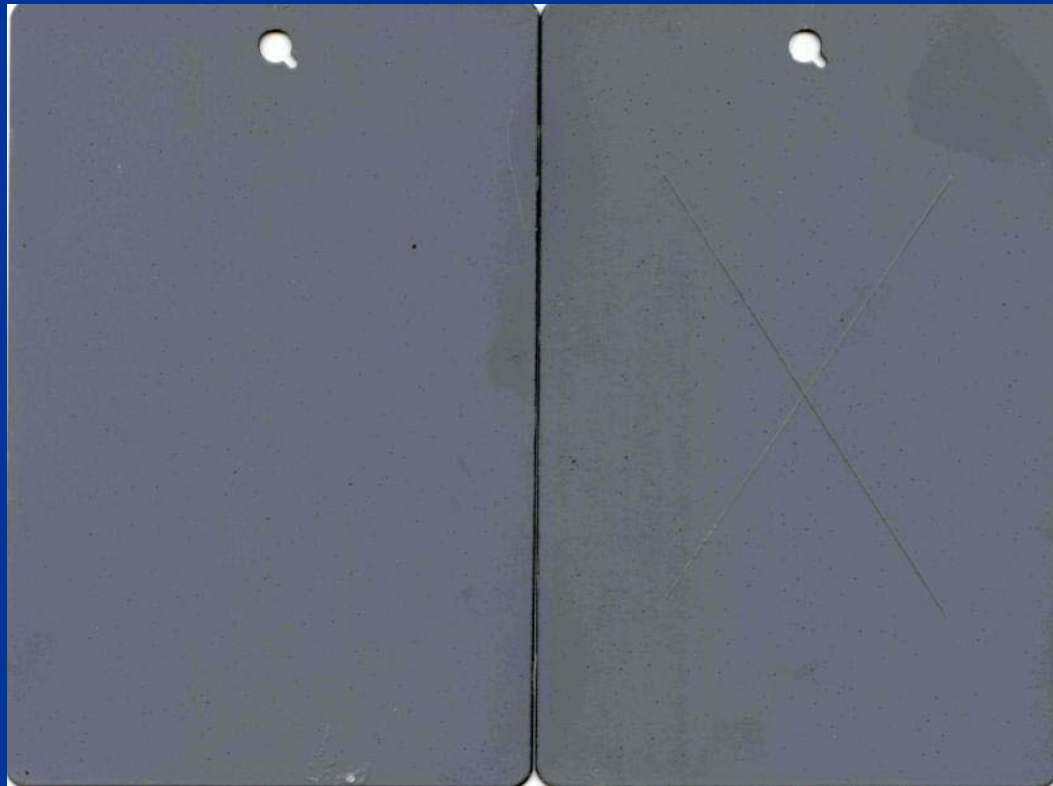
UVCPC Dem/Val

- Long term outdoor exposure
 - Gloss drift

Sample ID		20°	60°	85°
PCRG Semi Gloss Initial		8.8	45.8	78.1
PCRG 7-month semigloss		3.0	25.7	66.9
PCRG 12-month semigloss		2.2	21.9	60.2
PCRG 18-month semigloss		0.9	9.2	41.6

UVCPC Dem/Val

- Long term outdoor exposure
 - Aluminum after 18 months (~12,900 hours)



UVCPC Dem/Val

- Long term outdoor exposure
 - Steel after 7 & 18 months



UVCPC Dem/Val

- Actual components coated
 - Ammunition can



UVCPC Dem/Val

- Actual components coated
 - Aircraft jack hydraulic reservoirs



UVCPC Dem/Val

- Actual components coated
 - F-16 main wheel (before)



UVCPC Dem/Val

- Actual components coated
 - F-16 main wheel (after)



UVCPC Dem/Val

- Actual components coated
 - F-15 nose wheel (before)



UVCPC Dem/Val

- Actual components coated
 - F-15 nose wheel (after)



UVCPC Dem/Val

- Actual components coated
 - Coast Guard MC-130 landing gear door



Summary

- Overall, the COTS UVCPC did well
 - Better overall test results than previous Low Temp powder
 - Positives
 - Excellent B117 corrosion resistance over aluminum
 - Good corrosion resistance over zinc phosphated steel
 - Excellent Filiform corrosion resistance
 - Good room temperature flexibility
 - Erosion resistance on par with legacy 2K coatings

Summary

- Overall, the COTS UVCPC did well (cont.)
 - Could use some improvements going forward
 - Coating
 - Lower melt/flow temperature
 - Improve -60°F flexibility
 - Increase hardness to 2H or greater pencil
 - Improve impact flexibility
 - Better heat resistance
 - Improve weatherability (gloss)
 - Reformulate for direct-to-metal

Summary

- Overall, the COTS UVCPC did well (cont.)
 - Could use some improvements going forward
 - Robotics
 - Better profiling
 - Use profiling radiometers
 - Better thermal profiling
 - Better control during operations (thermal, UV)
 - IR and UV feedback to robot
 - Powder Coating
 - Incorporate non-contact uncured powder thickness gauge

Questions?

UVCPC Back up slides

UVCPC Adhesion

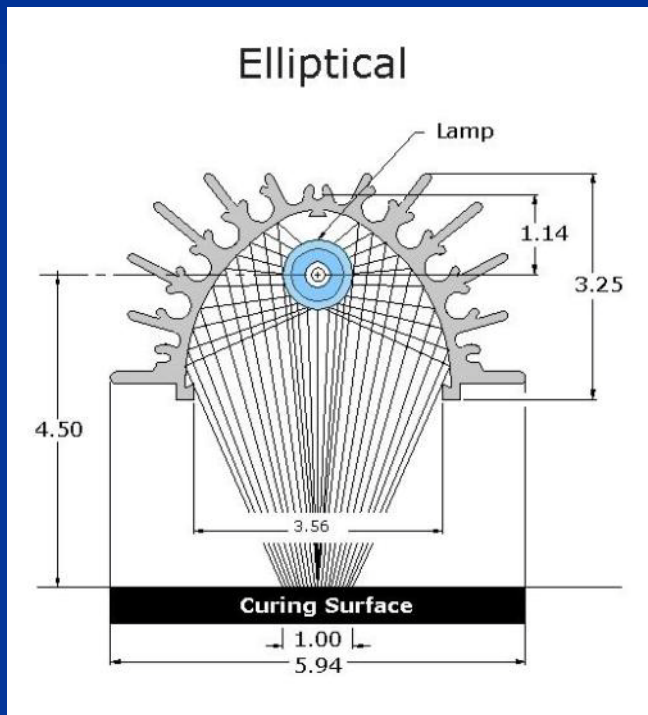
- **Adhesion of UVCPC over 2000 series aluminum**
 - Adhesion results could not be duplicated between CTIO and PCRG
 - Key differences between locations was power of UV lamps
 - Formulation developed under a 300 Watt/in lamp
 - Originally thought it was photoinitiator based
 - “Flash” effect considered
 - Determined to test on the robotic curing system at NASWI
 - Nordson lamp is power adjustable unlike the CTIO/PCRG lamps
 - Robot can duplicate conveyor speeds (5 fpm vs. 9 fpm)
 - Robot can execute multiple passes in programming
 - Felt that the system could duplicate either lab
 - However, the results were completely unexpected
 - Realized the lamp at NASWI is a non-focused lamp
 - NASWI results led to the belief that both chemistry and kinetics play a role in the cure and adhesion on metallic substrates

UVCPC Adhesion

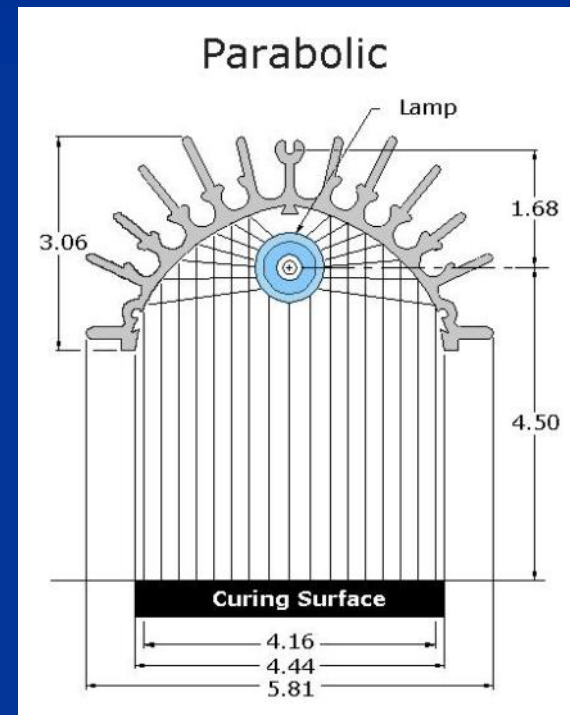
- Adhesion of UVCPC over 2000 series aluminum
 - The robotic curing system was able to cure with 5B adhesion
 - 5086, 6061, 3003 aluminum, and 4130 steel
 - None of the test panels had been prepared
 - Wiped free of dust
 - No pretreatment
 - No scuffing of surface (except steel which was bead blasted)
 - On 2000 series untreated, unprepared aluminum, 3B to 4B adhesion was possible
 - Kinetics plays a role as well as free radical scavengers
 - Free radical concentration at an instant in time
 - Focused lamps vs. unfocused lamps

UVCPC Adhesion

- Adhesion of UVCPC over 2000 series aluminum
 - Focused vs. unfocused reflectors



Used by CTIO and PCRG



Used by NASWI

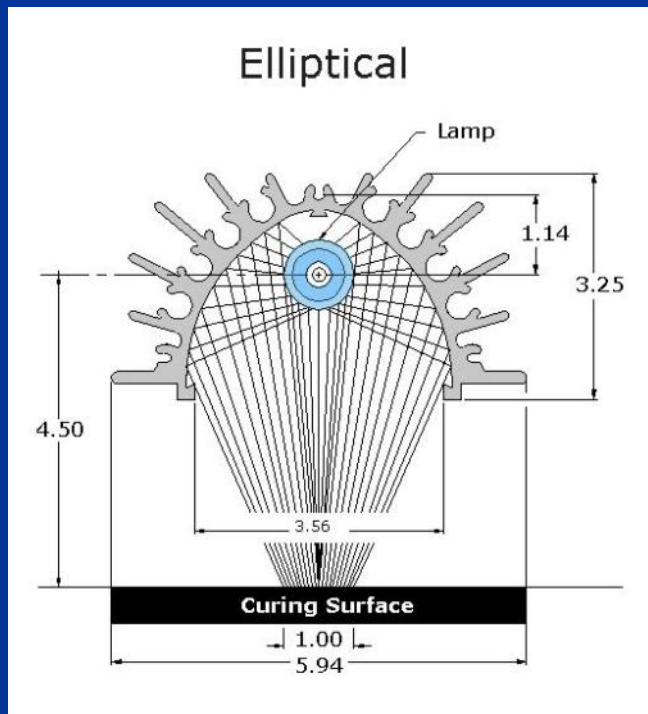
UVCPC Adhesion

- Adhesion of UVCPC over 2000 series aluminum
 - Focused vs. unfocused reflectors
 - Dose at each location (typical)

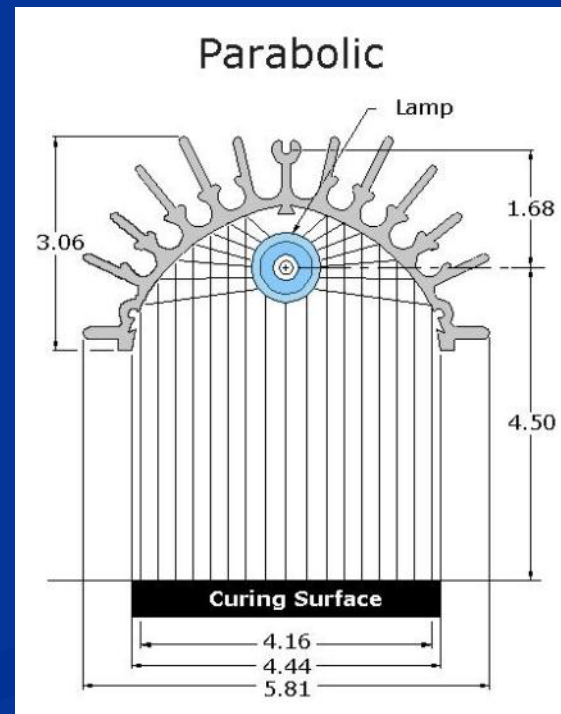
	WPAFB lamp (focused) J/cm ² 2-pass, 9 fpm	PCRG lamp (focused) J/cm ² 2-pass, 5 fpm	NASWI lamp (unfocused) J/cm ² 1-pass, ~4 fpm
UVA	2.54	2.22	1.53
UVB	1.83	1.39	1.62
UVC	0.13	0.17	0.22
UVV	12.7	10.41	12.23

UVCPC Adhesion

- Adhesion of UVCPC over 2000 series aluminum
 - Focused puts almost full dose in a 1" path
 - Unfocused puts similar dose down across ~4" path
 - Between 0.6 (WPAFB) and 1 (PCRG) second for full dose in focused
 - About 5 seconds (NASWI) for full dose in unfocused



Used by CTIO and PCRG



Used by NASWI

UVCPC Adhesion

- Adhesion of UVCPC over 2000 series aluminum
 - Kinetics of the cross linking reaction in UVCPC
 - Time based equations

$$v_i = 2k_d f[I]$$

Eq. (1) initiation

$$v_p = k_p [M][M \cdot]$$

Eq. (2) propagation

$$v_t = 2k_t [M \cdot]^2$$

Eq. (3) termination

UVCPC Adhesion

- Adhesion of UVCPC over 2000 series aluminum
 - Concentration of free radicals directly related to dose received
 - For a given “instant” in time:
 - WPAFB instantaneous free radical conc. is 3.4 times PCRG lamp
 - WPAFB instantaneous free radical conc. is 5.4 times NASWI lamp
 - Results in a relative increase of 11.6, or 29 time increase in v_t between WPAFB, PCRG, and NASWI lamps

$$v_p = k_p [M] [M \cdot]$$

$$v_t = 2k_t [M \cdot]^2$$

- If v_t is $\geq v_p$, then:
 - Premature termination
 - Excessive shrinkage
 - Low cross link density
 - No or poor adhesion

UVCPC Adhesion

■ Summary of Adhesion Issue:

- Copper or other free radical scavengers have an effect
 - Scavenger “effect” can be overcome with:
 - Certain chromate conversion coatings
 - Anodizing
 - Epoxy based wash primer
 - Adjustment “tweak” in formulation
- Kinetics based on free radical concentration at an instant in time
 - Overcome termination rate by spreading the dose
 - A little longer cure is a “better” cure (5 seconds vs. 1 second)
- These factors have now been demonstrated by actual test

UVCPC Demonstration

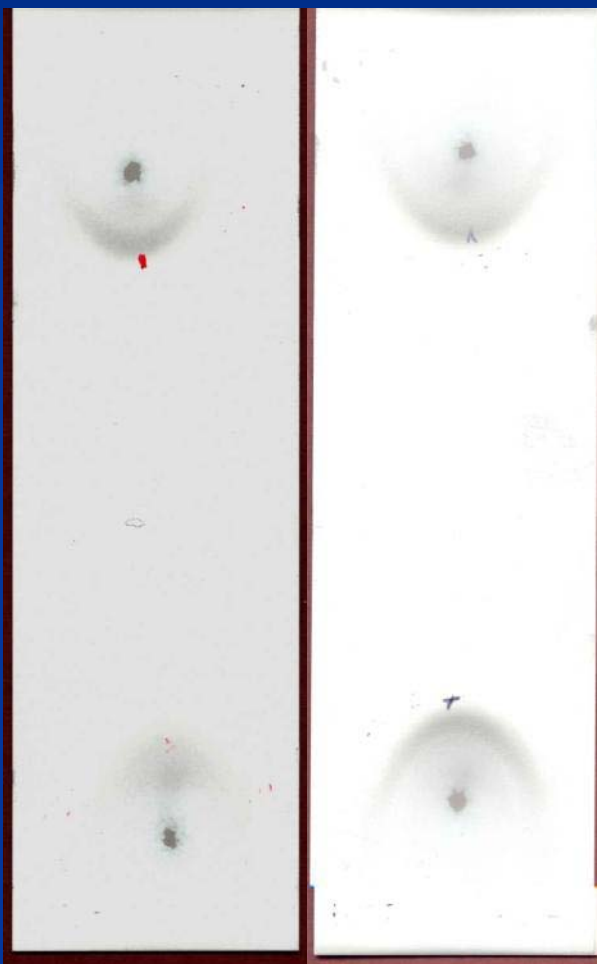
- General test results
 - Strippability



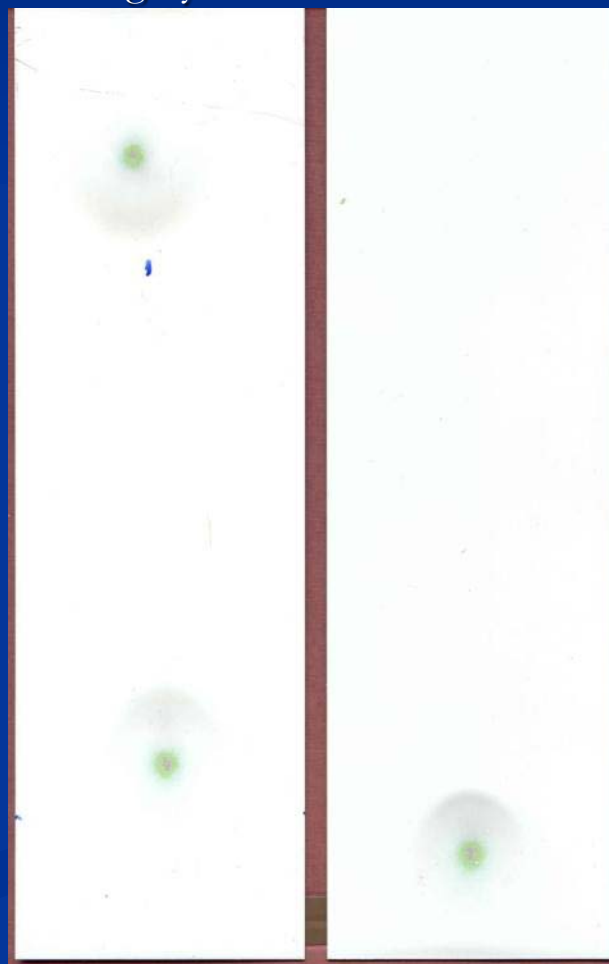
UVCPC Demonstration

■ Falling sand testing

UVCPC over 2024 Anodized



Legacy over 2024 Anodized



UVCPC Demonstration

- Actual components coated
 - Coast Guard MC-130 landing gear door
 - Entrained moisture created huge bubble during IR phase



UVCPC Demonstration

- Actual components coated
 - Coast Guard MC-130 landing gear door
 - Entrained moisture created huge bubble during IR phase



UVCPC Demonstration

- Actual components coated
 - Coast Guard MC-130 landing gear door
 - Entrained moisture created huge bubble during IR phase



UVCPC Demonstration

- Better Robotic Profiling
 - Use of small radiometers
 - Extended use of thermal profiling



UVCPC Demonstration

- Better Powder Coating
 - Use of non-contact uncured powder thickness gauge



UVCPC Demonstration

- Estimated Cost of Improvements
 - Hardware - \$6K
 - Robotics modifications - \$12K
 - Coatings reformulation and revalidation - \$120K