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PPG

Enabling Energy
Glass & Coatings for Solar Power

High Performance Reflector Panels for Concentrating Solar Power Assemblies

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Outline

- Objective
- Overview
- Technical Approach
- Key Results/Accomplishments
  - ➢ Environmental durability test results (Test Matrix 5 and 6)
  - ➢ Benchmarking of alternative encapsulants
  - ➢ Improvement of PPG encapsulant
  - ➢ Novel alternative encapsulation process
  - ➢ Reflective coating performance
  - ➢ Impact on LCOE
- Key Challenges
- Next Steps
- Summary

Project Objective

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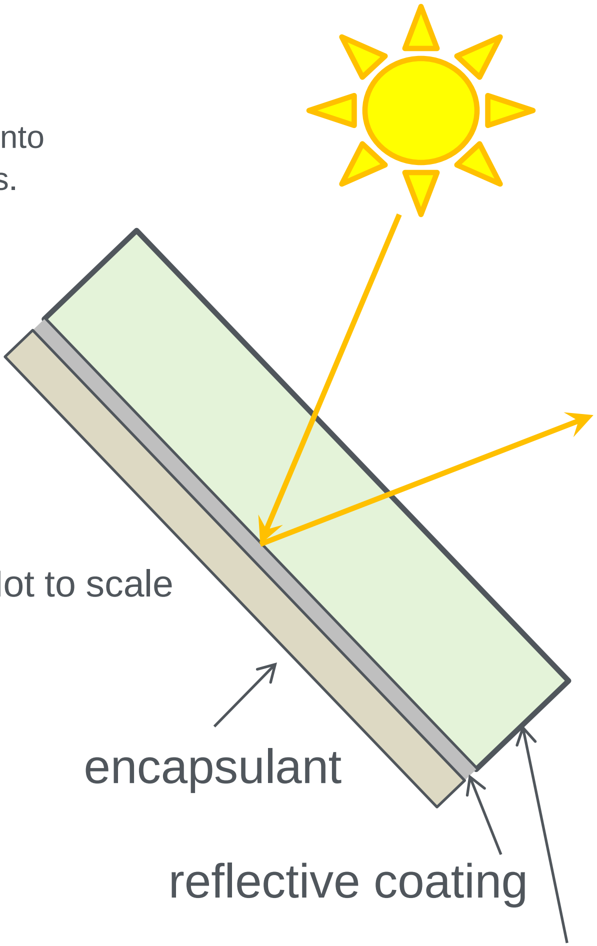
Objective: Develop and commercialize large-area second-surface glass-based mirrors having superior value (performance & cost → reduce LCOE)

This objective will be accomplished through research and development activities into alternate materials, structures, and fabrication processes for reflector components.



Overview

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Timeline

- Preliminary PPG work: 2007 – early 1Q2008
- Phase I: March – September 2008 (complete)
- Phase II: October 2008 – September 2010 (complete)
- Phase III (in-progress): October 2010 – April 2012

Barriers/Challenges*

- Task: Develop Advanced Reflector/Concentrator
- Barriers/challenges addressed
  - Optical performance of reflectors
  - Reliability (durability/product longevity) of reflectors → 20+ years outdoors required
  - Fabrication/manufacturability (e.g. tempering, bending) of reflectors
  - Economics

External Interactions

- NREL
- Encapsulant application
- Bending feasibility
- Corrosion mechanism studies

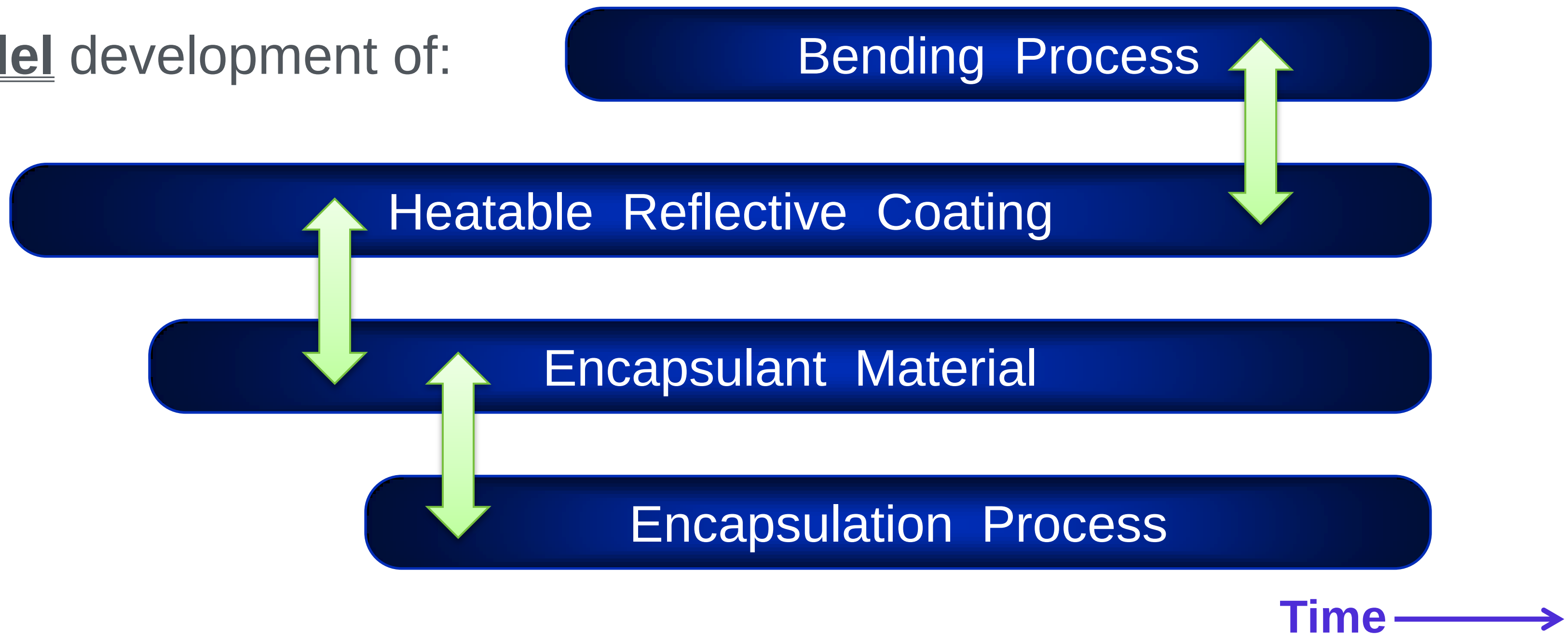
*Reference: http://www1.eere.energy.gov/solar/pdfs/solar_program_mypp_2008-2012.pdf

Technical Approach

Three product types:

1. Flat "annealed" (non-temperable)
2. Flat temperable
3. Bent

Parallel development of:



while assessing and improving **durability** and checking compatibility with other materials (e.g. adhesives)

Key Accomplishments (by Project Phase; Slide 1 of 2)

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- Phase I
  - Identified candidate encapsulant materials/processes
  - Executed initial durability testing
  - Demonstrated lab-scale coat-flat-then-bend feasibility for CSP geometries
  - Verified economics → ~ 5% reduction in levelized cost of electricity (LCOE)
- Phase II
  - Breakthrough encapsulant identified; defined encapsulation process parameters for Phase III scale-up
  - Demonstrated manufacturing-scale bendability; defined bending process parameters for Phase III scale-up
  - Executed validation tests on experimental prototype mirrors (“Test Matrix 5” → complete)
  - Completed Phase II work → DOE approved “Go” to Phase III

Key Accomplishments (by Project Phase; Slide 2 of 2)

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- Phase III
  - Objectives
    - **Decision: focus on flat non-tempered and tempered mirrors for DOE portion of project**
    - Scale up
    - Complete final testing
    - Commercialize
  - Accomplishments to-date
    - Completed Test Matrix 5
    - Executed manufacturing-scale encapsulation trial (conventional) to benchmark commercially-available encapsulants vs. PPG (January 31-February 2, 2011)
    - Executing validation tests on experimental prototype mirrors (“Test Matrix 6” in-progress)
    - Improved PPG Pb-free encapsulant formulation
    - Developing alternative novel encapsulation process (in parallel with “conventional” curtain-coating process); built and demonstrated pilot-scale process
    - Demonstrated deposition of reflective coating on large-area glass substrates at targeted production throughputs (May 9-10, 2011)

Milestones & Status

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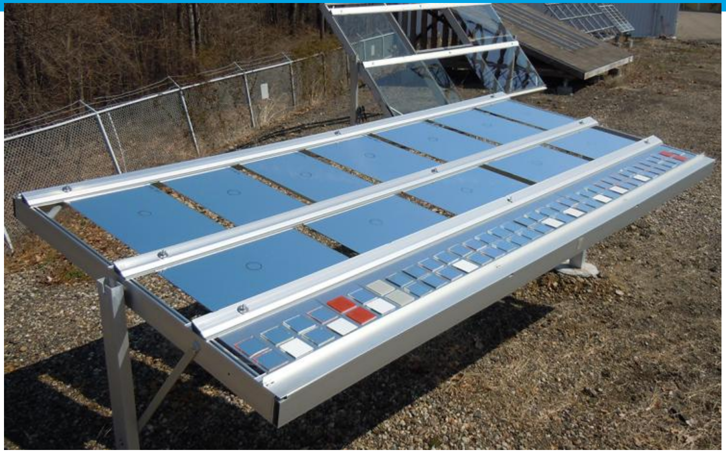
Phase	Milestone	Status
1	Identification of protective coating candidates	Complete
1	Update on progress towards design verification and bending evaluation	Complete
1	Critical: Go / No Go recommendation	Go
2	Identification of process parameters for scaled-up manufacturing process (i.e. encapsulant application)	Complete
2	Identification of process needs for large scale, high-rate mirror fabrication (i.e. bending)	Complete
2	Prototype mirror samples for validation	Complete
2	Critical: Go / No Go recommendation	Go
3	Production mirror samples suitable for validation	In-progress
3	Finalize initial target customers and supply samples from robust manufacturing process	
3	Critical: Technical report and presentation on anticipated impact of this technology	

Accomplishment: Environmental Durability (“Test Matrix 5” Results)

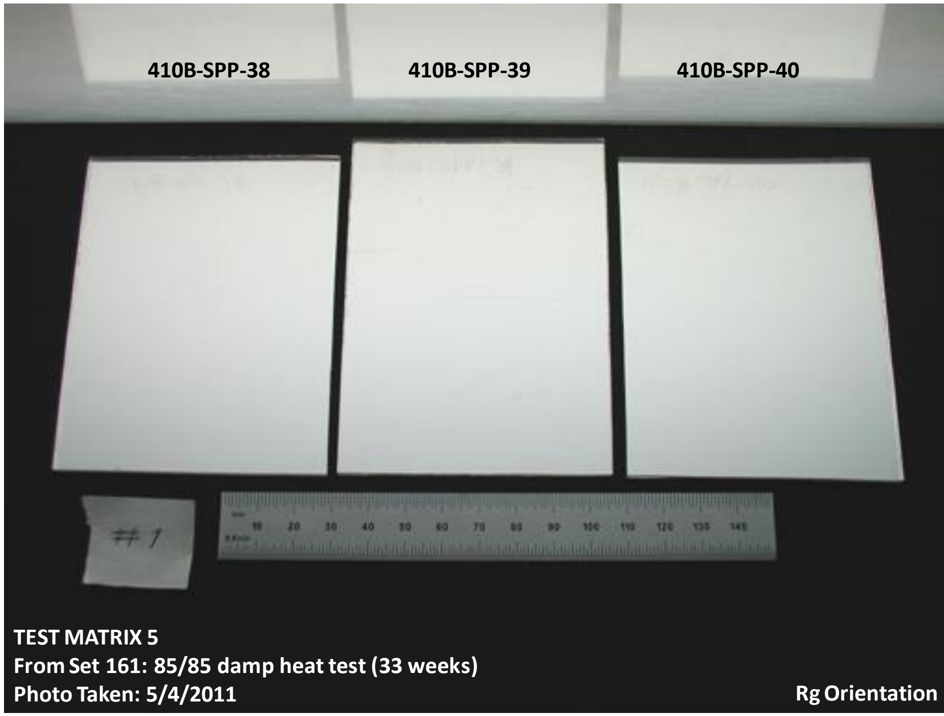

Cheswick (Pittsburgh), PA exposure site

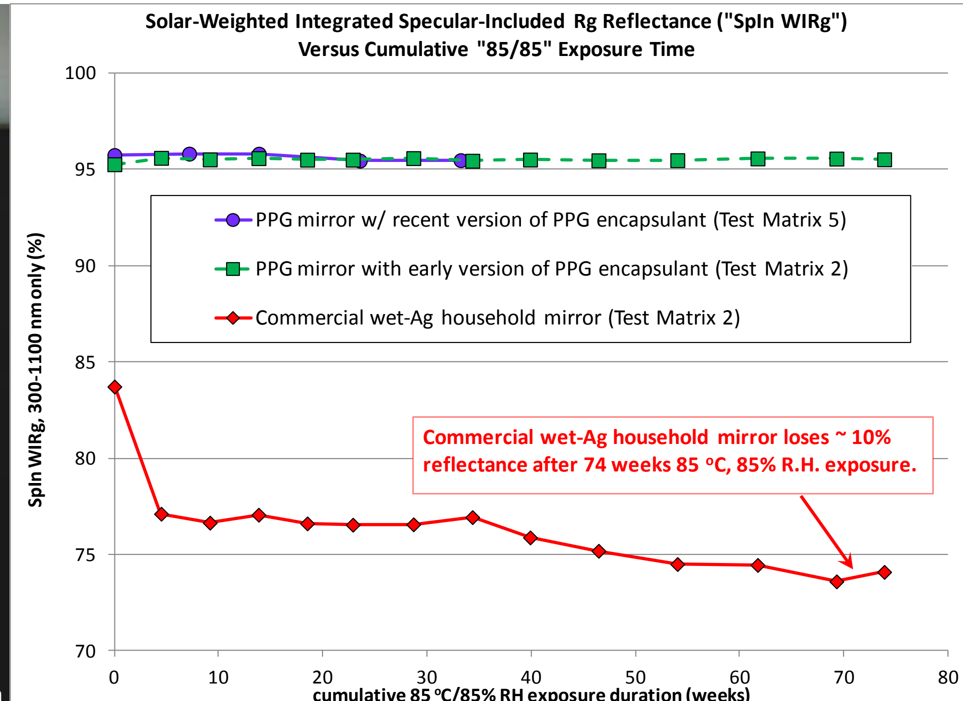

Fresno, CA exposure site

- 15+ exposure protocols, including:
  - CASS* Fog → very corrosive → primary screening test (fast)
  - “85/85”** damp heat → “harshest test for wet-Ag solar mirrors” (NREL input) (but, long feedback loop → weeks/months)
- All Test Matrix 5 exposures completed (except outdoor exposures → ongoing)
- Good performance in most tests
  - Encapsulant adhesion issues in some tests → modified formulation (part of Test Matrix 6, in-progress)

*CASS = Copper-Accelerated Acetic Acid-Salt Spray test (ASTM B368, DIN 50021)
**85 ^{o}C/85% R.H.

Accomplishment: Test Matrix 5 Results
(85 ºC/85% R.H. "Damp Heat" Test)





Samples tested in triplicate → no visible damage after 33 weeks 85 ºC, 85% R.H. exposure (Test Matrix 5 → exposure terminated)

KEY TAKE-AWAY

Encapsulated PPG mirrors sustain high reflectance and fare better than commercial wet-Ag household mirror in 85 ºC, 85% R.H. damp heat exposure.

Accomplishment: Test Matrix 5 Results
(240 Hour CASS Fog Exposure)

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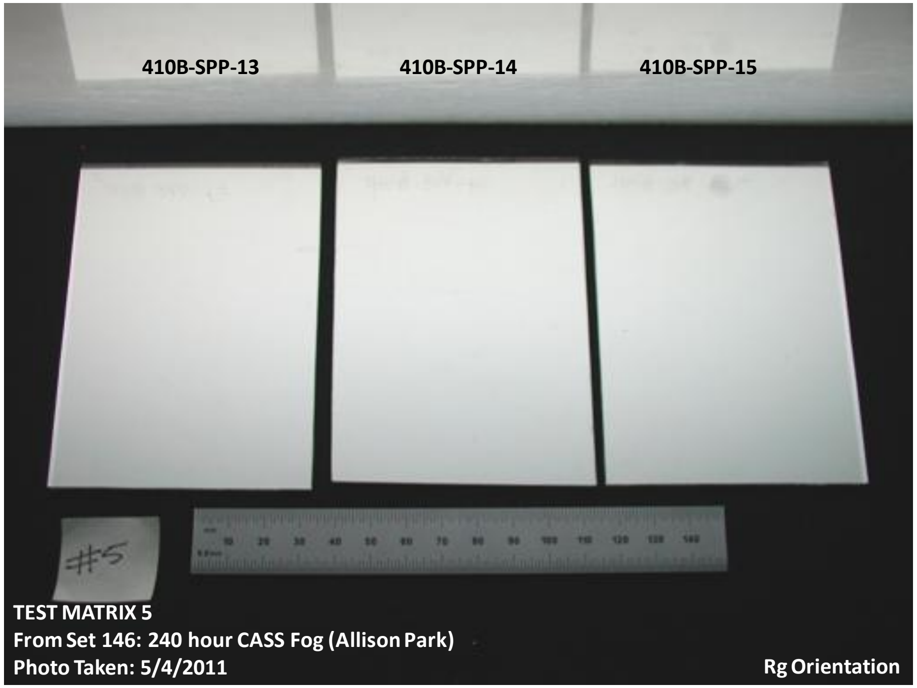


Samples tested in triplicate → no visible damage after 240 hours CASS Fog exposure.

t-Test: Paired Two Sample for Means --> solar-weighted integrated reflectance, 300-1100 nm		
	initial/pre-exposure	*final/post-exposure*
Mean	95.79	95.87
Variance	0.0002	0.0003
Standard Deviation	0.02	0.02
Observations	3	3
Pearson Correlation	0.2260	
Hypothesized Mean Difference	0	
df	2	
t Stat	-7.304	
P(T<=t) one-tail	0.009116	
t Critical one-tail	2.9200	
P(T<=t) two-tail	0.01823	
t Critical two-tail	4.303	

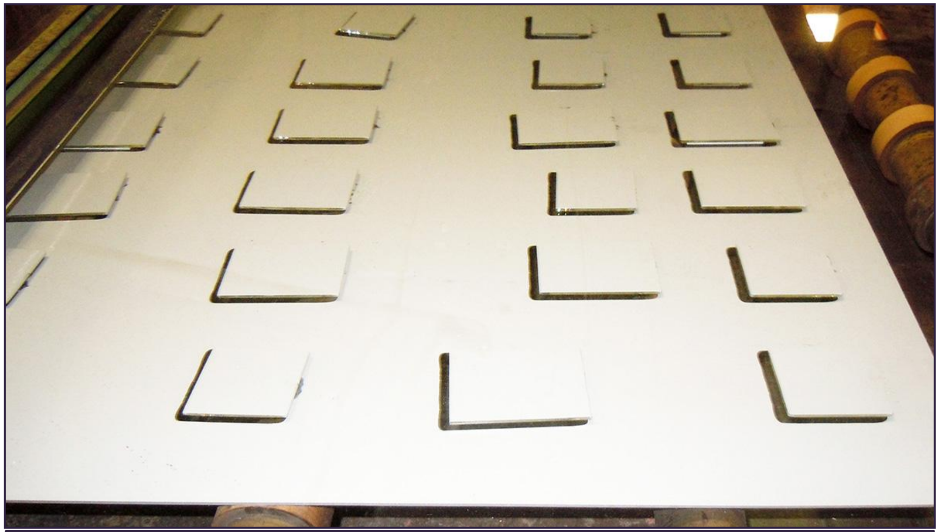
No loss of reflectance after 240 hours CASS Fog exposure

<u>KEY TAKE-AWAY</u>

PPG Pb-free encapsulant well protects reflective coating in 240 hour CASS Fog test.

Accomplishment: Manufacturing-Scale Encapsulation Trial → Benchmark Alternative Encapsulants

17.5 inch x 72 inch full-size mirrors passing through curtain coater



Test coupons (e.g. 3 inch x 4 inch) having different edgework types riding on carrier plate through coating process

- Manufacturing-scale trial (100 inch wide line, curtain coating process) January 31-February 2, 2011
- Applied three commercially-available CSP-grade solar mirror encapsulants (up to 72 inch x 84 inch): two Pb-free ("Paint 1", "Paint 3"), one Pb-containing ("Paint 2")
- Different "edgework" types
- Specimens included in Test Matrix 6 (in-progress).

Test Matrix 6: Mirror "Edgework Types" (not to scale)

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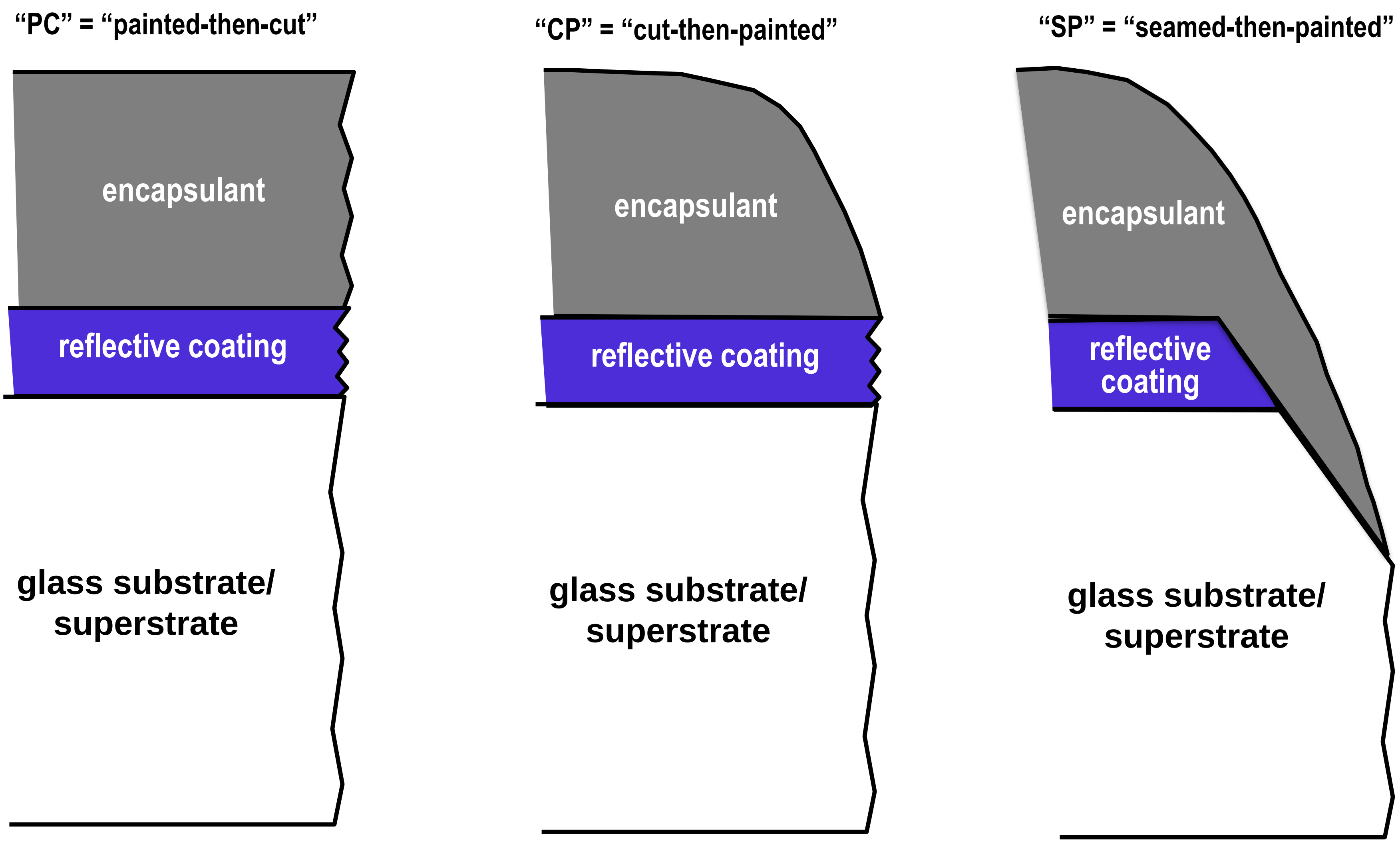
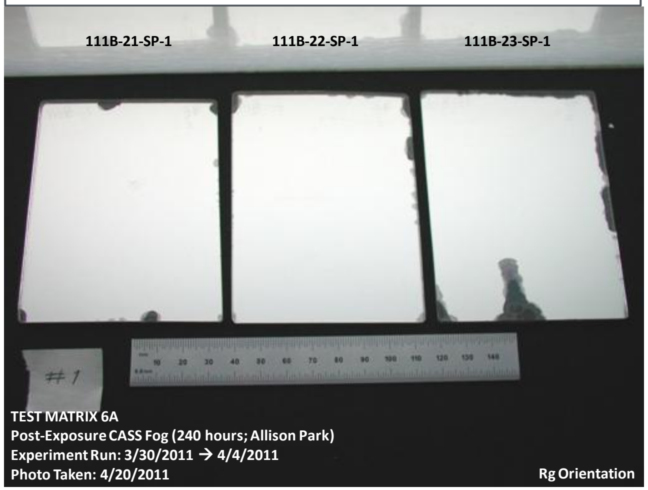


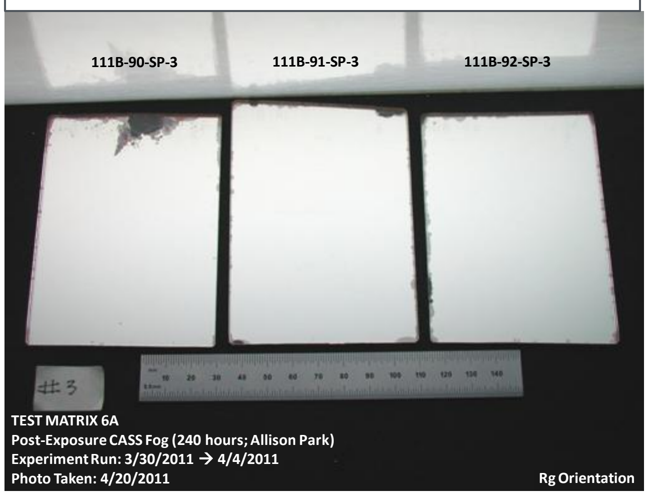
Accomplishment: Benchmark Alternative Encapsulants (Test Matrix 6 → ~1,200 specimens)

"Paint 1" ("Supplier A")



"Paint 2" ("Supplier B")

"Paint 3" ("Supplier B")

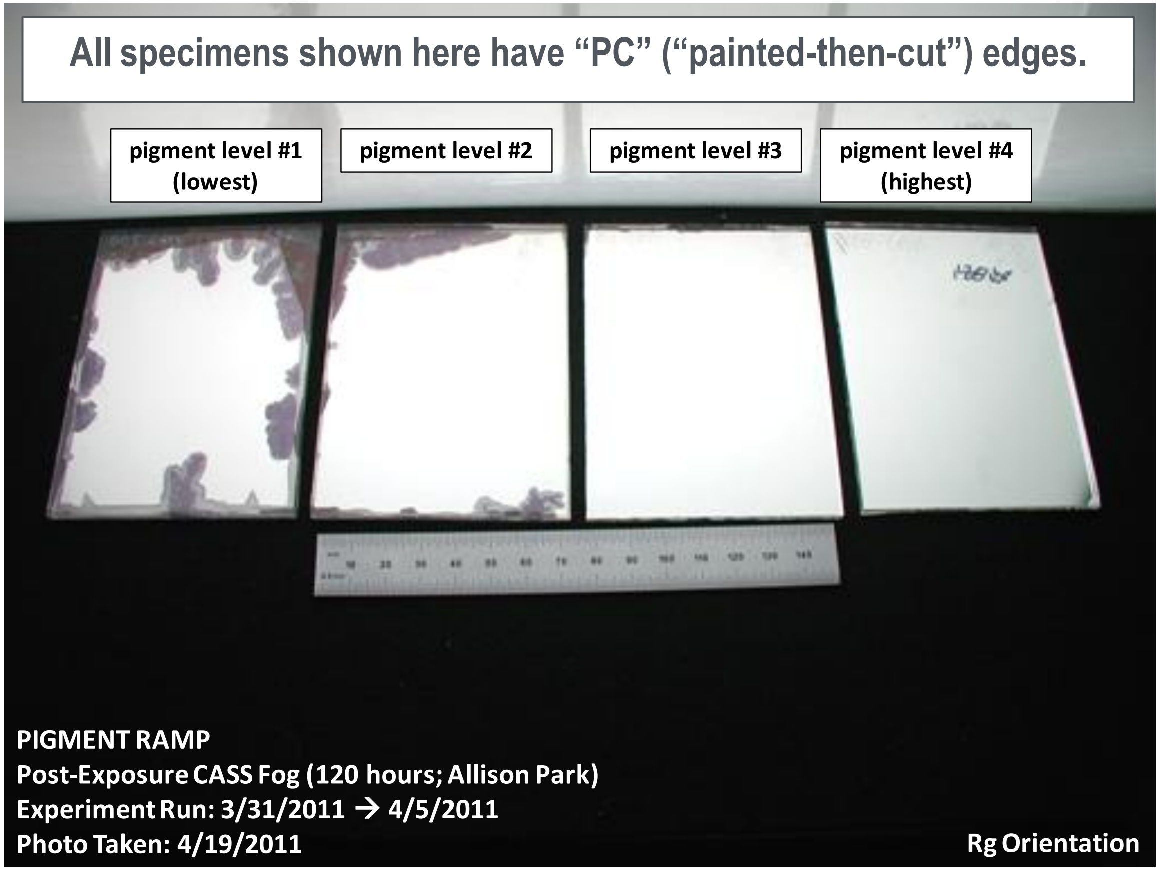


"Paint 4" : PPG Pb-Free Encapsulant

- Commercially-available CSP-grade encapsulants are not performing as well as expected in CASS test
- No clear difference between commercially-available Pb-free paints (Paints 1, 3) and Pb-containing paint (Paint 2) in CASS test
- **Best-performer in CASS Fog test is PPG Pb-free encapsulant (Paint 4).**
- Note: (1) Paints 1-3 curtain-coated on manufacturing-scale line → some encapsulant defects on small samples → negative impact on durability?; (2) Paint 4 (PPG) coated using lab-scale curtain coater
- Recent/current work: optimize pigment concentration to further improve protective robustness of PPG encapsulant (see next slide)

*CASS = Copper-Accelerated Acetic Acid-Salt Spray test (ASTM B368, DIN 50021)

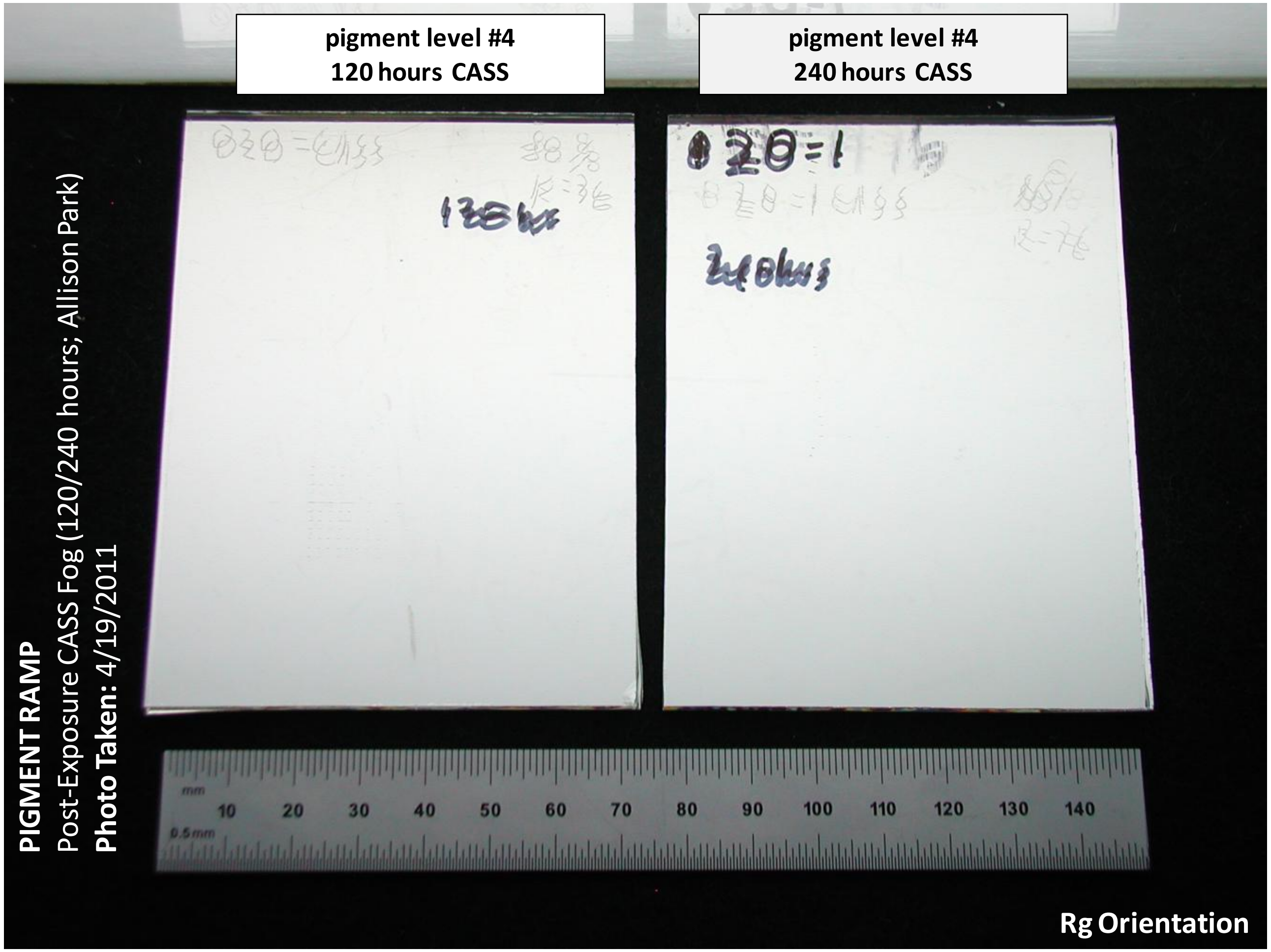
Accomplishment: Improved PPG Encapsulant Formulation



- Optimize corrosion-inhibitive pigment concentration → good CASS durability
- Curtain-coatability of optimized formulation demonstrated → planning for production scale-up
- Manufacturing-scale encapsulation trial: target September 2011.

*CASS = Copper-Accelerated Acetic Acid-Salt Spray test (ASTM B368, DIN 50021)

Accomplishment: Improved PPG Encapsulant Formulation



KEY TAKE-AWAY

PPG's improved Pb-free encapsulant, with increased corrosion-inhibitive pigment, well protects reflective coating for at least 240 hours CASS Fog exposure even for specimens with "PC" ("painted-then-cut") edges.

*CASS = Copper-Accelerated Acetic Acid Salt Spray test (ASTM B368, DIN 50021)

Accomplishment: Improved PPG Encapsulant Formulation

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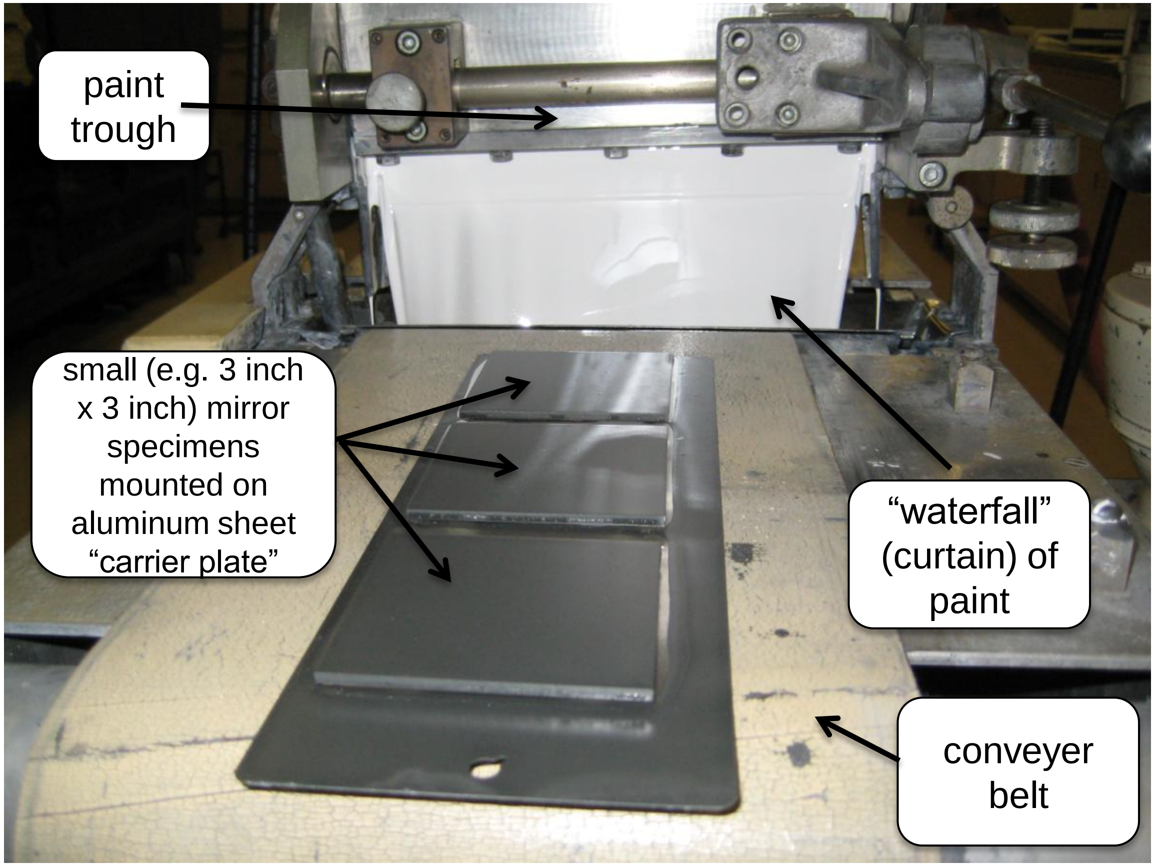

- Curtain-coatability of improved PPG encapsulant formulation demonstrated on lab-scale (6 inch wide) coater → currently optimizing formulation for production scale-up
- Manufacturing-scale encapsulation trial: target September 2011.

Accomplishment: Alternative Encapsulation Process

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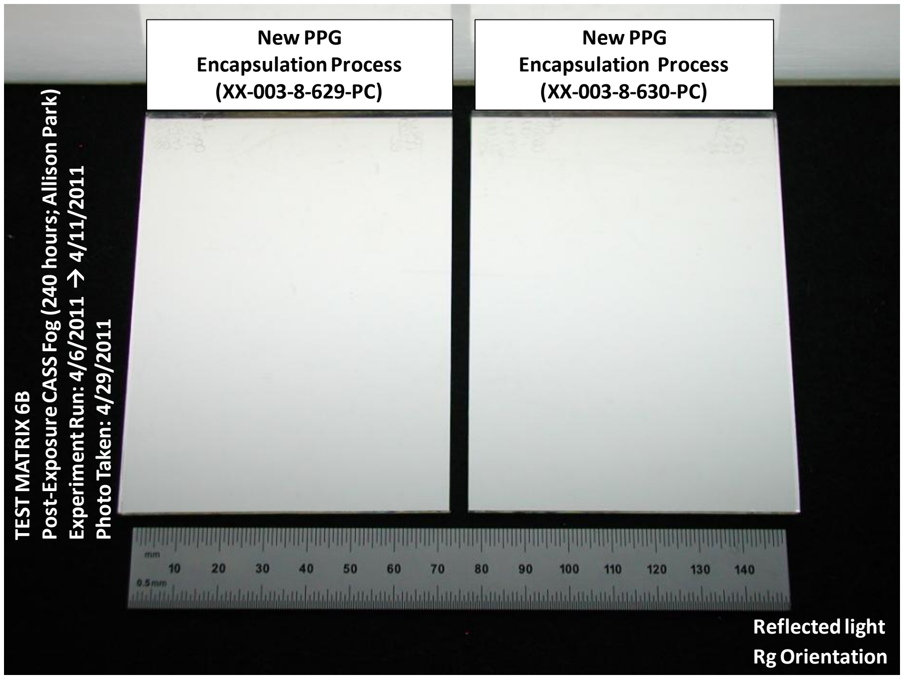
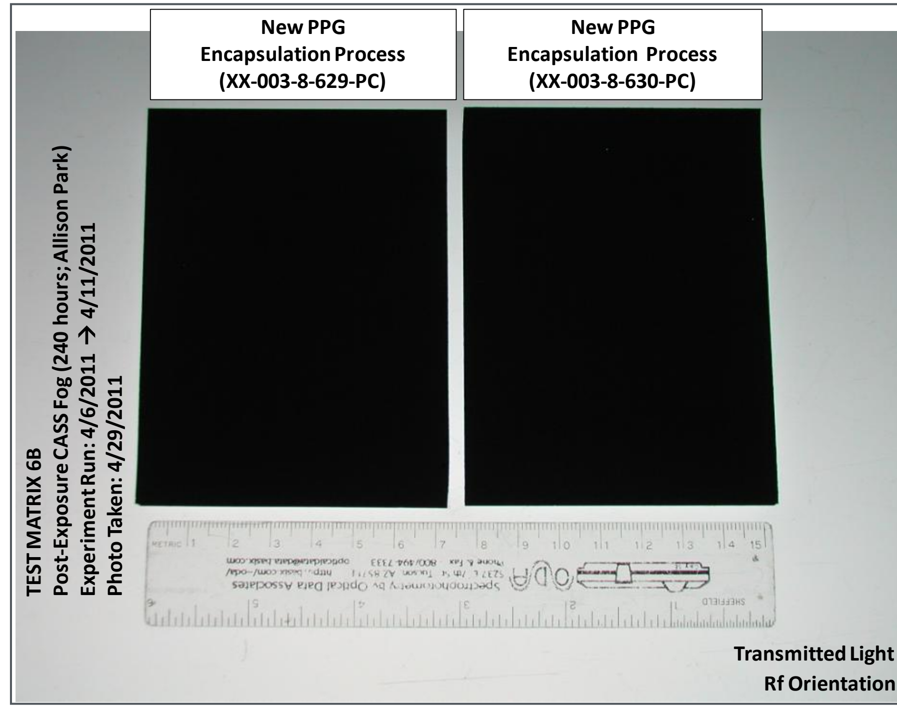
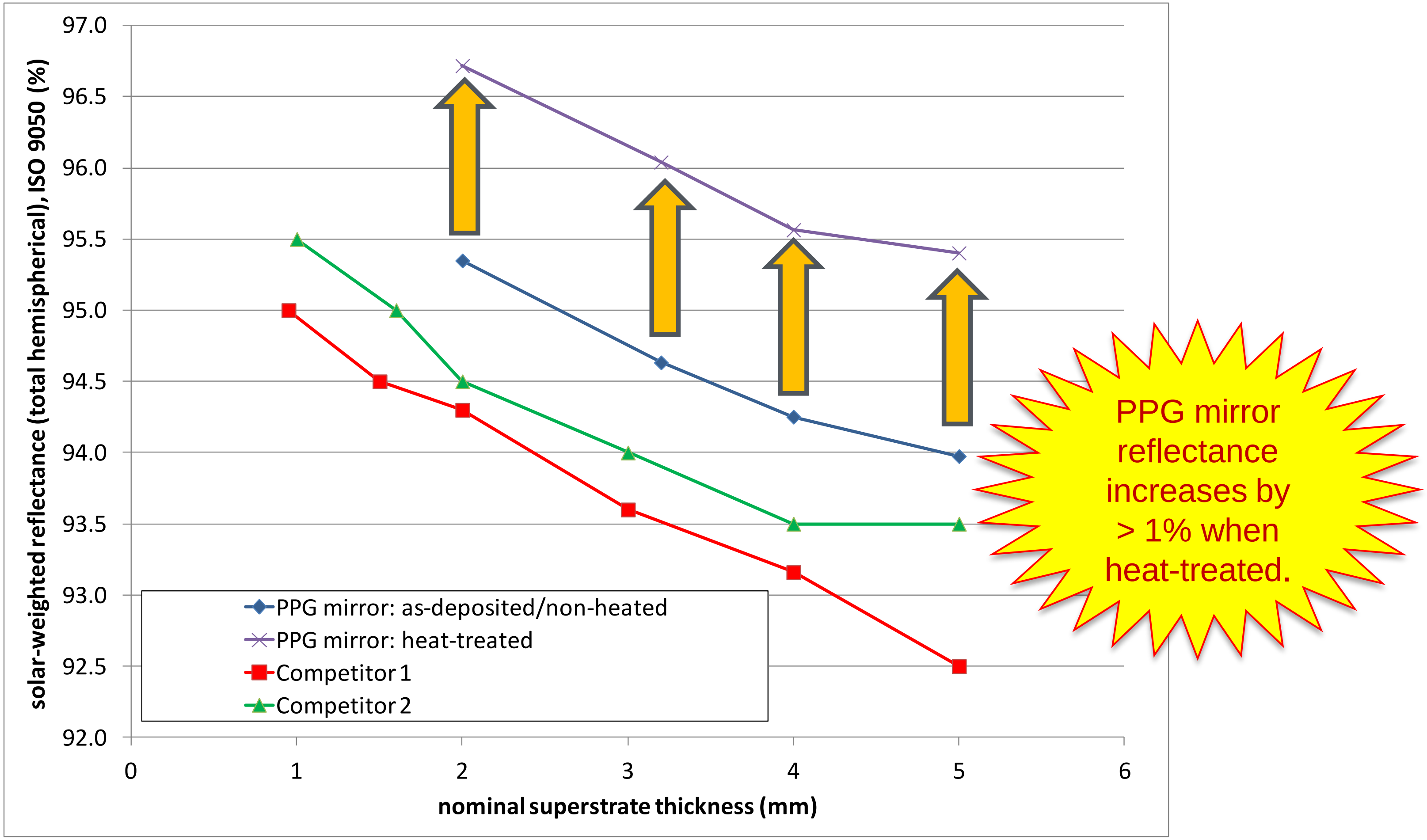




- Novel encapsulation process in-development → alternative to conventional application techniques (e.g. curtain coating, roll coating)
- Reduces VOCs vs. conventional solvent-borne process
- High transfer efficiency
- Pilot-scale coater built → coat up to 24 inch x 36 inch panels
- **Good CASS Fog durability at lower pigment levels even for "PC" ("painted-then-cut") edges**

*CASS = Copper-Accelerated Acetic Acid-Salt Spray test (ASTM B368, DIN 50021)

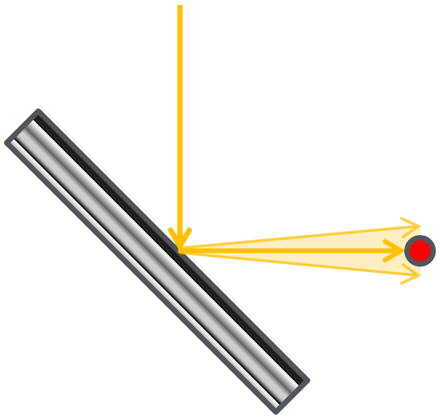
Accomplishment: Reflective Coating Optical Performance

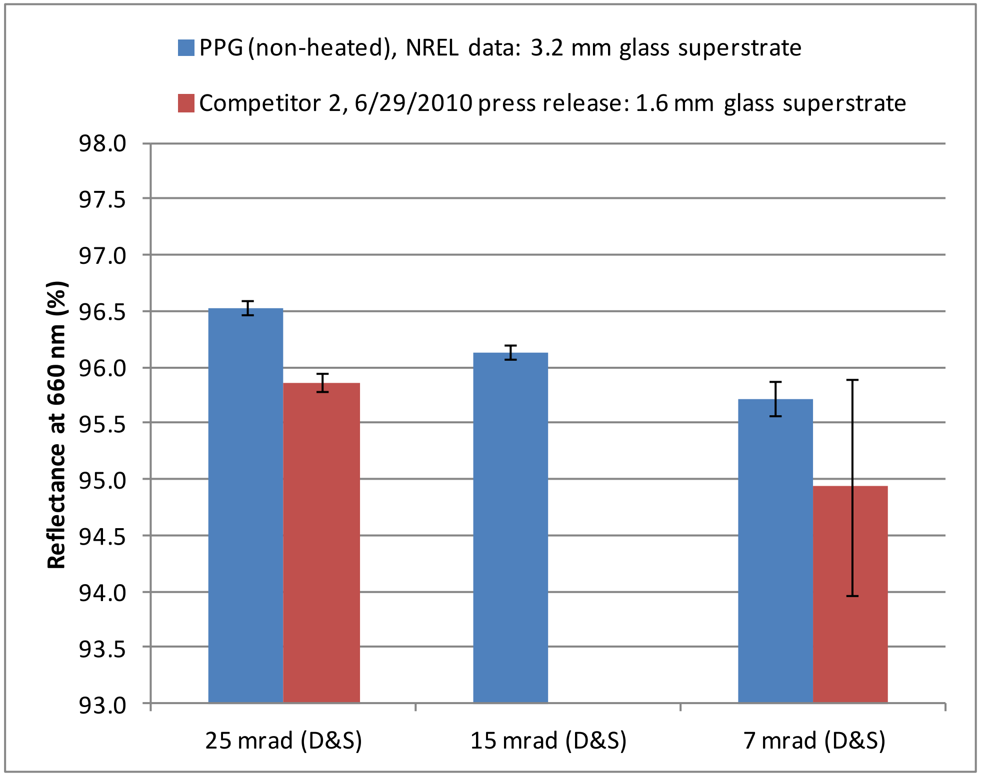


KEY TAKE-AWAYS

1. **Heat-treatment increases PPG mirror's reflectance by more than 1%.**
2. **PPG mirror has higher reflectance than Competitors 1 & 2 reported values at equivalent superstrate thicknesses.**

Accomplishment: Specularity of Reflective Coating





Specularity requirements → dependent on CSP technology

Parabolic Trough: 15 mrad
Dish: 2 mrad
Tower: 1-2 mrad
CLFR: 25 mrad

KEY TAKE-AWAY
PPG's 3.2 mm thick mirror's specularity at 660 nm is comparable to, or better than, Competitor 2's 1.6 mm thick mirror.

Accomplishment: Impact on LCOE

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mirror type	mirror reflectance, solar-weighted (%)	total direct costs ($MM)	% change in total direct costs vs. baseline (SEGS VI) case	real LCOE ($/Mwh)	% change in LCOE vs. baseline (SEGS VI) case
SEGS VI	92.8	569.5	0.0%	86.3	0.0%
S&L 2008	92.8	543.8	-4.5%	82.9	-3.9%
PPG	94.1	532.4	-6.5%	81.2	-5.9%

SAM Version:	2.5.0.2
System:	200MW Baseline 500C w/6hr TES
Climate:	CA Daggett.tm2
Federal ITC Percent:	10
Utility Rates:	SCE
Financials:	Utility - IPP
Solar Multiple:	2
Field Spec:	LS-3 w/modified %R, HiTec 500C, Molten Salt Storage, Schott PTR70
Baseline %R:	Competitor #1: Ag/Cu with low-Pb encapsulant (per C. Kennedy, NREL)

Parabolic trough baseline case assumed for LCOE analyses per SAM version 2.5.0.2

KEY TAKE-AWAYS

1. **PPG mirrors reduce total direct costs by ~ 5.5-6.5% vs. baseline case.**
2. **PPG mirrors reduce LCOE by ~ 5-6% vs. baseline case.**

Challenges
(Technical & Non-Technical)

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- No CSP industry mirror durability standards
- No access to competitive CSP mirrors (or data) for benchmarking (reflectance and durability)
- Long feedback loops on some durability tests
- PPG encapsulant
  - "In-can" shelf-stability
  - Protective efficacy (use CASS Fog test to screen/optimize)
  - "Drop-in" compatibility with existing manufacturing encapsulant application/curing infrastructure
  - Cost

Next Steps

- Demonstrate deposition of reflective coating at expected commercial line speed on production coater; produce large-area mirrors for manufacturing-scale application trial of PPG encapsulant
  - **Completed May 9-10, 2011**
  - **Demonstrated up to 72 inch x 84 inch**
  - **Expect scalable to larger sizes**
- Complete lab-scale development of PPG encapsulant (2Q2011); optimize/refine/confirm:
  - "In-can" shelf-stability
  - Protective efficacy (use CASS Fog test to screen/optimize)
  - Compatibility with existing encapsulant application/curing process
  - Cost
  - Produce appropriate volume for manufacturing-scale trials
- Execute manufacturing-scale application trial of PPG encapsulant; produce specimens for final round durability tests: Sept. 2011
- Execute final round durability tests ("Test Matrix 7"): 4Q2011-1Q2012
- Write final DOE project report: 2Q2012

Summary

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Using DOE funding and non-DOE funding, PPG is continuing development of a new second-surface glass mirror for CSP applications:

- High reflectance → advantage: PPG
- Coated glass can be tempered or bent (before encapsulation)
- Bending feasibility demonstrated (but current focus on flat mirrors)
- Reflectance increases after heat-treatment
- PPG Pb-free encapsulant developed and improved → full-scale trial target 3Q2011
- Novel alternative encapsulation process demonstrated at pilot scale (up to 24 inch x 36 inch)
- Promising environmental durability test results (Test Matrix 5); Test Matrix 6 in-progress
- Executed manufacturing-scale encapsulation trial to benchmark alternative commercially-available encapsulants (January 31-February 2, 2011)
- Demonstrated manufacturing-scale reflective coating deposition at full production speeds (May 9-10, 2011)
- Environmental advantages of PPG approach: (1) no wet-Ag process wastes, (2) Pb-free encapsulant