POLYMERIC MIRROR FILMS: DURABILITY IMPROVEMENT AND IMPLEMENTATION IN NEW COLLECTOR DESIGNS

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Awardee: 3M
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Presenter: Dr. Daniel Chen

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Outline

• Background and Objectives
• Technical Approach and Results
• Summary and Key Lessons

• CSP Cost Reduction and Solar Collectors
• Film based Solar Collectors
• Conclusions
Project Objectives and Outcomes

Objectives

• Develop novel optical coatings for silvered polymeric mirrors with PMMA front surfaces
• Contribute to cost reduction in CSP solar field
• Demonstrate manufacturing processes for these optical coatings and incorporate onto mirrors
• Validate the impact of these novel optical coatings in field trials (Abengoa, Gossamer Space Frames)

Expected Outcomes

• Decrease the rate of loss of specular reflectance by 50%
• Decrease the rate of irreversible soiling by 50%
• Reduced frequency of cleaning and O&M costs
• Expand mechanical cleaning options
• Positive impact on LCOE by enabling reflective film based collector designs
3M Silvered Polymeric Mirrors: Substrates for Coating Development

Description
- Broadband solar reflector based on metalized polymer film
- Silver as reflective layer

Key Features
- Film-based reflector enables design flexibility & optimization
- High reflectivity and specularity
- Break resistant
- Low weight
- Scalable manufacturing

<table>
<thead>
<tr>
<th>Property</th>
<th>3M Solar Mirror Film 1100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar Weighted Hemispherical Reflectance (G173)</td>
<td>94.5%</td>
</tr>
<tr>
<td>Specular Reflectance at 25 mradian acceptance angle</td>
<td>95.5%</td>
</tr>
</tbody>
</table>

Source: S. Meyen et. al, Standardization of Solar Mirror Reflectance Measurements Round Robin Test, SolarPACES 2010
Projects using Solar Mirror Films

Abengoa Solar, El Tosoro Chile
10 MW thermal
Uses 3M SMF 1100 Mirror Film
Commissioned Fall 2012

Photo Courtesy Abengoa Solar

Abengoa Solar, Englewood, CO USA
1.2 MW thermal
Uses 3M SMF 1100 Mirror Film
Commissioned June 2010

Photo Courtesy Abengoa Solar
Mirror Films: Key Durability Concerns

- Resistance to UV degradation
- Abrasion resistance
- Interlayer delamination

Courtesy: C. Kennedy, NREL

Graph showing % reflectance over exposure time (Yr) and Equivalent NREL Exposure Time (Yr)
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Optimization of Coating Properties

Balancing performance of virgin coatings against durable adhesion and compatibility with processing is critical to durable function.
## Mirror Durability Considerations

<table>
<thead>
<tr>
<th>Failure Mode</th>
<th>Root Cause(s)</th>
<th>Impact</th>
<th>Test Methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corrosion</td>
<td>Coating failure</td>
<td>Mirror graying</td>
<td>Damp heat</td>
</tr>
<tr>
<td></td>
<td>Edge sealing failure</td>
<td>Loss of reflectivity</td>
<td>Outdoor exposure</td>
</tr>
<tr>
<td>Abrasion</td>
<td>Installation</td>
<td>Loss of specularity</td>
<td>Taber abrasion</td>
</tr>
<tr>
<td></td>
<td>Windborne sand</td>
<td></td>
<td>Falling sand</td>
</tr>
<tr>
<td></td>
<td>Low surface hardness</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radiative degradation</td>
<td>Poor UV protection</td>
<td>Hazing</td>
<td>Xenon arc</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Loss of reflectivity</td>
<td>UV exposure</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Outdoor exposure</td>
</tr>
<tr>
<td>Delamination</td>
<td>Low interlayer adhesion</td>
<td>Loss in specularity</td>
<td>Water immersion</td>
</tr>
<tr>
<td></td>
<td>Liquid moisture with</td>
<td></td>
<td>Salt water immersion</td>
</tr>
<tr>
<td></td>
<td>edge seal failure</td>
<td></td>
<td>Outdoor exposure</td>
</tr>
<tr>
<td>Yellowing</td>
<td>Chemical interactions</td>
<td>Loss of reflectivity</td>
<td>UV exposure</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Colorimeter</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Outdoor exposure</td>
</tr>
<tr>
<td>Thermal degradation</td>
<td>CTE mismatch</td>
<td>Delamination</td>
<td>Thermal cycling</td>
</tr>
<tr>
<td></td>
<td>Water intrusion</td>
<td></td>
<td>Freeze-thaw</td>
</tr>
</tbody>
</table>
Technical Approach

Technical approach balances chemistry, durability and weathering to create a reliable solution at optimal cost.
Key Accomplishments:
Durable Coatings with Durable Adhesion

Demonstrated 30-75% improvement in abrasion resistance, retention of performance after >5000 h or accelerated weathering

* 3M Proprietary Exposure Cycle
Key Accomplishments: Durable Coatings with Durable Adhesion

Surfaces of Weathered Samples
4000 h*, 60,000 x Magnification

PMMA

Hardcoated PMMA

Coatings can demonstrate significant improvement in surface durability and uniformity over acrylic surfaces

* 3M Proprietary Exposure Cycle
Key Accomplishments: Coatings with Enhanced Cleanability

Additives may improve non-contact cleanability relative to PMMA
Retention past 4000 h of accelerated weathering
## Weathering results on production material

### Accelerated Weathering Feb 2013

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Test</th>
<th>0 hrs</th>
<th>500 hrs</th>
<th>1000 hrs</th>
<th>1500 hrs</th>
<th>2000 hrs</th>
<th>2500 hrs</th>
<th>3000 hrs</th>
<th>$\triangle$/final – initial</th>
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<tbody>
<tr>
<td>101027-003</td>
<td>Specularity</td>
<td>93.7</td>
<td>93</td>
<td>93.1</td>
<td>93.4</td>
<td>92.8</td>
<td>93.1</td>
<td>92.7</td>
<td>-1</td>
</tr>
<tr>
<td></td>
<td>THR</td>
<td>92.7</td>
<td>92.6</td>
<td>92.6</td>
<td>92.6</td>
<td>91.9</td>
<td>92.0</td>
<td>91.8</td>
<td>-0.9</td>
</tr>
<tr>
<td>101027-004</td>
<td>Specularity</td>
<td>94.2</td>
<td>94</td>
<td>93</td>
<td>93.3</td>
<td>92.9</td>
<td>93.0</td>
<td>92.7</td>
<td>-1.5</td>
</tr>
<tr>
<td></td>
<td>THR</td>
<td>92.7</td>
<td>92.3</td>
<td>92.2</td>
<td>92.6</td>
<td>91.9</td>
<td>92.0</td>
<td>92.0</td>
<td>-0.7</td>
</tr>
<tr>
<td>Control</td>
<td>Specularity</td>
<td>94.3</td>
<td>94.1</td>
<td>93.7</td>
<td>NA</td>
<td>93.8</td>
<td>93.5</td>
<td>93.2</td>
<td>-1.1</td>
</tr>
<tr>
<td></td>
<td>THR</td>
<td>94.4</td>
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<td>92.7</td>
<td>92.6</td>
<td>-1.8</td>
</tr>
</tbody>
</table>
**Scale-Up**

- **Status**
  - Successful scale-up to full width (49”)
  - Volume in thousands of linear yards
  - Post processing complete to laminates

- **Challenges**
  - Web handling
  - Pre-mask adhesion

<table>
<thead>
<tr>
<th>Week 2</th>
<th>Week 12</th>
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</thead>
<tbody>
<tr>
<td>Process three different pre-masked film to choose the right pre-mask</td>
<td>1st Full width factory trial</td>
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</table>

<table>
<thead>
<tr>
<th>Week 17</th>
<th>Week 19</th>
</tr>
</thead>
<tbody>
<tr>
<td>2nd full width hardcoat run. Simultaneous coating of primer and hardcoat</td>
<td>1st full width adhesive coating trial</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Week 22</th>
<th>Week 25</th>
</tr>
</thead>
<tbody>
<tr>
<td>2nd full width Silver coating</td>
<td>2nd full width Adhesive coating</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Week 27</th>
<th>Week 30</th>
</tr>
</thead>
<tbody>
<tr>
<td>2nd full width Adhesive coating</td>
<td>Lamination to panels</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Week 32</th>
</tr>
</thead>
<tbody>
<tr>
<td>Panels from 2nd full width product on sun at test sites</td>
</tr>
</tbody>
</table>

Evaluation of hardcoated pre-mask film (surface, peel, specularity)

Sheeting and sampling to outdoor weathering sites
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Hardcoat Project: Summary and Key Lessons

• Summary
  – We have successfully developed coating formulations which significantly increase the abrasion resistance of mirror films
  – We have demonstrated manufacturing scale-up of these films to full width and production volumes
  – Implementation of these films in commercial test sites is planned for Q2 2013 (Abengoa, Gossamer Space Frames)

• Key Lessons
  – Importance of testing and test design
  – Interaction effects in film construction
  – Lab to manufacturing – scale-up, details matter
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Background

- High growth in new solar energy capacity, 10X increase since 2007
- PV dominant, over 90% share
- Cost reduction a key driver, over 70% reduction in PV module pricing since 2007
- CSP – dramatic cost reductions needed to remain competitive
- New solutions for the solar field a key opportunity
Positive outlook for solar energy in general, but current forecasts has CSP developing into a niche solution.
Opportunities for LCOE Reduction

• Lower costs
  – Novel designs – reduced materials
  – Lower cost components
  – Higher volume
  – Easier assembly
  – Reduced O&M costs

• Higher performance
  – Higher optical efficiency
  – Increased structural and shape accuracy
  – Higher operating temperature

LCOE = \frac{\text{Cost}}{\text{Performance}}

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Glass mirror based solar collector
Film based solar collector
Large Aperture Parabolic Trough

- Increasing aperture size leverages other solar field fixed costs
- Luz designs envisioned up to 10m aperture (LS-4). Design had a capital cost target of <$3000/kWe
- Flagsol Heliotrough, 15+% cost improvement for 6.8m aperture design
- Kolb and Diver estimate up to 15% LCOE reduction going from 5 to 10 m aperture

(2) U. Herrmann, CSP Summit, San Francisco, 2010

Larger aperture – an established means to reduce cost for parabolic trough CSP
Next Generation Solar Collector Design Approach

- **Design Concept**
  - Large Aperture parabolic trough
  - High concentration factor (100X +)
  - Increases productivity while minimizing solar field equipment

- **Elements**
  - Reflective film
  - Panel technology
  - Space frame


Integrated solution approach can address both cost reduction and performance improvement
Large Aperture Trough (LAT) Demonstration Loop

• Description
  – Solar Collectors: 12m x 7.3m
  – Concentration Factor: 103
  – Loop: 16 solar collectors
  – Output: 840 kWt / 275 kWe

• Location
  – Plant: SEGS I
  – Location: Daggett, CA
  – Host: Cogentrix
Test Loop – SEGS I
Large Aperture Trough (LAT)
Engineered by Gossamer Space Frames and 3M

Parabolic Trough Demonstration Loop
Aperture 7.3m
Concentration factor 103

Host
SEGS I - Cogentrix
Daggett, CA (Mohave Desert)
NREL Field Deployed VSHOT

Assumptions

- Errors in the longitudinal direction are neglected.
- The reflective surface has perfect specular reflectance.
- The receiver tube has 100% absorbance.
- A 70 mm receiver tube is modeled without a glass envelope.
- DLR-measured sun shape is used as the source.
- 49,000 rays normal to the aperture are traced.
VSHOT Example Results
Example Acceptance Window Plot

G_{A_{1N_p^9}s^13_M} FLray.csv

Transverse contour error (mrad)

Mirror aperture position (m)
## VSHOT Summary Results

<table>
<thead>
<tr>
<th>SCE</th>
<th>Build Type</th>
<th>Average RMS Slope error (mrad)</th>
<th>Maximum RMS Slope error (mrad)</th>
<th>Minimum RMS Slope error (mrad)</th>
<th>Average Intercept Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1A 3S</td>
<td>Standard</td>
<td>3.60</td>
<td>4.22</td>
<td>3.31</td>
<td>95.20%</td>
</tr>
<tr>
<td>2A 1N</td>
<td>Modification 1</td>
<td>2.45</td>
<td>3.51</td>
<td>1.45</td>
<td>98.80%</td>
</tr>
<tr>
<td>2A 2N</td>
<td>Modification 2</td>
<td>2.27</td>
<td>2.77</td>
<td>1.74</td>
<td>99.30%</td>
</tr>
</tbody>
</table>

![Graph showing mirror aperture position](image_url)
8m Aperture Trough

Courtesy: G. Reynolds, Gossamer Space Frames
Mirror Films: Heliostat Applications

• Background
  – Work driven by Sandia National Labs (Cliff Ho)\(^1\)
  – Mirror films typically not thought of as feasible for long focal range designs

• Objectives
  – Determine feasibility of mirror based heliostats
  – Explore new heliostat design options with mirror films

Comparison: Glass vs Mirror Film Facets

Current commercially available reflective films have potential for long focal length applications.
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Conclusions

• CSP
  – Solar Energy growing into a significant energy source globally (10X growth in 5 years)
  – CSP needs dramatic cost reduction in order to remain relevant

• Mirror Films
  – Mirror films enable new design space in solar collectors
  – Larger aperture parabolic trough collectors offer opportunity for cost reduction – reduced to practice at demonstration loop level
  – Feasibility of mirror films for long distance heliostats demonstrated

• Future Work (DE-EE005795 – 3M / Gossamer / Sandia / NREL)
  – New reflective films with higher SWTHR and specular reflectance
  – Advanced heliostat and solar collector design
Acknowledgments

Cogentrix – S. Frymeyer, K. Anderson, R. Lawerence, K., Koele

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National Renewable Energy Lab – C. Kennedy, A. Gray, M. Gray

Sandia National Lab - Cliff Ho

감사합니다

Danke  Эукаристиес  Dalu  Köszönöm  Tack

谢谢  Merci  Gracias  Seé  ありがとう
3M ECP 305+ Long Term Outdoor Exposure (NREL)