CSP FY03 Milestone Report

Summary of Status of Most Promising Candidate Advanced Solar Mirrors and Absorber Materials (Testing and Development Activities)

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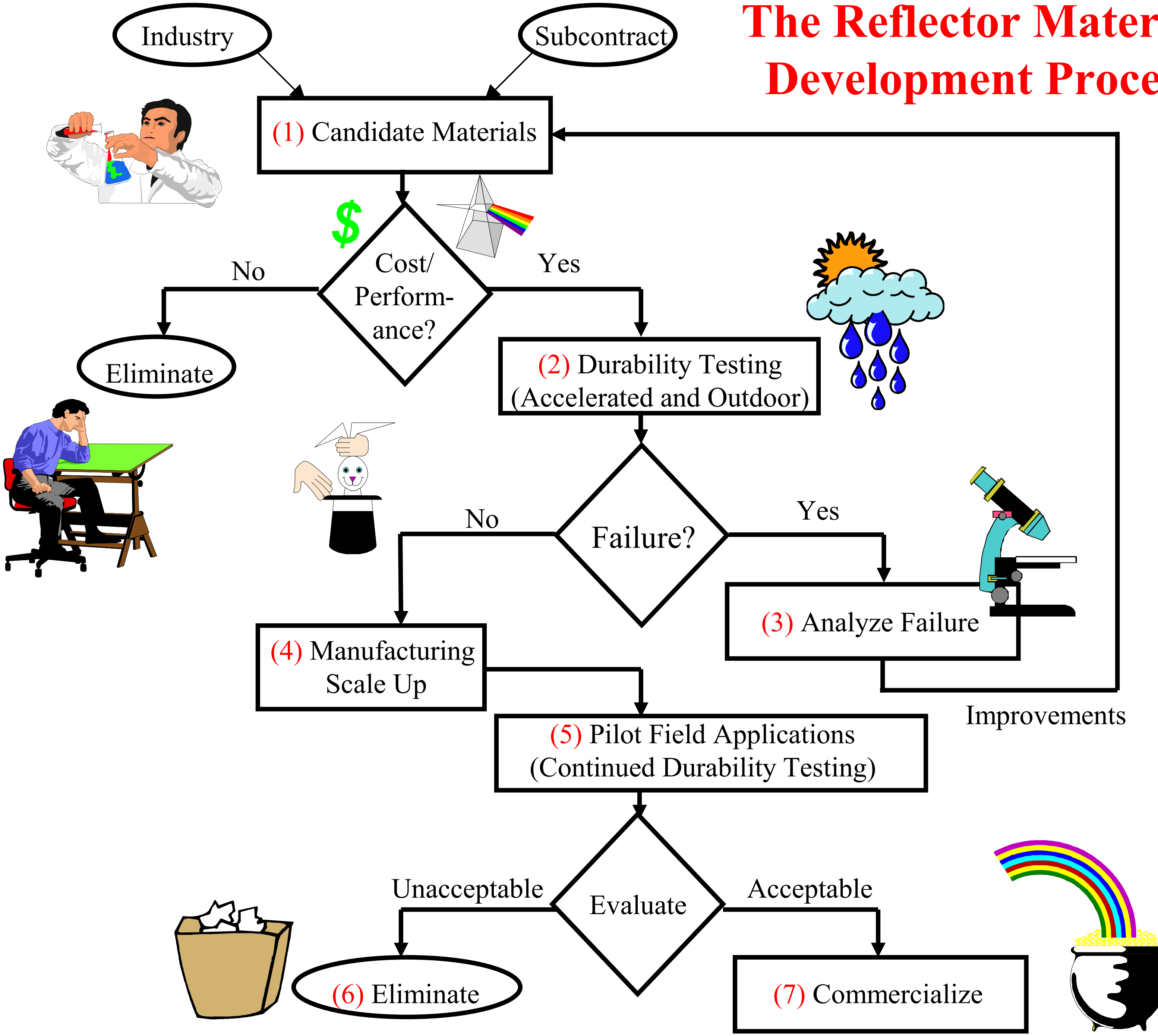
Introduction

Sun♦Lab directs the development of advanced reflector and absorber materials through collaborative efforts with solar manufacturers and by interacting with the coatings industry. This allows crucial gaps in the technology to be addressed and suggestions by industry experts or from the literature to be explored. This milestone report provides an update on the status of top candidate solar reflector materials that have been identified since 1999. Candidates are categorized as being “near-term” or “longer-term”; in addition, consideration of several candidates has been discontinued for various reasons. A viewgraph approach is used to convey relevant information. One viewgraph per candidate is used. The viewgraph identifies the material, shows a diagram of the material construction, and (in bullet format) provides important aspects of where the material is in the development process; these bullets are referenced back (using numbers highlighted in red) to the figure on the following page that gives a schematic overview of the material development process from candidate conception to commercialization.

Samples are prepared in two ways. First, materials being developed by industry for non-solar applications (aerospace, indoor lighting, decorative products, etc.) are often submitted for evaluation. Second, industry experts may propose development of solar-specific materials that are partially funded by Sun♦Lab subcontracts. This approach is critical to assure that the best candidate materials for potential solar use are identified (1). Candidate materials are then evaluated on the basis of their initial (unweathered) performance and potential for low cost. Roughly 90% specular reflectance across the solar spectrum, and the possibility of achieving $1/ft^2 are desired. If a candidate material does not meet these criteria then they are eliminated from consideration and its “back to the drawing board” to look for materials with better credentials. Materials that meet the cost and performance guidelines are then subjected to accelerated and outdoor durability testing as small coupon-sized samples (2). If candidates fail during testing, they are analyzed to determine their degradation mechanisms (3); by understanding why materials lack the requisite durability, their formulation can oftentimes be improved and retested. Larger-sized samples of materials that do not fail are requested/generated during manufacturing scale-up (4) so that the material can be deployed in the field (5) to assure that unexpected catastrophic failures do not occur and to demonstrate the feasibility of candidate materials in real-world applications. Materials that fail in the field are eliminated from further consideration (6); those that exhibit acceptable field durability are transferred to industry for commercialization (7). Following the overview diagram slide, the next viewgraph provides a summary of progress during FY03.

The reflector development and testing effort has been significantly curtailed due to budget cuts in FY02 and FY03. Reflector R&D efforts have been to limited to continuing testing which in turn has been limited by available resources (staff time, equipment, etc.).

The Reflector Material Development Process



Summary of Progress During FY03

Candidate Reflector Material		Status 9/01	Status 9/02	Status 9/03
Mirror Type	Potential			
Thick Glass Mirrors	Near-Term	Spanish glass mirrors and Pilkington mirrors being considered for Solar Tres (2-4)	After 1 year WOM exposure, Pilkington mirrors better than Spanish glass mirrors; some adhesive related degradation observed (2,3)	After 22 months WOM exposure, Pilkington mirrors better than Spanish glass mirrors; some adhesive related degradation observed (2,3)
Thin Glass Mirrors	Near-Term	New thin glass formulations by industry under test (2,3)	Mirror testing continuing; results for new constructions not yet definitive (2); failure analysis of industry samples performed (3)	Mirror testing continuing; results for new constructions not yet definitive but commercial back protective paint applied after mirror manufactured not beneficial (2).
Commercial Laminate	Near-Term	Pilot plant run produced; being deployed (5)	Pilot plant run durability unsatisfactory (3); 7 improvements to baseline construction delivered end of FY02(2); pilot plant run of best construction planned for FY03 (4)	Testing on 7 improvements to baseline construction performed and ongoing (2,3); additional 25 improved constructions delivered (1) and undergoing testing (2,3); pilot plant run of best construction postponed to FY04 (4)
Front Surface Aluminized Reflector	Near-Term	Problems discovered during solar tests; improvements made; being deployed in prototype solar systems (5)	New overcoat formulation has exhibited improved optical durability after ~2 years exposure outdoors and in WOM (2)	Overcoat formulation exhibited improved hemispherical durability but specularity has degraded after 2.5 years exposure outdoors and in WOM (2,3); New improved construction received and under test (2)

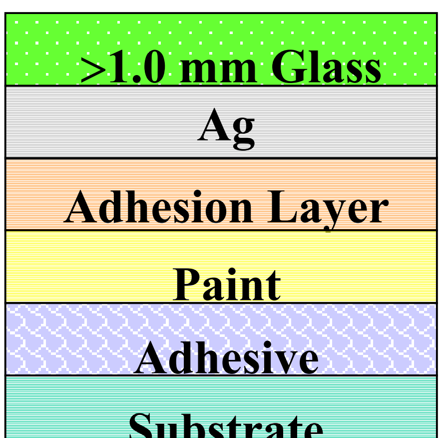
Summary of Progress During FY03

Candidate Reflector Material		Status 9/01	Status 9/02	Status 9/03
Mirror Type	**Potential**			
SAIC IBAD "Super Thin" Glass	Longer-Term	Material produced using roll coater during FY01 (4); Commercialization planned for FY03 (5,7)	Roll-coater deposition rate doubled (4) & new cost analysis initiated (5) during FY02; Deposition rate increase (5), structural improvements (3), & deployment (5) planned for FY03	Optimized deposition conditions at 20 nm/s rate (5), structural improvements (3), durability testing (2), new cost analysis performed (5) during FY03; go-no/go decision on future R&D funding. If go, modifications to structure in response to cost analysis planned for FY04 (3); deployment (5) postponed based on go-no/go decision .
Front Surface Mirror (FSM)	Longer-Term	Samples have failed (3)	New samples have been provided and are being tested (1,2)	After 6 months exposure, hemispherical and specular reflectance unchanged on one set of samples , but specularity degraded on second set of new samples (1,2).
All-Polymeric	Longer-Term	New improved samples will be provided; 3M working on hard coats; need to be tested (2)	Intellectual property issues have delayed delivery of new samples (1)	Intellectual property issues have delayed delivery of new samples (1)
SolarBrite 95	Discontinued	Failed during solar tests; product withdrawn from market (6)		
Sun♦Lab Reactive Pulsed DC Magnetron Sputtering of "Super Thin" Glass	Discontinued	Work discontinued 4/00; samples have two years WOM exposure, no degradation (2)	After 1.5 years WOM exposure, some samples have exhibited cracking/delamination; others have maintained original reflectance (2)	After 2.5 years WOM exposure, many samples have exhibited cracking/delamination; others have maintained original reflectance (2)

Near-Term Candidate Materials

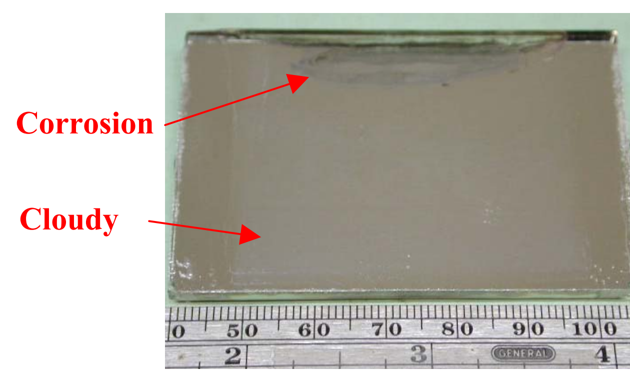
Thick (>1mm) Glass Mirrors

- Mirrors have excellent durability in terms of corrosion of reflective layer, are readily available, and have the confidence of the solar manufacturing industry, but are heavy and fragile; curved shapes are difficult & require slumped glass which is expensive, but have been commercially deployed (7).
- Initial hemispherical reflectance is ~88 - 92% and cost is ~\$1.50 to 4.00 /ft^2.
- Testing of samples of Pilkington and "Spanish" glass mirrors (copper-less and lead-free paint), bonded to steel with four different candidate adhesives, was initiated during FY01 (2-4); considered for possible use at Solar Tres.
- After ~2 year accelerated WOM exposure, Pilkington mirrors exhibit better optical durability than Spanish mirrors—on average, the Pilkington mirrors degraded 1% while the Spanish glass mirrors degraded 3% ; adhesive-related degradation is more prevalent with Spanish glass mirrors—depending on the adhesive, Spanish mirrors degraded between 1.3 % to 4.2 % while Pilkington mirrors degraded between 0.8% to 1.6%.

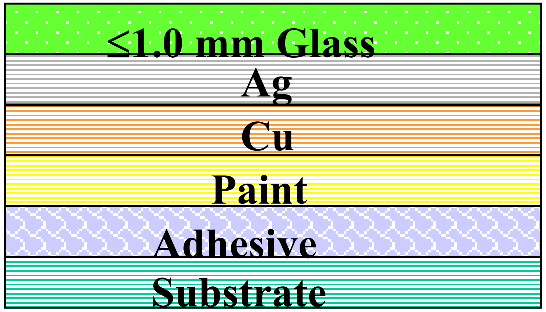


Wind Damage to Glass Mirrors

Spanish Glass adhesive-related degradation after 2 years WOM exposure



Thin (≤1 mm) Glass Mirrors



Corrosion in deployed mirrors :

Corrosion

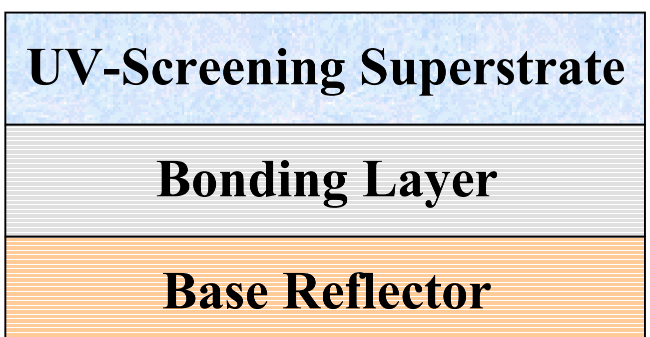
Corrosion after 12 months WOM exposure where mirror protected with commercial (non-mirror) paint:

Corrosion

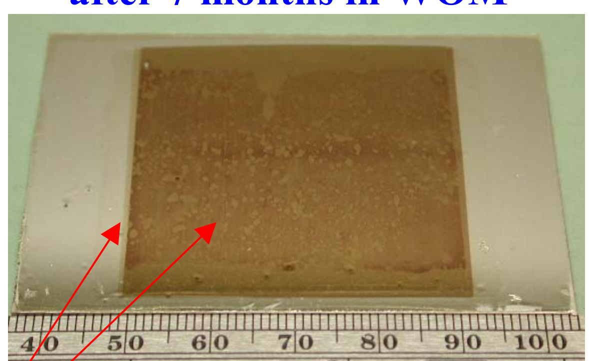
- Thin glass mirrors use traditional wet silvered processes on thin, relatively lightweight glass; they have greater material costs, are more difficult to handle, and have higher associated labor costs (25-40%) than advanced reflector technologies.
- Initial hemispherical reflectance is ~93 to 96% and cost is ~\$1.50 to 4.00 /ft^2.
- The solar industry has confidence in thin glass mirrors deployed in commercial installations (7).
- Choice of adhesive affects the performance of weathered thin glass mirrors.
- Corrosion is seen in deployed mirrors (4,5). Corrosion-related failure analysis of field samples for industry performed during FY01 and FY02.
- During FY01, degradation mechanism(s) were determined and standard mirror painting practices were surveyed (3).
- Results of accelerated testing of new sample constructions (mirror type / back protective paint / adhesive / substrate) not yet definitive, analysis and reporting delayed due to budget constraints (2). Testing indicates commercial (non-mirror) back protective paint applied post mirror manufacturing not beneficial; mirror paint system suitable for outdoor applications must be identified and applied during manufacturing, mirror paint system R&D not performed in FY03 due to budget constraints.

Commercial Laminate Reflector

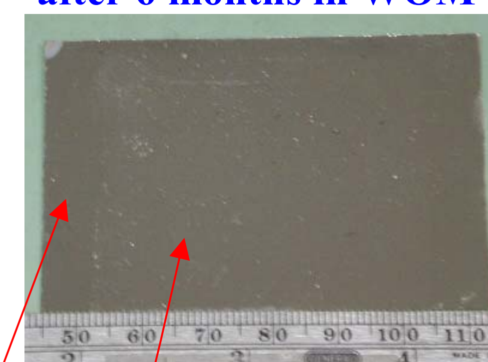
- Joint patent by Sun♦Lab and industry partner (ReflecTech).
- The reflector material is a commercial silvered polymer with a laminated UV-screening film to provide outdoor durability.
- Initial hemispherical reflectance is ~92% and cost is ~$1.50 / ft^2.
- Outdoor and accelerated testing of prototype samples since FY99 (1, 2); 2000 ft^2 pilot plant run of most promising construction, based on exposure testing, produced by ReflecTech in FY01 (4); additional 2000 ft^2 produced in FY02 (4); durability of pilot run significantly less than anticipated (3).
- To improve performance, 7 variations to baseline construction were manufactured and delivered at the end of FY02; 25 variations were manufactured in FY03 (1, 2); testing was performed during FY03 and ongoing (3); and pilot plant production (4) of best construction was delayed to first quarter of FY04 to allow sufficient time for durability testing.
- Material will be field tested at SEGS system; interest by solar manufacturers (5).



FY01 Pilot Plant run after 7 months in WOM



FY02 improvement after 6 months in WOM



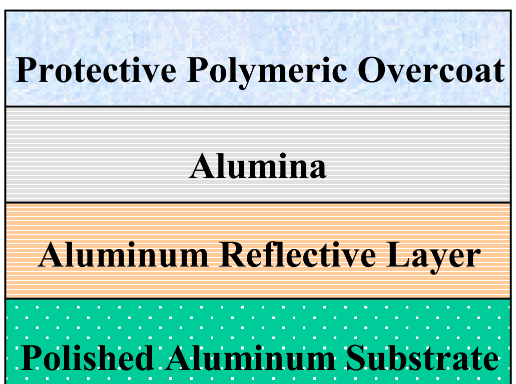
Exposed area — dark brown

Non-exposed area

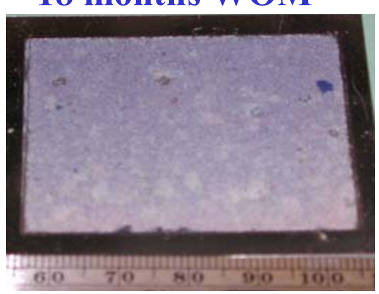
Exposed area —no change-slight white haze due to surface soil

Front Surface Aluminized Reflector

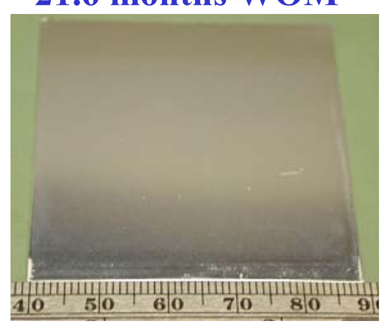
- Front surface aluminized reflectors use a polished aluminum substrate, an enhanced aluminum reflective layer, and the formation of a protective oxidized topcoat (alumina). These reflectors have inadequate durability in industrial environments.
- Addition of acrylic polymeric overcoat to protect alumina improved durability. Samples have survived >5 years outdoor exposure in Golden, Colorado and Phoenix, Arizona and >3 years outdoor exposure in Miami, Florida and Köln, Germany under SolarPACES project. Contact with SolarPaces not maintained due to budgetary (time) constraints (2).
- Acrylic overcoated material failed in accelerated testing; replaced by fluoropolymer overcoat, new formulation shows improved hemispherical durability but specularity has degraded with exposure at Arizona, Florida, NREL, and WOM. Recent specularity results need to be transmitted to DLR, analysis previously delayed due to budgetary (time) constraints (2,3).
- New samples received end of FY03 (2).
- Structural facets were fabricated during FY00 for field deployment, but have not been deployed (5).
- Product is commercially available from Alanod in cooperation with the DLR in Germany (7) for <\$2/ft^2; initial reflectance ~90%.



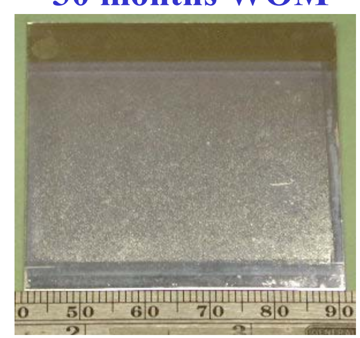
Acrylic Overcoat failed after 18 months WOM



Fluoropolymer Overcoat after 21.6 months WOM

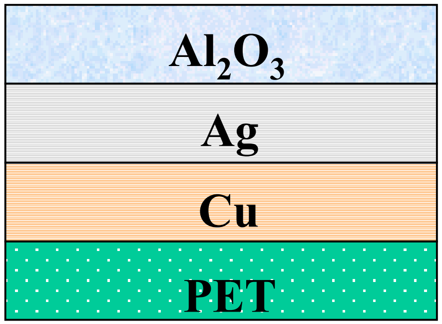


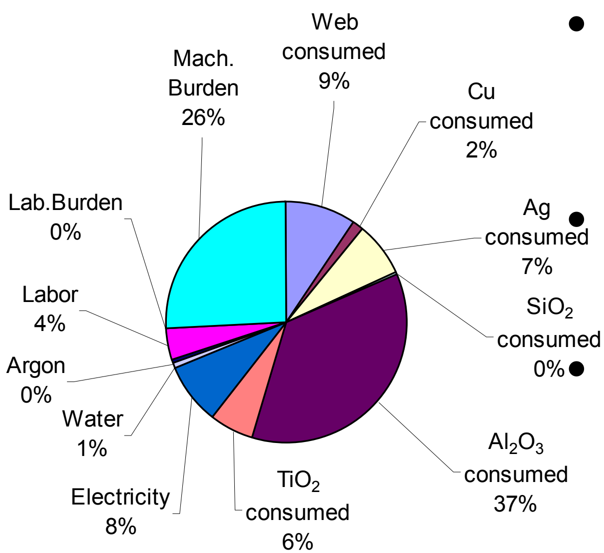
Fluoropolymer Overcoat after 30 months WOM



Longer-Term Candidate Materials

SAIC IBAD "Super Thin Glass" Mirror



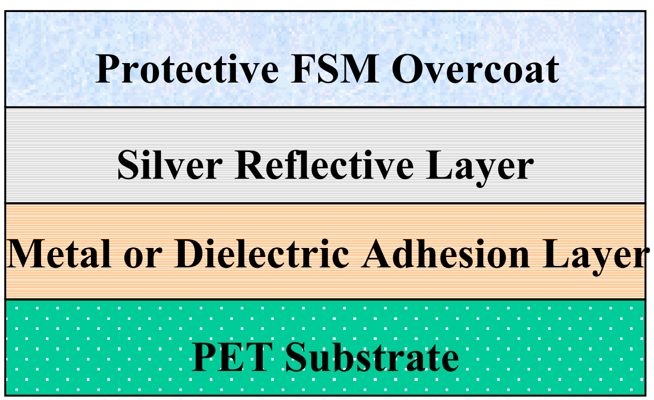


Projected breakdown of costs for super thin glass reflector (total cost = $10.14/m²)

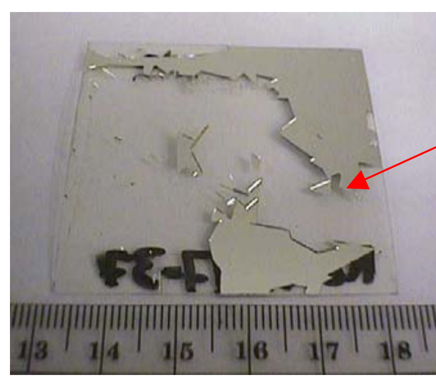
- Benefits of flexible substrate and the durability of glass. Ion Beam Assisted Deposition (IBAD) is used to deposit the very hard (cleanable) dense (protective) alumina topcoat. Samples are highly reflective (>95%) and durable. Subcontracted effort by SAIC McLean, VA.
- Batch deposition rate increased to 22 nm/s in FY00—samples accumulated 5000 hours accelerated solar simulator exposure and 42 months of WOM and outdoor exposure in Arizona, Colorado, and Florida; substrate switched to high-temperature specular steel in FY01 (2,3,4).
- First materials produced at 5-10 nm/s on laboratory roll-coater during FY01— roll-coated samples accumulated 3000 hours accelerated solar simulator exposure and 18 months WOM and outdoor exposure in Colorado (2,3,4).
- Deposition rate on laboratory roll-coater doubled to 20 nm/s at end of FY02 (4); deposition conditions at 20 nm/s optimized and incorporated structural improvements in FY03 (3). Durability testing ongoing (2).
- New cost analysis (7) performed during FY03. Cost of reflector dependent upon substrate; alumina thickness, deposition rate, and cost; and machine burden. Material can be manufactured at ~$1/ft² with 1 μm-thick alumina with deposition rate of 60 nm/s on PET substrate on roll-coater.
- Plan to make go/no-go decision for further R&D funding early FY04 based on the cost for continued development, the risk for going forward, and the current anticipated application for the material, in response to cost analysis. If go, in response to cost analysis, decrease alumina thickness (3) and increase deposition rate (4) during FY04.

Front Surface Mirror (FSM)

- Solel front surface mirror (FSM) consists of polymer (PET) substrate with a metal or dielectric adhesion layer, a silver reflective layer, and a proprietary dense protective top hardcoat. The reflector has excellent initial reflectance (96%).
- Durability testing of a prototype FSM (provided by Luz prior to insolvency) demonstrated outstanding durability (reflectance >95% for more than 5 years and >90% for 6.5 years of accelerated exposure testing) before being discontinued after 7 years WOM exposure with 88% reflectance.
- Solel informally provided new samples to Sun ♦ Lab for evaluation in FY99; samples delaminated and corroded during accelerated exposure testing (2,3).
- New improved samples on PET and aluminum substrates were provided at the end of FY02; testing is ongoing. After 6 months of exposure, the hemispherical reflectance is unchanged for both substrates, but specular reflectance has degraded for samples with PET substrate (2).



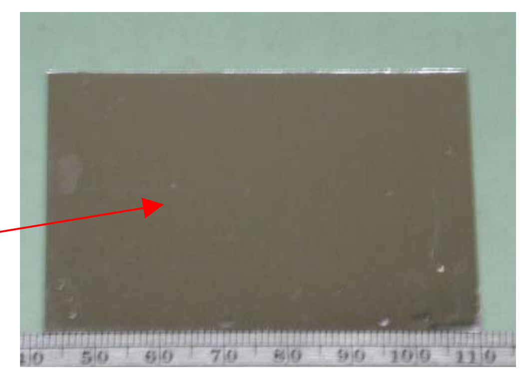
Delamination of FY99 samples after 6 months in WOM:



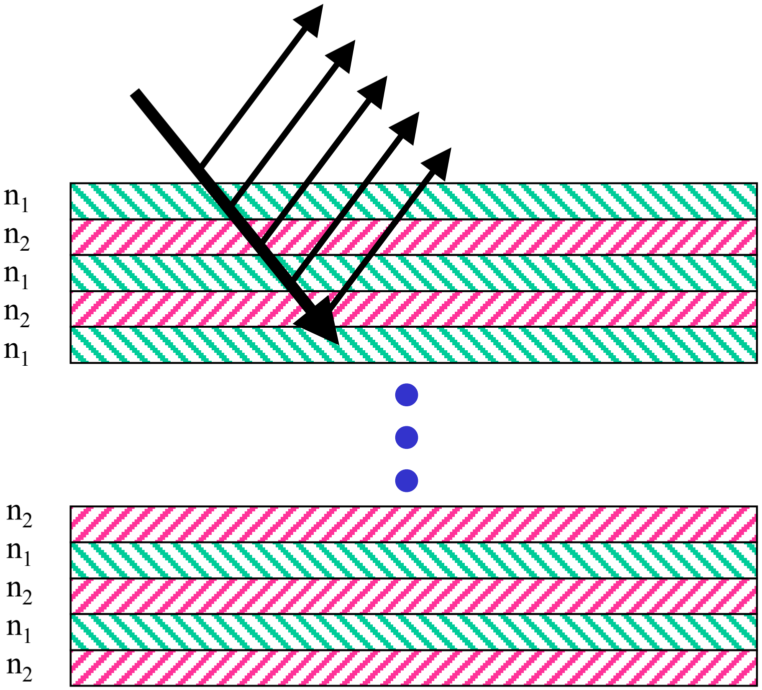
Delamination

No Delamination

FY02 samples after 6 months in WOM:



All-Polymeric Reflector



Yellowing after 3 months in WOM:

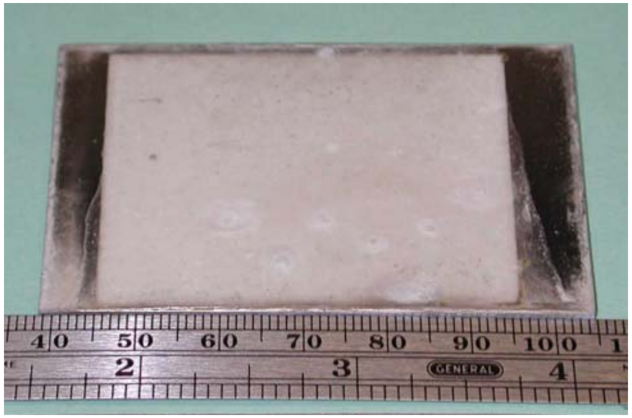
- 3M's multilayer "Radiant Film" technology
- Alternating polymers are coextruded; multiple reflectance produced due to mismatched indices of refraction. Benefit of a polymer substrate (light weight, curvable, and low cost), potential for very high broadband reflectance (~99%), and no metal reflective layer to corrode. Spectral characteristics can be tailored to application.
- Samples provided in FY99 for evaluation had high reflectance in narrow band but had a problem with UV durability. The samples yellowed after 3 months of accelerated exposure.
- Multiple requests during FY02 and FY03 for test samples with improved UV screening layers and (possibly) abrasion resistant hardcoats (1,2). Samples promised, but as yet not delivered.
- Delivery of samples delayed by 3M's intellectual property concerns.

Discontinued Candidate Materials

SolarBrite 95

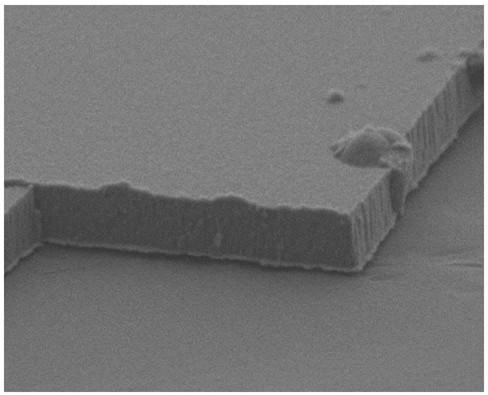
- Reflector material was a silvered UV-stabilized polyester (PET) film having a metallic back-protective layer laminated by a proprietary thermoset adhesive to an aluminum substrate. A painted coating was applied to the backside of the metal substrate.
- Initial hemispherical reflectance ~92% and cost was ~$1.50-4.00 / ft^2.
- Coupon-sized samples under test had poor durability; the UV stabilized PET yellowed after 8 months of accelerated exposure and 20 months outdoors (3).
- Structural facets for field deployment were fabricated during FY00 (5)
- Alcoa's commercial product is no longer being produced, but Southwall recently contacted NREL as they provided Alcoa with the PET and will be manufacturing SolarBrite (6)

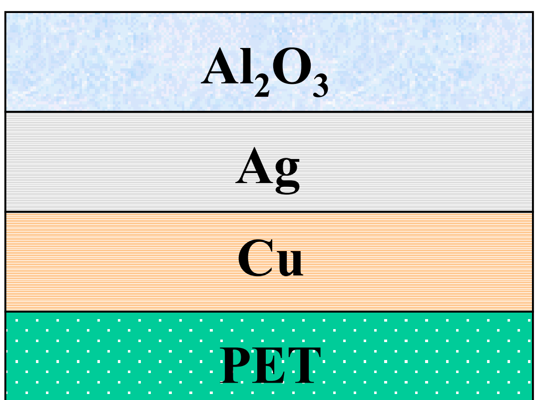
Failure after 20 months in Florida:



Sun♦Lab Reactive Pulsed DC Magnetron Sputtered "Super Thin Glass" Mirror

SEM of Al_2O_3/Ag/PET:





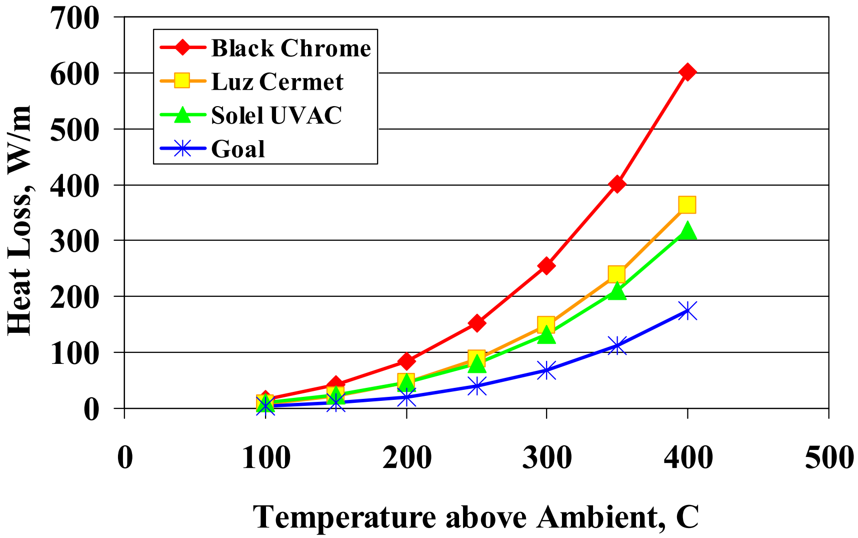
- Reactive pulsed DC magnetron sputtering was used to deposit very hard (cleanable), dense (protective), flexible, lightweight topcoats. This process has demonstrable manufacturing scale-up capability. Cost projected ~$1.00 /ft^2.
- The effect of relevant deposition process parameters upon properties of deposited layers was understood.
- Research (i.e., new sample preparation) was stopped during FY00 as per DOE directive.
- After 3.2 years accelerated WOM exposure, some samples (prepared prior to close-out) have maintained their initial performance (reflectance>95%); many have exhibited cracking and delamination failure (2).

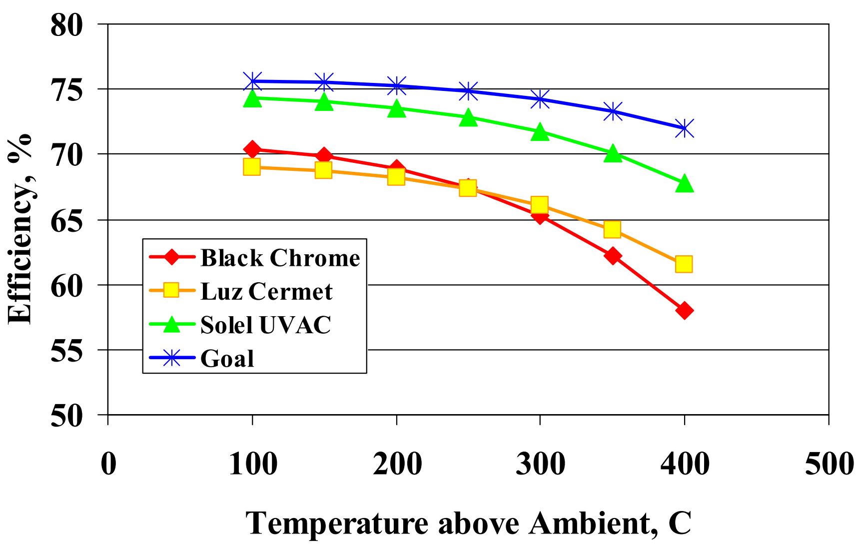
Absorber Materials

Summary of Progress During FY03

Candidate Absorber Material		Status 9/00	Status 9/01	Status 9/02	Status 9/03
Absorber Type	**Potential**				
UVAC HCE	Commercial	KJCOC established baseline performance of existing Luz HCE receivers; purchased 350 Solel UVAC HCE receiver tubes; installed ~200 for performance test at SEGS VI and remainder for reliability testing at SEGS VI & VII.	KJCOC installs protective shields (IBS) over bellows after initial high failure of UVAC glass-to-metal-seals. Performance data shows >20% increase in performance of UVAC over original Luz receivers.	KJCOC, outfitted a full LS-3 test loop with newer, 2001 batch UVACs. The test loop 33-34 A-D located at SEGS VII with insulated bellow shields and 24 Solel-designed bellow shields.	KJCOC recalibrates flow loop instrumentation. UVAC loop continues to perform at ~20% above the original Luz receiver loop. Glass to metal seal failures were reduced when IBS installed. New UVAC bellows shields have not been validated yet.
IST Black Ni	Short-term		Support requested by IST for their Black Ni conversion process late FY01; sample procurement started (1).	Provide steel samples early FY02 to IST for their Black Ni conversion process that have been polished and coated with nickel; samples measured (1).	Provided second set of samples early FY03 (1).
NREL prototype	Long-Term		Preliminary review to determine feasibility of developing selective coating for 450°C at end of FY01 (1).	Extensive literature review to identify candidate selective coating for 450°C and above (1).	Initial optical modeling of candidate selective coating have excellent emittance and ongoing modeling is improving absorbance; preliminary deposition of coating started (1).

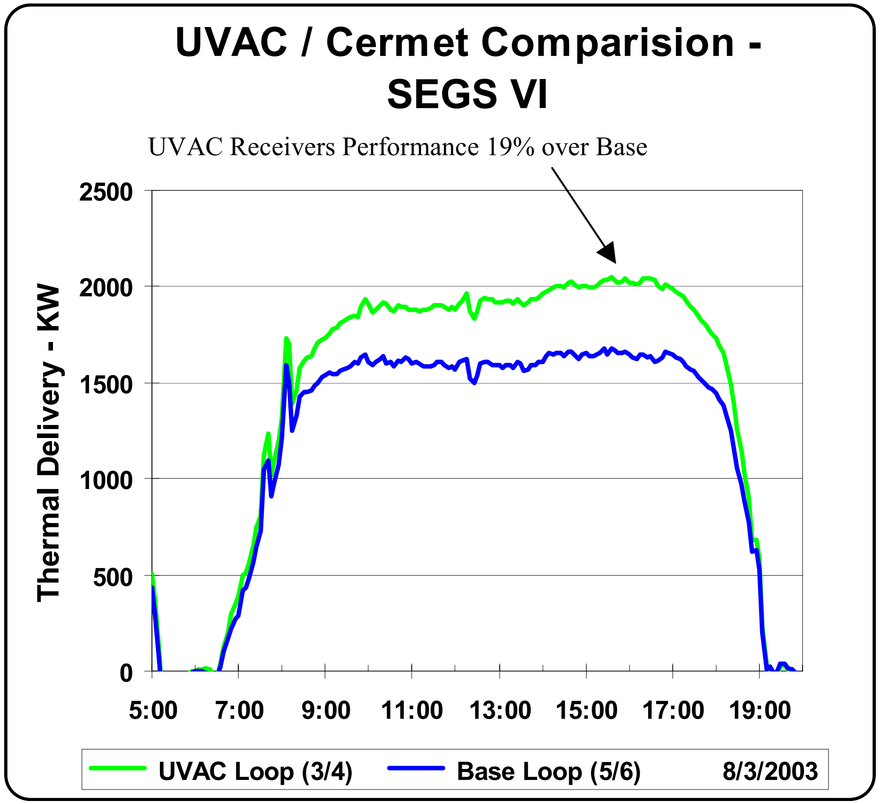
High Temperature Selective Coating Development





- Selective coating properties impact collector optical performance and thermal losses.
- Improvements in the receiver can significantly enhance collector efficiency.
- Coating Goals:
  - Properties (α=0.95, ε=0.07 @ 400C)
  - Stable in air at 450C.
  - Improved durability of glass-to-metal-seal

Solel UVAC Receiver Testing



- KJCOC established baseline performance of existing Luz HCE receivers; purchased 350 Solel UVAC HCE receiver tubes; installed ~200 for performance test at SEGS VI and remainder for reliability testing at SEGS VI & VII
- KJCOC installs protective shields (IBS) over bellows after initial high failure of UVAC glass-to-metal-seals. Performance data shows >20% increase in performance of UVAC over original Luz receivers.
- KJCOC, outfitted a full LS-3 test loop with newer, 2001 batch UVACs. The test loop 33-34 A-D located at SEGS VII with insulated bellow shields and 24 Solel-designed bellow shields.
- KJCOC recalibrates flow loop instrumentation. UVAC loop continues to perform at ~20% above the original Luz receiver loop. Glass to metal seal failures were reduced when IBS installed. New UVAC bellows shields have not been validated yet.

IST Black Ni Absorber

- In FY02 in support of IST subcontract, purchased (80) 1018 cold rolled steel and (80) 316L stainless steel steel substrates.
- Contracted to have 80 samples mechanically polished to mirror finish.
- Contracted to have 80 samples electropolished, resulting in 20 samples as-received, 20 mechanically polished, 20 electropolished, 20 both mechanically polished and electropolished
- Contracted to have samples coated with 1.5 mil nickel sulfamate, 1.5 mil electroless nickel, and 0.75 mil electroless nickel.
- Delivered to IST for conversion to Black nickel to be followed by protective sol-gel coat. IST's black nickel had low absorbance and high emittance.
- Repeated in FY03, but in addition company that deposited nickel also demonstrated conversion to Black Nickel.

NREL Prototype Absorber

Comparison of theoretical optical properties for NREL's modeled prototype absorber with actual optical properties of existing materials.

	NREL Model #1	Old Cermet	UVAC A	UVAC B
Solar Absorptance	0.897	0.938	0.954	0.935
Thermal Emittance@				
25°C	0.009	0.061	0.052	0.069
100°C	0.013	0.077	0.067	0.084
200°C	0.021	0.095	0.085	0.103
300°C	0.034	0.118	0.107	0.125
400°C	0.055	0.146	0.134	0.150
450°C	0.068	0.162	0.149	0.164
500°C	0.083	0.179	0.165	0.178

- For CSP applications, the spectrally selective surface should be thermally stable above 450ºC, ideally in air, with a solar absorptance greater than 0.96 and a thermal emittance below 0.07 at 400ºC.
- Extensive literature study performed in FY02 to identify candidate materials.
- The international community currently leads this area and there exists no US research or manufacturer of high-temperature spectrally selective coating.
- Solar selective coatings with optical properties approaching the goals have been modeled for materials with high thermal stability. Emittance is excellent, but model needs to be refined to improve absorptance.
- Plan to deposit modeled coatings in FY04.