CSP FY 2005 Milestone Report

“Provide status of test results of candidate solar mirror samples and identify promising candidates”

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Introduction

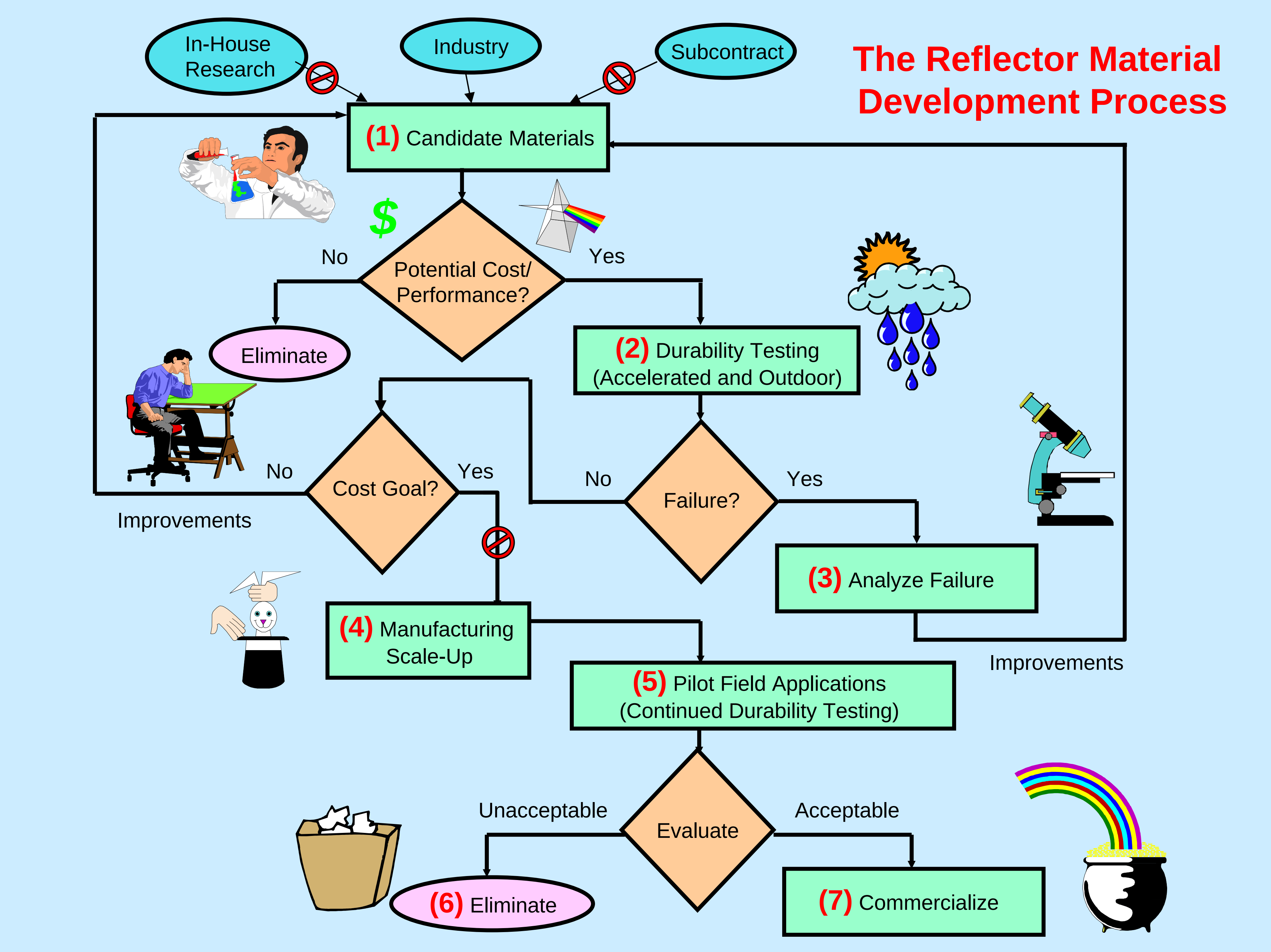
The Advanced Material team at NREL directs the development of advanced reflector materials through collaborative efforts with solar manufacturers and by interacting with the coatings industry. Crucial gaps in the technology can be addressed and suggestions by industry experts or from the literature can be explored. This milestone report updates the status of top-candidate solar reflector materials identified since 1999. Candidates are categorized as “commercially available” or “longer-term”; in addition, consideration of several candidates has been discontinued for various reasons.

A viewgraph approach is used to convey relevant information, with one viewgraph per candidate. The viewgraph identifies the material, shows a diagram of the material construction, and provides bullets of important aspects of where the material is in the development process. These bullets refer back (using numbers in **red**) to the figure on the following page, which gives a schematic overview of the material development process from candidate conception to commercialization. A timeline for each mirror type is included. Optical durability test results are presented graphically as plots of optical performance versus exposure time [1].

Historically, samples have been prepared in three ways: First, materials developed by industry for non-solar applications (e.g., aerospace, indoor lighting, decorative products) are often submitted for evaluation. Second, industry experts may propose development of solar-specific materials partially funded by NREL subcontracts. Third, innovative concepts were prepared “in-house.” This approach is critical to ensure that the best candidate materials for potential solar use are identified **(1)**. However, funding cuts necessitated discontinuing the in-house work in FY 2000 and the subcontracted work in FYs 2003 through 2005. Candidate materials are then evaluated on the basis of their initial (unweathered) performance and potential for low cost. The goal is roughly 90% specular reflectance across the solar spectrum and the possibility of achieving $1/ft^2. If a candidate material does not have the potential to meet these criteria, it is eliminated from consideration and it’s “back to the drawing board” to look for materials with better credentials. Materials with the potential to 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 often be improved and retested. However, recent decreases in funding levels have led to minimal failure analysis being performed. 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 ensure that unexpected catastrophic failures do not occur and to demonstrate the feasibility of candidate materials in real-world applications. Again, recent funding levels have led to limited field deployment. 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)**.

Recently, many CSP companies—especially concentrating photovoltaic (CPV) companies—have contacted the Advanced Material team requesting information and help. The reflector development and testing effort at NREL has been significantly curtailed due to budget cuts beginning in FY 2000 and continuing through FY 2005, with NREL efforts reduced to durability testing of existing materials. However, we remain the world leaders in solar mirror durability. This fact indicates that industry has not taken the lead, and that no one else is doing the needed development work to ensure the future availability of a durable, low-cost solar reflector.

1. The solar-weighted hemispherical reflectance is plotted as a function of total UV dose outdoor exposure. The total annual UV dose for outdoor exposure at Miami, FL (FLA) is equivalent to 280 MJ/m^2 per year, 330 MJ/m^2 per year at Phoenix, AZ (APS) and Golden, CO (NREL), and 1030 MJ/m^2 per year for the accelerated Ci65 WeatherOmeter (WOM). The primary gridlines divide the total UV dosage by 330 MJ/m^2 per year (or multiples of 330) and a secondary x-axis above the graph shows the corresponding equivalent NREL exposure time in years. NREL exposure year is used for the label when the exposure is only outdoors at NREL, and equivalent NREL exposure year is used when the samples are exposed at a combination of the WOM and/or outdoor sites. Some plots exhibit sharp changes in hemispherical reflectance with exposure. These changes are typically caused by measurements taken in different areas of the sample or by discontinuing a degraded sample. Individual curves are typically an average of multiple samples; when a failed sample is discontinued, the average can increase, as the poor performer is no longer included in the average value associated with a particular type of material. The failure criteria is reflectivity loss greater than 10% or mechanically failure (e.g., delamination). The data (symbols) represent average values for whatever numbers of sample replicates are available; error bars are for ± one standard deviation and indicate the variation and non-uniformity of the samples as they weather.


The Reflector Material Development Process
In-House Research
Industry
Subcontract
(1) Candidate Materials
Potential Cost/ Performance?
No
Yes
$
Eliminate
(2) Durability Testing (Accelerated and Outdoor)
Failure?
No
Yes
(3) Analyze Failure
Improvements
Cost Goal?
No
Yes
Improvements
(4) Manufacturing Scale-Up
(5) Pilot Field Applications (Continued Durability Testing)
Evaluate
Unacceptable
Acceptable
(6) Eliminate
(7) Commercialize

Updated Status of Candidate Mirrors

Candidate Reflector Material		Status 9/05	Outlook
Mirror Type	Availability		
Flabeg Thick Glass Mirrors	Commercially Available	Flabeg converted mirror line to 5-mm glass, copper-free process, and a new lead-free paint system in FY 2003 **(1)**. The manufacturer reports durability is expected to be equivalent. Side-by-side exposure testing began second quarter FY 2004 **(2)**. After 1 year accelerated and outdoor exposure, new mirrors are performing slightly better than the original mirrors.	Historically, previous construction with copper back-layers and old paint system has been robust outdoors; new construction changed considerably and should not be assumed to have same durability. New Flabeg thick-glass mirrors have not been under test long enough to demonstrate the 10-year or more-aggressive 20-year lifetime goal, outdoors in real time.
Alternate Thick Glass Mirrors	Commercially Available	Spanish glass mirrors and Pilkington mirrors being considered for Solar Tres **(2-4)**. Pilkington mirrors exhibit better optical durability than Spanish mirrors in accelerated WOM exposure testing, and adhesive-related degradation more prevalent with Spanish mirrors.	Predicting an outdoor lifetime based on accelerated exposure testing is risky, and neither Pilkington nor the Spanish mirrors exposed outdoors show degradation up to this point. But based on accelerated exposure testing, at this time Pilkington mirrors are probably the more durable mirror.
Thin Glass Mirrors	Commercially Available	Major thin-glass-mirror manufacturers converted their mirror lines to new copper-free process and lead-free paint system between FYs 2000 and 2004 **(1)**. Significant concern expressed in FY 2004, 2005 by CPV manufacturers regarding durability of new thin-glass mirrors made with copper-free process and lead-free paint system **(3)**.	Although glass mirrors with copper back-layers and heavily leaded paints have been considered robust outdoors, the new copperless back-layer and lead-free paint systems were designed for interior mirror applications and do not have the same durability. Development of a mirror-backing paint system suitable for outdoor applications, to be applied during mirror manufacturing, will be required to provide sufficient durability **(1)**.
ReflecTech Silver Polymer Mirror	Commercially Available-4thQ-FY04	Prototype of pilot run had equivalent of 10 years of accelerated outdoor exposure by ACUVEX. Second pilot run of most-promising construction with improved UV screen FY 2004; durability testing ongoing; being deployed **(5).**	Actual outdoor exposure testing of first pilot run is only 2.5 years. New pilot run incorporated considerable changes and exposure testing was recently initiated; further testing will be needed to determine its actual lifetime **(1,4)**.

Updated Status of Candidate Mirrors

Candidate Reflector Material		Status 9/05	Outlook
Mirror Type	**Availability**		
Front-Surface Aluminized Reflector	Reintroduced FY06	Failed during solar tests; product withdrawn from market FY04, Alanod made improvements and will reintroduce to market FY06 **(6)**.	Alanod reports new material has improved durability and delamination/specularity issue resolved.
All Polymeric	Discontinued for outdoor applications	High reflectance only in narrow band; not UV stable **(1)**. Improved samples promised for testing since FY 1999, but never delivered.	Little hope of receiving samples designed for solar applications without subcontract. All-polymeric would need significant improvements to broaden reflectance band and improve durability. Specularity may be of concern.
Solel Front-Surface Mirror (FSM)	Longer term	Durability testing of a prototype FSM demonstrated outstanding durability in WOM exposure **(1)**. Improved samples' hemispherical reflectance has degraded slightly after 2 year WOM exposure, but specular reflectance degraded for samples with PET substrate **(2)**.	Accelerated testing results promising, but outdoor exposure is more severe than WOM exposure for front-surface mirrors. Probably can receive small quantity of samples, but little hope of receiving samples without subcontract and Solel desires all front-surface-mirror intellectual property rights.
SAIC IBAD Super Thin Glass	Subcontract ended	Deposited on laboratory roll-coater at 20 nm/s **(3,4)**; Durable after more than 3.5 years accelerated and outdoor exposure; testing continuing **(2)**. New cost analysis **(7)** shows product can be manufactured at <$1/ft^2. Subcontract ended 9/30/04.	The material can be a transitioned to a commercial roll-coating company with SAIC's consultation if NREL establishes the relationship. Prior to transition, a short (4–6 month) subcontract to evaluate different web materials, adhesion promotion and anti-soiling layers, and a lower-purity alumina is warranted.
SolarBrite 95	Withdrawn from market	Failed during solar tests; product withdrawn from market FY 2001**(6)**	Low expectations that a reflector with UV-stabilized PET as front surface will have durability greater than 2 years outdoors based on testing of numerous PET samples.
Sun♦Lab Reactive Pulsed DC Magnetron Sputtering and IBAD of "Super Thin" Glass	Research discontinued, DOE directive	Research discontinued 4/00. After 4.5 years' WOM exposure, many samples have exhibited cracking/delamination; others have maintained original reflectance **(2)**	High probability of achieving reflector with equivalent durability and possibly lower costs than SAIC IBAD Super Thin Glass, but would require further development work.
3M ECP-305+, SA-85, SS-95	Withdrawn from market	ECP-305+, SA-85 have demonstrated durability after more than 9 and 12 years of outdoor exposure. Materials withdrawn due to corporate reorganization, production issues, all-polymeric development, and ECP-305+ tunneling black eye **(6)**.	Interest expressed by CPV industry about restarting production because of excellent durability and patents have expired/are expiring. Incorporation of adhesion-promoting layers should improve ECP-305+ tunneling.

Glass Mirrors Timeline

1 Flabeg thick-glass mirrors w/Cu backlayer and proprietary outdoor 3-layer paint system deployed at SEGS plants

2 Servais patents copperless back layer

3 CPG switched from ECP-305+ to Naugatuck thin-glass mirrors

8 Began testing thin-glass mirrors from ~6 manufacturers at OET sites

9 ~ Time frame lead content in paint reduced to 2%

10 Soltys patents copperless back layer

11 Pilkington introduces copperless and lead-free thick-glass mirrors for interior applications

15 Sandia provides Pilkington copper-less and lead-free thick-glass mirrors to test for Solar Tres

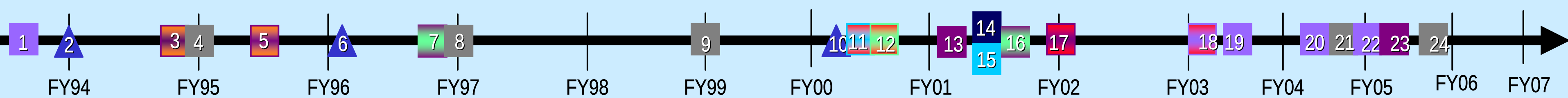
16 Mirror Matrix of standard Nauga-tuck w/Cu; Naugatuck w/o Cu prototypes; Glavebel w/o Cu thin-glass mirrors

17 ~Time frame Naugatuck converts mirror line to copperless and lead-free thin-glass mirrors

21 Received many questions concerning problems with durability of copperless/lead-free thin-glass mirrors from numerous CPV manufacturers

22 New Flabeg thick-glass mirrors with copperless backlayer and proprietary outdoor 3-layer lead-free paint system deployed at SolarGenix projects

23 Naugatuck provided thin-glass samples with multiple Valspar no-lead paint layers



4 ~Time frame lead content in paint reduced to 4%

5 ~Time frame SAIC switched from ECP-305+ to Naugatuck thin-glass mirrors

6 Sinko patents lead-free paint

7 Adhesive-dependent degradation to thin-glass mirrors identified

12 ~Time frame Glaverbel introduces copperless and lead-free thin-glass mirrors for interior applications

13 Degradation to thin-glass mirrors (caused by adhesive) observed in field

14 Sandia provides "Spanish" (Cristaleria Espanola S.A—Saint-Gobain, Spanish branch) copperless and lead-free thick-glass mirrors to test for Solar Tres

18 ~Time frame Flabeg converts thick-glass mirror line to copperless backlayer and proprietary outdoor 3-layer lead-free paint system

19 New Flabeg thick-glass mirrors with copperless backlayer and proprietary outdoor 3-layer lead-free paint system deployed at SEGS

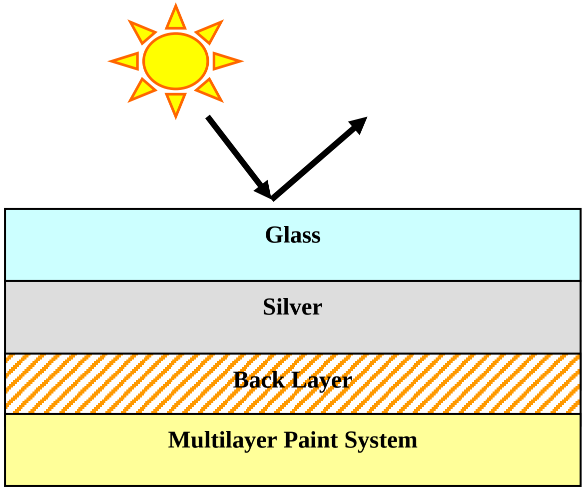
20 Side-by-side comparison of old vs. new Flabeg thick-glass-mirror exposure testing started

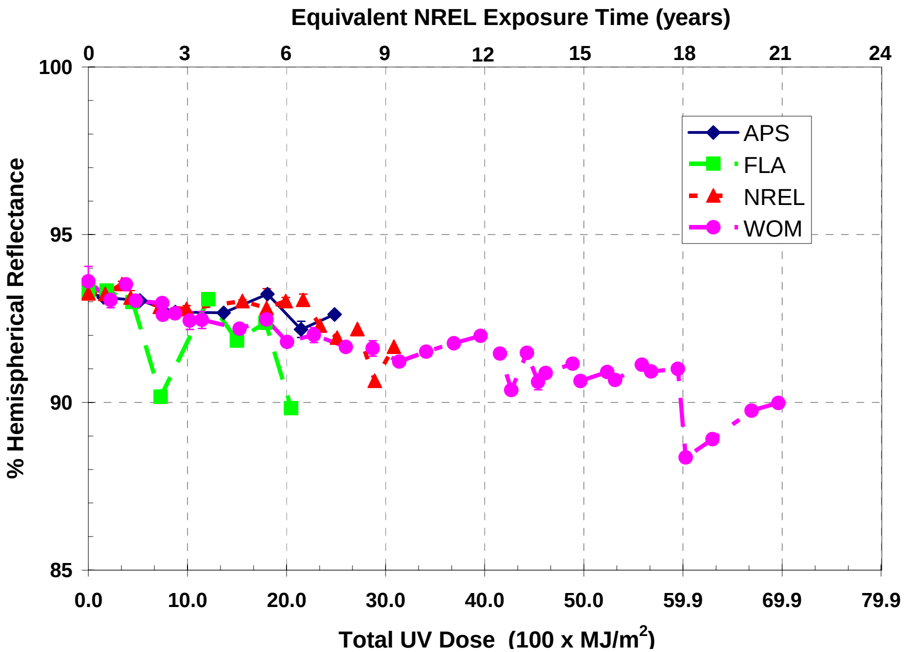
24 Began testing Asian thin-glass mirrors

- Flabeg
- Naugatuck
- Pilkington
- Glaverbel
- Spanish
- Informational
- Patent
- Material/ Research Discontinued

Flabeg (4–5 mm) Glass Mirrors

- Glass 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 and require slumped glass, which is expensive, but have been commercially deployed **(7)**.
- Trough mirrors (used by the Solar Electric Generating System [SEGS] plants in California), manufactured by Flabeg, use silvered, thick, slumped glass with a proprietary multilayer paint system designed for outdoor exposure; they currently cost \$43.2–\$64.8/m^2 (\$4–\$6/ft^2) for large-volume purchases. For trough applications, it is desirable for the mirror costs to be reduced to \$21.6–\$27/m^2 (\$2–\$2.5/ft^2).
- Initial hemispherical reflectance is 93.3%, and the original Flabeg mirrors with copper back-layers, proprietary multilayer paint system, and 4-mm glass are durable.
- Two significant changes in mirror manufacture have occurred in the classical wet-chemistry process because of environmental concerns: the method of forming a copper-free reflective mirror, and the use of lead-free paints.
- Flabeg converted its mirror line to 5-mm glass, the copper-free process, and a new lead-free paint system in FY 2003 **(1)**. The manufacturer reports durability is expected to be equivalent. Side-by-side exposure testing began in the second quarter FY 2004 **(2)** . After one year of accelerated WOM and outdoor exposure in Colorado, the new mirrors with copper-free and lead-free paint systems are performing slightly better than the original mirrors.

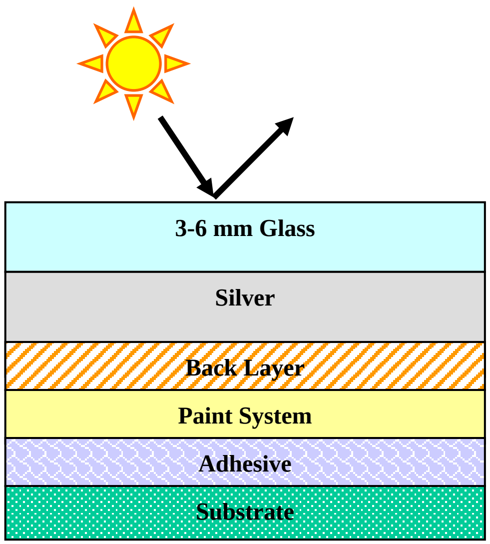


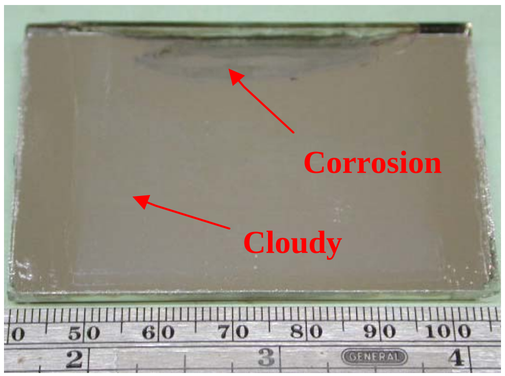


Loss of solar-weighted reflectance of original Flabeg thick-glass mirrors as function of accelerated WeatherOmeter (WOM) and outdoor exposure at Phoenix, AZ (APS), Miami, FL (FLA), and Golden, CO (NREL) in Total UV Dosage.

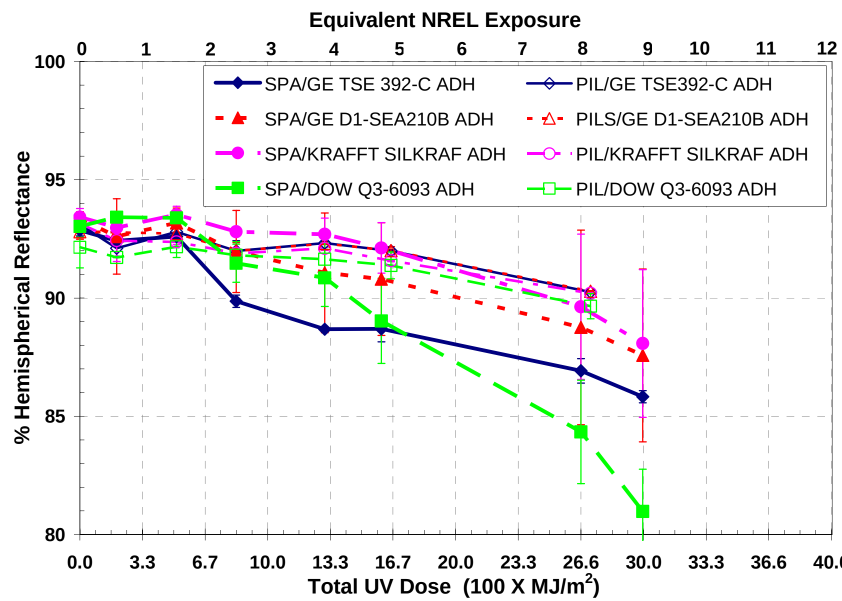
Alternate Thick (3–6 mm) Glass Mirrors

- Pilkington (UK) commercially introduced the copper-free process in 2000 for thick (4-mm) soda-lime glass for domestic use. Testing of samples of Pilkington and “Spanish” (Cristaleria Espanola S.A—Saint-Gobain Spanish branch) glass mirrors (3-mm, copper-free, and lead-free paint), bonded to steel with four different candidate adhesives, was initiated in FY 2001 **(2-4)** for possible use at Solar Tres.
- Initial hemispherical reflectance for the Spanish mirrors is 93.3% and for the Pilkington is 92.8%. The mirrors cost ~\$15 to 16/m^2 (\$1.40 to 1.49/ft^2).
- Neither Pilkington nor Spanish mirrors exposed outdoors for 60 months show degradation up to this point.
- Pilkington mirrors exhibit better optical durability than Spanish mirrors in accelerated WOM exposure testing. Spanish mirrors degraded 19.0%, whereas Pilkington mirrors degraded 6.8% after 40 months of accelerated WOM exposure.
- Adhesive-related degradation is more prevalent with Spanish glass mirrors. Depending on the adhesive used to bond the mirror, Spanish mirrors degraded 5.3% to 12.0%, whereas Pilkington mirrors degraded 2.5% to 2.9% after 34 months of accelerated WOM exposure.



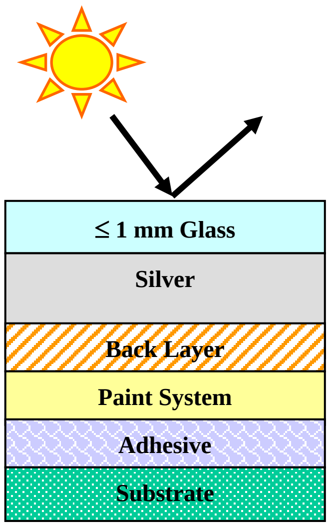


Spanish Glass adhesive-related degradation after 2 years WOM exposure.

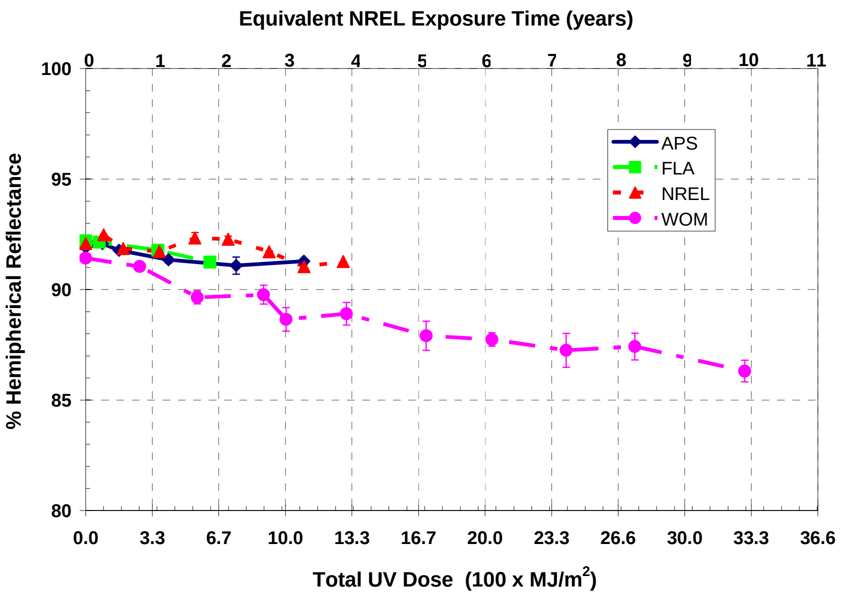


Loss of solar-weighted reflectance of thick Pilkington and Spanish reflectors with Cu-less back-layer, Pb-free paint, and four adhesives as a function of WOM exposure.

Thin (≤1 mm) Glass Mirrors



Corrosion in deployed mirrors:



Loss of solar-weighted reflectance of Naugatuck thin-glass mirrors with Cu back-layer and Pb-free paint as a function of outdoor exposure at APS, FLA, and NREL and accelerated WOM exposure.

- Thin-glass mirrors use the wet-silvered, copper-free processes on thin (1-mm), 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 ~\$16.1 to 43.0/m^2 (~\$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 were performed FYs 2001 through 2005. During FY 2001, 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) 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. R&D on mirror paint systems not performed in FY 2004 and 2005 due to budget constraints.
- Significant concern expressed in FY 2004 and 2005 by CPV manufacturers regarding durability of new thin-glass mirrors made with copper-free process and lead-free paint system **(3)**. Exposure testing initiated in FY 2005 on new thin-glass samples provided by CPV industry.

Polymer Reflectors Timeline

1 3M SS-95
3M SA-85

2 ECP-300 Development
ECP-300
ECP-305
ECP-305+ Development

3 Cu back-layer (i.e., ECP-305+) US Patent granted to NREL

4 Subcontract begins

9 CPG ECP-305+
Tunneling black eye — did not follow recommendations

10 CPG tunneling black eye — reasons and solutions identified

11 CPG switches from ECP-305+ to Naugatuck thin-glass mirrors

16 World-wide orders necessitate 3M scale up ECP-305+ to full production

17 Starts scale-up to full production

18 ~ Time frame 3M discontinues ECP-305+

19 Joint invention — R. Gee and NREL

24 ~ Time frame 3M discontinues SS-95 and SA-85

25 1st Subcontract begins

26 ~ Time frame SolarBrite withdrawn from solar market

27 U.S. patent application

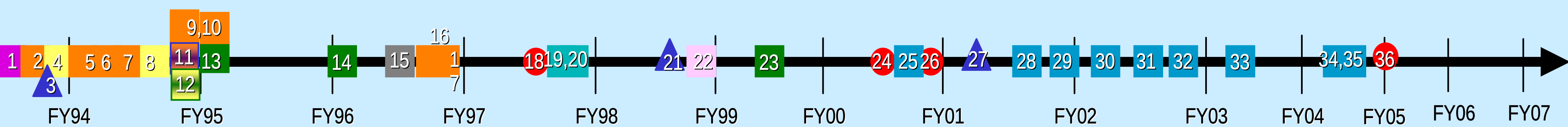
32 7 rolls of improved samples provided

33 Further sample improvements

34 2nd pilot run by Bekeart

35 Available commercially

36 ReflecTech 2nd subcontract ends



5 Tunneling problem and solutions identified

6 Pilot run

7 Adhesion layers identified would help prevent tunneling — never incorporated

8 Subcontract ends

12 ~Time frame Dow transfers All-Polymeric technology to 3M

13 Subcontract begins

14 Subcontract ends

15 CPG out of business

20 First samples made

21 Provisional patent filed

22 Entered solar market

23 Provides improved samples

28 1st pilot run by MSC

29 Subcontract ends

30 Exclusive LOI signed w/ Bekeart

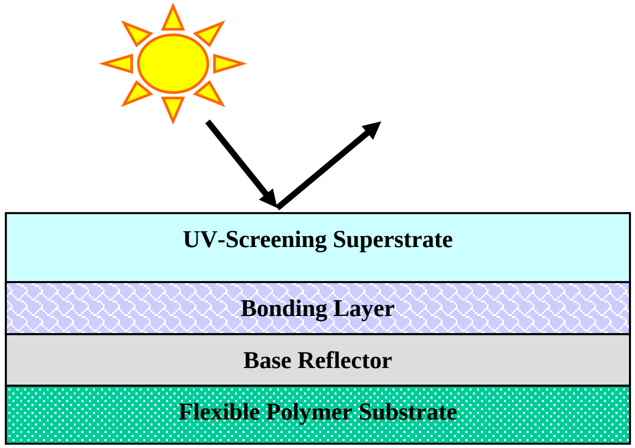
31 2nd subcontract begins

3M SS-95/SA-85
3M ECP-305+
Dow Chemical All-Polymeric
3M Northbridge All-Polymeric
RelecTech
SolarBrite
Informational
Patent
Material/ Research Discontinued

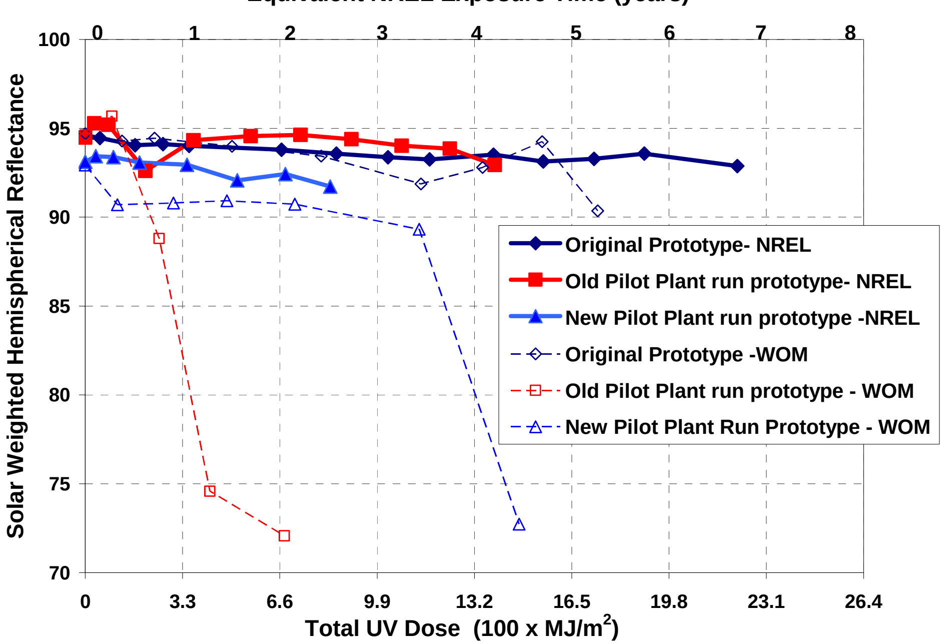
ReflecTech Metallized Polymer Film

Subcontract Ended

- The reflector material is a commercial silvered polymer with a laminated UV-screening film to provide outdoor durability. Joint patent by NREL and industry partner (ReflecTech).
- Initial hemispherical reflectance is ~93% and cost is ~$1.50 / ft^2.
- Outdoor and accelerated testing of experimental samples since FY 1999 **(1,2)**; pilot-plant run of most-promising construction, based on exposure testing, produced by ReflecTech in FY 2001 **(4)**; durability of pilot run in WOM significantly less than anticipated **(3)**.
- To improve performance, seven variations to baseline construction were manufactured and delivered at the end of FY 2002; testing was performed during FY 2003 and is ongoing **(3)**. Pilot-plant production of most-promising construction with improved UV screen was delivered third quarter of FY 2004 **(4);** durability testing is ongoing.
- No degradation observed for either initial pilot run or improved prototype materials after 10 years of accelerated outdoor exposure in ACUVEX (~7x–8x suns concentration).
- Material is being field-tested at SEGS and Solargenix Power Roof system; interest expressed by other solar manufacturers **(5)**.



Loss of reflectance of initial pilot run and most promising new variation as a function of outdoor exposure in Colorado and accelerated WOM exposure >

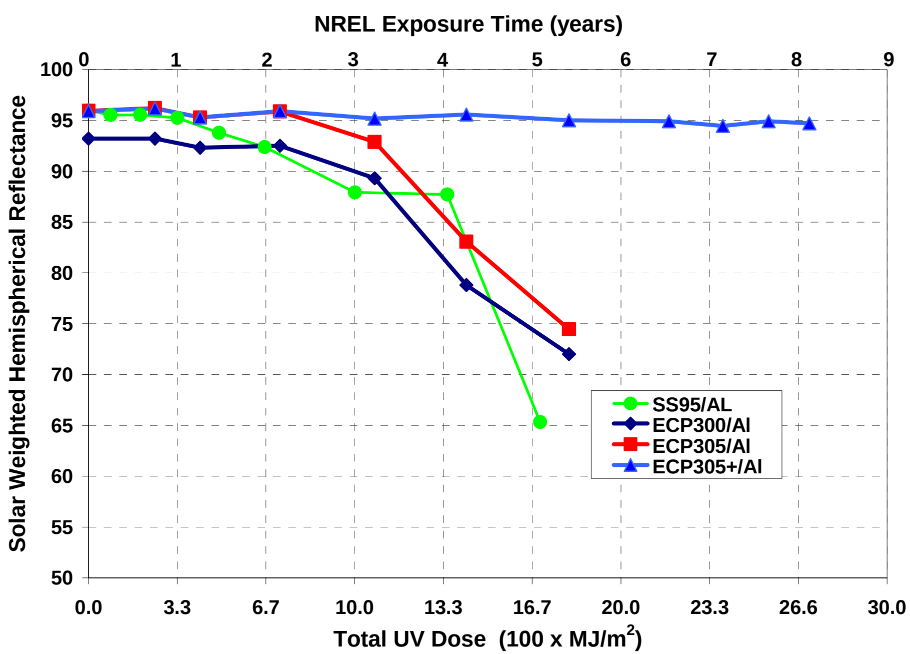


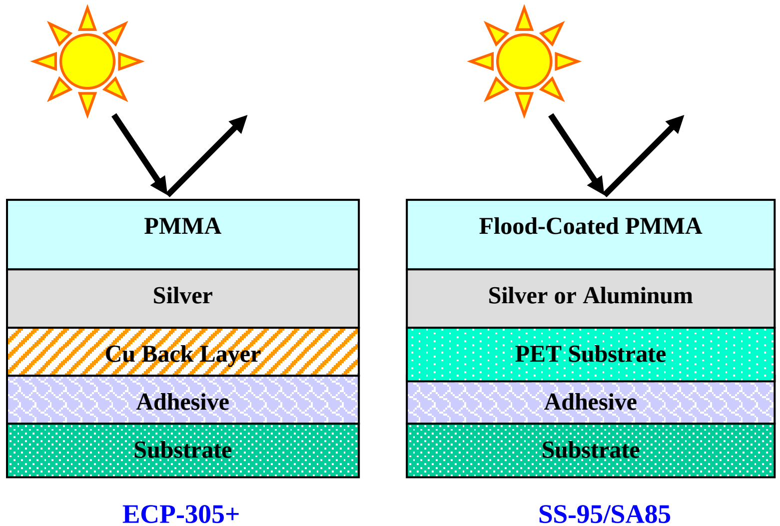
Alternative Metallized Polymer Films

Discontinued

Interest expressed in FYs 2003–2005 by CPV industry about restarting production of the following products based on their demonstrated durability and because intellectual property has expired:

- **ECP-305+:** Silvered acrylic reflector developed jointly by 3M and NREL. Initial reflectance ~94.5%. Durable for more than 9 years of outdoor exposure. Outdoor exposure testing is continuing until failure. 3M discontinued production in 1997 **(6)**.
- **SS-95:** Silvered PET with a thin acrylic flood coat. Manufactured as an indoor lighting product. Initial reflectance ~95%. Durable for more than 4 years outdoors without additional UV screening layer. Outdoor exposure testing with and without an additional UV-screen layer is continuing until failure. 3M discontinued production in 2000 **(6)**.
- **SA-85:** Aluminum-vapor-coated PET with acrylic coating. Initial reflectance ~87%. Durable for almost 12 years of outdoor exposure. Outdoor exposure testing is continuing until failure. 3M discontinued production in 1997 **(6)**.

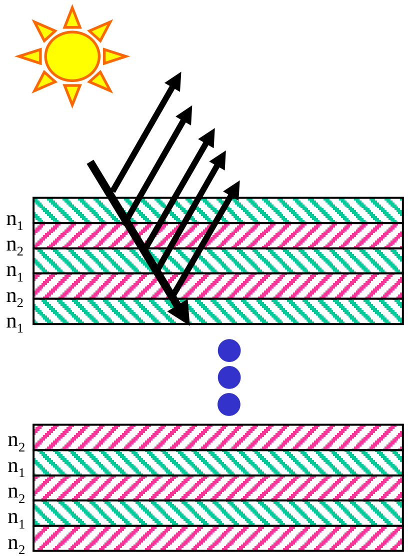




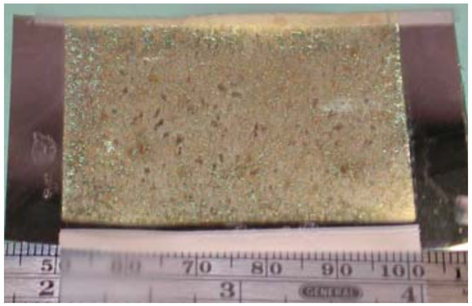
< **Loss of reflectance alternative metallized polymer films as a function of outdoor exposure at NREL.**

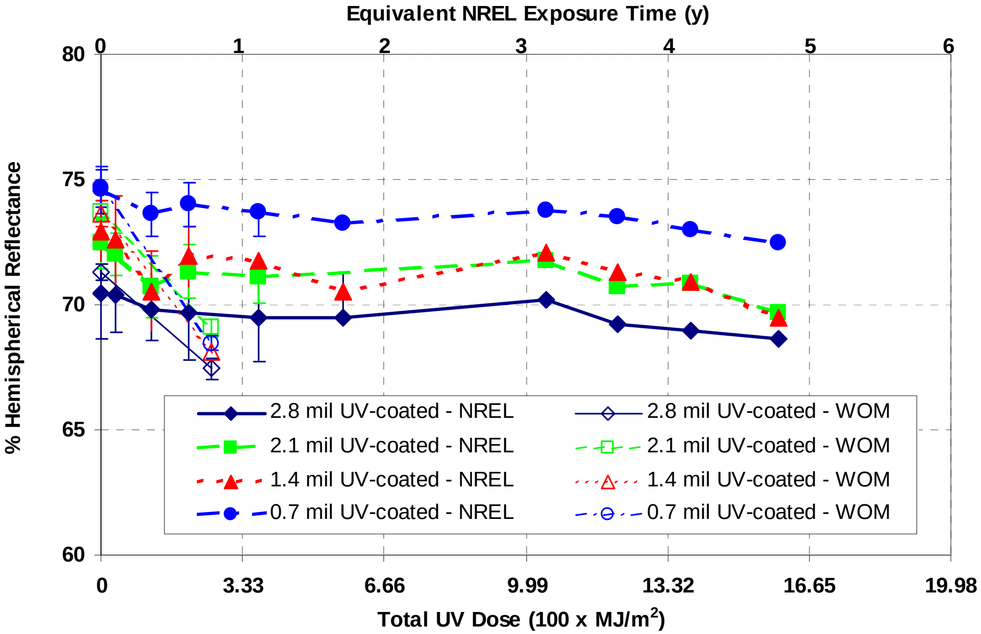
3M All-Polymeric Reflector

Discontinued



Yellowing after 3 months in WOM:





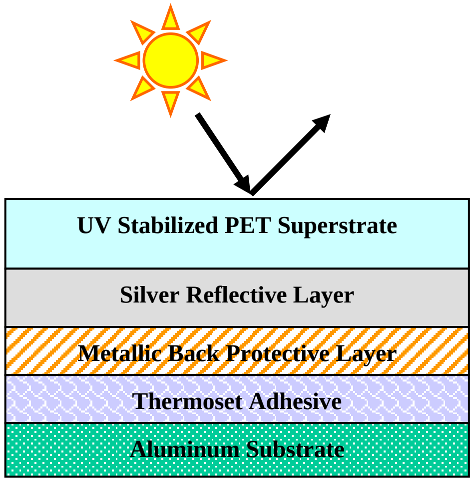
- 3M's multilayer "Radiant Film" technology
- Alternating polymers are coextruded; multiple reflectance produced due to mismatched indices of refraction. Benefit of a polymer substrate (light weight, curvable, and low cost), potential for very high broadband reflectance (~99%), and no metal reflective layer to corrode. Spectral characteristics can be tailored for the application.
- Samples provided in FY 1999 for evaluation had high reflectance in narrow band (~99% between 400 and 1000 nm), but had a problem with UV durability. The samples yellowed after 3 months of accelerated exposure. However, samples exposed outdoors in Colorado have not yet noticeably yellowed after 56 months of exposure.
- Multiple requests from FYs 2002 through 2005 for test samples with improved UV screening layers and (possibly) abrasion-resistant hardcoats **(1,2)**. Samples promised, but not as yet delivered. NDA pursued.
- Delivery of samples delayed by 3M's intellectual property concerns and an extensive prioritization process that has delayed programs and decisions for months.

< **Loss of reflectance over solar spectrum (250–2500 nm) of 3M all-polymeric films as a function of outdoor exposure at NREL and accelerated WOM exposure.**

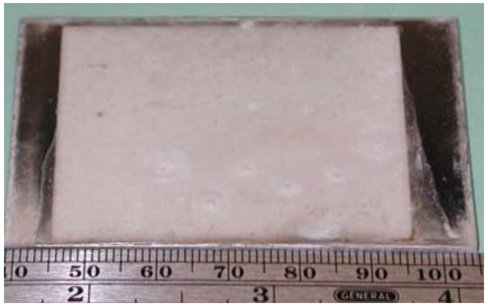
SolarBrite 95

Discontinued

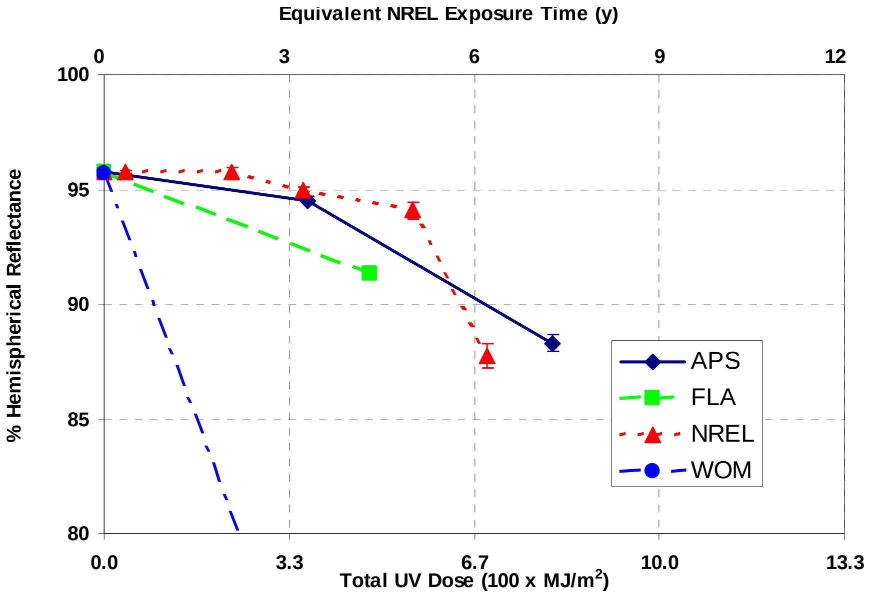
- Reflector material was a silvered UV-stabilized polyester (PET) film having a metallic back-protective layer laminated by a proprietary thermoset adhesive to an aluminum substrate. A painted coating was applied to the backside of the metal substrate.
- Initial hemispherical reflectance ~92% and cost 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 FY 2000 **(5).**
- Alcoa's commercial product is no longer being produced, but Southwall contacted NREL FY 2003 because they provided Alcoa with the PET and may be manufacturing SolarBrite **(6).**



Failure after 20 months in Florida:



Loss of reflectance of SolarBrite 95 as a function of outdoor exposure at APS, FLA, NREL and accelerated WOM exposure >



Aluminum Mirrors Timeline

1 Received Metalloxyd anodized aluminum samples

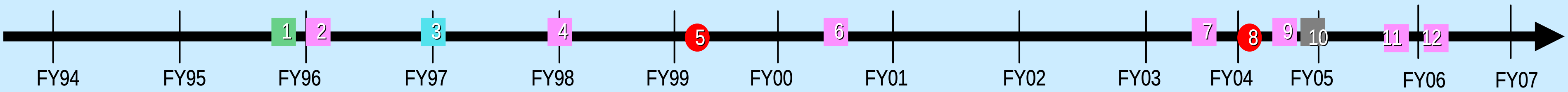
2 Received Alanod physical vacuum deposited (PVD) aluminized aluminum samples

3 Received Regiolux anodized aluminum samples

7 Received many questions concerning problems with durability of Alanod aluminum mirrors from CSP and CPV manufacturers

8 Alandod withdrawn from solar market. Alanod working to find solution to delamination and specularity-loss problem

12 Alanod reintroduced reflector for solar market



4 Received improved anodized aluminum mirror with acrylic protective polymeric overcoat

5 Metalloxyd merged with Alanod

6 Received samples where acrylic protective polymeric overcoat was replaced

9 Received samples w/ enhanced reflectivity (only for interior use)

10 Multiple interest expressed by CPV industry about SA-85 and enhanced aluminum w/ polymer substrate

11 Received improved anodized aluminum samples w/ enhanced reflectivity & durability.

Metalloxyd

Alanod

Regiolux

Informational

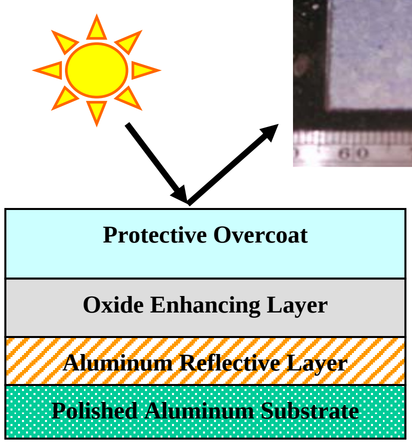
Patent

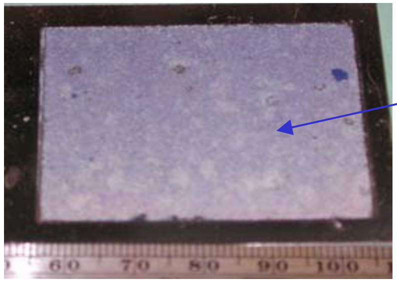
Material/Research Discontinued

Front-Surface Aluminized Reflector

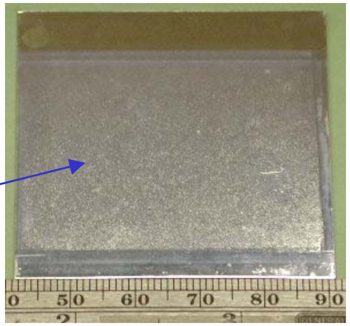
Being reintroduced FY 2006

- Front-surface aluminized reflectors use polished aluminum substrate, an enhanced aluminum reflective layer, and the formation of a protective oxidized topcoat. These reflectors have inadequate durability in industrial environments.
- Addition of acrylic polymeric overcoat to protect oxide improved durability. Samples have survived >5 years' outdoor exposure in Golden, CO, and Phoenix, AZ, and >3 years' outdoor exposure in Miami, FL, 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 degraded with exposure in Arizona, Florida, NREL, and WOM. Specularity results transmitted to DLR **(2,3)**.
- New samples received FYs 2003, 2004 **(2)**.
- Product removed from market FY 2004 for outdoor applications **(6)**. Alanod worked to improve durability and new samples received FY2005 are undergoing testing **(3,2)**.
- Alanod will reintroduce product early FY2006 **(4)**. Product will be commercially available from Alanod in cooperation with the DLR in Germany **(7)** for ~$2/ft^2; initial reflectance ~90%.

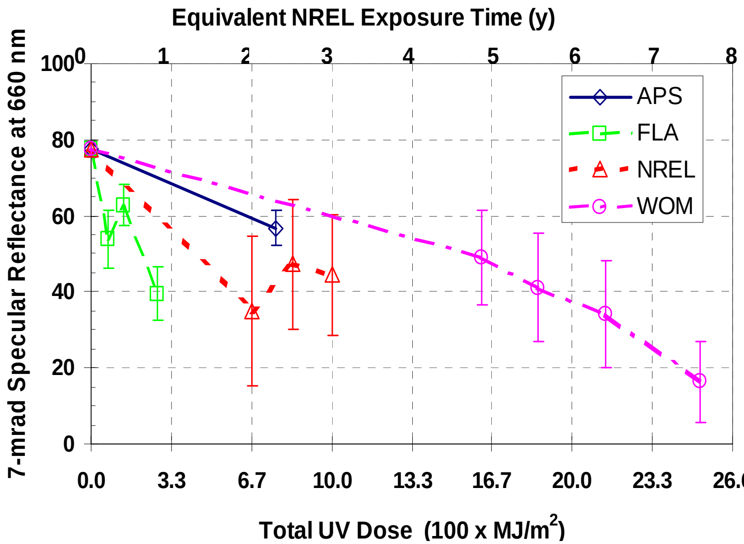




Acrylic overcoat failed after 18 months WOM



Fluoropolymer overcoat after 30 months WOM



Loss of 7-mm specular reflectance at 660 nm (78%) of Alanod Miro/4270kk aluminized reflectors as a function of APS, FLA, and NREL outdoor exposure and accelerated WOM exposure.

Front-Surface Reflectors Timeline

1 Front-surface oxide mirrors made by RF sputtering

2 Luz supplies front-surface SiO_2 samples

3 Wins RFP for IBAD Al_2O_3 "Super Thin Glass" proposal

8 Samples produced at Armstrong

9 1st cost analysis — MIT

10 Samples replicated at Penn State

11 Level steel foil substrate #1

16 IBAD SiO_2 Super Thin Glass mirror

17 Produced miniature facets

18 Designed and built cool stage

19 Solel provides new FSM #1

23 Work stopped per DOE directive on NREL Pulsed DC Al_2O_3 Super Thin Glass mirror

24 1st subcontract ends

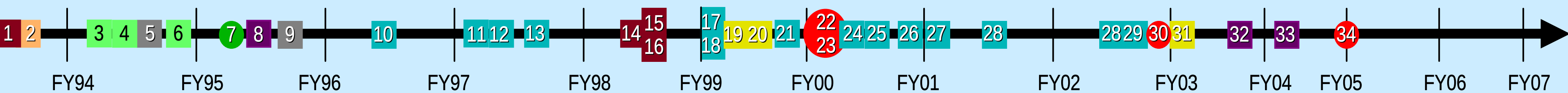
25 2nd subcontract begins

30 Luz SiO_2 samples WOM exposure stopped

31 Solel provides improved FSM #4

32 2nd cost analysis — Swisher

33 Modify 2nd cost analysis — Swisher



4 Withdraws IBAD Al_2O_3 Super Thin Glass proposal due to corporate restructuring

5 Front-surface mirrors supplied by 6 companies

6 Armstrong grants rights for IBAD Al_2O_3 Super Thin Glass to SAIC

7 1st subcontract begins

12 Systems upgraded at SAIC

13 Samples produced at SAIC

14 Multi-chamber deposition system installed

15 Pulsed DC Al_2O_3 Super Thin Glass mirror

20 Solel provides improved FSM #2, 3

21 Deposition rate increased to 20 nm/s

22 Work stopped per DOE directive on NREL IBAD SiO_2 Super Thin Glass mirror

26 Designed, built, and installed laboratory roll-coater

27 Level SS foil substrate #2

28 Deposited samples at 10 nm/s on roll-coater

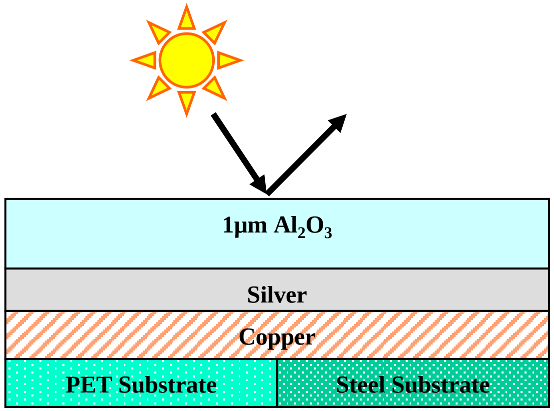
29 Deposited samples at 20 nm/s on roll-coater

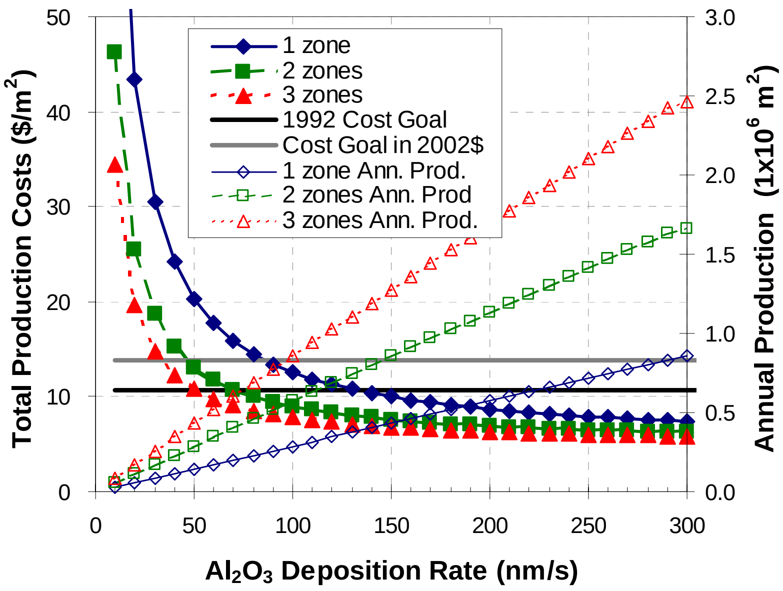
34 SAIC 2nd subcontract ends

- NREL Development
- Luz
- Armstrong
- SAIC IBAD "Super Thin Glass"
- Solel
- Cost Analysis
- Informational
- Patent
- Material/Research Discontinued

SAIC IBAD "Super Thin Glass" Mirror

Subcontract Ended



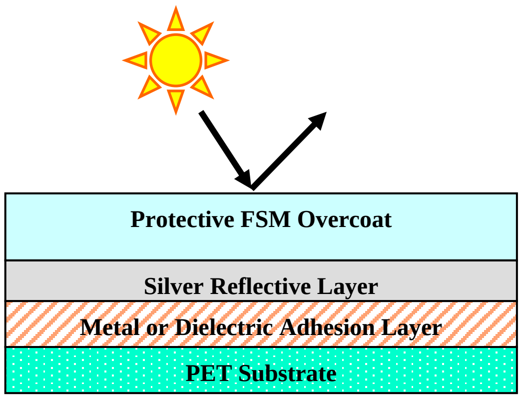


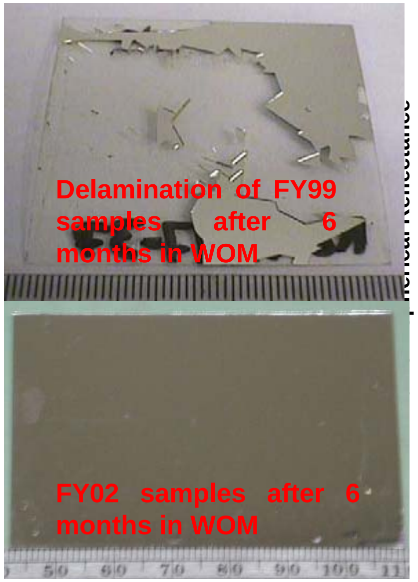
Cost analysis comparing multiple zones. Modified ASRM, 1-µm Al_2O_3; 10 to 200 nm/s rate; PET substrate; 30% yield; 1200-mm-wide web; high-purity Al_2O_3 ($200/kg).

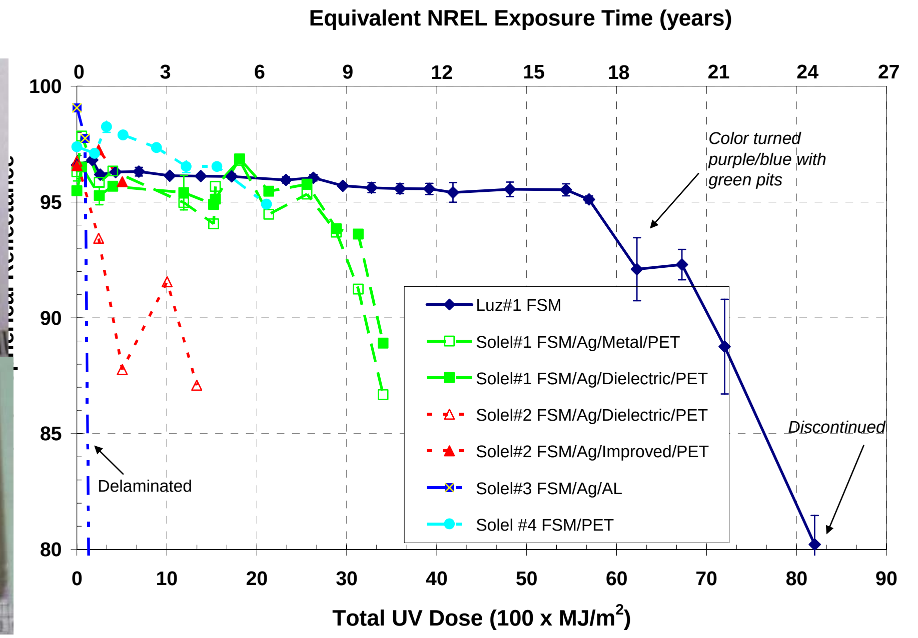
- Benefits of flexible substrate and the durability of glass. Ion-beam assisted deposition (IBAD) is used to deposit the very hard (cleanable) dense (protective) alumina topcoat. Samples are highly reflective (>95%) and durable. Subcontracted effort by SAIC, McLean, VA.
- Batch deposition rate increased to 22 nm/s in FY00—samples accumulated 5000 hours accelerated solar simulator exposure and more than 5 years of WOM and outdoor exposure in Arizona, Colorado, and Florida; substrate switched to high-temperature specular steel in FY 2001 **(2,3,4)**.
- First materials produced at 5–10 nm/s on laboratory roll-coater during FY 2001. Roll-coated samples accumulated 3000 hours accelerated solar simulator exposure and 3 years WOM and outdoor exposure in Colorado **(2,3,4)**.
- Deposition rate on laboratory roll-coater doubled to 20 nm/s at end of FY 2002 (4); deposition conditions at 20 nm/s optimized and incorporated structural improvements in FY 2003 **(3)**. Samples have demonstrated superior durability and durability testing ongoing **(2)**.
- New cost analysis **(7)** performed during FY 2003 and reworked in FY 2004. Cost of reflector dependent on substrate; alumina thickness, deposition rate, and cost; and machine burden. Material can be manufactured at <$1/ft^2 with 1-µm-thick alumina with deposition rate of 50 nm/s on PET substrate on roll-coater.
- Subcontract ended September 30, 2004.

Front-Surface Mirror (FSM)

- The Solel front-surface mirror (FSM) consists of a 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 NREL for evaluation in FY 1999; samples delaminated and corroded during accelerated exposure testing **(2,3)**.
- New improved samples on PET and aluminum substrates were provided at the end of FY 2002; testing is ongoing. After more than 2 years of exposure in the WOM and outdoors in Colorado, the hemispherical reflectance of the FSM with the aluminum substrate degraded 0.8% in the WOM and 1.1% outdoors and for the PET substrate, 2.5% in the WOM and 6.2% outdoors; but specular reflectance has degraded significantly more for samples with the PET substrate **(2)**.
- Although FSM accelerated WOM exposure is very encouraging, SAIC IBAD Super Thin Glass mirror demonstrated that outdoor exposure in Colorado and Florida for FSMs is more severe than WOM exposure.



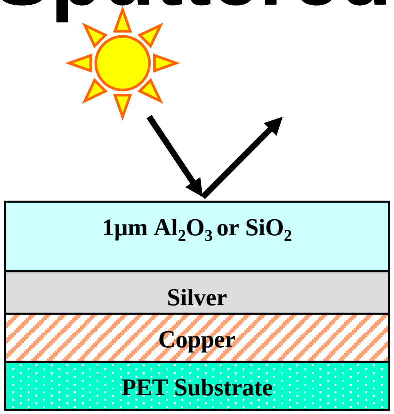


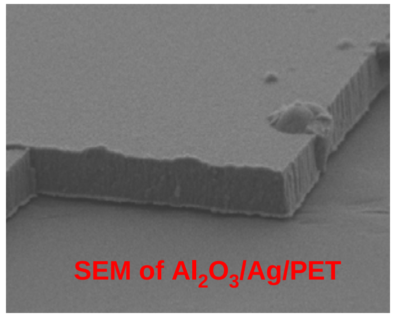


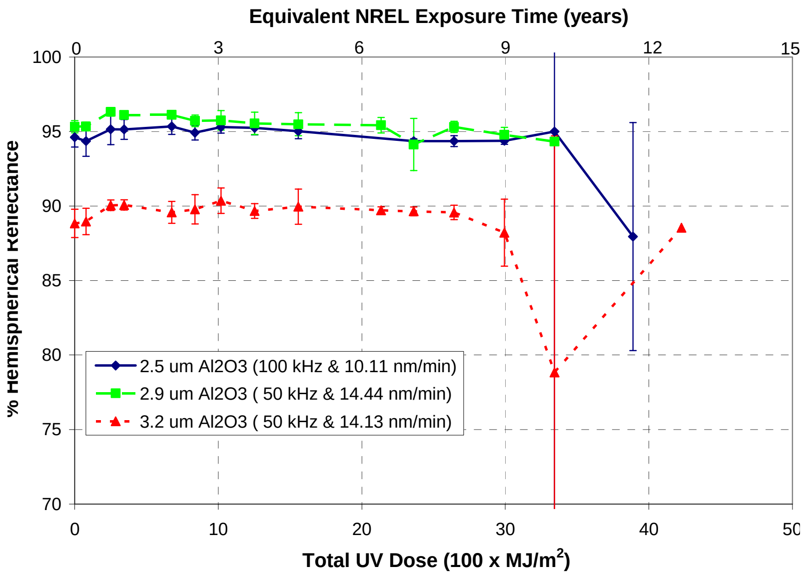
Loss of reflectance for FSM as a function of accelerated WOM exposure.

NREL Reactive Pulsed DC Magnetron-Sputtered or IBAD "Super Thin Glass" Mirror

Discontinued







Loss of reflectance for NREL reactive pulsed DC sputtered Al_2O_3 Super Thin Glass mirror as a function of accelerated WOM exposure. [Drop in reflectivity, followed by increase, and associated large error bars caused by sample discontinuation.]

- Reactive-pulsed DC magnetron sputtering (Al_2O_3) and IBAD (SiO_2) were used to deposit very hard (cleanable), dense (protective), flexible, lightweight topcoats. These processes have demonstrable manufacturing scale-up capability. Cost projected ~\$1.00 /ft^2.
- The effect of relevant deposition process parameters on properties of deposited layers was understood.
- Research (i.e., new sample preparation) was stopped during FY 2000 per DOE directive. Exposure testing is continuing to failure.
- After 4.5 years accelerated WOM exposure, some samples (prepared prior to closeout) have maintained their initial performance (reflectance >95%); many have exhibited cracking and delamination failure **(2)**.
- Although accelerated WOM exposure is very encouraging, SAIC IBAD Super Thin Glass mirror demonstrated that outdoor exposure in Colorado and Florida for front-surface mirrors is more severe than WOM exposure.
- Cost expected to be less than SAIC IBAD Super Thin Glass mirror.