Final Technical Report for DOE/EERE Solar Technologies Office

FOA Name: SunShot Incubator Program

FOA Number: DE-FOA-0000923

Project Title: Development of an Abrasion-Resistant Antisoiling Coating for Front-Surface Reflectors

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Executive Summary

A high-performance reflective film has been successfully developed for Concentrating Solar Power (CSP) solar concentrators. Anti-soiling properties and abrasion resistance have been incorporated into the reflector to reduce reflector cleaning costs and to enhance durability. This approach has also resulted in higher reflectance and improved specularity.

From the outset of this project we focused on the use of established high-volume roll-to-roll manufacturing techniques to achieve low manufacturing costs on a per ubit area basis. Roll-to-roll manufacturng equipment has a high capital cost so there is an entire industry devoted to roll-to-roll "toll" manufacturing, where the equipment is operated "around the clock" to produce a multitude of products for a large variety of uses. Using this approach, the reflective film can be manufactured by toll coaters/converters on an as-needed basis.

We successfully developed and manufactured a functional prototype of our advanced reflector (using full-scale high-volume equipment owned by a toll coater/converter) that has these attributes:

- Solar-weighted Hemispherical Reflectance of nearly 94% (ASTM E891)
- Excellent Cleanability – anti-soiling properties to reduce reflector cleaning costs (Cleanability Index >99%)
- Superior Abrasion Resistance – resists scratching and allows direct contact cleaning techniques (specular reflectance loss below 1% after Taber abrasion)
- Improved Specularity – highly specular reflected light (beam spread of reflected light below 1.6 milliradian, rms)
- Excellent Mechanical Durability (passes ASTM D3359 cross-hatch test)

Additional data from accelerated weathering tests will be needed to demonstrate that a 20+ year outdoor lifetime can be expected. To this end, we have prepared reflector specimens of this advanced reflector for accelerated weathering tests at the National Renewable Energy Laboratory.

The success of this project strongly supports the U.S. DOE's SunShot Initiatives goal of lowering the levelized cost of electricity (LCOE) for CSP to 5 to 6¢/kWh$_e$ by 2020. Satisfying this goal requires reduction in the cost of CSP reflectors, increased reflector optical performance, and reducing the costs of routine reflector washing to maintain high reflectance. Our project has been successful in all three of these important areas.

Background

The motivation for this project was a long-standing need within the CSP industry for improved reflectors, a core part of all CSP collector systems. Glass mirrors have dominated this commercial space for many years, but they are relatively expensive, heavy, fragile, and can require frequent cleaning to maintain reflectance. The many advantages possible with the successful development of a non-glass reflector are noted below (abridged), excerpted from a technical report[1] submitted to DOE by Abengoa Solar, a company known for extensive use of glass reflectors.

> *"Glass mirrors are currently the industry standard for utility-scale solar power operations. However, these glass mirrors impose certain limits, their weight and fragility inhibiting potential design leaps needed to make solar power more competitive with fossil fuels."*
>
> *"There are many benefits to replacing glass mirrors with alternatives that do not display some of the limitations of current glass reflectors:*
> - *Design Constraints: The design constraints of glass provide the most compelling need. Currently, solar collectors must support the heavy weight of glass, which adds material and expense. A reflective film can provide significant reductions to the solar collector structure and allow for a variety of innovative designs.*
> - *Shape Limitations and Optical Efficiency: In testing, engineered facet panel backing materials have been able to hold improved shape and optical precision. This enables improved optical efficiency and innovative design solutions.*
> - *Transport Difficulty: Glass is both heavy and breakable, which makes it difficult and expensive to transport. Some breakage during transport is common. Reflective film is far lighter, transported in large rolls and does not shatter.*
> - *Breakability in the Field: Mirrors are broken in the field every year, due to strong weather events and other occurrences, and must be replaced. In reflective films much more limited areas are affected by any damage. For example a small hole as opposed to shattered sections.*
> - *Size: Glass mirrors become extremely difficult to handle at large sizes. Because of this, typical solar mirrors are produced at less than 1.7 m wide."*

With U.S. DOE support, Abengoa Solar pursued the development of an advanced non-glass reflector, but unfortunately it was not successful. Their reflector concept required a vacuum-deposited protective alumina layer that is extremely thick by vacuum deposition standards (up to 4 microns). This thick vacuum-deposited layer posed an inherent economic barrier, and made the approach uneconomic.

Our technical approach overcomes the problem found by Abengoa Solar. We will use standard web roll-coating techniques to apply a protective coating. This coating

[1] Abengoa Solar, Final Report for FOA# DE-FC36-08GO18036, March 28, 2013

process does not require vacuum deposition equipment, so is much more economic and is well suited for low-cost manufacturing.

We have achieved these improvements through R&D directed at the incorporating the advantages of nanotechnology into our reflector configuration. Nanotechnology can modify the surface properties of materials[2], and improves abrasion resistance[3] and enhances cleanability[4]. We have incorporated these benefits so that they simplify the stack of materials used in this new reflective film, making the product easy to manufacture. And as noted above, we have relied upon established manufacturing processes that are suited for high-volume production so that manufacturing costs are reduced. Additionally, our new reflective film approach results in reflectance superior to glass mirrors and prior reflective films.

Project Objectives

The specific near-term performance metrics for this advanced reflector are:

- High reflectance (94%, ASTM E891)
- High abrasion resistance (reflectance loss <1% after ASTM D4060 abrasion)
- Strong adhesion of the coating/layers (ASTM D3359 cross hatch test)
- Antisoiling properties that reduce wash frequency and lower reflector wash costs
- High clarity of the front-surface coating; RMS specularity below 1.6 mrad
- Lower manufactured cost (below $10/m2)

Achieving these project cost and performance objectives clearly supports the SunShot Initiatives CSP goals (LCOE of 5-6¢/kWh_e by 2020). Lowering LCOE to these levels for CSP will definitely require a reduction in the cost of CSP reflectors. Increased reflector optical performance will also support the reduced LCOE goals too. Reduced operation and maintenance (O&M) reflector washing expenses helps too. Routine reflector washing is the largest O&M cost for a CSP system. Together, these features offer reflector technology improvements that are critical prerequisite to achieving the aggressive CSP goals of the SunShot Initiative.

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[2] Optical Dynamics, "Engineered Polmer Nanoparticle Composites for Flexible Transparent Films", 11th Annual Coatings for Plastics Conference, Chicago, IL, April 2008.

[3] R. H. Cayton, P. G. Murray, and D. Nelson, "Nanoparticle Additives for Enhanced Scratch Resistance in UV-Cured Coatings", *PCI Magazine*, October 1, 2010.

[4] Nissan Chemical America Corporation, "Current and Impending Developments in Silica Nanoparticle Use in UV-Curable Systems", RadTech 2010 Technology Expo and Conf., Baltimore, MD, March 2010.

Reduced capital costs is the most direct way of lowering the LCOE of CSP systems. The costs of state-of-the-art reflector alternatives provide an important reference for comparison. Curved glass mirrors for parabolic troughs range from \$25/m^2 to \$35/m2 when mass produced, depending on quantity and quality. And ReflecTechPLUS, the best commercially-available reflective film to our knowledge, is priced near \$20/m^2 in volume. Achieving a cost goal below \$10/m2 would clearly represent a major cost reduction, and contribute significantly to lower CSP system costs.

Improved reflectance also directly contributes to lowering LCOE. Each 1% increase in reflectance reduces the amount of needed reflective area by at least 1%, with the associated cost reduction in the concentrator area as well as the associated components (supports, controls, etc.). Reflectors with antisoiling characteristics reduces the frequency of washing required to keep reflectance near its peak. This lowers O&M costs, another contributing factor in reducing LCOE.

Several other attributes of our advanced reflector are harder to assess. For example, as noted by Abengoa (see prior Background section), there are financial benefits in having a reflector that does not break, both in service as well as while it is being transported. Further, Abengoa notes that the high weight of glass reflectors imposes design constraints on the entire concentrator, with associated costs penalties, albeit difficult to determine. Other design constraints that they noted are the practical limits in manufacturing and handling of glass mirrors, plus the limitations on shape (and general design/architecture) imposed with glass reflectors.

The project Statement of Project Objectives (SOPO) is summarized below.

- The first activity was determining the baseline performance of two types of state-of-the-art CSP reflectors: ReflecTechPLUS and silvered glass mirrors. This data is useful in comparing and assessing the degree to which this project has advanced the state of the art.

- The bulk of the technical work was covered in a SOPO task with five subtasks.
    - Subtask 1.1 -- laboratory preparation of reflector specimens that demonstrate that this new reflector construction had good inter-layer adhesion.
    - Subtask 1.2 -- laboratory preparation of reflector specimens that demonstrate improved reflectance.
    - Subtask 1.3 -- laboratory preparation of reflector specimens that demonstrate improved abrasion resistance.
    - Subtask 1.4 -- laboratory preparation of reflector specimens that demonstrate antisoiling properties.
    - Subtask 1.5 -- completion of small pilot-scale runs of the reflector construction using roll-to-roll web coating/converter equipment to demonstrate that it is manufacturable and demonstrates improved optical and mechanical characteristics.

- Task 2 detailed the various measurements and measurement protocols to be used for testing and characterizing the reflector specimens. This covered measurement of solar-weighted hemispherical reflectance, reflector specularity, inter-layer adhesion, abrasion resistance, cleanability, accelerated weathering, and reflector surface properties (i.e. water contact rolling angle, hardness, surface roughness, and water drop rolling angle).

- Task 3 covered outreach and engagement with the CSP industry, in particular those companies that could be potential customers for the new reflective film.

- Task 4 covered project management activity: project coordination and administration, DOE collaboration, and the preparation of reports.

The project Statement of Project Objectives (SOPO) focused on the various technical issues in an orderly manner. The Deliverables were structured to address the key issue of adhesion to the silver layer, while progressively improving reflectance, abrasion resistance, and cleanability.

The technology-related project milestones consisted of 5 deliverables:

- ✓ D0: Characterize the properties of ReflecTechPLUS film and silvered/curved glass mirrors.
- ✓ D1: Prepare lab specimens that demonstrate adequate adhesion of reflector coating to silver and reflectance of 92%.
- ✓ D2: Prepare lab specimens that demonstrate reflector has good abrasion resistance and Cleanability Index above 97%.
- ✓ D3: Complete a first pilot run to demonstrate improved reflectance of 92.5%, adequate adhesion, high specularity, good abrasion resistance, and Cleanability Index Above 97%.
- ✓ D4: Prepare lab specimens that demonstrate reflector has further improved reflectance of 93.5%, improved adhesion, improved abrasion resistance, and improved Cleanability Above 98%.
- ✓ D5: Complete a second pilot run to demonstrate reflector has <u>all</u> the desired characteristics: high specularity, high abrasion resistance, high adhesion, high Cleanability Index, and improved reflectance.

The project culminated in the completion of a second pilot run (Deliverable D5) with a reflector that demonstrated all the desired characteristics, while being manufactured on large-scale roll-to-roll equipment.

Project Results and Discussion

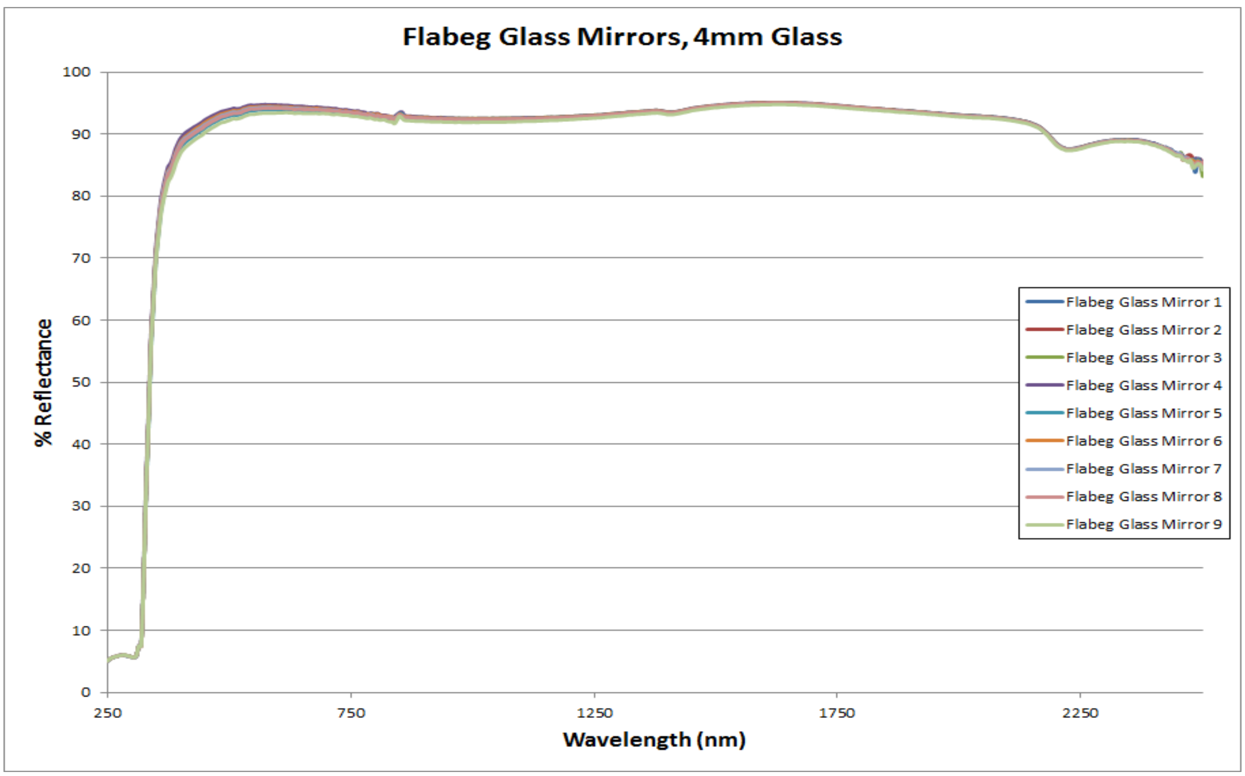
Establishing Baselines for Technical Comparison

The first project deliverable (D0) was to establish a baseline against which we can make comparisons and gauge improvements. Reflector specimens of curved Flabeg glass mirrors were used as a comparison, as were specimens of ReflecTechPLUS, a commercially-available reflective film.

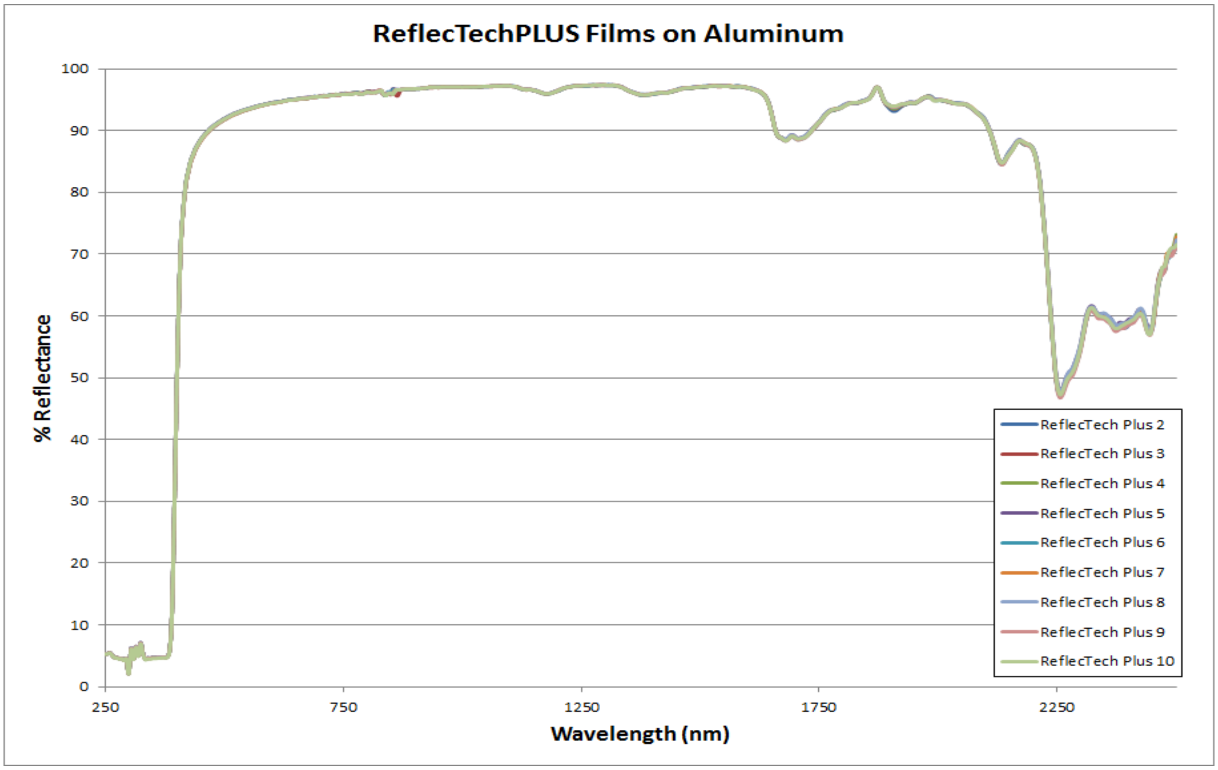
The ReflecTechPLUS specimens were obtained from SkyFuel Inc (the manufacturer of this reflective film) already pressure laminated by SkyFuel onto an aluminum sheet metal substrate. The curved glass mirrors (Flabeg-manufactured mirrors for an LS-3 collector) were obtained from NextEra at their SEGS-II plant in Daggett, CA.

The specimens needed for the various tests and measurements were prepared to the different sizes needed for each test. For the reflective film samples, a sheet metal shear was used to cut to the needed sizes. For the curved glass mirrors, a glass-cutting band saw was used.

The standard curved glass reflectors had an average solar-weighted hemispherical reflectance of 92.6% (ASTM E891). It is noteworthy that these measured values are a little lower than the oft-cited values of ~93% for curved glass mirrors. The spectral reflectance of all the measured glass mirror samples is shown below.



ReflecTechPLUS reflective film was measured to have a solar-weighted hemispherical reflectance of 91.2% based on ASTM E891. The spectral reflectance of all the ReflecTechPLUS samples is shown below.



The abrasion resistance of ReflecTechPLUS was measured using the ASTM Taber abrasion test. Three specimens had an average loss of 2.6% in specular reflectance following 30 Taber abrasive cycles.

The Cleanability Index of ReflecTechPLUS was measured after each of 6 cycles, and averaged 97.1%. And the crosshatch tests showed no loss of adhesion, all ReflecTechPLUS samples passed ASTM D3359. The surface hardness of ReflecTechPLUS was found to be 3B (per ASTM D3363).

Advanced Reflector Development Steps

Our first objective was to establish a front-surface reflector construction with good mechanical properties, and demonstrate that the various layers in the reflector construction adhere adequately to each other. That was the primary focus of our work during the first quarter, as we tried different coating formulations with various adhesion promotion additives. Adhesion was measured using ASTM D3359 crosshatch tests. The highest classes of adhesion are denoted by ASTM as Classes 3B, 4B and 5B. All three of these highest crosshatch levels require little to no removal of crosshatch squares. Class 3B allows flaking/removal of the coating along the cut edges/intersections (up to 15% loss of coating), while Class 4B allows up to 5%, Class 5B is the highest level, where the cut lines are completely smooth. Our best adhesion results (Class 4B) occurred when thiolene additives were incorporated into the UV-curable coating. Still, the crosshatch results were somewhat inconsistent, with some samples performing better than others. So, although deliverable D1 was achieved, further improvement in adhesion was noted to be desirable going forward.

The next technical goal was to demonstrate that roll-to-roll manufacturing equipment could be used to successfully manufacture the new reflector construction, with results consistent with those previously achieved through hand preparation in the laboratory. Although it was recognized that further work was needed to ultimately achieve all the technical and optical goals we laid out for the new reflector, it was important to demonstrate that commercial-scale equipment would show results consistent with our lab-produced specimens.

Next, the first pilot run was successfully completed. In preparation for this pilot run we had previously prepared a roll of silvered polyester film (52 inch width). The pilot run began with checks of the UV intensity of the banks of UV-curing lamps, and were found to be in accordance with our specifications. The roll of silvered polyester was then mounted onto the coating line, and the coating was loaded into the coating tank and mixed/circulated. A small amount (< 300 linear feet) of the silvered polyester film was then coated/cured as a first check of the process/product. The desired coating thickness was not achieved, so adjustments were made to line speed and the process was repeated and rechecked. The abrasion resistance was checked using an ASTM steel wool abrasion test, and an ASTM cross-hatch test was performed to assess adhesion of the coating. Specular reflectance was also checked using our portable specular reflectometer. All the characteristics were acceptable so we proceeded with the pilot run. Again, specimens were taken from the coated/cured rolls and testing (steel wool abrasion, cross hatch, and specular reflectance) were all acceptable. We prepared samples from the pilot-run rolls and submitted them to NREL for testing (for Deliverable D3). NREL measurements showed that the D3 requirements were satisfied, but adhesion was again the primary area of concern.

With adhesion still a concern, we refocused our research effort on ways to enhance adhesion. We prepared additional sample constructions based on a wider range of nanocoatings that were reformulated to further improve adhesion by varying photo-initiator and UVA package content and loading levels, and by the addition of adhesion promoting acidic chemical modifiers. Ultimately, we found that a thin primer layer significantly enhanced adhesion of the abrasion-resistant nanocoating. The primer has excellent adhesion to silver, and is softer and more flexible than the nanocoating. Through lab testing we established that the proper thickness of this primer layer (2.5 to 3) microns is very important to achieving strong adhesion of the nanocoating layer, while also maintaining a high level of abrasion resistance.

The first two sets of lab-prepared reflector specimens with the primer layer were delivered to NREL on December 26, 2015. These specimens were found to have good adhesion (passed cross hatch) but insufficient abrasion resistance. The primer formulation was then altered to one that resulted in less migration of the primer into the nanocoating, and new reflector specimens were prepared in the lab. Three sets of reflector samples (Sets D4-C, D4-D, and D4-E) were submitted to NREL on February 24, 2016. NREL provided rapid turnaround for these and found much improved abrasion resistance and good overall results that satisfied the D4 requirements.

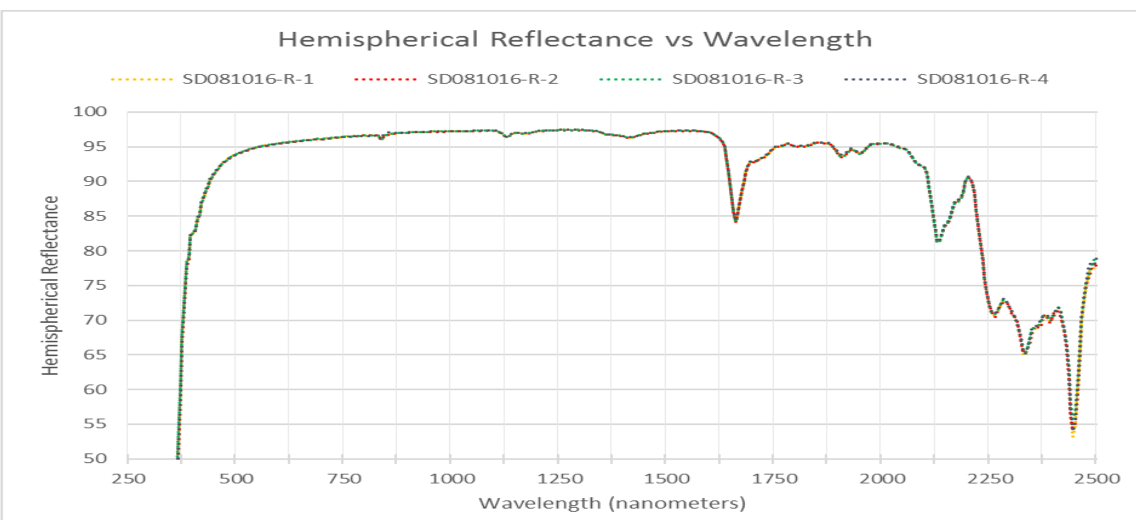
We continued to pursue further improvements in the primer, knowing that the D5 Deliverable requirements were even more ambitious than those of D4. A primer was found that exhibited even less propensity to migrate into the nanocoating. This formulation was therefore selected for the upcoming D5 pilot run, using full-scale manufacturing equipment.

The primer layer thickness was “dialed in” through several short “make ready” runs by adjusting the solvent content of the primer solution. Once these adjustments resulting in the proper thickness, several hundred feet of silvered polyester was coated with the primer. The primer was dried through a long overhead oven, and then rewound. Next, several more “make ready” runs were made by adjusting the solvent content of the nanocoating and, once completed, the nanocoating was added.

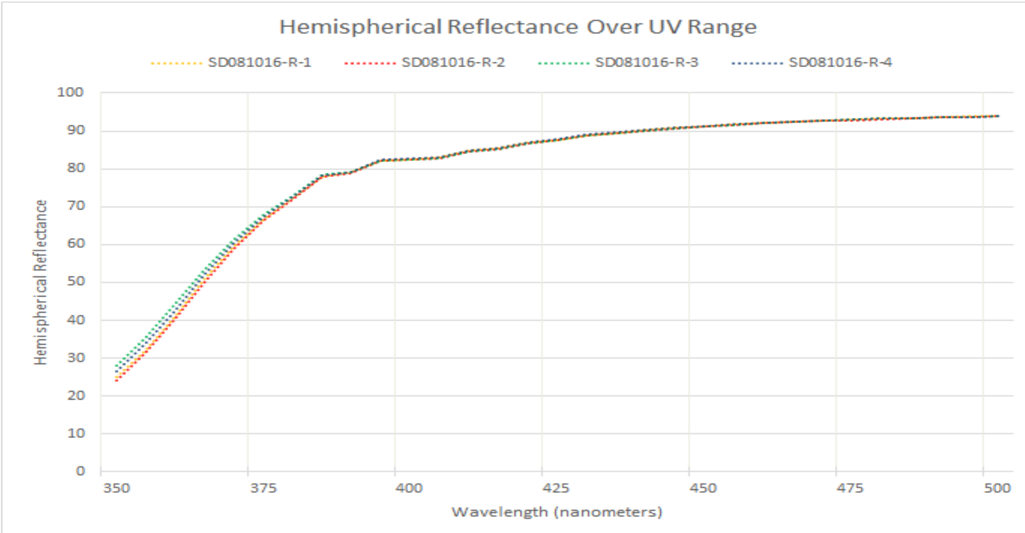
The finished roll of reflector material was checked and passed all our inspection and laboratory tests. The finished roll was shipped to Sundog Solar Technology, and samples were subsequently provided to NREL for testing and measurement to verify the D5 Deliverable requirements were met. These results are detailed below.

<u>Results of Final Pilot Run: Final Deliverable</u>

Reflectance -- The NREL-measured spectral reflectance scans of the final Deliverable D5 pilot run reflector specimens are shown in the figure below. Four reflector specimens were measured. As shown in the figure, the spectral reflectance values are so close to each other that is difficult to distinguish the four samples from each other, indicating there is good uniformity.



Of particular interest is the spectral reflectance values in the 350 to 400 nm range, the range of high-energy UV light that can damage materials and thereby reduce the lifetime of reflectors. The figure below highlights this wavelength range. We can see that the reflectance falls below 50% at about 365 nm. A “50% cutoff” point occurring near 365 nm is what we desire in order to protect the underlying layers of the reflector from the most damaging UV degradation. The cutoff point is influenced by the type and amount of UV absorbers contained in the outermost layer (i.e. the nanocoating layer).



The solar-weighted hemispherical reflectance values (ASTM E891) for these reflector specimens measured at NREL from the pilot run are tabulated below.

Scan Number	BBB6428	BBB6429	BBB6430	BBB6431
Sample ID	SD081016-R-1	SD081016-R-2	SD081016-R-3	SD081016-R-4
Sample Description	Uncleaned	Cleaned	Uncleaned	Uncleaned
SWV(DirNor15)	93.8	93.7	93.8	93.9

We note that these reflectance values, within the experimental uncertainty range of the instrument itself, satisfy the 94% technical goal of the project.

Cross-Hatch Adhesion Tests -- Adhesion had been a persistent concern throughout this project, but the final pilot run showed we overcame this issue at the end of this project. All the samples from the pilot run that were tested at NREL for adhesion passed the ASTM D3359 cross hatch test, with the highest Class 5B ranking. The edges of the crosshatch cuts are smooth, and no squares of the lattice were lifted or removed.

Abrasion Resistance -- Taber abrasion tests were completed by NREL to determine the drop in specular reflectance after 30 abrasion cycles on their Taber abrader (ASTM D4060). The NREL results are tabulated below for all four of the samples that were tested. The specular reflectance of the specimens is measured before Taber abrasion, and then again after 30 Taber abrasion cycles. Two different D&S specular reflectometers were used, and they provide slightly different values as shown in the table. The average values are also calculated and tabulated below.

Taber		Initial		30 Cycles		Δ	
Sample	Description	D&S Avg	Average	D&S Avg	Average	D&S Avg	Average
SD081016-1	Sundog 081016	95.0	95.0	94.3	94.2	-0.6	-0.8
		95.0		94.1		-0.9	
SD081016-2	Sundog 081016	95.3	95.4	94.9	94.8	-0.4	-0.6
		95.5		94.7		-0.8	
SD081016-3	Sundog 081016	95.6	95.5	95.0	94.9	-0.6	-0.7
		95.5		94.8		-0.7	
SD081016-4	Sundog 081016	95.4	95.5	95.1	95.2	-0.3	-0.3
		95.5		95.2		-0.3	

After 30 Taber cycles, the average loss in specular reflectance (averaged over all 4 specimens, and using the values from both reflectometers) was 0.6%. This is very good, and more than satisfies the D5 Deliverable requirement. It is notable that the reflectance losses ranged from 0.8% to 0.3%, and that the amount of reflectance loss decreased with each tested specimen. This is a trend in the ASTM D4060 test that we have noticed throughout the performance of this research project, which makes this test less reliable than preferred. Still, as a relative/comparative test, the Taber test is useful and informative. The average 0.6% reflectance drop measured here is superior to that of ReflecTechPLUS, a reflector that also has very good abrasion resistance.

Specularity -- The specularity of the pilot-run reflective film was determined based on reflectance measurements taken at different acceptance angles. The better the specularity, the smaller will be the root-mean-square value of the beam spread from the reflective surface. (See next section for a more detailed explanation.) The NREL measurements are shown in the table below. Three sets of data are provided. The first set is based on NREL measurements taken with the reflective film taped along its perimeter to a glass substrate. The second set is based on NREL measurements taken with the reflective film mounted into a specimen holder (see photo below) that holds the film very flat and places it slightly into tension. The third set is based on NREL measurements taken with the reflective film adhesively bonded onto mill-finish aluminum.

	Samples Taped Along Perimeter to Glass			Samples Mounted Into Specimen Holder			Samples Bonded to Aluminum		
Sample ID	SD081016-S-1	SD081016-S-2	SD081016-S-3	SD081016B-S-1	SD081016B-S-2	SD081016B-S-3	SD081016B-S-1	SD081016B-S-2	SD081016B-S-3
ρS(20 mr)	95.9	95.9	95.9	95.9	95.9	95.9	95.9	95.9	95.9
D&S 1									
7 mr	93.6	27.6	59.6	94.3	94.5	94.5	87.5	93.2	92.7
15 mr	95.4	89.7	97.3	95.3	95.4	95.4	93.6	95.2	95.3
25 mr	95.8	95.7	95.7	95.6	95.8	95.8	94.8	95.6	95.6
D&S 2									
7 mr	89.5	29.3	73.5	94.0	94.3	94.4	88.9	92.7	92.3
25 mr	95.7	95.7	95.6	95.8	95.7	95.8	95.3	95.6	95.6
46 mr	96.3	96.3	96.3	96.4	96.3	96.3	96.0	96.1	96.1
$\sigma_{1, mrad}$	1.4	3.8	2.3	1.2	1.2	1.2	1.6	1.3	1.4

The first data set (samples taped along perimeter) result in rms beam spread values from 1.4 mrad to 3.8 mrad. This large range is the result of the large variability in the 7-milliradian acceptance angle reflectance readings. The D&S specular reflectometer is very sensitive at these small acceptance angles, and the instrument readings can change greatly with the slightest misalignment or with any non-flatness present in the reflective film. Often, a slight touch to the film to straighten the film against a flat substrate can produce large measurement variations. The second dataset (reflective film held flat within the specimen holder) values are quite consistent, even at 7-mrad. The resultant rms beam spread values do not have the large variability of the first dataset. All three reflector specimens measured while in the specimen holder were calculated to have a specularity value of 1.2 mrad. This more than satisfies the D5 Deliverable requirement to be at or below a 1.6 mrad beam spread value. The third dataset (reflective film adhesively bonded to mill-finish aluminum) results in an average beam spread (rms value) of 1.4 mrad. This is also very good, and is only slightly larger than the specimen holder values, owing to the small non-uniformities introduced by the adhesive below the reflective film plus the underlying aluminum surface roughness.

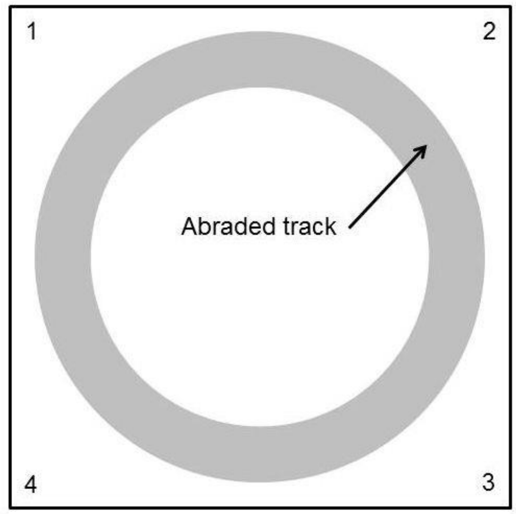
Cleanability -- The Cleanability Index of the final pilot run D5 reflector specimens was measured to be above 99% (after 6 soiling/cleaning cycles), as shown below. And the Day 6 Cleanability Index was measured to be in excess of 99%. These are very good values, and indicate we have indeed improved reflector cleanability -- even better than we established as a project goal.

Cleanability Tests														
Deliverable D5														
		Day 1		Day 2		Day 3		Day 4		Day 5		Day 6		
Construction	Pre SR	SR After Water	Clean. Index (%)	SR After Water	Clean. Index (%)	SR After Water	Clean. Index (%)	SR After Water	Clean. Index (%)	SR After Water	Clean. Index (%)	SR After Water	Final Clean. Index (%)	Average Clean. Index (%)
D5	94.5	94	99.5	93.9	99.4	94.0	99.5	93.8	99.3	93.7	99.2	93.9	**99.4**	**99.3**
Note: SR = specular reflectance at 25 mrad														

Measurement and Test Protocols

Cross-Hatch Adhesion Tests -- Reflector specimens can be checked for adhesion of the front-surface topcoat to the underlying material(s) using the cross-hatch test ASTM 3359. The size of the reflector specimens must be at least 3 x 3 inches, sufficient to allow the cross-hatch tool specified within the ASTM standard to score/cut the topcoat. The cross-hatch cutting device (with multiple preset blades) is held at a 30 to 45-degree angle from the specimen while cutting. In accordance with the standard, adhesive tape will be applied over the cross-hatched area and the tape is firmly smoothed into place over the area of the incisions. Then the tape will be rapidly pulled away/off the sample (back over itself at close to an angle of 180 degrees). After the adhesive tape is removed, the reflector specimen is closely inspected and the number of detached “squares” of the coating is counted.

Taber Abrasion Tests -- Abrasion resistance has been quantified using the Taber abraser unit to apply abrasive stress in a circular pattern around a 4 x 4 inch reflector sample, as shown in the figure. Then a Devices and Services Specular Reflectometer is used to optically assess abrasive damage to the reflective surface. We use a modified version of ASTM D4060 (which quantifies abrasion resistance by weight loss) by using a Devices and Services specular reflectometer to directly monitor the performance parameter of direct interest, namely, specular reflectance, as a function of the number of cycles applied by the Taber abraser unit. A 250-gram weight is used. Specular reflectance is measured at 660 nm, $\rho(\theta,\lambda=660)$, at a 25 mrad acceptance angle. Specular reflectance is measured at four spots on each 4” x 4” sized sample before abrasion and after 30 abrasion cycles.



Mirror sample after Taber abrasion

Solar-Weighted Hemispherical Reflectance -- Solar-weighted hemispherical reflectance (SWHR) is measured using a dual-beam UV-VIS-NIR spectrophotometer with an integrating sphere attachment. Use of such devices with a secondary reflectance standard, ρ_{std}, (traceable to the National Institute of Standards and Technology) allows the absolute reflectance to be measured as per ASTM E903-82.

At each wavelength, ρ_{samp} is calculated from the measured instrumental response, ρ_{meas}, as:

$$\rho_{samp}(\lambda) = \frac{\rho_{meas}(\lambda) - \rho_{0\%}(\lambda)}{\rho_{100\%}(\lambda) - \rho_{0\%}(\lambda)} * \rho_{std}(\lambda)$$

where $\rho_{100\%}$ is the instrumental response associated with measuring the standard reflector, and $\rho_{0\%}$ is the instrumental response when the sample beam is blocked (dark noise). The spectral measurements are then convoluted with an appropriate standard terrestrial solar spectrum [ASTM E891] to compute a SWHR, $\rho_{2\pi}(\lambda=250$ - 2500 nm).

$$\rho_{2\pi}(\lambda = 250 - 2500\text{nm}) = \frac{\int_{\lambda=250}^{\lambda=2500} I(\lambda)\,\rho_{samp}(\lambda)\,d\lambda}{\int_{\lambda=250}^{\lambda=2500} I(\lambda)\,d\lambda}$$

where, for reflector materials, $I(\lambda)$ is the direct normal terrestrial solar spectrum.

Specularity -- Specularity is a measure of the amount of beam spreading (scattering) that occurs when light is reflected by the reflector. The beam spread can be characterized as an rms value (in milliradians, typically) by measuring the specular reflectance of the reflector at multiple acceptance angles. The D&S portable specular reflectometer has multiple acceptance angle settings, and is the instrument we will use for the determination of reflector specimen specularity.

The level of specularity is expressed as the half-width (σ_{spec}) of the (assumed Gaussian) distribution of the reflected light

$$\rho_s(\theta,\lambda) = \rho_{2\pi}(\lambda)\left\{1 - \exp\left[\frac{-\theta^2}{2\sigma_{spec}{}^2(\lambda)}\right]\right\}$$

A single wavelength of light (λ = 660nm) will be used, the wavelength utilized within the D&S specular reflectometer.

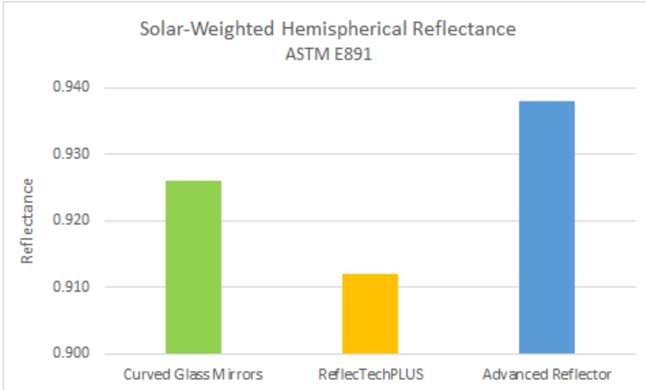
Cleanability Index Measurements -- The anti-soiling effectiveness of the various reflector specimens is determined by measuring the ability of samples to retain specular reflectance after a series of dirt application / cleaning cycles. This test methodology is intended as a screening test to rapidly compare and rank a variety of reflector samples. Many industry practitioners use the general approach of soiling/cleaning/measurement cycles, as do ISO and military tests.

The cleanability index (CI) is calculated as the ratio of specular reflectance after cleaning to the initial (before soiling) specular reflectance. The test protocol involves the following:

- Measure initial specular reflectance of unsoiled mirror: $\rho_{s,0}$(t=0)
- Apply dirt to mirror surface (the dirt is typical of that used in the automotive industry and is composed of: silica sand, carbon dust, NaCMC, and salt)
- Allow dirt to reside on the mirror sample overnight
- Clean mirror with pressurized deionized (DI) water (high pressure water spray: 12 inch distance of nozzle to panel; 1000 psi; 20 second duration)
- Re-measure specular reflectance of cleaned mirror: $\rho_{s,C}(t_i)$
- The Cleanability index after i^{th} cleaning cycle is: CI(i) = $\rho_{s,C}(t_i)$ / $\rho_{s,0}$(t=0)
- Repeat 6 cycles

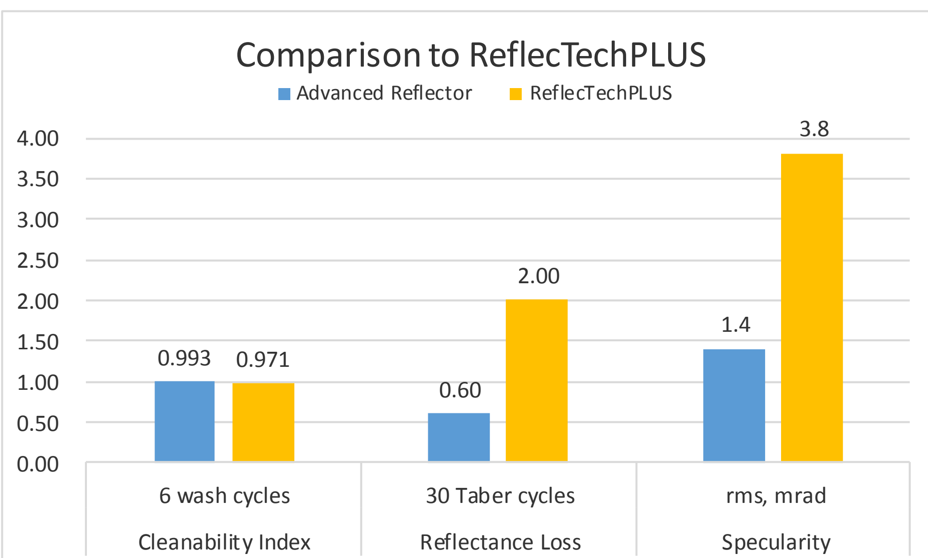
Significant Accomplishments and Conclusions

The two most significant attributes of this advanced reflective film are its low cost and high reflectance.



Solar-weighted hemispherical reflectance values were all measured on the same piece of NREL equipment (a Perkin Elmer UV-VIS-NIR spectrophotometer), using ASTM E891. All these values use the most recent NBS-traceable reflectance standard that NREL is now using, so all these values are lower than values reported in past years. For example, curved glass mirror reflectance is generally reported to be somewhat higher, as is ReflecTechPLUS reflectance. But since all the reflectance values reported here were measured at NREL with the same equipment and reference standards, they can be compared to each other with high reliability.

Additional useful technical comparisons of the advanced reflective film can be made against ReflecTechPLUS, the best commercially available reflective film. The chart below compares these two reflective films on the basis of cleanability, abrasion resistance, and specularity.



- The Cleanability Index is a measure of how the films maintain their peak reflectance and recover their reflectance after 6 cycles of soiling/washing. A "perfect" reflector would have a value of 1. The advanced reflector is shown to have an advantage. The details of the Cleanability Index tests are provided in an earlier section of this report.

- Abrasion resistance is measured by subjecting the reflective films to aggressive abrasion (using a Taber abrader, following ASTM D4060) and measuring the resultant loss in specular reflectance. The advanced reflector is more abrasion resistant than ReflecTechPLUS; losing only 0.6% points of its initial 95%+ specular reflectance. ReflecTechPLUS is also very abrasion resistant, so serves as an excellent baseline for comparison. The 2% drop for ReflecTechPLUS is the average of a) what NREL measured/reported during this project, and the value reported in the literature based on previous testing at NREL.

- Specularity is a measure of the beam spread (widening) of reflected light from a mirror. The value is reported as the root-mean-square value of the beam widening, in milliradians. A perfect mirror would have an rms value of 0 milliradians. The advanced reflector specularity value of 1.4 milliradians shows that it is considerably more specular than ReflecTechPLUS. We show an rms value of 3.8 milliradians for ReflecTechPLUS, the value reported by SkyFuel in their published literature.

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