

# Advances in Concentrating Solar Power Collectors: Mirrors and Solar-Selective Coatings

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Concentrating solar power (CSP) technologies use large mirrors to collect sunlight to convert thermal energy to electricity. Opportunities are emerging for deploying CSP systems worldwide and in the Southwest United States. However, the cost of solar-collector technologies needs to be halved to achieve the long-term U.S. Department of Energy (DOE) Solar Program goal of developing parabolic trough power plants, power towers, and dish/Stirling systems that are cost-competitive with conventional fossil-fuel power technologies. For mirrors, this cost reduction is accomplished through technology advances by moving from heavy glass mirror reflectors to lightweight reflectors such as thin-glass, polymer, and front-surface mirrors that include surface coatings to reduce soiling. Increasing the operating temperature of the parabolic-trough solar fields from 400°C to >450°C will increase their efficiency and reduce the cost of electricity. For receivers, current coatings do not have the stability and performance necessary to move to higher operating temperatures. The objective is to develop new, more-efficient selective coatings with both high solar absorptance ( $> 0.96$ ) and low thermal emittance ( $< 0.07$ ) that are thermally stable above 450°C, ideally in air, with improved durability and manufacturability, and reduced cost. The production process and performance of solar reflectors and the progress toward developing a durable, high-temperature solar-selective coating for parabolic-trough receiver tubes will be discussed.

## 1. INTRODUCTION

Concentrating solar power (CSP) technologies use heat to generate electricity in much the same way as a conventional thermal power station, unlike photovoltaic (PV) devices, which generate electricity directly from sunlight. CSP systems focus the sun's rays with a series of large mirrors or parabolic troughs onto a receiver, which contains a mineral oil or molten salt. As this liquid heats up (reaching temperatures as high as 400°–600°C), it passes through a heat exchanger and generates steam, which is then used to drive a steam turbine or heat engine. The turbine or engine then drives a generator to produce electricity. Several types of systems have been developed over the years, including parabolic troughs, solar towers, and dish/engine systems.

Solar towers employ fields of mirrors to reflect light onto a central receiver atop a tower. This heats molten salt or water flowing through the receiver that is used to generate electricity through a conventional steam generator. Molten salt retains heat efficiently, so it can be stored for days before being converted into electricity. The first demonstration projects, Solar One and Solar Two, ran until 1999 in California. The technology had been dormant since that time, but several new projects are being constructed.

Parabolic troughs use long fields of parabolic, single-axis-tracking mirrors that concentrate sunlight 30–60 times onto an evacuated receiver tube at the focal point of the reflector, thus heating the heat-transfer fluid (i.e., synthetic oil) flowing through the receiver. Parabolic-trough solar technology has been demonstrated by nine utility-scale plants installed between 1984 and 1991 in California's Mojave Desert. These plants, referred to as Solar Electric Generating Systems (SEGS), represent 354 MW of installed electric-generating capacity that operate daily and provide power to the electricity grid. The technology had been dormant since 1993 due to low energy prices, but several new projects are now being developed or constructed. The SEGS plants, the first and largest trough plants ever built, have proven the parabolic-trough technology to be a robust and reliable power technology in an industrial-utility operating environment. Its key advantages are proven performance, manufacturing simplicity, use of standard equipment and materials, improvement in cost effectiveness via incremental steps, and low technical or

financial risk to the investor.

A dish/engine system uses a concave mirrored dish (similar to a very large satellite dish). The dish collects and concentrates the sun's heat onto a receiver, which absorbs the heat and transfers it to the fluid within the engine (typically a Stirling engine). The heat causes the fluid to expand against a piston or turbine to produce mechanical power. The mechanical power is then used to run a generator or alternator to produce electricity. At present, there is an experimental array of six 25-kW dish/Stirling systems being tested at Sandia National Laboratories in Arizona and 1000 MW of projects in the planning/development phase. In concentrating photovoltaics (CPV), a related technology, the engine is replaced with PV solar cells designed to operate under concentrated sunlight. The cells are built into concentrating collectors that use a dish to focus the sunlight onto the cells. The devices use very little of the expensive semiconducting PV material, while collecting as much sunlight as possible; but CPV collectors are limited to areas with high solar resource and require sun-tracking hardware, which limits their use.

From a utility perspective, one benefit of CSP is that it can provide regular and predictable baseload power, often with capacity factors of more than 60%, because heat can be stored relatively easily (unlike electricity) and the amount of sunshine is predictable in certain areas of the world. Using molten-salt storage liquids, it is possible for CSP plants to run throughout the night, generating electricity from the excess heat stored up during the day. Although this is technically feasible, in practice, not all of the current developers have decided this is economic, and many have opted for shorter storage periods, usually around an hour. This allows them to continue sending power to the grid in the event of a sudden change in weather, while giving the grid operators a full hour of warning and avoiding any non-compliance penalties.

## **2. POTENTIAL GLOBAL MARKET**

Recent siting studies show that CSP systems deployed at sites in the southwestern United States with high direct-normal solar resource potential and low slope (<1%), excluding environmentally sensitive lands and urban areas, would provide several times the total U.S. electric power generation [1]. In fact, the DOE has estimated that if 9% of the state of Nevada—an area of about 10,000 square miles—were covered in parabolic-trough solar plants, it could supply the electric power needs for the entire United States. Opportunities are emerging for deploying CSP systems in the Southwest United States. More than half the states have adopted green-power requirements in the form of a renewable portfolio standard (RPS) and renewable energy mandates. These state RPS mandates have successfully jump-started growth in the generation and use of renewable power. For example, the following is a summary of some projects in the United States: a 1-MW parabolic-trough power plant in Arizona was completed in December 2005; the newly completed 64-MW parabolic-trough plant in Nevada went on line in June 2007; two 20-year power purchase agreements (PPAs) were signed in 2005 to construct 800 MW of solar dish/Stirling projects in Southern California over a 4-year period, with options to expand to 1.75 gigawatts (GW); and an agreement to purchase power from a 553-MW solar parabolic-trough power plant to be located in California's Mojave Desert was announced in July 2007. The Western Governors Association (WGA) estimates that 4 GW of new CSP plants could be built in the United States by 2015 [1]. CSP could realistically reach hundreds of GW in the Southwest, or greater than 10% of the U.S. electric supply.

After a 15-year hiatus, there are currently more than 2600 MW of CSP in the planning/development phase, spread across the United States, Spain, North Africa, and the Middle East. However, the two most advanced markets by far are the United States and Spain. In 2004, Spain became the first country in the world to establish a dedicated feed-in tariff for CSP. The boost provided by the feed-in tariff has been supported by further legislation. This action, together with an increasing demand for power in Spain's growing economy, has caused a flurry of activity in the sector, and there are now around 200 MW of CSP approved and up to 800 MW on the horizon. In March 2007, the first commercial solar power tower in the world, the 11-MW PS10 project, began producing electricity for 6000 homes in southern Spain near

Sevilla. PS10 is the first solar plant of a planned 300-MW solar park that will be constructed in the same area by 2013. Construction began in October 2006 on PS20, a second-generation 20-MW tower; a third power tower, the AZ 20 project, is being planned. In addition to these three plants, a fourth power tower is being planned for southern Spain. The 17-MW Solar Tres (Solar Three) project is a continuation of the technology used in Solar Two in California, and will employ molten-salt technology similar to that used in the U.S. demonstration project. This will create a 16-hour back-up facility and the ability to generate electricity 24 hours a day. A large number of potential parabolic-trough plants are also being developed in Spain. Two identical 50-MW parabolic-trough plants are being built in Spain, with at least two more planned. The first trough project, Andasol I, will be completed in 2008. Also in the pipeline are 300 MW of parabolic-trough projects to be built by the power-tower developer, made up of six 50-MW arrays located around the town of Sanlucar el Mayor. In addition, another developer has announced a string of nine or ten parabolic-trough projects totaling 500 MW spread across southern and central Spain.

Projects are being developed in countries outside of the United States and Spain. Israel requires that 30% of total electricity production come from private power plants, including 10% from renewable energy. Israel will issue a call to prequalify for the international tender within the next few months for Israel's first 250-MW solar parabolic-trough plant to be constructed in the Negev Desert, and the final selection will probably occur in early 2008. The plant is planned to begin operating in 2009. Israel is thought to have a national CSP program under way that includes plans to have about 500 MW of CSP capacity by 2010 and another 1,000 MW by 2015. In March 2004, Algeria passed a feed-in law with a renewable energy target of 5% of electricity production by 2010; this has led directly to a 150-MW integrated solar combined-cycle system (ISCCS) project with a 30-MW solar field. This combined 30-MW solar parabolic-trough and gas-powered electric plant has been contracted to be built in Hassi-R'mel, with a tariff awarded of 4.235 cents/kWh (excluding gas) and 5.3% solar. Egypt plans to build a 150-MW ISCCS with 30-MW solar field in Kuraymat, near Cairo, that is expected to be completed in 2009. In July 2007, a contract was awarded to build a 228-MW ISCCS with a 30-MW solar field in Ain Beni Mathar, Morocco. Other CSP projects in various stages of development include: 535-MW ISCCS with 30-MW solar field in Agua Prieta, Sonora, Mexico; 400-MW ISCCS with 60-MW solar field in Yazd, Iran; and 100-MW molten-salt power tower in Upington, South Africa. In addition to the 2600 MW of CSP in the pipeline, three CPV dish power stations were completed in 2005 in Australia, with a rated output totaling 720 kW that will generate 1,555 MWh/yr. The construction of a new \$420 million, 154-MW CPV heliostat power station in northern Australia was announced in October 2006; the project will connect to the national electricity grid and generate 270 GWh/yr, enough electricity for more than 45,000 homes.

Even greater than the large potential markets in the United States are the developing worldwide CSP markets that are projected to reach hundreds of GW by 2040. The International Energy Agency (IEA) projects that the installed capacity will more than double because worldwide demand for electrical power is increasing. More than half the capacity will be in developing countries, principally in areas with good solar resources, limited fossil-fuel supplies, and lacking a power distribution network. A 2006 report by Greenpeace and the European Solar Thermal Industry Association estimated that CSP total installed output of 36,850 MW can be achieved worldwide by 2025 [2]. By 2040, solar-thermal power plants could provide a total output of 600,000 MW and will meet 5% of the world electricity demand, more than the amount currently provided by hydroelectric or nuclear power [2].

### **3. POTENTIAL TO REDUCE LEVELIZED COST OF ELECTRICITY**

The current levelized cost of electricity (LCOE) from these plants is \$0.10-\$0.12 per kWh (real 2004 dollars). The DOE Office of Energy Efficiency and Renewable Energy (EERE) Solar Energy Technologies Program goal is to reduce the cost to \$0.06-\$0.08 per kWh by 2012. The cost of the solar-collector technologies needs to be halved to achieve the long-term goal of developing parabolic-trough power plants that are cost-competitive with conventional fossil-fuel power technologies as dispatchable

intermediate-power generation in the wholesale power market (LCOE of \$0.04-\$0.06/kWh). The factors driving cost reductions for parabolic-trough power plant technology include advances through research and development (R&D), volume production, and scale-up in power plant or project size. Parabolic-trough R&D efforts focus on improving the technology's performance and cost competitiveness by implementing advanced concentrator, receiver, and thermal-storage designs.

CSP technologies are capital intensive—about half the total capital cost will be invested in the solar collectors for the first commercial power plants. The newly constructed 64-MWe Nevada Solar One used 162,400 ( $\pm$  a few thousand spares) 1.5 m x 1.2 m mirrors in the plant (or 4567.5 m<sup>2</sup> mirrors/MW) and 18,240 receivers or heat-collection elements (or  $\sim$ 285 HCEs/MW). The planned 553-MW parabolic-trough power plant in California would require on the order of  $2.5 \times 10^6$  m<sup>2</sup> of mirrors and  $1.6 \times 10^5$  HCEs. The reflectors represent about 30% of the collector cost. However, the potential impact of reflector cost can be much higher ( $\sim$ 50% of the cost of a dish or heliostat and  $>$ 75% of the cost of a trough collector) because structural and reflector costs are closely related. The cost of the solar-collector technologies needs to be reduced by half to achieve the long-term goal of developing CSP plants capable of being cost-competitive with conventional fossil-fuel power technologies. Thus, improved solar reflectors play an important role in achieving the required cost reductions (2–4X) for solar collectors and the widespread application of CSP generation. The DOE CSP Program's goals are for an advanced solar reflector with specular reflectance above 90% into a 4-mrad half-cone angle that survives for at least 10 years under outdoor service conditions, with a large-volume manufacturing cost of less than \$10.76/m<sup>2</sup> (\$1/ft<sup>2</sup>) [3]. Unofficially, more aggressive goals of 95% reflectivity and a 15–30-year lifetime have been advanced. Adjusting for inflation, the cost goal would be equivalent to \$15.46/m<sup>2</sup> (\$1.44/ft<sup>2</sup>) when corrected from 1992 to 2006 dollars [4]. CSP systems must operate reliably for decades under extremely harsh environmental conditions, which include solar ultraviolet (UV) irradiance, wind, rain, blowing sand, soiling, and high and low temperatures. This constitutes a formidable challenge in manufacturing low-cost, highly durable reflectors. Optimized designs, volume production, and increased competition should help reduce prices. In the longer term, further cost reduction can be achieved through technology advances. For mirrors, this is accomplished by moving from heavy glass mirror reflectors to lightweight front-surface reflectors with surface coatings that reduce soiling.

The overall solar-to-electric efficiency of parabolic-trough solar power plants can be improved and the cost of solar electricity reduced by improving the properties of the selective coating on the receiver and increasing the solar-field operating temperature to  $>$ 400°C. The potential for storing solar-thermal energy for use during non-solar periods and to dispatch the power when it is needed is one advantage of parabolic-trough power plants. As a result, thermal energy storage (TES) allows parabolic-trough power plants to achieve higher annual capacity factors—from 25% without thermal storage up to 70% or more with it. A potential substantial reduction in the cost of the TES system can be realized by using molten-salt in both the solar field and TES system. This eliminates the need for expensive heat exchangers and allows the solar field to be operated at higher temperatures than current heat-transfer fluids allow. New, more-efficient selective coatings will be needed that have both high solar absorptance and low thermal emittance at elevated temperatures. Although the coatings are designed to be used in evacuated environments, the coatings need to be stable in air in case the vacuum is breached. Current coatings do not have the stability and performance desired for moving to higher operating temperatures. For efficient photothermal conversion, solar absorber surfaces must have low reflectance ( $\rho$ ) at wavelengths ( $\lambda$ )  $>$  2  $\mu$ m and a high reflectance ( $\rho$ ) at  $\lambda$   $<$  2  $\mu$ m. The cutoff may be higher or lower depending on the operating temperature. For parabolic-trough applications, the spectrally selective surface should be thermally stable above 450°C, ideally in air, and have a solar absorptance ( $\alpha$ ) greater than 0.96 and a thermal emittance ( $\epsilon$ ) below 0.07 at 400°C or higher. Achieving the improved properties is very important if parabolic troughs are going to move to higher temperatures.

The Advanced Optical Reflector task at NREL directs the development of advanced reflector and absorber materials through collaborative efforts with solar manufacturers, by interacting with the coatings

industry, and by in-house research. This allows crucial gaps in the technology to be addressed and suggestions by industry experts or from the literature to be explored. We will provide an update on the status of the commercial solar reflectors [4] and describe our progress toward developing a durable advanced selective coating [5].

#### 4. COMMERCIAL CANDIDATE REFLECTORS

**4.1. GLASS MIRRORS:** Glass mirrors are produced by traditional wet-chemistry processes: clean glass is sensitized with  $\text{SnCl}_2$ , Ag and Cu layers are applied by chemical processes, the mirror-backing paint is typically applied by curtain painting, and the paint is force-cured by heating. A new copper-free process that replaces the copper layer (used to adhere the mirror-backing paint that inhibits silver corrosion) is increasingly being used in commercial mirror manufacturing [6]. The copper-free process ( $\sim 100\text{-}\text{\AA}$  layer of  $\text{SnO}_2$ ) has several advantages compared to the older copper protective layer: improved chemical resistance; promotes paint-layer adhesion like the Cu layer;  $\text{SnO}_2$  is a good diffusion barrier for oxygen and water and is immune to further oxidation; the Ag/ $\text{SnO}_2$  system does not suffer from copper/silver interdiffusion implicated in mirror degradation; and it does not produce copper-containing waste streams that must be environmentally processed and treated for recycling [7]. However, the copper-free process requires the silver to be deposited on fresh, clean glass and under stringent quality control.

The mirror-backing paint systems are typically based on solvent-borne alkyd resins, which are relatively complex paint systems and are proprietary to the mirror paint manufacturers. Paint formulations containing lead pigments provide the best protection against corrosion. Historically, solar systems built 10–20 years ago used glass mirrors with multiple-layer paint systems, where one layer contained specially formulated, highly leaded (10%–20% lead by weight) paints. The original Flabeg trough mirrors (produced between 1975 and 1985 and used by the SEGS plants in California), which have proven to be durable [8], used silvered 4-mm-thick, low-iron slumped glass, copper back-layers, and a highly leaded multilayer paint system designed for outdoor exposure. Likewise, McDonald Douglas mirrors that have proven durable in the field for nearly 20 years used a highly leaded multilayer paint system. Unfortunately, although the coatings with high lead content (containing more than 10% lead by weight) are robust, they have mostly been phased out, and are unavailable today because lead pigments are toxic and their use is discouraged for environmental and health reasons. Now, highly leaded paints contain 0.5%–2% lead by weight. Mirror-backing paint companies have developed new lead-free paint systems that perform quite well in accelerated tests, but, notably, are intended for indoor conditions. A ( $\text{Ni}^{2+}$  and  $\text{Co}^{2+}$ )-bis-hydrogen cyanamide is considered to be one of the best-performing, lead-free, corrosion-inhibitor pigments on the market at this time [9]. Other lead-free paints incorporate metal cyanamide derivative pigments and corrosion inhibitors in an organic resin [10–12]. These lead-free paint systems are capturing significant market share in the indoor mirror market.

Glass mirrors have excellent durability in terms of reflective-layer corrosion, are readily available, have the confidence of the solar manufacturing industry, and are commercially deployed. However, they are heavy and fragile and require slumped glass for curved shapes, which is expensive. In addition, two significant changes in the mirror manufacturing process have recently occurred because of environmental concerns that impact the mirror durability. The copper-free process requires stringent quality control, and the lead-free paints were developed for interior applications. Consequentially, the basic mirror composition of commercially available mirrors is radically different from historically durable solar mirrors, and alternatives are limited because the glass, chemical silvering, and mirror paint industries have consolidated.

**4.1.1. Thick-Glass Mirrors:** Trough mirrors (used in commercial solar parabolic-trough plants) manufactured by Flabeg have proven to be very durable, with almost 20 years of field exposure with the loss of only a few percent in reflectance. They use silvered thick (4- or 5-mm-thick), slumped low-iron glass that is protected with a proprietary multilayer paint system designed for outdoor exposure. Flabeg

replaced their old paint system with a new low-lead paint system in 2003, where the lead was reduced to the point where the durability was supposed to remain equivalent to their original, historically durable mirrors. The base paint of the new three-layer paint system now contains 2.5% lead, the intermediate paint now contains 1% lead, and the white top-coat remains acrylic-based with high UV stability [13]. The material is commercially available from Flabeg in Germany for \$43.2–\$64.8/m<sup>2</sup> (\$4–\$6/ft<sup>2</sup>). The initial solar-weighted hemispherical reflectance (SWV) is ~93.3%; initial specular reflectance at 25 mrad is ~91.8% and at 7 mrad is ~89.9%. Side-by-side exposure testing of the original and new construction began in 2004. After two years of accelerated and outdoor exposure in Colorado, the new mirrors with the reduced lead paint system are performing similarly to the original mirrors.

Pilkington (UK) commercially introduced the copper-free process in 2000 for thick (3–6-mm) soda-lime glass for domestic use. Testing of samples of Pilkington (4-mm copper-free) mirrors and “Spanish” (Cristaleria Espanola S.A; i.e., Saint-Gobain) glass mirrors (3-mm, copper-free, and lead-free paint), bonded to steel with four different candidate adhesives, was initiated in 2001 for possible use at Solar Tres. Initial hemispherical reflectance for the Spanish mirrors is 93.3% and for Pilkington is 92.8%, and the mirrors cost ~\$15 to 16/m<sup>2</sup> (\$1.40 to 1.49/ft<sup>2</sup>). Neither Pilkington nor Spanish mirrors exposed outdoors for 72 months show any degradation up to this point. Pilkington mirrors exhibit better optical durability than the Spanish mirrors in accelerated exposure testing (AET). Spanish mirrors degraded 19.0%, whereas Pilkington mirrors degraded 2.8% after 53 months of AET, and degradation related to the adhesive is more prevalent with Spanish glass mirrors. Depending on the adhesive used to bond the mirror, the Spanish mirrors degraded 4.7% to 12.0%, whereas Pilkington mirrors degraded 1.7% to 2.9% after 50 months of accelerated exposure.

*4.1.2. Thin-Glass Mirrors:* Thin-glass mirrors also use traditional wet-silvered processes, the copper-free process, and lead-free paints on thin (< 1 mm) relatively lightweight glass. Glaverbel in Belgium developed and patented the copper-free process, and launched the copper-free process and the lead-free paint systems in their commercial mirror line in 1998. In 2000, Naugatuck in the United States produced their pilot run of mirrors using this process on thin (1.0- and 1.2-mm-thick) glass. Companies within the CSP (mainly dish/Stirling) and CPV industries use thin-glass mirrors bonded to metal substrates as the reflective surface in the solar concentrator dish. Several forms of degradation have been observed on mirror facet elements comprising thin-glass mirrors bonded to stainless-steel substrates with pressure-sensitive and contact adhesives that have been deployed outdoors as part of operational CSP and CPV systems. The choice of adhesive has been observed to affect the performance of weathered thin-glass mirrors, and corrosion has been observed in deployed mirrors, including mirrors using the new copper-free protective layer and lead-free paints. In addition, some thin-glass silvered copper-free lead-free mirrors sold for outdoor applications have not passed the minimum ASTM standards [i.e., 120-h Copper Accelerated Acetic Acid Salt Spray (CASS) test, 480-h salt spray and damp heat] to qualify for indoor applications. CPV manufacturers have expressed significant concern regarding the durability of thin-glass mirrors made with copper-free and lead-free paint systems.

A matrix of sample constructions was prepared to identify the most-promising combinations of paints and adhesives for use with copper-free, lead-free solar reflectors [14]. Data after more than 3 years of AET indicate that the Glaverbel mirror tended to outperform the Naugatuck copper-free mirrors in test. However, this could have been because at the time the mirrors were manufactured and the experiment initiated: the Glaverbel mirrors were commercial production copper-free mirrors and the Naugatuck mirrors were first prototype copper-free mirrors; Naugatuck used a single-coat paint system compared to Glaverbel’s use of a two-coat paint system; and because of the differences in the regulations defining lead-free mirror paint between the European Union and the United States. In the European Union, lead-free paints can have 0.15% Pb, whereas in the United States, lead-free paints must be 0.00% Pb (< 1 ppm). Preliminary results from the mirror matrix study led Naugatuck to make changes in their glass-cleaning process that improved the adhesion of the silver and to replace the one-coat paint system previously used in their manufacturing line with a two-coat lead-free paint system. In addition, they are

exploring adding humidity- and adhesive-resistant protective coatings to their solar mirror product. The initial hemispherical reflectance is ~96.4%; initial specular reflectance at 25 mrad is ~97.3% and at 7 mrad is ~96.8%; and cost is ~\$16.1 to 43.0/m<sup>2</sup> (~\$1.50 to 4.00 /ft<sup>2</sup>). Preliminary exposure testing results appear encouraging and testing is ongoing. Although glass mirrors with copper back-layers and heavily leaded paints have been considered robust for outdoor use, the new copper-free back-layer and lead-free paint systems were designed for interior mirror applications and their outdoor durability must be determined.

**4.2. SILVERED POLYMER SOLAR REFLECTORS:** A silvered polymer solar reflector was developed through collaborative research with ReflecTech. In 2001, a small pilot run demonstrated that production could be achieved using standard commercial film converter equipment. This initial pilot-run material shows minimal loss in solar-weighted reflectance after 5 years of real-time outdoor exposure in Golden, Colorado. In addition, there was no significant loss in SWV for samples after the equivalent of 10 years of accelerated outdoor exposure in ACUVEX (natural sunlight in Phoenix, Arizona, concentrated 7 to 8 times with a Fresnel reflector while samples are cooled with a fan to near-ambient conditions and sprayed with deionized water for 8 min per natural sun hour). However, AET results showed significant reflectance loss earlier than anticipated. Prototype materials to test modifications to the baseline construction were produced. These tests were successful in identifying changes to the baseline construction that dramatically improved the AET durability of the reflective film. Some of these improvements were then incorporated into a new pilot-plant production run delivered in 2004. However, initial hemispherical and specular reflectivity was low due to a vacuum problem during the manufacturing process. ReflecTech produced and delivered samples from two versions (06-48 and 06-60) of the most recent pilot-plant production run with improved hemispherical and specular reflectivity in 2006. Neither ReflecTech version exposed outdoors in Colorado for 6 months shows any degradation to this point. However, the 06-60 version is outperforming the 06-48 in AET. The durability testing is ongoing. The ReflecTech material is being field-tested at SEGS in a SolarGenix Power Roof system, and it has been installed in 685 mirror modules on a JX Crystals 100-kW CPV project in China.

**4.3. ALUMINIZED SOLAR REFLECTORS:** Aluminized reflectors use a polished aluminum substrate, an enhanced aluminum reflective layer, and a protective oxidized top-coat. The major concern has been poor durability of such materials in urban and industrialized (polluted) locations. An improved anodized aluminum mirror incorporated a protective polymeric overcoat onto aluminized aluminum. However, the specularly degraded with outdoor exposure in Arizona, Florida, and Colorado (NREL), and with accelerated exposure. Alanod stopped selling this material for outdoor use in 2004 because of problems with the delamination of the overcoat and the associated loss of specularly. Alanod worked to improve the reflector durability and their in-house testing capability. The fluoropolymer overcoat was replaced with a nanocomposite oxide protective layer. New samples received in 2005 are undergoing testing. Alanod reintroduced the product in 2006 for sale as Miro-Sun (and two related solar mirror products, 4270 KKSP and 4270 KO, with the coatings tuned for PV applications). The material is commercially available from Alanod in Germany for ~\$2.50/ft<sup>2</sup>. The initial SWV is ~91.8%; initial specular reflectance at 25 mrad is ~83.7% and at 7 mrad is ~63.9%. Preliminary exposure testing results appear encouraging and testing is ongoing. Alanod is now working to develop a silvered solar reflector likely to be called Miro-Silver. It is expected to be ready for durability testing in late 2007.

## 5. DEVELOPMENT OF HIGH-TEMPERATURE SOLAR-SELECTIVE COATING

**5.1. LITERATURE REVIEW:** To identify potential high-temperature absorbers, the literature was reviewed for medium- to high-temperature absorber coatings [15]. Several materials have the appropriate optical properties and should be durable at operating temperatures above 500°C. Various transition metals—particularly those formed from the refractory metals of groups IVA, VA, and VIA and their binary and ternary compounds—have been suggested for high-temperature applications because of their high melting point and chemical inertness [16]. The titanium, zirconium, or hafnium metal boride, carbide, oxide, nitride, and silicide

materials have some of the highest melting points in nature, with HfC having the highest melting point at 3316°C. These materials also have a high degree of spectral selectivity, high hardness, improved wear, corrosion, and oxidation resistance [17, 18]. A double-cermet film structure has been developed that has higher photothermal conversion efficiency than surfaces using a homogeneous cermet layer or a graded film structure [19]. Surface texturing is a common technique to obtain spectral selectivity by the optical trapping of solar energy. The emittance can be adjusted (higher or lower) by modifying the microstructure (microcrystallites) of the coatings with ion-beam treatments [20]. However, there is a trade-off between a highly absorbing coating and one with low emittance. Highly absorbing coatings appear rough, porous, and absorb solar energy; coatings with low emittance are very smooth, dense, highly reflective, and mirror-like to thermal energy. Combining several concepts, a high-temperature solar-selective coating could be developed from materials with intrinsic solar selectivity and high-temperature stability using multiple cermet layers, along with appropriate surface texturing and incorporating multiple antireflective (AR) coatings. The optical properties of the refractory metal compounds have a high degree of flexibility; with further research, multiple-layer cermets with noble metals could be viable high-temperature absorbers for the CSP program.

**5.2. HIGH-TEMPERATURE OXIDATION-RESISTANT COATINGS:** At this point, none of the existing commercial coatings have proven to be stable in air at 400°C. Achieving the goal for a solar-selective coating that is stable in air at temperatures greater than 450°C requires high thermal and structural stabilities for both the combined and individual layers, excellent adhesion between the substrate and adjacent layers, suitable texture to drive the nucleation and subsequent growth of layers with desired morphology, enhanced resistance to thermal and mechanical stresses, and acceptable thermal and electrical conductivities. Other desirable properties are good continuity and conformability over the tube, as well as compatibility with fabrication techniques. The material should have a low diffusion coefficient at high temperature and be stable with respect to chemical interactions with the oxidation product, including any secondary phases present, over long periods of time at elevated temperature. Selecting materials with elevated melting points and large negative free energies of formation can meet these objectives. Stable nanocrystalline or amorphous materials are the most desirable (and practical) for diffusion-barrier applications, especially in light of material and process limitations. However, there will be a trade-off in the microstructure between a highly oxidation-resistant coating (i.e., amorphous or nanocrystalline) and a solar-selective coating with both high absorption (i.e., columnar or porous microstructure) and low emittance (i.e., smooth or highly dense). High thermal stability is manifested by high melting points, single-compound formation, and lack of phase transformations at elevated temperature.

**5.3. OPTICAL MODEL:** Designs of solar-selective coatings with multiple layers were optically modeled using thin-film design software [21]. Multilayer coatings were modeled because they were significantly easier to model than cermets, with the expectation of later converting the best multilayer design into a cermet. The absorptance was increased and the number of layers was reduced from the initial design by further modeling to a construction that is significantly easier to deposit. Solar-selective coatings with optical properties exceeding the goals (absorptance of 0.959 and emittance of 0.061 at 400°C) and lower thermal losses than the commercial coatings were modeled for materials with high thermal stability. The modeled performance exceeds the goal specification by about 1% overall, as 1% in emittance is about equivalent to 1.2% in absorptance. NREL is pursuing the intellectual property of the modeled coatings. Incorporating improved AR coatings, cermets, and texturing the surface should further improve the solar-selective coating; however, trade-offs exist between simultaneously obtaining both low emittance and high absorptance. There is significant uncertainty regarding the real property values of the modeled selective coatings, and the key issue is making the coating and testing its actual properties.

**5.4. DEPOSITION OF MODELED COATING:** Deposited solar-selective coatings that reproduce the modeled coatings are likely to be successful and meet the CSP optical and durability requirements. To begin solar-selective prototyping, the ion-beam-assisted deposition (IBAD) electron-beam (e-beam) chamber in the NREL multichamber vacuum system was used based on the versatility and lower cost for initial material prototyping. The e-beam gun uses 7-cc crucibles to deposit six materials sequentially or can co-deposit two different materials simultaneously. Dielectrics can be evaporated directly or reactively, and an ion gun can be used to improve the quality, composition, and density of the coating.

AR coatings are typically one-quarter-wavelength stacks of dielectrics of alternating high and low



refractive indices. Layer thickness control is therefore critical to the optical properties, and deposition parameters are critical to the microstructure, which defines the mechanical and thermal properties. Accordingly, the deposition system was upgraded to improve the quartz-crystal thickness control, to co-deposit with two e-beam guns, and to improve safety.

The individual layers and the modeled coating were deposited by directly and reactively evaporating the compound layers from substoichiometric compounds and by elemental co-deposition. The optical performance of the NREL coating was quite encouraging even though the deposited coating's measured optical performance was lower than the modeled performance—despite having deposited the coating with known significant errors, including significantly overshooting the layer thickness because of manual control and non-stoichiometric deposition of the reflective layer. An optical coating is only as good as the optical monitoring and control during deposition. In most cases, to achieve high yield for demanding requirements, it is necessary to minimize the optical thickness errors below 1%, particularly at sensitive turning points [22]. NREL's initial monitoring and control errors exceeded 5% for the deposited thin-film thickness; therefore, the coating's measured performance was, as expected, inferior to the modeled coating. To resolve the compositional errors, the optimal compound stoichiometry and the thin-film phase-formation sequence will be determined. To resolve the thickness errors, the deposition monitor and control will be upgraded with the addition of an optical monitor, providing positive feedback between the quartz-crystal monitor and the optical monitor, and automating the coating process. Automation will remove human error from the coating deposition process. And by providing steering and cutting at sensitive turning points, mid-course corrections can be made for any thickness errors in order to deposit a coating that matches the model. In addition, by varying the ion assist, the optimal coating density will be determined that gives both high absorption and low emittance with excellent oxidation resistance. Combining these methods, the thickness and compositional errors will be eliminated in the final coating.

**5.5. CHARACTERIZATION & STABILITY OF SOLAR-SELECTIVE COATING:** Developing spectrally selective materials also depends on reliable characterization of their composition, morphology, and physical and optical properties. The key for high-temperature usage is low  $\epsilon$ . The protocols are being developed and the capabilities built for accurate and precise measurements of the thermal/optic properties of the selective coating at NREL. In part, this has included conducting a round-robin experiment with commercial laboratories and purchasing a Perkin-Elmer 883 infrared spectrophotometer.

The long-term thermal stability above 400°C, ideally in air, is an important requirement for the solar-selective coating. Compared to the desired lifetime (5–30 years), durability or thermal stability is typically tested by heating the selective coating—typically in a vacuum oven, but sometimes in air—for a relatively short duration (hundreds of hours). To determine the durability and thermal stability of commercial and NREL's spectrally selective coatings under development, a high-temperature inert-gas oven was purchased that allows the coatings to be exposed at their operating temperatures and conditions for long periods of time. As data become available, development can begin of a criterion for high-temperature selective surfaces applicable for concentrating applications.

## 6. CONCLUSIONS AND NEXT STEPS

DOE, the WGA, state RPS mandates, and feed-in tariffs have successfully jump-started growth in CSP technologies that would require 7 to 10 million square meters of reflector and more than 600,000 HCEs over the next 5 years. Progress has been made and durability testing of advanced solar reflectors supplied by industry is ongoing. Currently, glass, ReflecTech, and Alanod mirrors are commercially available and, based on accelerated exposure testing, should meet the 10-year lifetime goals. However, predicting an outdoor lifetime based on accelerated exposure testing requires the AET to replicate the failure mechanisms observed outdoors. Recently, the construction of all the solar reflectors has significantly changed. Because of this, all of the solar reflectors commercially available have been in outdoor real-time exposure testing for less than 3 years.

Using computer-aided design software, a solar-selective coating with  $\tau = 0.959$  and  $\epsilon = 0.061$  at 400°C composed of materials stable at high temperature has been successfully modeled optically. This exceeds the goal specification by about 1% overall, because 1% in emittance is equivalent to about 1.2% in absorptance.

Producing the modeled coating prototype is crucial. The individual layers were deposited by directly and reactively evaporating the compound layers from substoichiometric compounds and by elemental co-deposition; but because of thickness and compositional errors, the deposited coating did not match the modeled performance. To resolve the errors, an optical monitor will be added and the coating process automated, and the optimal compound stoichiometry, thin-film phase-formation sequence, and morphology will be determined. The intention is to explore the feasibility of depositing the coating by lower-cost methods and to perform a rigorous cost analysis after a viable high-temperature solar-selective coating is demonstrated by e-beam.

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