**Cherly Kennedy, Senior Scientist, Concentrating Solar Power, Advanced Optical Materials Project Leader at the Department of Energy's National Renewable Energy Laboratory** has provided the following detailed information on reflective materials used in solar thermal arrays:

"As part of our DOE task mission we work to develop advanced solar mirrors and absorber coatings and test the optical properties and durability of solar materials (i.e., mirrors, glazings, Fresnel lenses, and solar selective coatings) provided by industry as a service to the solar industry. In most cases, the number of samples is limited, we do not charge for these services, and neither party signs a Nondisclosure Agreement (NDA). Typically, the industry contact tells me what is considered proprietary and that information is just not disclosed. If the work becomes more extensive, than an NDA or one of the technical agreements described at http://www.nrel.gov/technologytransfer are more appropriate. The reflectors that are commercially available for solar applications are thick and thin glass mirrors, silvered polymer mirrors from ReflecTech and 3M, and an enhanced aluminized reflector from Alanod. All have their positive and negative points.

"The SEGS trough plants and the new 64-MWe Nevada Solar One trough plant in Nevada use silvered low-iron thick (4-mm) slumped glass mirrors from Flabeg because of their historical durability. Hemispherical reflectance of 4-mm low-iron glass silvered mirrors is ~94.5%, the specular reflectance at 25-mradian full-cone angle (mrad) is ~94.5% and at 7-mrad is ~94.2%. The mirrors currently cost \$43.2–\$64.8/m2 (\$4–\$6/ft2) for large volume purchases. For trough applications, it is desirable for the mirror costs to be reduced to \$21.6–\$27/m2 (\$2–\$2.5/ft2). Recently, AFG [now owned by Asahi Glass Company (AGC)], Guardian Glass, PPG, Saint-Gobain, and Rio Glass companies have developed thick glass mirrors for

CSP applications. Rio mirrors are tempered and Guardian are laminated (1-mm silvered glass laminated to 3-mm glass) glass mirrors for CSP parabolic troughs. Pilkington (now owned by Nippon Sheet Glass), Virginia, and Gardner mirror companies have expressed interest in providing thick glass mirrors for solar applications.

"Several parabolic dish manufacturers use silvered thin (1-mm) flat glass mirrors from Naugatuck and Glaverbel (now AGC). Hemispherical reflectance of 1-mm low-iron glass mirrors is ~96.4%, the specular reflectance at 25-mrad is ~95.6% and at 7-mrad is ~94.6%; cost depends on purchase volume and ranges from ~$16.1/m2 to $43.0/m2 (~$1.5/ft2 to $4.0/ft2). The flat glass is applied to a substrate and during final assembly the entire stack is slightly curved. These segments are assembled to form a parabolic dish, for a CSP dish-Stirling or a Concentrating Photovoltaic (CPV) designs; but a similar architecture could be used in a trough, heliostat, or solar oven.

"A silvered polymer mirror jointly developed by NREL and ReflecTech is available through Sky Fuels has been used in some trough and CPV designs. Hemispherical reflectance is ~94.%1, the specular reflectance at 25-mrad is ~93.7% and at 7-mrad is~ 72.1%. Cost depends on purchase volume and ranges from ~$14.0/m2 to $32.3/m2 (~$1.30-$3/ft2). The material is sold in rolls or applied to the substrate. It is recommended for 1-axis curvatures but could be used in dishes and heliostats if the material is cut in gores (i.e., clothing darts). ReflecTech will soon be available with an Abrasion Resistant Coating (ARC) to prevent scratching of the polymer surface with contact mechanical cleaning.

"Recently, 3M decided to reintroduce a new Solar Material Film (SMF) 1100 which is an improved version of the ECP-305+ polymer solar reflector jointly developed by 3M and NREL. 3M took the ECP-305+ off the market more than 15 years ago because of a corporate restructuring and a delamination issue. The hemispherical reflectance of the ECP-305+ was ~95.4% and the specular reflectance was ~95.3% at 25-mrad and ~94.4% at 7-mrad, 3M said they could sell ECP-305+ for $2.25 back in 1992 ($1.35 when accounted for in, I think, the 1985 dollar). We have samples of ECP-305+ that have been in exposure testing for more than 14 years in CO, AZ, and FL that are still in test. The new SMF 1100 has adhesion layers to prevent delamination and will be available with an abrasion resistant, anti-soiling coating. I received the first versions for the new SMF 1100 in December 2010..

"Alanod markets an enhanced aluminum mirror that is of interest to some CSP and CPV manufacturers. NREL and Alanod worked together to develop an enhanced (with ¼ λ's to boost reflectivity) anodized aluminum mirror with a polymer protective overcoat. A couple of years ago, NREL identified a problem with a loss of specularity after long-term outdoor exposure and at the same time Alanod was receiving word of delamination of the overcoat occurring in the field. Alanod stopped selling their Miro/4270kk for outdoor use because of this delamination problem and associated specularity decrease. The company worked hard to find a solution and to improve the abrasion resistance of the reflector. They reintroduced and began marketing an improved Miro-Sun aluminized reflector with a sol-gel nanocomposite protective overcoat. Hemispherical reflectance is ~91.6%, specular reflectance at 25-mrad is ~85.0% and at 7-mrad is ~77.3%. The cost is ~$21.5/m2 (~$2/ft2). Alanod began producing the nanocomposite sol-gel protective overcoat in-house on the Miro-Sun in November 2009 with a harder, smoother, and clearer top surface; resulting in improved specular reflectance and durability. They have developed versions where the reflectance is maximized for use with Si photovoltaic solar cells. Recently, Aluminum Coil Anodizing (ACA), Alucobond , Alcoa and Alcan have expressed interest in providing aluminum mirrors for solar applications.

"There are no commercial solar front surface mirrors.  The front surface mirror closest to commercial deployment was developed by NREL and Science Applications International Corporation (SAIC).  It is a low-cost advanced solar reflective material (ASRM) combining the best of both thin-glass and silvered-polymer reflectors. The alumina ($Al_2O_3$) coating is deposited by ion-beam-assisted physical vapor deposition (IBAD).  Hemispherical reflectance is ~96.7%, the specular reflectance at 25-mrad is ~96.1% and at 7-mrad is ~91.2%.  Materials undergoing testing demonstrate excellent durability under accelerated and outdoor weathering.  Samples have been outdoors in Arizona for more than 11 years without degrading. From an NREL cost analysis, a commercial roll-coating company can produce the ASRM, including purchasing the roll coater, for less than $10.76/m2 ($1/ft2) by limiting the alumina thickness to 1.4 mm with high-purity alumina, if purchased in bulk quantities, and by depositing the alumina at deposition rates higher than 50 nm/s with multiple zones on a wide PET web.  The ASRM could also be deposited in a batch process.  Further development of the ASRM has been transitioned to a commercial company, Abengoa Solar, below.

"I am serving as NREL's technical advisor for the Concentrating Solar Power (CSP) projects selected by DOE for awards developing advanced solar mirrors to reduce the cost of solar power to less than $0.10/kWh by 2015. All of the contracts have successfully moved into Phase II and III of their proposals. Specifically:

**3M (St. Paul, MN)**

3M will develop abrasion-resistant, anti-soiling protective acrylic front surfaces on silvered polymeric mirrors (i.e., SMF 1100) as low-cost replacements for thick glass mirrors in parabolic trough CSP installations. The project objective aims to reduce the installed system cost and levelized cost of energy for CSP trough installations.

**Alcoa (Alcoa Center, PA)**

Alcoa will develop an aluminum intensive collector (supporting structure and [i.e., protected aluminum-based) reflector] to reduce the installed system cost and levelized cost of energy for CSP trough installations.

**PPG Industries (Pittsburgh, PA)**

PPG Industries will develop and commercialize large-area, low-cost, high performance (i.e., glass-based) mirrors, through alternate materials, structures, and fabrication processes for reflector components, to enable lower cost CSP parabolic trough technology.

**Abengoa Solar** (formerly Solucar) **(Lakewood, CO)**

Abengoa Solar was also selected to develop a low-cost, advanced polymeric reflector (i.e., the SAIC IBAD alumina front surface reflector) for CSP applications to lower the cost of CSP parabolic trough power plants.

"We have also been working to develop new, more-efficient advanced solar selective coatings for receivers with high solar absorptance ($a > 0.96$), low thermal emittance ($e < 0.07$; >450ºC), thermally stable >550ºC, ideally in air, with improved durability and manufacturability and reduced cost and potentially can encourage development of US &/or 3rd receiver manufacturer.

"Carl Bingham from NREL said he typically uses stainless or aluminum at the solar furnace, but is sure stainless is likely too expensive for this application and aluminum will not handle the temperature. The other materials he can think of are pretty exotic and likely expensive, but he is checking with Roland Pitts at NREL and someone at CRES more familiar with solar cookers. My substrate experience is from high-temperature (T>400°C) receiver tubes so likewise the materials are pretty expensive.

Absorber coatings  may be deposited on stainless steel grade 316, Ti (321), Nb (347), and alloys (Monel 400) for high-temperature molten salt applications.  Absorber coatings may also be deposited on stainless steel (304), glass, copper, or aluminum tubular or flat substrates for mid-temperature (100ºC < T<400ºC) applications. Some formed black polymer materials are used for low-temperature (<100°C) hot water heaters.   We do have a the Granta Design CES Selector 2009 Aero & Polymer Edition that can help select materials depending on a variety of material, thermal, and cost parameters and plot them in a succinct Ashby Diagram, that may be of assistance.

"NREL tests the reflectivity and durability of solar mirrors, glazings, and absorber coating.  Typically, we measure the hemispherical reflectance of the samples from 250 to 2500 nm using a Perkin-Elmer Lambda 9 and 900 UV-VIS-NIR spectrophotometer with a 60-mm, integrating-sphere attachment relative to National Institute of Science and Technology (NIST) traceable standards (the standard is chosen based on the reflective surface).  The direct normal air-mass 1.5 (DIRNOR15) solar-weighted hemispherical reflectance is calculated from data collected in the 250-2500-nm range. The transmittance of the samples can be measured from 200 to 2600 nm using a sphere and from 190 to 3200 nm without the sphere.  We have a Perkin-Elmer Lambda 1050 spectrophotometer with Universal Reflectance Attachment (URA) and 150-mm sphere.  The URA allows us to make high-sensitivity, absolute reflectance measurements from 190 to 3300, and can automatically and reproducibly change the angle of the sample.

"Developing spectrally selective or absorber materials also depends on reliable characterization of their composition, morphology, and physical and optical properties. The key for high-temperature usage is low ε.  NREL has been developing the protocols and building the capability for accurate, precise measurements of the thermal/optic properties of the selective coating. We can measure the hemispherical reflectance of the samples from 250 to 2500 nm the PE λ-9 , 900, and 1050 UV-VIS-NIR spectrophotometer with the integrating-sphere in the 250-2500-nm range or with the URA attachments. The reflectance of the samples from 2.5 to 50 µm can be measured using a PE IR 883 IR spectrophotometer with a reflectance attachment and NIST traceable gold reflectance standard. Recently, new National Institute of Standards and Technology (NIST) traceable gold IR standards were purchased and instead of the V reflectance attachment previously used a 3X Beam Condenser Specular Reflectance accessory was purchased to more accurately measure the samples with the 883. We purchased a Surface Optics Corporation (SOC) 100 HDR Hemispherical Reflectometer (Nicolet FTIR) under the American and Recovery Act (ARRA) that can measure the IR reflectance of absorber coatings at the receivers operating temperatures (up to 650°C) that should be delivered in February or March.

"The specular reflectance is measured at 7-, 15-, 25-, and 46-mrad cone angle with two Device and Services (D&S) Field Portable Specular Reflectometer at 660 nm. We also have a SOC 410-Vis Directional Hemispherical Reflectometer and ET100 Emissometer. The SOC instruments are handheld reflectometers that allow precise, reproducible measurements in the lab or in the field of specular reflectance in the visible spectral region and thermal emittance in the infrared spectral region. The SOC 410-VIS measures the specular reflectance in four bands between 400-540 nm, 590-720 nm, 480-600 nm, 900-1100 nm. The signal intensity is normalized against an internal standard. Total, diffuse, and specular reflectance is reported for the data at 20° incidence. The SOC ET100 measures directional thermal emittance at two incidence angles, 20° and 60° and predicts Hemispherical Total Emittance. Emittance measurements can be measured with a Gier-Dunkle DB 100 Infrared

Reflectometer at room temperature.  A filter is used to simulate a 100°C measurement, i.e., by weighting the measurement by a 100°C blackbody curve.

"We perform outdoor exposure testing at Golden, Colorado; Miami, Fl, and Phoenix, AZ.  NREL has the capability to perform accelerated aging of materials using natural sunlight.  We purchased an Atlas EMMAQUA under the ARRA that can accelerate natural sunlight in Golden, CO, 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 8 min per natural sun hour that should be installed this spring. NREL has two Ultra-Accelerated Weathering Systems (UAWS). The original dish has been operating for 10 years at 100X < 500 nm and  the new UV dish includes an environmental chamber; the same 100X < 500 nm, but 4 times the sample testing area.  The UAWS is a recharge system so the cost of the testing would need to be covered by the company requesting testing or the appropriate DOE program.

"Accelerated exposure testing is performed in Atlas Ci5000 Weather-Ometers (WOM).  The WOM's use a xenon-arc light source with filters designed to closely match the terrestrial air-mass 1.5 solar spectrum and allow control of exposure temperature and ambient humidity.  The WOMs operate continuously at 60°C and 60% relative humidity (RH).  The Ci5000 uses light levels about twice outdoor exposure.  A single day of testing (24 hours) is roughly equivalent to six times for the Ci5000 in terms of light intensity.  We also have a Ci5000 with extended temperature capability for cyclic testing with light, a Ci 5000 that simulates a rain cycle, a Tenney cyclic tester (dark), and a humidity/salt spray tester. We also perform accelerated testing in a BlueM that operates continuously at 80°C and 80% RH, but the samples are not exposed to the light. The BlueM does not have the same acceleration factor as the WOM, but from other experiments we believe the acceleration factor is at least 25X the outdoor exposure at NREL for glass mirrors. We can use a Q-Panel QUV with 340A fluorescent bulbs that match the UVA solar spectrum from 290 to 340 nm. The QUV operates continuously in 4 hour cycles; 4 h of light exposure with 40ºC, followed by 4 h of 100% RH.  A single day of testing is roughly equivalent to 1.5 times the outdoor exposure.   We have a 1.4kW solar simulator (1.4kW-SS ) that uses a filtered xenon-arc light source and can achieve intensities of about five times the outdoor exposure in a wavelength band between 300 and 500 nm. The 1.4 kW-SS sample chamber is divided into four quadrants allowing samples to be exposed at two different RH and temperatures.  The chamber allows four 25.4 mm x 25.4 mm or eight 12.7 mm x 25.4 mm samples to be exposed per quadrant.  Within each quadrant, samples can be either exposed or shielded from the light (but exposed to temperature and humidity). We purchased two new solar simulators under the ARRA that should be delivered in March or April that will need to be installed.

"We perform accelerated stability testing of absorber coatings in the BlueM damp heat oven and a Blue M Inert Gas Oven (IGS).  The IGS can operate up to 600°C in an inert gas (i.e., air, $N_2$).   We purchased a High-Temperature (650°C) Vacuum Oven under the ARRA and a High Temperature (1500˚C) Box Furnace that should be delivered in February; both will need to be installed.

"NREL's sample size is typically 1¾" x 2⅝" (45 mm x 65 mm), although we can measure larger or odd shaped samples or cut samples down to size. We typically like to measure triplicates of samples for each site and chamber (depending on chamber space availability).  Samples are measured initially and after exposure testing at periodic intervals of approximately 1, 3, 6, 9, 12, 15, 18, 21, 24. ...months except in Florida and Arizona where the samples are measured annually. We test samples until they drop 10% of their initial value or fail catastrophically.

"We typically characterize >1000 samples/mo, Currently, we have roughly >10,000 advanced reflector, glazings, polymers, and solar selective samples under test for CSP (& CPV) industry. We have a database of solar materials that contains: >1500 experiments, >25,000 samples, >350,000 measurements, >23 yr. Over the last 18 months we have been restoring and upgrading our capabilities, which includes hiring new staff, installing new equipment, upgrading our database to be web accessible and secured (hopefully completed March-May), and developing the capability to measure 2-mrad specular reflectance. In addition, we can test the mechanical, thermal, permeation properties of most materials. In addition, NREL has the capabilities to test the surface analytical properties of materials which is described on http://www.nrel.gov/pv/measurements/. This testing is also a recharge center.

"The steady-state off-sun thermal losses of receivers used in solar parabolic trough power plants can be analyzed in NREL's parabolic trough receiver test stand. Electric heaters and thermocouples are placed inside the receiver being tested and the heater power use is recorded at a desired absorber temperature. This routine is repeated for several different absorber temperatures, generating heat loss curves for a receiver. NREL can survey the receiver temperature by using a vehicle with an infrared (IR) camera and Global Positioning System (GPS) receiver that is driven down each solar field row while the solar plant operates normally. A data acquisition system uses the IR camera to photograph the receiver glass temperatures and processes them automatically. The glass temperature indicates how efficiently the receiver is working. The cooler the receiver glass temperature for a given air temperature, wind speed, and internal heat-transfer fluid (HTF) temperature, the less the heat lost to the environment — leaving more heat to increase the temperature of the heat transfer fluid. Receiver's that have lost their vacuum or have hydrogen in their annuli show significantly increased glass temperatures (~300°F) and heat losses relative to evacuated receiver's. The glass temperatures of about 6000 receiver's can be determined in one day.

"NREL has the Optical Efficiency Test Loop (OETL) facility. The test loop supplies coolant to the receiver tubes of parabolic trough units. The coolant, a water-glycol solution, will be at near ambient conditions. The trough is put on sun and the heat input to the coolant is compared to the direct normal insolation, as measured at NREL's Solar Radiation Research Laboratory (SRRL). The ratio of the two will give the efficiency at the limit of no thermal losses, i.e., the optical efficiency. The system operates as a closed loop. The heat input to the coolant will be transferred to the environment by a 28 ton chiller system. Fine control of the coolant temperature will be maintained with the chiller and a 20 kW electric circulation heater. The tracker is two-axis and can accommodate troughs 20 m long by 5 m wide. Different manufacturers will supply prototype troughs for testing. Check the technology transfer page of the nrel.gov site."