Improved boost mirror for low-concentration photovoltaic solar power systems

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ABSTRACT

A new reflector surface and geometry using low-concentration mirror boosting of flat-plate photo voltaic devices is described. The overheating effects that have previously been seen using non-uniform, high reflectivity side mirrors have been reduced. The new high-stability reflector material has lower UV reflectivity that reduces panel ageing and over heating. A moderate reflectivity in the violet wavelength further cuts the level of overheating while sacrificing only minimally in electrical power output efficiency. The new surface maintains high, uniform reflectivity at green, yellow, red, and IR wavelengths. Mass-produced panels are undergoing tests, and some preliminary results are presented. Surface self-cleaning of hydrophilic and hydrophobic coating over the reflecting surface is also discussed. Other applications of the same mirror in the solar thermal field are briefly discussed. Some improved tracking PV geometry versions using the new material are presented.

Keywords: Spectral reflectivity, selective reflectance, aluminum, solar reflectors, UV degradation, photovoltaic, concentrators, low-concentration, boost mirrors, hydrophilic surfaces, self-cleaning

1. INTRODUCTION: NEED FOR IMPROVEMENTS IN PV MIRRORS

A substantial cost reduction of solar electric power from solar energy is needed. Low cost solar electricity may be more easily achieved by the using low-cost reflectors, which may be applied to direct a higher level of solar energy onto photovoltaic conversion devices, or for solar thermal plants such as parabolic trough plants with steam turbine converters, or with novel designs such as in Figure 1.

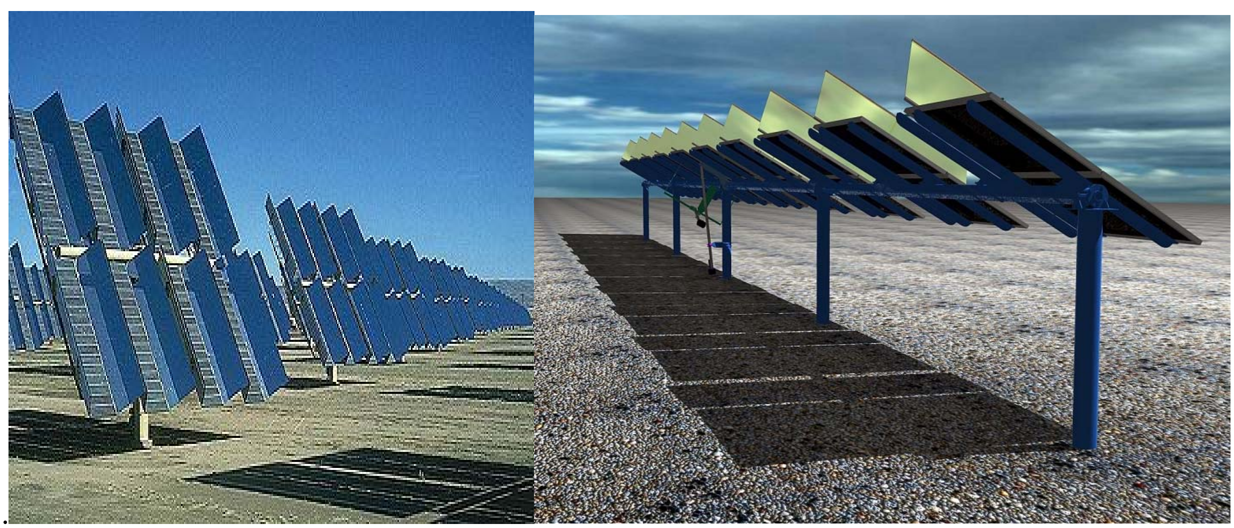

Fig. 1. Left: ARCO photovoltaic plant, Carrisa Plains, near California Valley, CA (1984) 2X side reflectors resulted in severe browning of the ARCO design. Right: artist rendering of proposed geometry.The new 1.5X design (right) allows better convection and radiation cooling. Moving boost mirrors can alter its concentration ratio on hot days. Tracking motors and controls for new design is simpler. The new geometry will be focus of future paper.

Early attempt to use boost mirrors to increase output and lower cost was attempted by Arco Solar in a now famous project in the 1980's that was installed at Carrisa Plains. Using back-silvered glass side "Vee" mirrors, this project tested the viability of using around 2X concentration with standard silicon panels. The test resulted in serious failures in a number of areas, particularly with the photovoltaic panel encapsulation material, ethylene-vinyl acetate (EVA). With the boost mirrors and high temperatures produced, the EVA degraded under the 2X concentration[1] (see Figure 1), resulting in the substantial loss of PV electric power, ultimately cutting panel lifetime to less than half. As the EVA degraded under the excess heat and UV light, acetic acid, a product of EVA decomposition, appears to have degraded back contacts. After extensive investigation over a number of years, the following was concluded that the damage was a result of "***combined U.V. radiation and temperature"***, and that "temperature or UV alone appear to be insufficient to cause the discoloration"[1]. In short, if the boost mirror system only contributed excess heat but not excess UV light, boost mirror systems may be practical and may not adversely affect overall PV panel life.

Since that time, projects using low-concentration photovoltaic designs have been built. Abengoa (see Figure 2) and others have apparently continued with the low-concentration photovoltaic concept, perhaps by employing more modern EVA formulations, and/or by using improved cerium-doped UV absorbing glass in photovoltaic panels to reduce browning. Cerium glass increases cost somewhat, and cerium glass is undesirable because of its tendency to "solarize" or to reduce its transmission over time due to the effects of UV in sunlight.

Fig. 2. Abengoa photovoltaic plant, Sanlúcar la Mayor, Sevilla (Spain). Commissioned May 1, 2006, it is the world's largest low concentration tracking PV plant with a rating of 1 Megawatt. Source: Abengoa web advertisement

Boost systems, such as shown in Figures 1 and 2, reduce the cost per watt of photovoltaic power. However, solar panel manufacturers have clear reasons for wanting to prohibit mirror systems. For one, solar light levels from mirrors are often are not uniform, and have "hot spots" that cause local heating. Non-uniform mirror distortion can cause such problems. Generally, since the photovoltaic panel manufacturers have no control of how uniform or how high in concentration a boost mirror system may be used by the purchaser, many manufacturers have chosen to simply declare their warranties void if their panels are used with mirrors.

With the foregoing discussion in mind, the "ideal PV boost mirror" is envisioned to include the following features.

1. UV content of the reflected light is reduced by incorporating a better, long-life, light-stable, preferably inorganic absorber in the reflector. The primary goal here is to avoid increasing the UV flux level and increasing instead only the less damaging and more easily converted wavelengths to the PV cell, reducing pay-back period without reducing the life of the panel. The UV absorber should be uniform and not be cloudy in appearance.

2. The reflective structure should be flat and smooth, so laminated mirror designs are preferred in order to eliminate hot spots.

3. Radiation cooling of the PV panel is improved by using materials with better long-wave IR characteristics than glass, which does not have the ability to transmit the long-wave thermal radiation from the photovoltaic panel.
4. The reflector material is designed to be scratch-resistant and should not accumulate dust and dirt.
5. The directionality of reflection should be made as high as possible.

After consideration of the five goals, an approach was selected that is detailed in the following section.

2. IMPROVED UV-REDUCING ALUMINUM BOOST MIRRORS

2.1 Improved UV Blocker for Aluminum

A search was performed to establish options to produce what would appear to be a specular gold tint reflector with UV blocking characteristics. Various gold tinted aluminum reflector samples were collected from various aluminum vendors. The tests showed a range of results, with some samples showing little or no UV absorption, while others had high UV absorption. An excellent candidate sample was found from one vendor, Aluminum Coil Anodizing (ACA) of Streamwood, Illinois. This vendor's sample was identified as having an metal ion-based inorganic pigment. Samples were sent to NREL for accelerated UV testing. The samples showed very high UV stability and yet still showed high reflected light directionality (low diffuse reflectance). As is shown in Figure 3, the tinted samples showed good visible and near-IR reflectivity, and lower reflectivity in the ultra-violet region. No change in transmission, or "solarization" was evident, which was an important goal. This particular sample was used only to establish the stability of the tint material.

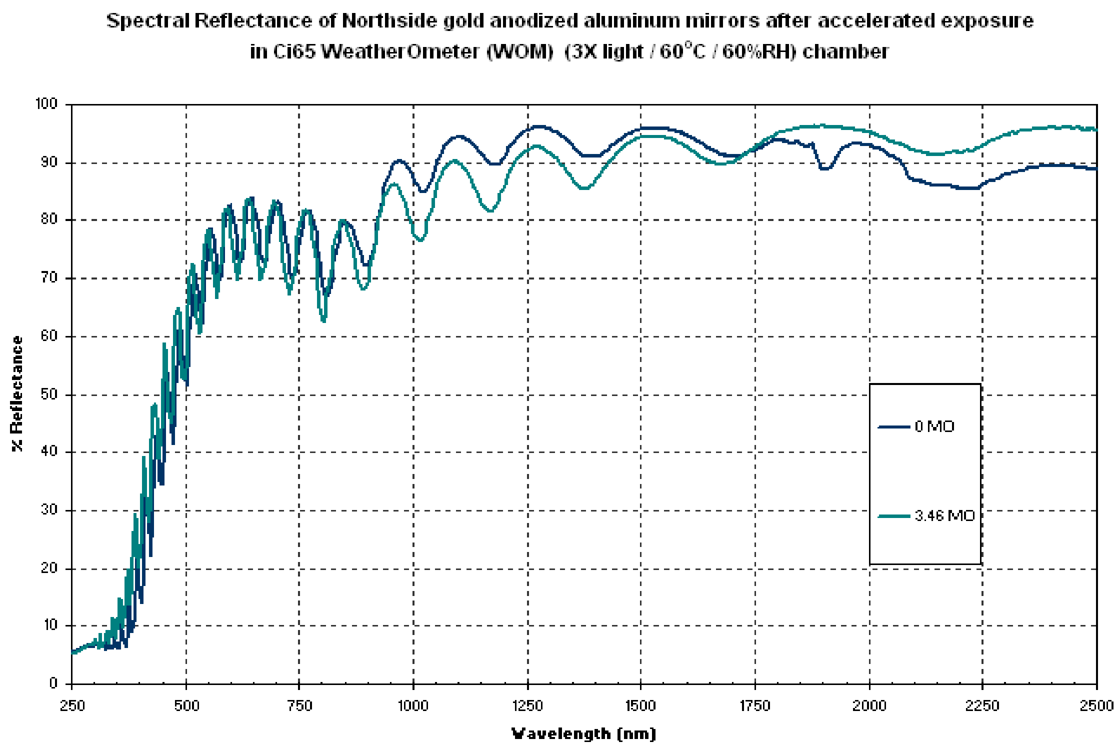

Fig.3. Weather-o-meter tests on type 757 gold-tinted aluminum showed exceptional stability with accelerated life under UV of the raw tinting material. This material had far greater absorption in the visible than was desired, so later product runs used a considerably thinner layer of the absorber. Data taken by request to Kennedy (NREL).

Though the material with the reflectivity shown in Figure 3 had adequate stability, a lighter tint was deemed necessary to keep the conversion efficiency high. After a series of extensive reflectivity measurements of dozens of various tints were completed, a much lighter gold anodized shade, ACA type 794, was identified as one based on the same type of UV-stable dye[4], but as having superior visible reflectivity. Reflectivity measurements on the lighter gold, termed "SolaGold", were done by the author using a prototype reflectance measuring station that consisted of a 10x10 mm PIN silicon photodiode, a transimpedance amplifier, a high intensity discharge lamp source with a 10000 Kelvin color temperature, and a monochromator (Varian spectrophotometer model 192). Variations of readings on the order of 2% were observed due to the limits of the prototype's design. However, the readings did give a reasonable estimate for the material properties and were considered adequate to prove the design.

The SolaGold[5] light gold tint sample and a non-dyed sample coated with ACA's new, proprietary glass-like coating material termed "ProtectAL" (under license from Metal Coating Technologies[3]) were analyzed for reflectance. The 794 sample showed the very sharp reduction in UVA light which was the goal of the project. The ratio of the gold tinted material to the un-tinted material in the UV to 450 nm range was calculated, and a regression fit performed. The fit was good showing 0.9975 correlation value.

In the range from 500 nm to 1000 nanometers, the ratio of the reflectivity of the gold tint sample to the un-dyed sample followed the equation:

$$y = 6.571E\text{-}03x - 2.023E\text{+}0($$
$$R^2 = 9.901E\text{-}01$$

For the UV to blue range, i.e. from 350 nm to 450 nm, the ratio of the reflectivity of the gold tint to the un-dyed sample was a relatively constant value of 0.98. This extremely sharp cut-off filter for UV reduction with virtually zero change in visible and near-IR was highly unusual and virtually ideal for the application.

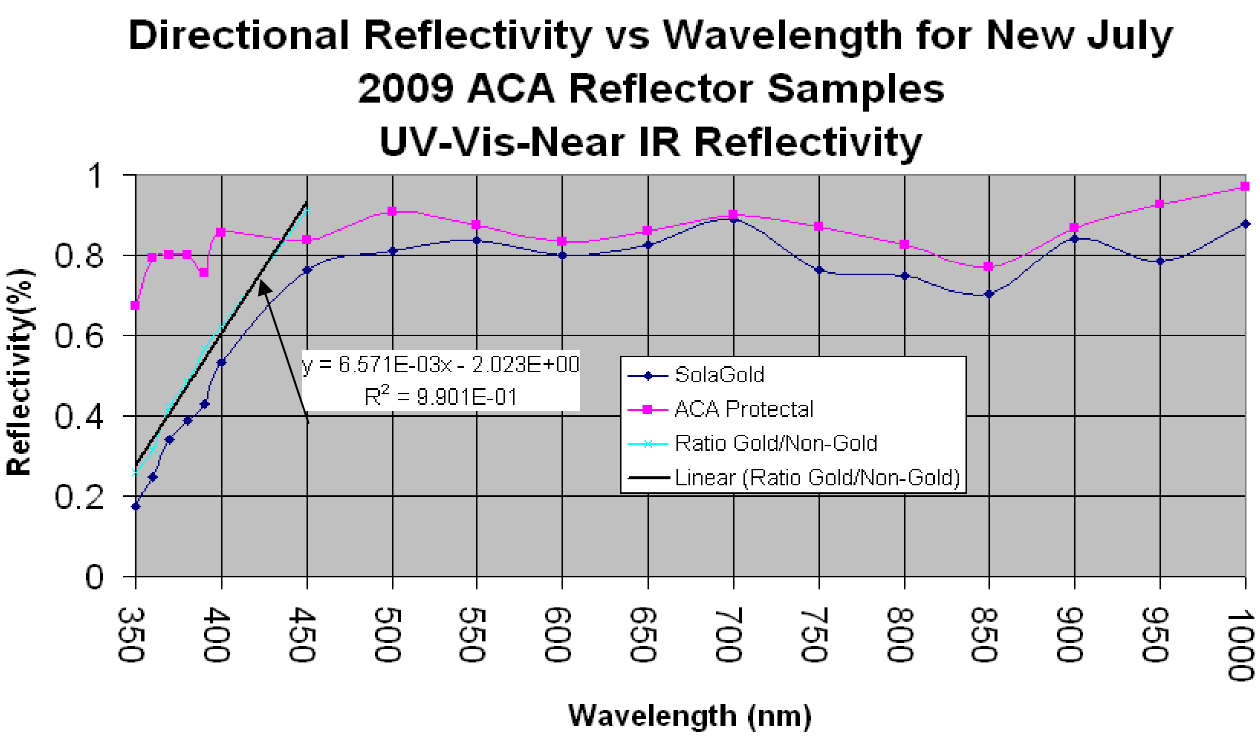

Fig.4. Reflectivity versus wavelength for UV to near IR, taken with the author's prototype equipment. A simple linear fit is shown for the ratio of the gold reflectivity to the non-dyed sample reflectivity.

With the mathematical model established for the reflectivity of the non-tinted sample, the summary of reflectivity of samples based on more precise NREL data was computed and is shown in figure 5 along with solar radiance for standard AM 1.5 conditions and silicon cell response.

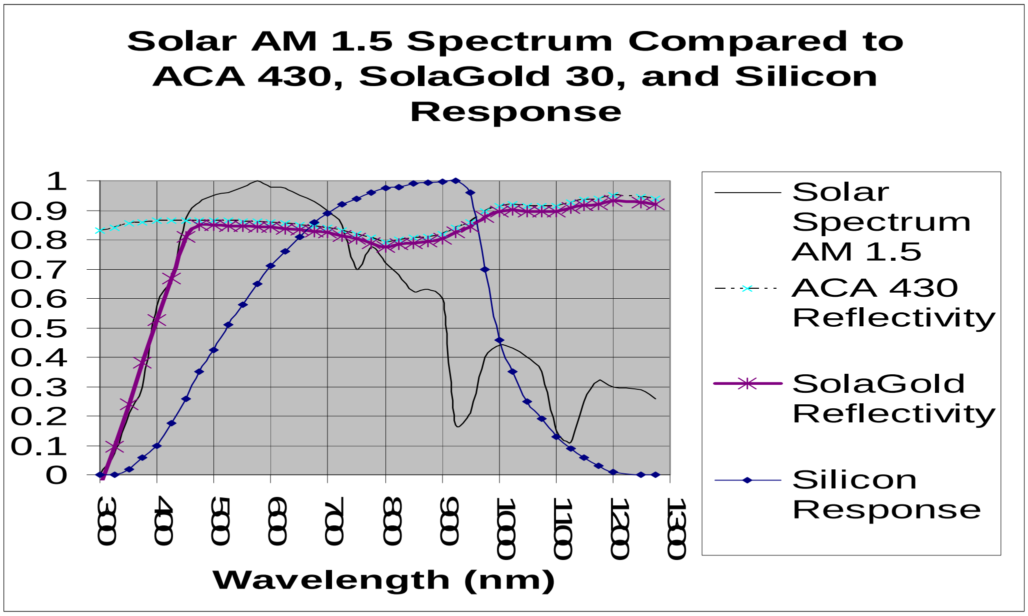

Fig. 5. Reflectivity of the ACA aluminum products compared with standard solar spectrum AM 1.5 and silicon solar cell response as reference.

The data for the NREL measurements of the reflector were then used to derive the reflectivity plot of the reflectors. Based on the data, figure 5 shows the reflectivity.

2.2 High IR Reflectivity

Another key parameter of interest was the measurement of near-IR reflectivity. To make this measurement, a FTIR spectrophotometer was used. As is shown in Figure 6, the near IR reflectance of both the tinted sample and the non-tinted sample (both covered with ProtectAL) appeared to be very high.

Reflectance in the mid-wave IR was also measured, and is shown in Figure 7. These mid-IR measurements were also taken using the FTIR unit supplied by Maxion Technologies, Inc. of College Park, Maryland. As is shown in the figure, a large difference was found in the long-wave reflectivity characteristics of the ACA materials in comparison to other solar mirror materials. The back-silvered glass mirror, the same type as was used at Carrisa Plains Arco modules, showed virtually zero long-wave IR reflectivity. A plastic aluminized reflective material, a product from 3M called “SA-85”, is shown for comparison. From the figure, infra-red radiation emitted by the photovoltaic panel, assumed to be at worst-case summer temperature of 70º C, will have a peak emission wavelength of about 10 microns. At this wavelength, the ACA products range in reflectance from around 95% to around 20%, with an average value over the emission range of around 30%. The glass mirror, in contrast, shows virtually no infra-red reflection, with a typical value of less than 10%. The plastic reflector material is somewhat more reflective, with an average value of around 50% over the emission range.

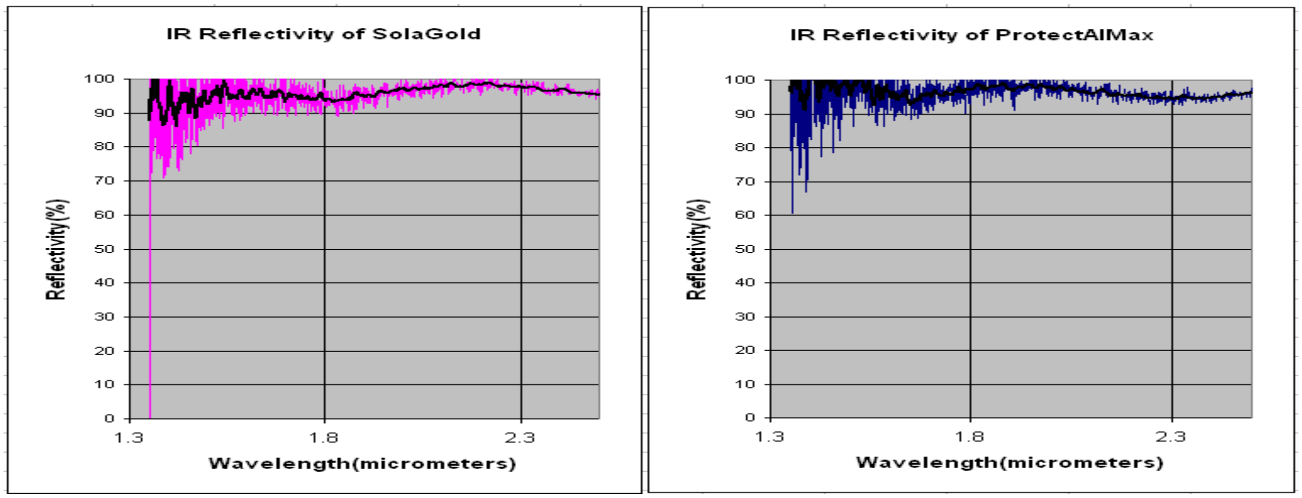

Fig. 6. Near IR reflectivity. Measurements were made with a FFT IR Spectrophotometer, courtesy of Maxion Technologies, Inc. of College Park, Maryland.

2.3 Hydrophilic Surface: Improved Morning Clarity and Dirt Rejection

A key difference was observed with the ACA "ProtectAL" glass-coated aluminum mirror samples. When dipped in water, droplets did not form, and water fully wetted the mirrors. This is contrary to the Alanod and Alcan samples, which shed water due to their hydrophobic surface. Whether ProtectAL hydrophilic or Alanod and Alcan hydrophobic reflectors were preferable was a subject requiring further study.

To study the effect of this aspect on solar system performance, samples were mounted on an outdoor rack. As shown in Figure 7, the ProtectAL hydrophilic samples appeared on mornings with dew to be visually clear, while the hydrophobic mirrors appeared cloudy.

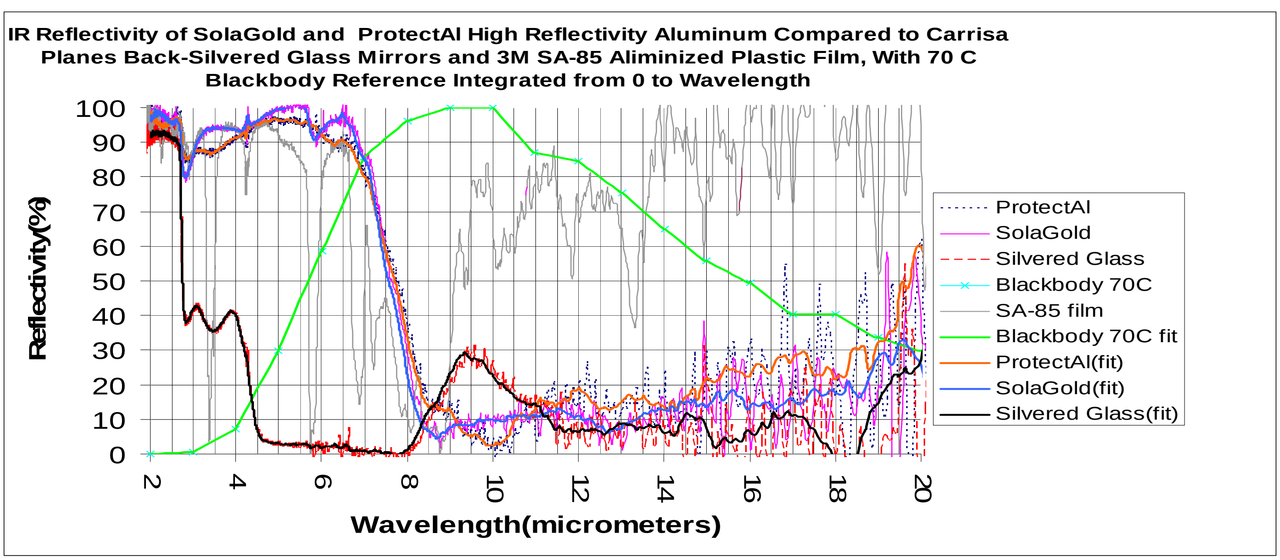

Fig. 6. Near IR reflectivity. Measurements were made with a FFT IR Spectrophotometer, courtesy of Maxion Technologies, Inc. of College Park, Maryland. Reference emitter is blackbody at 70C.

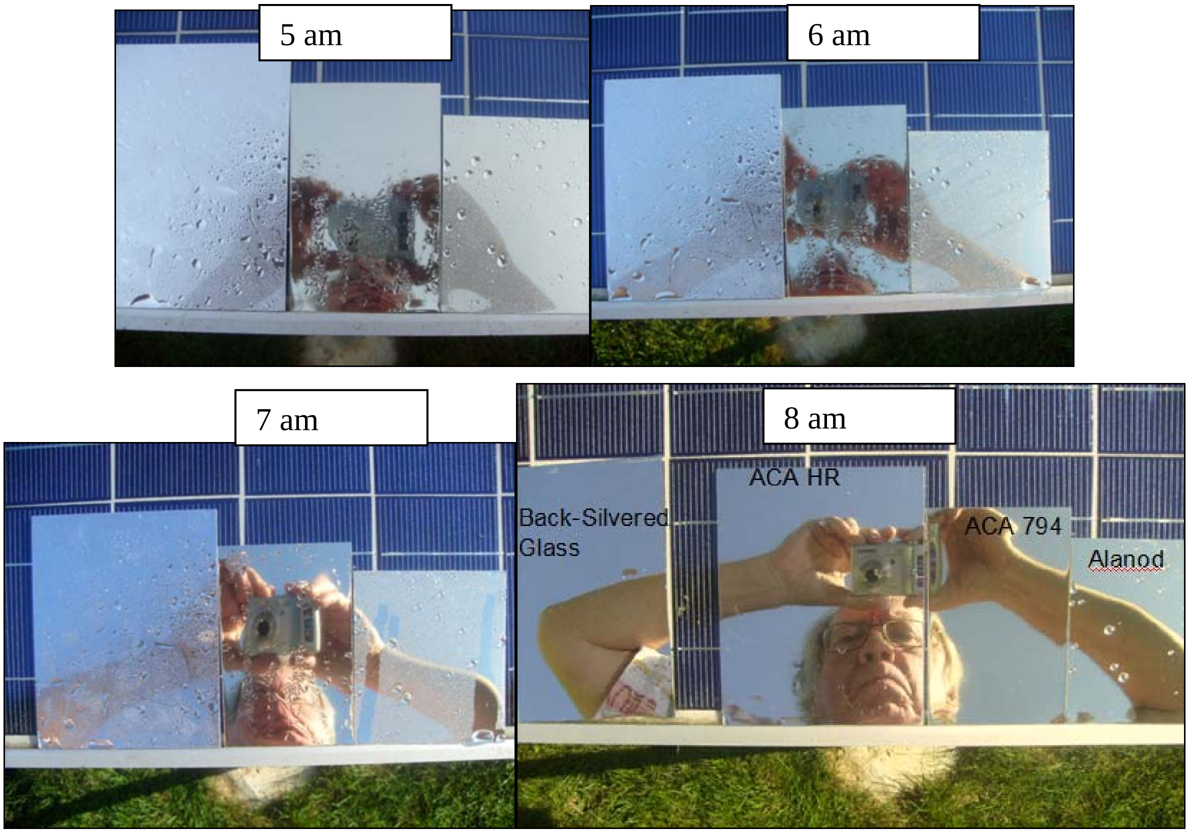

Fig. 7. Morning condensing humidity conditions(5,6,7, and 8 AM—Top left to bottom right) of "ProtectAL" surface (left sample) on aluminum, on a co-oxide UV absorber (middle sample), and Alanod's Hydrophobic Miro Sun PV (right) sample.

Figure 7 shows the overnight and morning condensation effects. The top left photo is at 5 AM solar time, before sunrise. Three samples are in each photo. The left sample, an ACA "ProtectAL" sample with no tint, shows condensation droplets with relatively low contact angle, indicating that this surface is somewhat between hydrophobic and hydrophilic. The center sample, the ACA sample with "ProtectAL" outer coating and an additional integral oxide tint (SolaGold), shows an extremely hydrophilic feature that appears to render it a better imaging surface when condensation is considered. The right sample, the hydrophobic Alanod Miro PV sample, beads up dramatically. The SolaGold sample appears to completely clear up by 8 AM solar time (summer), but the other samples appear to be still show larger water droplets.

An advantage of the hydrophilic surface may be that the hydrophilic surface wetting may result in a cleaning action allowing dirt to be floated off of the mirror surface. Further work is required to study this feature, which may result in substantial performance advantages in certain sites.

2.4 PV-Weighted Effective AM 1.5 and AM-1 Reflectance

A mathematical model of the response of a photovoltaic panel to light produced for the standard non-dyed and the dyed products was created. The mathematical model was based on single crystal silicon response curves available in the literature. The goal was to determine the expected heating of the silicon photovoltaic panel, and also the expected electrical output.

Figure 8 shows the results of the analysis. The figure shows the electrical power output of a silicon photovoltaic panel integrated from wavelength 0 (short wave UV) to a given wavelength. The upper two curves represent the result with a perfect 100% reflector, an un-dyed aluminum reflector, and a dyed aluminum reflector. The non-dyed material heating rate is 85% as much as would be achieved with a perfect reflector, and the electrical output with the non-dyed reflector shows an electrical output power of 84% as high as achieved with a perfect reflector.

On the other hand, the dyed "SolaGold" material electrical output is 81% as high as the perfect reflector, but the heating effect is only 79% as high as with the perfect reflector. Thus, the UV absorbing reflector introduces a slight cooling of the panel, which further improves efficiency and reduces the ageing of the panel.

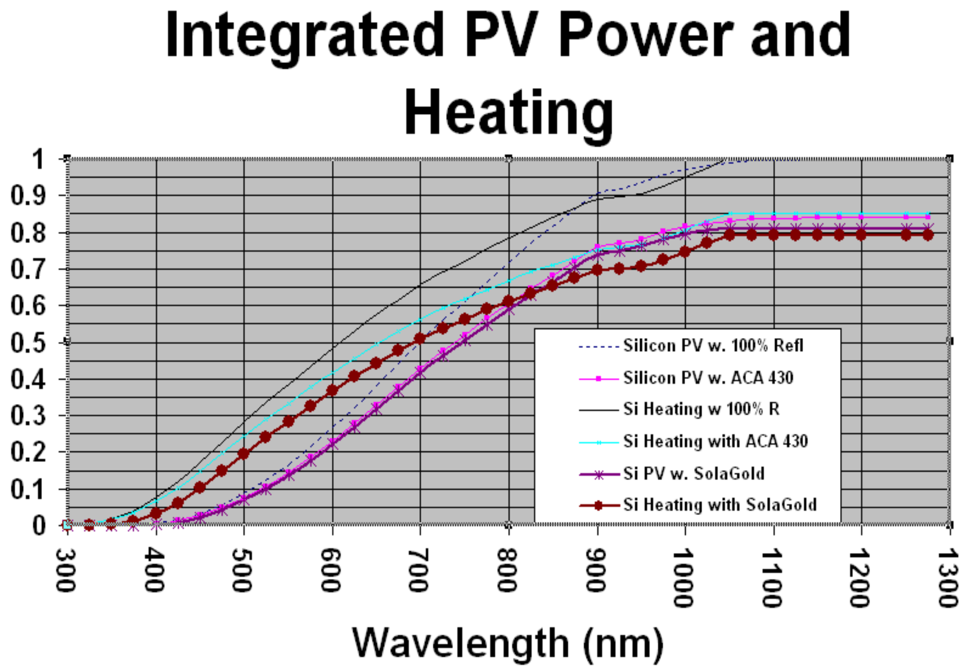

Fig. 8. Photovoltaic panel theoretical heating, and photovoltaic panel electrical output integrated from wavelength 0 to a given wavelength. The effective AM 1.5 and silicon response weights are applied with non-dyed and dyed aluminum reflectors.

2.5 Directional Reflectance Characterization

Figure 9 shows the results of the analysis of the directional reflectivity analysis. Directional reflectivity is usually characterized in terms of an angular dispersion that reflectors introduce as a result of surface roughness. A common instrument used for such characterizations is the D&S Model 15 device, which uses a 650 nanometer LED light source, a collimator lens, and a collector optical system that is designed to have a specific circular collection geometry. Frequently, the collection angles studied using the D&S device are a half-angle collection solid angle of 7 mrad or 25 mrad.

Several drawbacks are apparent with the D&S instrument. First, it is rather expensive. Secondly, the device does not display the effective image spread, but only gives a single digital value.

The author has developed a simple optical set up that is easy to reproduce and gives far more useful information about the mirror directional reflectance. The new instrumentation consists of a 650 nanometer laser with a line spreading optical head as a light source. The laser is placed 15 cm from the mirror sample to be analyzed. Light is reflected fro the mirror under test to a white screen placed roughly 0.5 meters from the reflector. A digital camera is used to record the image produced by projecting the laser line on the reflective sample. A software program is then used to analyze the reflected image.

Using this technique, the image analysis was performed on the ACA mirrors. Figure 9 shows the result. As shown, the mirrors appear to be highly directional. The US Department of Energy (DOE) has indicated a goal of 4 mrad for mirrors, and apparently the new materials meet these goals.

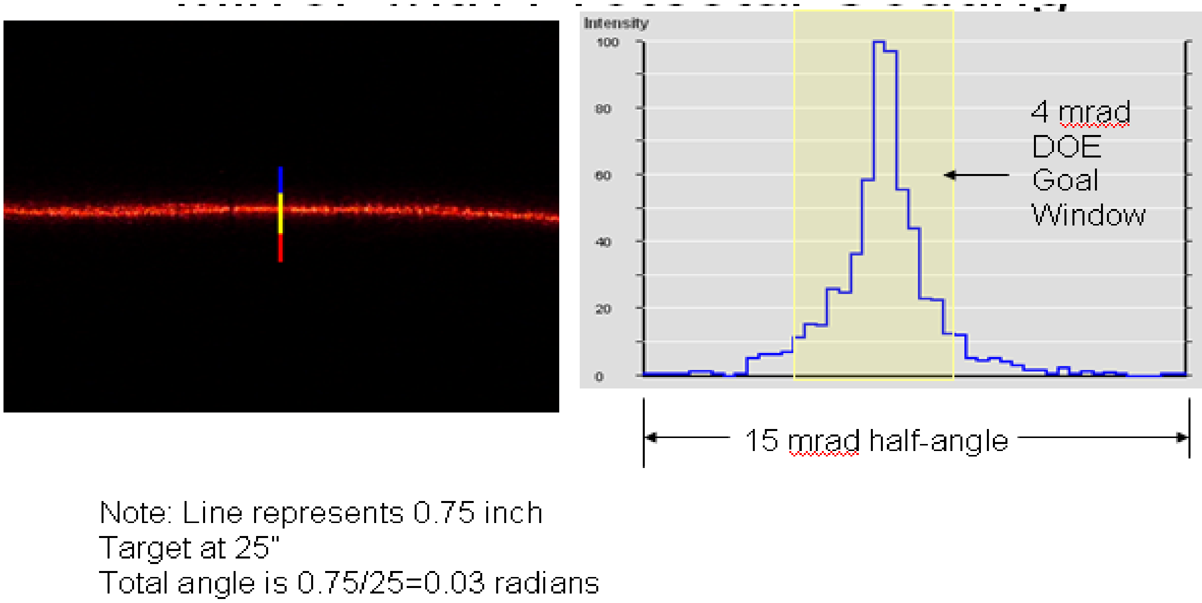

Fig. 9. Specular reflectance characterization performed by projecting a line of laser light on the sample, photographing the resulting image, and analyzing the intensity distribution of the line produced using photometric software.

3. SUMMARY

A new type of solar boost mirror proposed has been realized with good UV blocking charactistics, while maintaining high visible and IR reflectivity, resulting in high electrical output. The silicon-weighted optical reflectivity is estimated to be 81%. The tinted reflector results in a slightly reduced heating effect in comparison to non-tinted reflectors. The UV-absorbing characteristics of the new tinted reflector are dramatic with 80% UV absorption at 350 nanometers. The material should help avoid problems of UV damage found in early low-concentration PV systems without requiring high-cost cerium glass.   A new aluminum protective surface was studied by measuring optical directionality, near-IR, mid-IR, and other features. The aluminum reflector appears to be well-suited for both PV concentrator applications and for solar thermal trough plants.

4. REFERENCES

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[3] Dr. Hamlin Jennings, Metal Coating Technologies LLC, Evanston, IL (private communication).

[4] Dr. John Papp, Aluminum Coil Anodizing Corporation (ACA), Streamwood, IL (private communication).

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SolaGold™ and ProtectAL™ are both products with patents pending.