# Solar Radiation Durability of Materials Components and Systems for Low Concentration Photovoltaic Systems

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*Abstract*—

Low Concentration Photovoltaic Systems (LCPV), where solar irradiance is concentrated by a factor of 1-10, present real opportunities for cost competitiveness. In these systems electrical output per unit area of active materials increases nearly linearly with concentration factor, thereby reducing the cost of active materials per watt by up to a factor of 10. All PV systems are exposed to multifactor and cyclic environmental stressors including solar irradiance, temperature and humidity which can each cause degradation over time. This issue is compounded in LCPV because concentration of solar irradiance can amplify these stressors. While primary optical elements of LCPV systems are typically only exposed to normal sun irradiance, secondary optical elements are exposed to multiple sun intensities which can degrade them faster. Concentrating sunlight intensifies the problem of thermal management and since most LCPV systems use crystalline silicon cells, increased temperature decreases overall efficiency. From this point of view, it is very important to have foresight about materials in PV system before they have been used. This paper will discuss solar and environmental durability of acrylic and mirror components of PV systems from a standpoint of durability and reliability of LCPV. Photodarkening and photobleaching were observed in a typical silicone at 3.8 kW/m$^2$ irradiance and measurements we used to calculate the Induced Absorbance to Dose (IAD) values of 0.3 and -1.25 ΔAbs/cm per GJ dose. At 48 kW/m$^2$ irradiance, only photodarkening appears with 0.2ΔAbs/cm per GJ dose. In addition, photodarkening and photobleaching were also observed in PMMA sample with IAD values of 0.2 and -0.4 ΔAbs/cm per GJ dose, respectively.

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***Index Terms*—concentrating photovoltaic, solar radiation durability, lifetime and degradation science, reliability.**

## Nomenclature

LCPV: low concentration PV, MAPV: mirror augmented PV, LC2PV: low concentration, low cost PV, IAD: induced absorbance to dose, L&DS: Lifetime and Degradation Science

## I. Introduction

During the oil crisis in the 1970s, scientists tried to find alternative energy sources in order to fulfill the increasing requirements of our modern society. As a direct method for harnessing the sun's energy, photovoltaic systems have a large potential to supply a significant fraction of global electricity needs. Despite the ubiquitous nature of solar energy, it has some drawbacks when compared to traditional energy sources. To provide a low levelized cost of energy, PV needs long lifetimes. At current electricity costs, photovoltaic systems require 10-20 year lifetimes in order to be a cost competitive to traditional power sources. Photovoltaic systems requires little to no maintenance and once a PV array is paid off, it can continue producing power indefinitely without incurring costs. As crystalline silicon becomes the utility scale PV technology of choice it has become critical to optimize systems on many levels, including the metrics of dollars invested per watt peak production and levelized cost of energy (LCOE; the price of the system over its life divided by the total predicted energy output of the system). Both of these metrics can be lowered significantly by mirror enhancement of PV modules. Simply put, by focusing the sun's energy onto a PV array with low cost mirror systems it is possible to increase both the peak power output and lower the cost of delivered energy. Because mirrors cost less than a dime on the dollar when compared with PV modules, there is the possibility for significant savings on LCOE by utilizing MAPV. This value proposition rests in the notion that mirror augmentation will not decrease the life of modules due to increased UV degradation or increased temperature caused by increased infrared dosing. In addition, mirrors need to be designed and manufactured such that they can achieve long lifetimes when exposed to environmental exposure. As such MAPV needs to be proven to be safe for modules and cost effective before it can capture significant market share.

## II. Carrizo Plains: A Case Study of Solar Radiation Durability of Mirror Augmented Flat Panel C-Si Modules

Amplification of solar irradiance on crystalline silicon PV modules with mirrors was used in the mid 1980s at Arco Solar's Carrizo Plains (sometimes referred to as Carrisa or Carissa Plains) 5.2 MW PV power plant[i]. The Carrizo Plains power plant consists of 10 segments, each with its own power conditioning unit (PCU). Segments 1 through 9 had a combined total of 756 trackers with mirrors in a v-trough configuration (**Figure 1**) providing nominal 2:1 concentration, while segment 10 had 43 trackers without mirrors.[ii] All segments utilized single-crystalline flat plate modules. This project was expected to provide an alternative energy source to our modern society. However, it failed because it exhibited power degradation rates of 10% per year, with 40% power drop over the first four years as shown in **Figure 2**. It was observed that various models of PV degradation are linear, sub-linear or supralinear with respect to their degradation rates. In the case of Carrizo Plains, scientists tried to find the degradation mechanisms of the PV module. At first, it was suggested that the use of solar mirrors augmentation caused the degradation problem. Recently, Michael Kempe's research group from DOE's National Renewable Energy Laboratory (NREL) proposed that several design errors that have now been mitigated in present day modules led to the fast degradation. These errors included neglecting the UV absorbing glass front sheet, poor choice of PV cells, and various manufacturing parameters, such as choosing a fast-cure EVA rather than the JPL prescribed slow-cure EVA [iii]. According to Kempe's suggestions, these problems have been modified for all current technologies. Durability properties of encapsulation materials are crucial to the long-term performance of PV modules. Therefore, this story serves as a cautionary tale that the reliability and solar and environmental durability of PV systems, particularly LCPV systems that need long service lifetimes, are more complex than many have assumed.

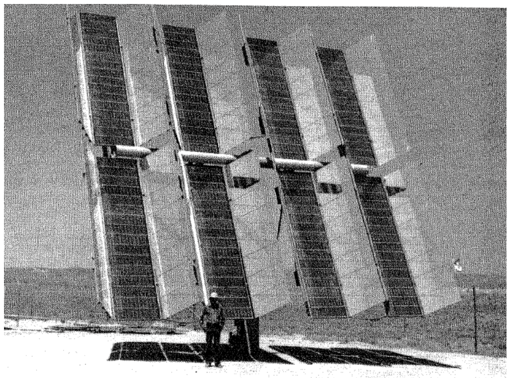


**Figure 1. Mirror augmentation tracker at Carrizo Plain[ii]**

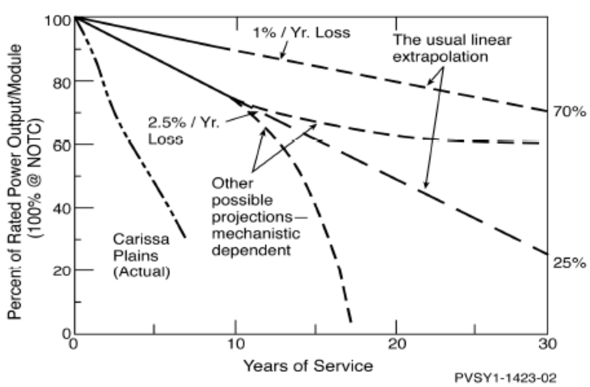



**Figure 2. Power degradation of the Carrizo Plains compared to typical degradation rates for current flat-panel PV modules[i]**

## III. Needs for Developing Lifetime and Degradation Science of Photovoltaic Materials

The U.S. Department of Energy (DOE), in its panel report on *Science for Energy Technology*[iv] (August 2010), highlighted the development of Lifetime and Degradation Science (L&DS) as critical to the future competitiveness of U.S. advanced energy and efficiency products. Specifically, the report identifies the need to provide PV manufacturers with the proper scientific basis for developing module materials, components, and systems, before they employ sure-to-rapidly-degrade elements or combinations. It then endorses the ability of L&DS to develop technologies with substantially longer lifetimes than the 20 years typical of current industry warranties. The NIST/UL Workshop on Polymers for Photovoltaic Systems (September 2010), reinforced these findings. It also focused on the needs for robust standards, qualification testing and service lifetime prediction to enable the PV industry to advance. The impetus for each to investigate such topics through PV is simple: the United States, once the leader in technologies such as solar photovoltaic systems, is now third, fourth or fifth.

Historically, degradation itself (the heart of L&DS) presents a well-known challenge to advanced energy companies. Examples at the Southwest Region Experiment Station (SWRES) for PV systems demonstrate this in full, as noted in the Nov. 4, 2010 article entitled "The New Mexico Solar Tour: Part 1 – Panel Degradation Cannot Lie, So Plan Smart." In context of this observation, the expected ("warrantied") degradation rates for PV modules register at 1%/yr to 0.5%/yr.

## IV. Exposures and Evaluations for Solar Radiation Durability

Standard methods for degrading materials are required in order to develop the critical metrics and methods that would allow for lifetime predictions. Research performed at DuPont was critical for these purposes. In researching novel compounds for PV applications, samples were exposed to AM 1.5 radiation at levels ranging between 1 kW/m$^2$ and 48.4 kW/m$^2$. When attempting to accelerate degradation of materials, it is imperative that degradation pathways be checked at multiple acceleration factors because in some degradation modes, unseen reactions can become active when exposed to stressors at levels that they would not be exposed to during their normal service lives. Evaluations of radiation degraded samples often include measurements of haze, yellowness index, and spectral response. The ASTM haze measurement is a useful optical property which quantifies total scattered light transmitted through a sample. Haze is a complex measurable since it can arise from surface roughness, bulk polymer crystallinity, and impurities and grain boundary mismatch. In addition to the ASTM haze, measurements can be made of the wavelength dependent haze which measures the percent scattered light at any given wavelength. Yellowness index (YI) is a broad spectrum measurement which indicates absorption of light by the material. Since it uses a broad range of frequencies in its evaluation it tends to be a very sensitive measurement and can indicate photodarkening or photobleaching [v]. Measurement of the changes in the spectral response of the materials before and after exposure can be used to find the wavelengths of interest, where changes in the polymer can be observed and linked to chemical changes. Using UV-VIS-NIR spectroscopy it is possible to find changes in the spectral response of materials and link them to the accumulated damaging radiation to which the sample was exposed. This metric is called the Induced Absorbance to Dose (IAD) and if reciprocity and linearity are shown to hold true IAD can be used to predict service lifetimes for materials which will be heavily dosed with solar radiation while in service.

## V. Illustrative Examples

It is important to develop a useful metric for quantifying photochemical processes such as photobleaching or photodarkening when evaluating CPV materials. The optical absorbance of a material is a significant parameter of concern in CPV applications. The optical absorbance is determined by:

$$A/cm = \frac{\log_{10}\left[T_{substrat} / T_{film}\right]}{t_{film}}$$

Where $T$ is the transmission, $t$ is the thickness of the film, and *A/cm* is the absorbance per centimeter. Another desirable radiation durability metric is the change in the spectral optical absorbance (ΔAbs./cm (λ)) for each increment of full spectrum solar radiation dose (in GJ/m$^2$) since this allows us to observe and study the sources of photochemical changes which arise over time with exposure. We call this the Incremental Absorbance to Dose, or IAD, which has units of ΔAbs/cm per GJ/m$^2$ dose. This metric allows us to track the rates of photochemical processes including photochemical bleaching and darkening of both intrinsic and extrinsic components of the material and is scaled in units of 1 GJ/m$^2$ dose.

$$Incremental\ \frac{Abs}{cm}\ per\ \frac{GJ}{m^2}\ Dose \equiv \frac{Abs_{i+1}(\lambda)/cm - Abs_i(\lambda)/cm}{Dose_{i+1} - Dose_i}$$

The following examples show the IAD metric in use. Figure 3 shows the spectral response of a typical silicone tested at 3.8 and 48 kW/m$^2$. By using a xenon arc light calibrated to the AM 1.5 standard, samples were exposed to multiple intensities of simulated sunlight and it is possible to see degradation modes by tracking their spectral response. By showing that the same degradation pathways are active at multiple levels of irradiance tested, one can show that the IAD metric holds constant[vi]. Photodarkening and photobleaching can be seen in both samples when compared to the virgin materialvii. The first plot

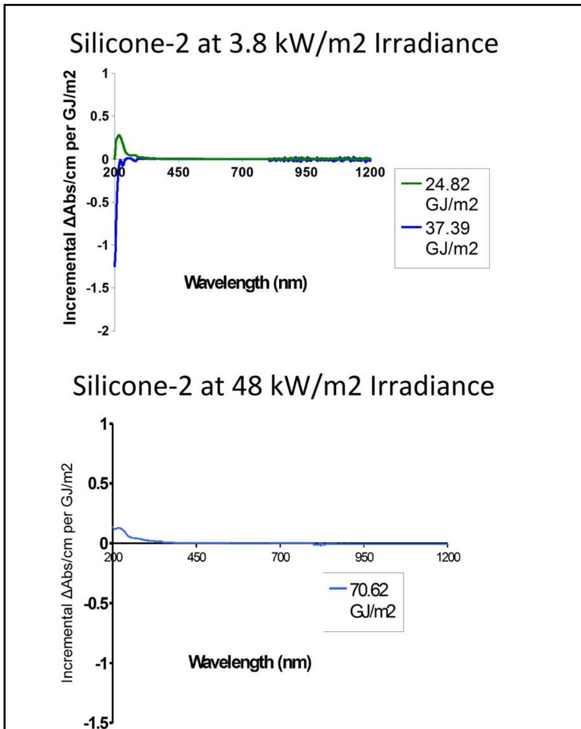
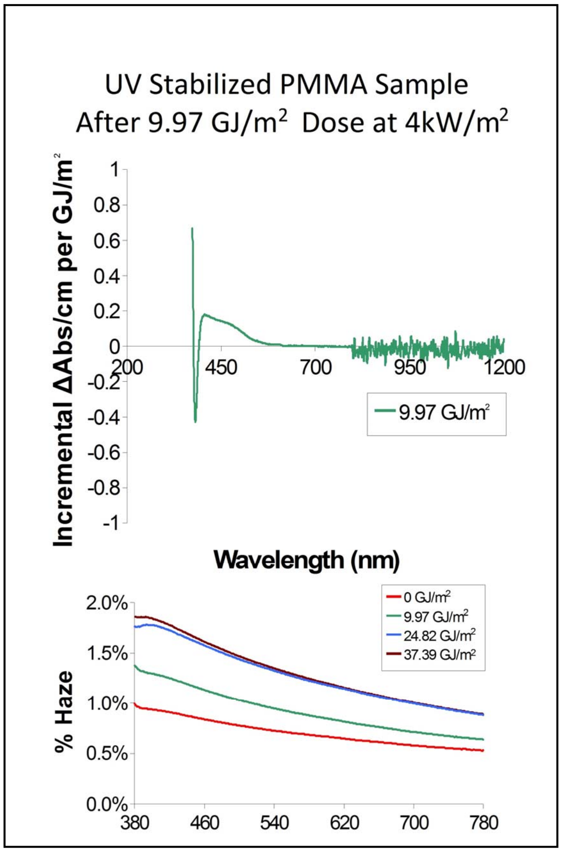



**Figure 3. Induced Absorbance to Dose (IAD) of a Commercial Silicone exposed to two different**

shows the data at 3.8 kW/m$^2$. Initially there is some photodarkening observed below 300 nm followed from some photobleaching after 37 GJ/m$^2$ exposure. The incremental absorbance to dose of photodarkening and photobleaching are at 0.3 and -1.25 ΔAbs/cm per GJ/m$^2$, respectively. The second plot shows the data at 48 kW/m$^2$. Some photodarkening appears below 300 nm at a peak of 0.2 ΔAbs/cm per GJ/m$^2$ dose. In addition to optical absorbance, UV-VIS-NIR spectroscopy was also used for haze measurement. The haze versus wavelength and the average haze (over the range from 380 to 780 nm) is calculated as

$$Haze = \frac{T_{diffuse}}{T_{total}} * 100\%$$

Note that the haze is only well defined in transparent materials; if the transmission drops towards zero, by definition the haze approaches 100%. Figure 4 shows a typical PMMA polymer that has been exposed to accelerated weathering using the same simulation technique. The IAD can be seen on the top where the UV stabilization is degrading due to exposure. The photodarkening appears between 400-600 nm and the incremental absorbance to dose is 0.2 per GJ/m$^2$ dose. The photobleaching appears at around 400nm with -0.4 incremental absorbance. To the bottom is the spectral haze measurement before and after various radiation and an increase in bulk haze can be seen.




## VI. LCPV Systems Under Consideration

When considering the value proposition of LCPV it is important to consider a spectrum of possible products and designs because it is currently unclear which technology will prevail. Despite setbacks and fears due to the massive failure at Carizzo Plains described earlier, Mirror-Assisted Photovoltaic (MAPV) systems still hold interest because of their potential power gains with respect to cost. MAPV installations have been seen in Spain, and new polymers and technologies are enabling the fabrication of UV-blocking mirrors. One hope is that by using UV blocking polymers on back surface mirrors the fears of accelerated UV degradation can be assuaged and module manufacturers will no longer void product warranties if users augment systems with these mirrors. If installed on a solar tracker, Mirror-Augmented PV modules could produce as much as double the power, and if installed on flat mounted modules, power gains realized could still approach 20%. Given that many utility scale PV power plants are installing tracking solar power systems already for power gains of 15-25%, MAPV stands to capture market share in this field. In addition to MAPV, development is underway on several fronts to commercialize Low Cost, Low Concentration PV systems (LC2PV). One such developer, Replex Plastics is aiming for 10x concentration using compound parabolic reflectors (CPCs) to illuminate small silicon solar cells. A typical CPC design is shown in figure 6. Such a system benefits from having wide acceptance angles, so single axis tracking is adequate. It is important when studying the degradation of this LC2PV design to note that the mirror acts as both the primary and secondary optical system. The irradiance map in Figure 7 shows that while the top of the mirror may see normal incident radiation the bottom of the CPC can be exposed to almost three times as much. Such acrylic CPCs would need to be made to stand radiation lifetimes of 30-60 years instead of the 10-20 years expected for modules performance. However, the value proposition of using 1/10 of the active materials of a traditional flat panel system and relatively inexpensive concentrating systems captures the attention of developers and academics alike.

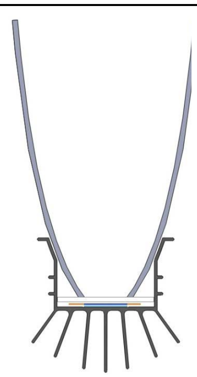


**Figure 6. Typical CPC construction (side view)**

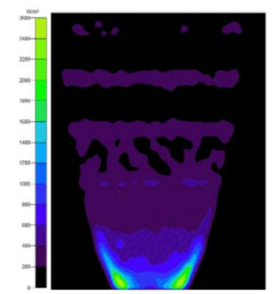



**Figure 7: Irradiance map of typical CPC**

## VII. Conclusions

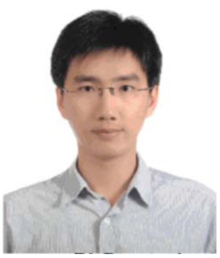
Exploiting alternative energy sources is inevitable in the path for our nation's future. Photovoltaic power generation is one technology with the most potential to avert another energy crisis in the future. Power degradation in photovoltaic modules is an important challenge that needs to be mitigated in PV system design and fabrication. However, the degradation mechanisms of photovoltaic systems are still unclear, leading to current 20 year warranty lifetimes for PV modules. In this study, we show methods that can be used to observe chemical changes and to predict service lifetime of materials. MAPV and LC2PV were introduced as two potential designs that may reduce the economic cost of PV power. The optical properties of materials used in these two models have been investigated. Our goal is to reduce degradation rate and extend the service lifetime of PV modules.

## VIII. Biographies

**Dr. Roger French** (*F. Alex Nason Professor, Department of Materials Science and Engineering*) joined CWRU in August 2010 after 24 years of conducting basic research and product development in DuPont's Central Research. Dr. French has a broad experience in developing and commercializing optical materials for many different applications and in optimizing these materials for improved radiation durability and lifetime.

Dr. French is also a nationally recognized expert in Lifetime and Degradation Science (L&DS) for commercial applications, evidenced by his work on attenuating phase shift photomasks, fluoropolymer pellicles for photolithography, immersion lithography imaging fluids, and materials for concentrating photovoltaic systems at DuPont. He has 22 issued patents and more than 145 publications. For this project, his technical responsibilities will focus on optical exposures.

**Myles P. Murray** is currently a Ph.D. graduate student at Case Western Reserve University in the department of Materials Science and Engineering. He received a Bachelor of Arts in Chemistry from Hendrix College's school for Green Environmental Chemistry. Before entering Case, Myles was an Environmental Monitoring Specialist with the Division of Air Quality in Cleveland, Ohio. Currently his research is focused on optical materials for photovoltaic systems and lifetime and degradation science.



**Wei-Chun Lin** is currently a Ph.D. graduate student at Case Western Reserve University. His previous working experience focused on surface analysis of organic materials at Academia Sinica in Taiwan. Before entering Case Western Reserve at 2010, he authored three journal articles and co-authored several papers. His current research focuses on optimizing mirror- augmentation photovoltaic modules and extending its reliability and service lifetime.

**Kara A. Shell** is currently a Project Engineer at Replex Plastics. She recently graduated from The Ohio State University with a Bachelor of Science Magna Cum Laude and a Master of Science in Mechanical Engineering. Her work at Replex involves the use of such advanced tools as 3D CAD Modeling, Integrated CAD/CAM programming, Finite Element Analysis, and Optical Ray Tracing. Shell is involved in all aspects of the product design process, from concept to prototype construction to the design and execution of experiments to evaluate prototypes.

**Scott Brown** is a Manufacturing Engineer at Replex with over 20 years in Engineering and Manufacturing specializing in Thermoforming, Metalizing, and Coatings. Brown has been involved in the solar effort at Replex Plastics since February 2009, bringing to bear previous experience in thermoforming, metalizing, and coatings. He is doing work on vacuum applied coatings; concentrator design and manufacturing methods, electrical interconnect design, and material and product durability testing.

**Mark A. Schuetz** is the Founder and President of Replex Plastics. He holds a Bachelor of Science in Mechanical Engineering and Master of Science from the Massachusetts Institute of Technology. Founded in 1991, Replex has become a world leader in the manufacture of convex acrylic mirrors, polycarbonate playground domes, and thermoformed closed circuit TV domes.

**Robert J. Davis** Dr. Robert J. Davis (Director, Ohio State Nanotech West Lab) is interested in advanced semiconductor device materials and processing. He also currently serves as Associate Director of the Ohio State Institute for Materials Research (IMR) and as Co-Director of the Ohio Wright Center for Photovoltaics Innovation and Commercialization (PVIC), an $18.6M effort funded by the Ohio Third Frontier Program to accelerate job creation in PV. His past affiliations include the IBM Watson Research Center, the Pennsylvania State University, and TriQuint Semiconductor of Dallas, TX . He holds a Ph.D. in Applied Physics from Cornell University.

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