SOLAR RADIATION DURABILITY OF MATERIALS, COMPONENTS AND SYSTEMS FOR PHOTOVOLTAICS

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ABSTRACT

In renewable energy technologies, a critical challenge is achieving expected service lifetimes of 20-25 years and beyond. Our approach to the physics of failure is to develop new metrology and metrics, coupled to degradation mechanisms and rates, as the basis for lifetime and degradation science (L&DS). Induced absorbance to dose (IAD), a new metric being developed for solar radiation durability studies of solar and environmentally exposed photovoltaic materials, is defined as the rate of photodarkening or photobleaching of a material as a function of total absorbed solar radiation dose. In a reliability engineering framework, these quantitative degradation rates can be determined at various solar irradiances making possible real time or accelerated testing. The potential to predict power losses in a photovoltaic system over time caused by the accumulation of this kind of degradation can be calculated for real time applications or extrapolated for accelerated exposure conditions. Comparisons of IADs at multiple irradiance levels leads to the acceleration prefactor (k_a) which may be useful for linking and quantifying the degradation mechanisms at play in a given system, and enable accelerated testing of materials, components and systems. Using matrix math and published data, comparisons have been made showing the reduction of solar irradiance incident on the PV absorber for two types of CPV systems; two silicones used in Fresnel lenses, and an acrylic PMMA used for mirror augmented PV systems.

INTRODUCTION

Photovoltaic (PV) systems are required to have long service lifetimes in order to achieve cost parity with non-renewable sources of electricity. As such, materials used in PV must be highly durable to solar radiation. While there are many qualification tests that a PV module must pass before it can be sold, these solely test initial performance and safety. Discussions at the NREL PV reliability workshop in 2011 came to the conclusion that while initial performance and safety qualification are imperative to the growth of solar as an industry, the value proposition of solar energy relies on metrics for lifetime performance, which are severely lacking. [1,2,3,4]

In response, a new field of Lifetime and Degradation Science (L&DS) has been developed which aims to develop new metrics for comparing materials, components, and systems for lifetime durability and performance. [5,6,7]

Reliability engineering is thought to fall into three main statistical regimes: infant mortality, random failures and failure at the end of life. Initial performance qualification testing allows for reasonable confidence intervals when mitigating infant mortality and can be useful in predicting random failures in PV modules, that is failures that occur imminently or randomly after deployment due to process and manufacturing defects. Lifetime performance however requires knowledge of the power degradation rate of a PV system or module, a quantity that is currently only quantified after deployment has already occurred.

Reliability engineering encompasses time to failure analysis and infant mortality and is useful in cases of varying stresses. [8,9] The physics of failure offers a framework whereby the mechanisms of degradation that lead to failure at the end of life help to predict useful life of a system.[9] The physics of failure takes its formulation from statistical quantities such as failure function density, failure rate distribution and leads to the hazard function. Typically failure modes are grouped into constant failure rate modes, linearly increasing failure rate modes, exponentially increasing failure modes, Weibull statistical models (parametric) and Arrhenius, or thermally activated modes.
Using the physics of failure formulation for reliability we have established new metrics for the subfield of PV material radiation durability.

RADIATION DURABILITY METRICS

The metric of Induced Absorbance to Dose (IAD) [10,11] is defined as a spectral material's property given by:

$$Average \; \frac{Abs}{cm} \; per \; \frac{GJ}{m^2} \; Dose \equiv \frac{Abs_f(\lambda)/cm - Abs_i(\lambda)/cm}{Dose_{total}} \quad (1)$$

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

Where λ is the wavelength of evaluation, and dose is given in GJ of AM 1.5 dose to which the sample has been exposed.
Acceleration factors are given by:

$$F = k_a \frac{S_{II}}{S_I} \qquad (3)$$

where S denotes a stress level and k_a is a new metric that is called the Acceleration Prefactor. For the case of irradiance considered here this equation is:

$$F = k_a \frac{I_{II}}{I_I} \qquad (4)$$

Where I is the irradiance measured in kW/m^2. Since IAD is normalized to dose, the acceleration prefactor, k_a can be defined as:

$$k_a(\lambda) = \frac{IAD_{II}(\lambda)}{IAD_I(\lambda)} \qquad (5)$$

Because Absorbance per centimeter (Abs/cm or A) is related by thickness to transmission according to the formula:

$$T = 10^{-At} \qquad (6)$$

Where t is the thickness and transmission is a given as the percent of transmitted flux at a particular wavelength. Subsequently, for a given amount of dose the A varies as:

$$\frac{Abs}{cm}(Dose) \equiv \frac{Abs_i}{cm} + IAD \times Dose_{total} \qquad (7)$$

By integrating the National Renewable Energy Laboratory's (NREL's) solar irradiance spectra from SMARTS [12] with IAD data it is possible to determine the reduction, due to photodarkening, of the solar radiation that could be converted into electricity in a given PV system using the equation:

$$\phi = \int T_\lambda E_\lambda d\lambda \qquad (8)$$

This allows for integration of IAD informed data to systems level analysis of power degradation over lifetime.

EXPOSURES AND METROLOGY

Exposures: Samples of commercially available materials were loaded into a diverging solar simulator with a concentrating lens allowing irradiance levels of up to 50 kW/m^2. Continuous power monitoring was performed in the working plane to ensure accuracy of total dose measurements. Samples were exposed in lab air and temperature was not controlled. The xenon light source was filtered to match AM 1.5 spectral response.

Evaluations: Center Mount Absorbance spectroscopy with an integrating sphere was performed on a Cary 5000 with a DRA 2500 as the primary analytical instrument. This eliminates the transmission effects of scattering. Spectra were corrected grating changes, filter changes and normalized at 600nm.

Assumptions: IAD is assumed to be constant rate failure mode all materials over time. For all results of lifetime performance of a material, total dose per year is taken as 9.3 GJ/m^2. Lifetime performance projections also disregard IAD values past 800nm, as the quality of the data decreases significantly in the infrared. Lifetime performance projections were made to be a first order approximation for a back surface mirror used for Mirror Augmented Photovoltaic Systems with a pathlength of 3mm, and a silicone printed Fresnel lens with an average pathlength of 1mm. It is important to note that it is possible to track changes in the spectrum (incremental IAD) or look at total spectral shift (Average IAD). When projecting forward a constant failure rate model is assumed to apply, and Average IAD is used.

RESULTS AND DISCUSSION

Figure 1 shows the average IAD of a PMMA acrylic after 76.37 GJ/m^2 The IAD curve shows increased absorbance, likely due to breakdown of light stabilizing additives.

Figure 2 shows the average IAD of Silicone 1 at 4 and 50 kW/m^2 respectively and the acceleration prefactor k_a. The spectra show residual darkening that is likely due to the two-part curing of this silicone, but it is apparent that photodarkening products are being formed at the same rate in both samples in the region from 275-350 nm where the acceleration prefactor, k_a is close to 1. It is also possible that because the material at 4 kW/m^2 was in in the solar simulator longer, thermal acceleration plays a factor in accelerating processes outside this range.

Figure 3 shows the Incremental IAD of Silicone-2, with the initial curing of this two-part silicone in evidence. Though there is initially bleaching, IAD appears to become slightly positive and more constant for the last results. If future IAD values correlate closely linearity over dose can be demonstrated.

RESULTS OF PROJECTED LIFETIME PERFORMANCE

Figure 4 shows a linear extrapolation (using a constant rate failure model) of the loss of flux through a 3mm sheet of PMMA over 10 years. The degradation of this Acrylic PMMA would affect the transmitted spectrum, reducing the total light that could be absorbed by the

photovoltaic material.

Figure 5 shows the change in irradiative flux through a 3mm Acrylic PMMA sheet as a function of time. At the end of 30 years, the total flux has decreased by over 40% of its initial value.

Figure 6 shows the change in irradiative flux through a 1mm sheet of Silicone-1 as a function of time. The total transmission through 1mm silicone is reduced by 4% over 30 years.

CONCLUSIONS

Applicability of IAD and Acceleration Prefactor we demonstrated in three materials. Reciprocity is shown for Silicone-1 at 4 and 50 suns between 275 and 350nm. Deviation from a k_a value of 1 may be due to the difference in dose, or the difference in test time, because samples were not irradiated in a controlled environment. Due to the curing chemistry of silicones, the data does not support linearity in Silicone-2, though IAD values come close to parity after the initial exposure to 9.97 GJ/m^2. Induced Absorbance to Dose (IAD) can be applied to systems level analysis for looking at power losses in a PV system. Development of Acceleration Prefactor as a metric may help identify linked degradation pathways. The concept of an Acceleration Prefactor may be applicable to other types of accelerated testing where different mechanisms behave in non-reciprocal ways. A reduction of transmitted flux of 4% over 30 years was predicted in 1mm Silicone-1, and 40% over 30 years for a 3mm Acrylic PMMA.

ACKNOWLEDGEMENTS

REFERENCES

[1] Xiaohong Gu et al. "Linking Accelerated Laboratory Test with Outdoor Performance Results for a Model Epoxy Coating System" Service Life Prediction of Polymeric Materials, Edited by Jonathan W. Martin et al. © Springer Science 2009, New York, NY

[2] C.R. Osterwald, "Terrestrial Photovoltaic Module Accelerated Test-to-Failure Protocol", Technical Report NREL/TP-520-42893 March 2008

[3] John H. Wohlgemuth et al. "Long Term Reliability of Photovoltaic Modules", Photovoltaic Energy Conversion, Conference Record of the 2006 IEEE 4th World Conference, 2006 V.2, 2050 - 2053

[4] Alelie Funcell "The Thresher Test, Crystalline Silicon Terrestrial Photovoltaic Modules Long Term Reliability and Degradation", General Test Requirements and Procedures Based on IEC 61215" http://www1.eere.energy.gov/solar/pdfs/pvmrw2011_csi_thresher.pdf

[5] R. H. French, J. M. Rodríguez-Parada, M. K. Yang, R. A. Derryberry, N. T. Pfeiffenberger, "Optical Properties Of Polymeric Materials For Concentrator Photovoltaic Systems" Sol. Energy Mater. Sol. Cells, (2011),doi:10.1016/j.solmat.2011.02.025.

[6] R. H. French, J. M. Rodriguez-Parada, M. K. Yang, M. F. Lemon, E. C. Romano, P. Boydell, "Materials for Concentrator Photovoltaic Systems: Optical Properties and Solar Radiation Durability", Proceedings of CPV-6: International Conference on Concentrating Photovoltaics, Freiburg, Germany, April 2010.

[7] David C. Miller et al. "Analysis of Transmitted Optical Spectrum Enabling Accelerated Testing of Multijunction Concentrating Photovoltaic Designs", Optical Engineering v.50 i.1 p.13003-01.

[8] McPherson, J.W. "Reliability Physics and Engineering: Time-To-Failure Modeling", ©Springer Science 2010 New York, NY.

[9] Mark White "Microelectronics Reliability: Physics-of-Failure Based Modeling and Lifetime Evaluation", JPL Publication 08-5 2/08, California http://trs-new.jpl.nasa.gov/dspace/bitstream/2014/40791/1/08-05.pdf

[10] R. H. French, J. M. Rodríguez-Parada, M. K. Yang, R. A. Derryberry, M. F. Lemon, M. J. Brown, C. R. Haeger, S. L. Samuels, E. C. Romano, R. E. Richardson, "Optical Properties Of Materials For Concentrator Photovoltaic Systems", Proceedings of 34th IEEE Photovoltaic Specialists Conference (PVSC), Philadelphia, PA June 7–12, 2009.

[11] R. H. French, "Low Concentration Photovoltaics: Reliability and Durability Issues", 2011 PV Module Reliability Workshop, Golden Colorado, Feb. 16-17, 2011.

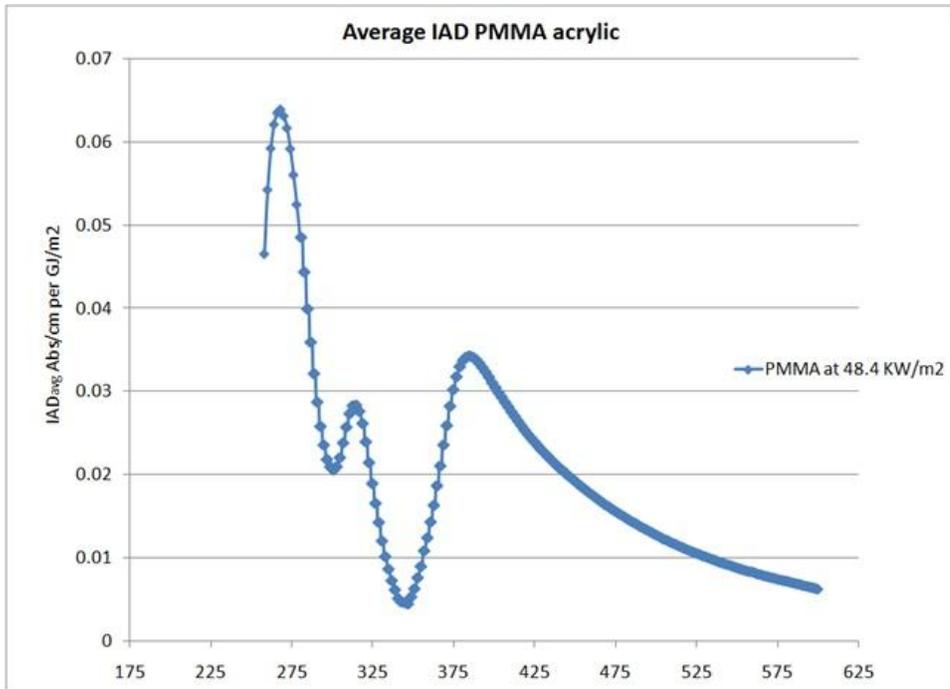[12] ASTM G173-03 Reference Spectra Derived from SMARTSv.2.9.2 http://rredc.nrel.gov/solar/spectra/am1.

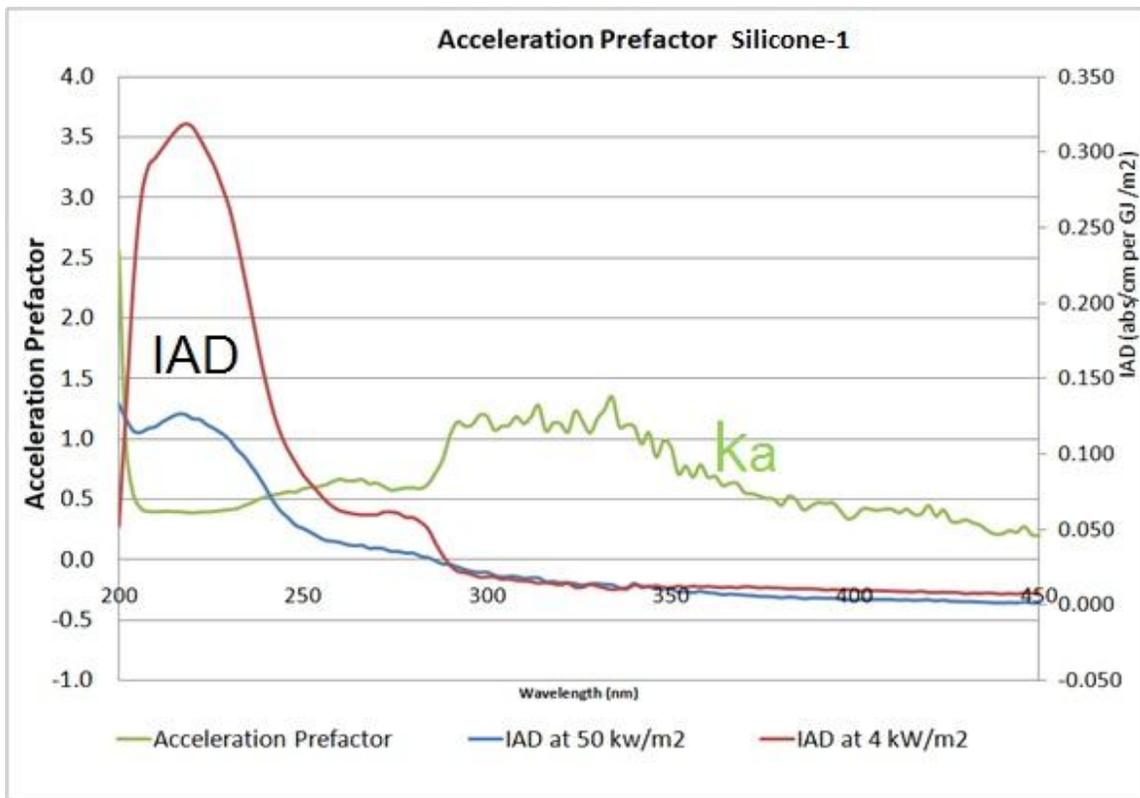**Figure 1: Average IAD of Acrylic PMMA Exposed to 76.37 GJ at 48.4 kW/m².**

Figure 2 Acceleration Prefactor in Silicone-1 exposed to 37.39GJ/m² at 4 kW/m² and 70.62 GJ/m² at 50 kW/m²
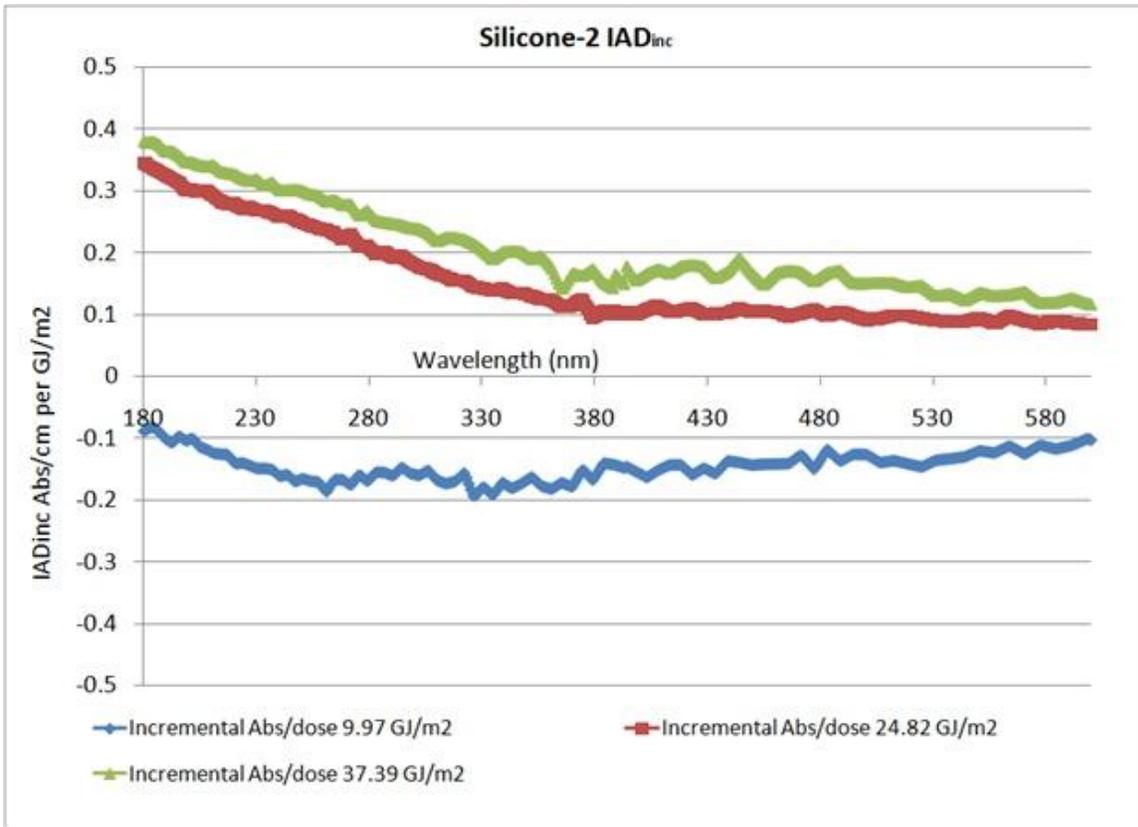
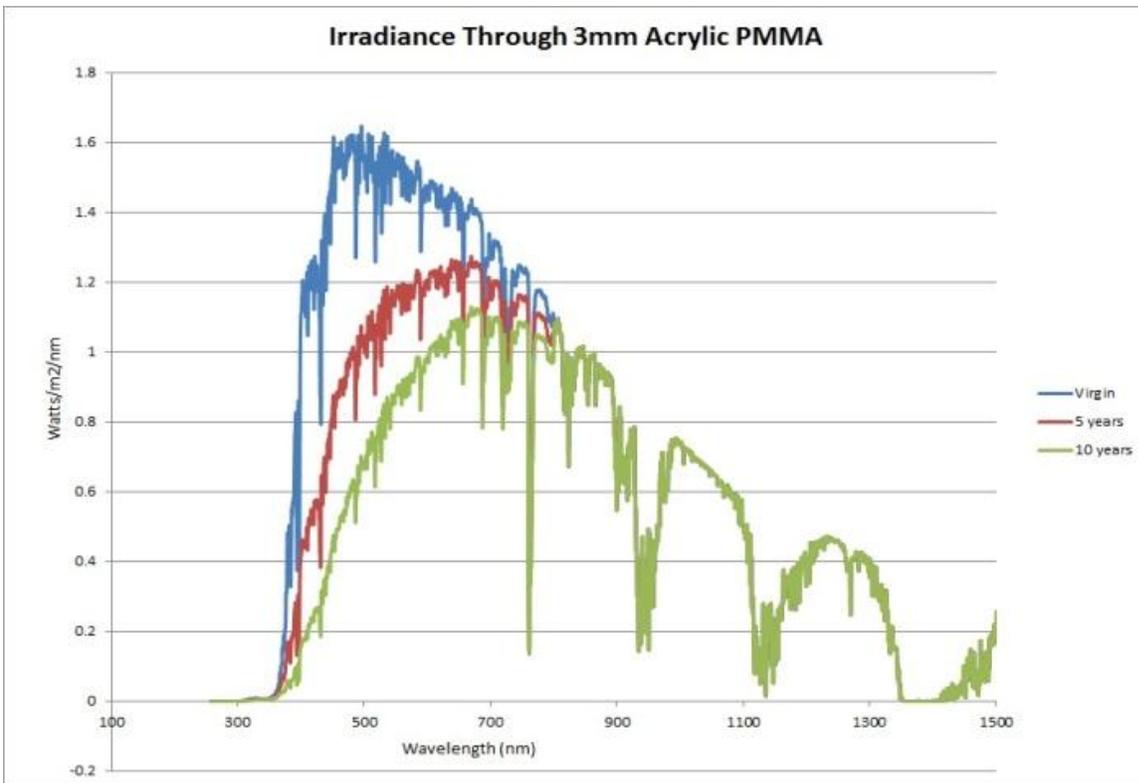**Figure 3. Incremental IAD in Silicone 2 at 4kW/m^2**

Figure 4 Irradiance Through 3mm Acrylic PMMA in virgin state, after five and ten years in direct sun.
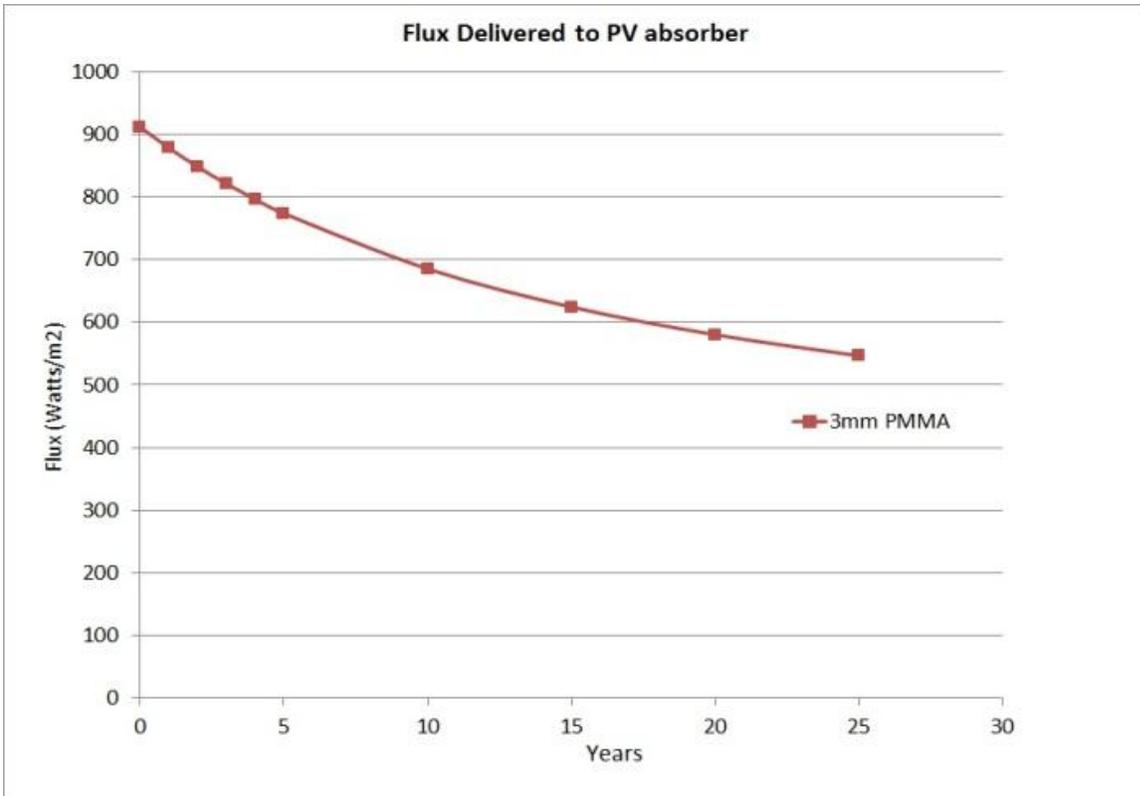
Figure 5 Flux Delivered to PV absorber through 3mm Acrylic PMMA as a function of time.
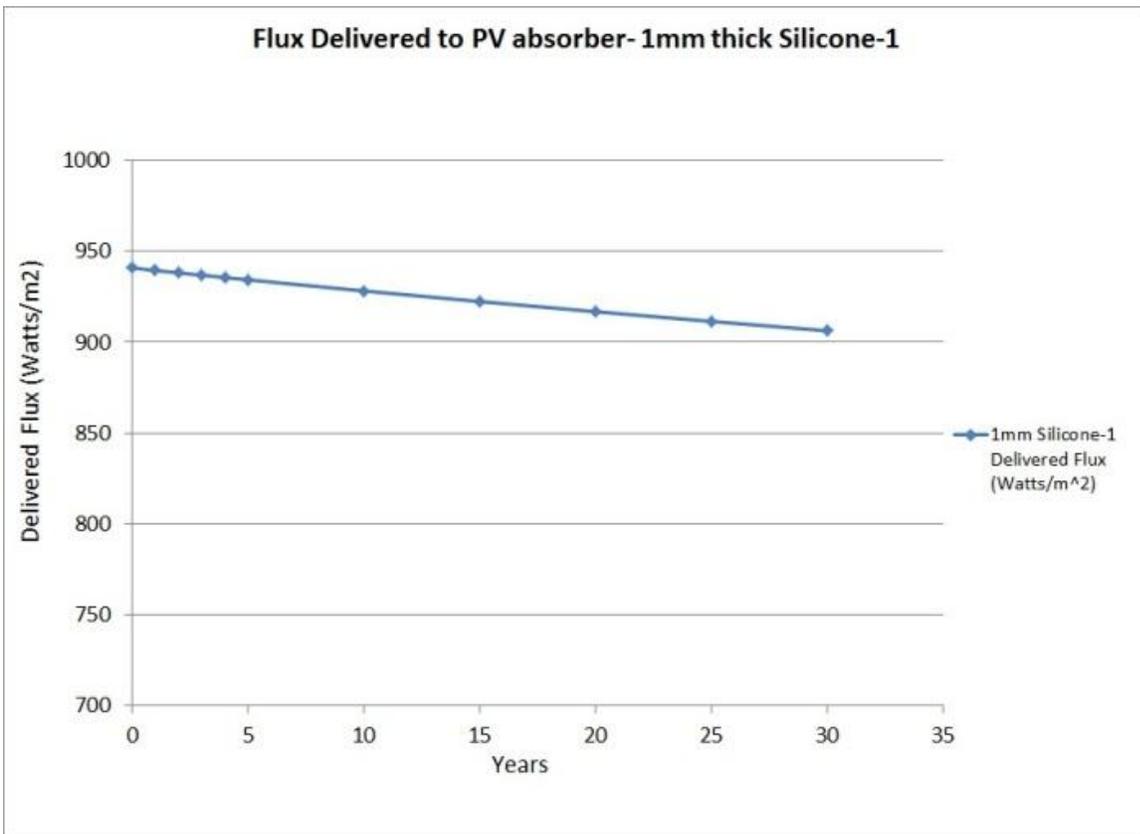

Figure 6 Flux Delivered to PV absorber through 1mm Silicone-1 as a function of time