Choosing a Silicone Encapsulant for Photovoltaic Applications

As presented at the CPV-7 Conference in Las Vegas, NV; April 4-6

Michelle Velderrain

NuSil Technology
1050 Cindy Lane
Carpinteria, CA USA
93013

Abstract. Growth in the solar industry has resulted in newer technologies, specifically concentrator photovoltaic (CPV) modules, to explore using new types of materials such as silicone encapsulants. CPV and LCPV module designs are to achieve the most efficient energy conversion possible however it is equally important to demonstrate long term reliability. Silicone is a material of interest due to its thermal stability and ability to absorb stresses incurred during thermal cycling. The refractive index of clear silicone adhesives is advantageous because it can be optimized using phenyl groups to match BK7 glass and other substrates to minimize light loss at the interfaces but it is relatively unknown how the optical properties change over time possibly yellowing in such a harsh environment. A 1.41 silicone encapsulant is compared to a 1.52 refractive index silicone. Optical Absorption (300nm-1300 nm), Water Vapor Permeability, Moisture Absorption and effects of oxidation at elevated temperatures will be compared of these materials to aid the engineer in choosing a silicone for their CPV application. Non-phenyl containing 1.41 RI silicones have been used for several years for bonding solar arrays in the satellite industry. Phenyl groups on the siloxane polymer can change various properties of the silicone. Understanding how phenyl affects these properties allows the engineer to understand the benefits and risks when using a RI matching silicone to minimize light loss versus a non-phenyl containing silicone.

Keywords: Moisture Permeability, silicone, NuSil, adhesives, sealants, optically clear, refractive index, relative humidity

INTRODUCTION

Designing and producing solar modules is extremely challenging and choosing the right materials is a critical part of the process. Clear silicone encapsulants have a long history of use in harsh environments such as cover glass adhesives for photovoltaic modules on satellites and Light Emitting Diodes (LEDs). Silicone is especially interesting in Concentrator Photovoltaic (CPV) applications since these modules are composed of materials with various coefficients of thermal expansion (CTE) and silicone's low modulus aids in providing stress relief during thermal cycling as well as having excellent optical transparency. This maximizes the amount of photon flux to the cell.

One of the challenges for CPV module designs is many of the polymeric materials being evaluated for module assembly, specifically in the light path, may have *some* long term weathering history, but not specifically under the harsh conditions that the CPV module will be exposed to especially where light is being concentrated 500X to 1000X through a Secondary Optical Element (SOE). Another factor that makes material selection difficult are the changes over time of specific properties, such as optical transmission, and its affect on the systems overall efficiency.

Ideally, the cell encapsulant must remain optically stable over several years to maintain photon flux to the cell. It must also be durable and not delaminate, discolor or crack.. Plus they must be adaptable to automated processing. The long term performance of silicones can vary based on design aspects such as the material composition of the optical elements, light concentration and thermal management.

Using refractive, index matching, clear silicone adhesives between the cell and the SOE can have some advantages by minimizing light loss at the interfaces. The refractive index of silicone encapsulants can be increased using phenyl groups; however, questions regarding the long term UV resistance of phenyl containing silicones is of concern. It is relatively unknown how changes due to thermo-optic discoloration (yellowing) over time in harsh environments created from 500X to 1000X light concentration will affect module efficiency. This paper will present some of the benefits and risks associated with using phenyl containing silicones versus non-phenyl containing silicones.

CHARACTERISTICS OF SILICONE FOR CPV ENCAPSULANTS

Refractive Index Matching Encapsulant

A common technique when designing optical components is using the refractive index (RI) of the materials to control the light path. One method is using encapsulants/adhesives that have the same RI of the optical elements. This will reduce light loss at the substrate interfaces and requires knowledge of the refractive index of the adjoining optical materials. This information is generally reported at the sodium D line (nD 589 nm). See Table 1.

TABLE 1. Refractive Indices of Common Optical Element Materials at 589 nm (nD)

Material Type	Common Names	nD
Fused Silicates	Glass, Quartz	1.46
Barium Silicates	Crown Glass, BK7	1.52
Polycarbonate	PC	1.59
Poly (methyl methacrylate)	PMMA, Acrylic Glass	1.49

Another important property of the optical material used in the light path is the optical cutoff. Materials that are transparent at lower wavelengths will expose the silicone to more damaging UV wavelengths. For example, Barium silicate Crown Glass (a.k.a. BK7) typically has an optical cutoff at 350 nm, where some fused silicates can have cutoff values as low as 190 nm.

Modifying Silicone Polymer for Refractive Index

Silicone solar cell encapsulants and adhesives are composed mainly of linear silicone polymers (> 70% w/w) that are crosslinked into cured elastomers (20A to 80A durometer) or gels (< 20 A durometer and soft with minimal elastic memory). Silicone polymers can be modified in 3 general ways: varying the organic groups on the backbone, polymer chain length and the end cap (also referred to as end blocker or chain terminator).

Polydimethylsiloxane (PDMS) has been used for over 50 years in a variety of applications ranging from space to medical devices[1]. PDMS based chemistry is characterized by a nD of 1.40 and has historically been the preferred choice for use as solar cell cover glass adhesives for satellite applications due to its known optical stability when exposed to high temperatures and UV light over extended periods of time (>1 year)[2].

Phenyl (Ph) containing silicones have been used in LEDs, specifically High Power LEDs that use blue light to create white light from phosphors dispersed into the silicone[3]. They have also been used as optical coupling materials for several years and range in refractive indices from 1.42-1.57. Phenyl silicones have other unique properties for applications that are not in optical path such as lowering the Tg so that the silicone remains flexible at -115 C, increase chemical resistance and operating life in thermally harsh environments. Figure 1. shows a generic representation of a dimethyl-diphenyl copolymer with vinyl chain terminators used for addition cure systems (A) compared to PDMS (B).

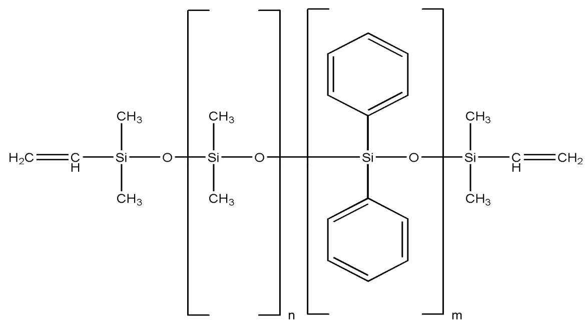

FIGURE 1A. Vinyl terminated polydiphenyldimethylsiloxane

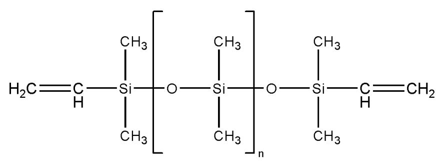

FIGURE 1B. Vinyl terminated polydimethylsiloxane

Protection from Environment

Both PDMS and phenyl containing silicones are electrically insulating where the dielectric strength is typically > 500 V/mil (20 kV/mm) and volume resistivity values are > 10^{12} Ω•cm.

Silicones are also generally hydrophobic and are known for their permeability to water vapor, oxygen, nitrogen, and other low molecular weight gasses. Water absorption values range from 0.02 – 0.20 (85˚C/85% RH/168 hours). Figure 2. shows the affect phenyl has in lowering the Water Vapor Transmission Rate (WVTR). The 1.57 RI silicone gel has an almost

85% lower WVTR than the PDMS gel tested when in the same conditions.

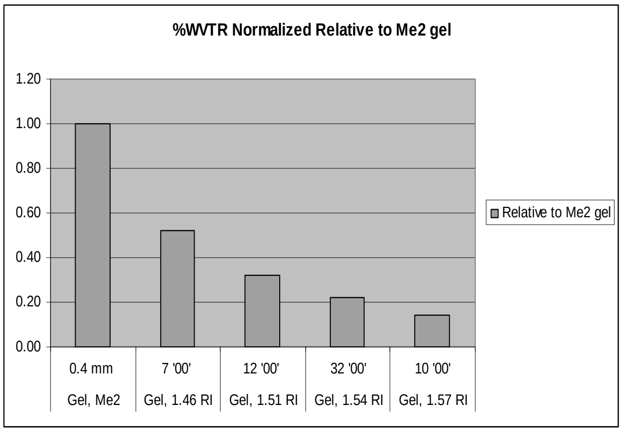

FIGURE 2 Water Vapor Transmission Rate 40°C/90% RH/ 2mm Sample Thickness

Optical Properties

PDMS and phenyl containing polymers are known to be optically clear in the visible region and near IR (Figure 3.)

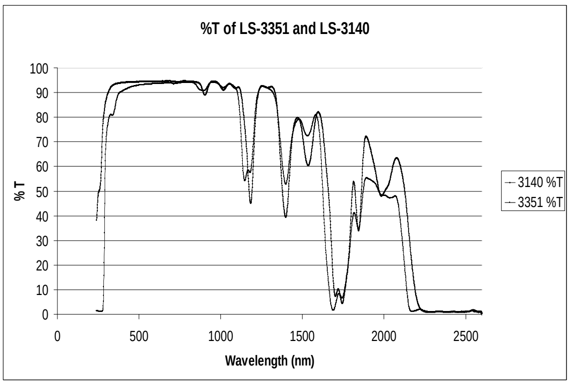

FIGURE 3. %Transmittance (%T) of 1.41, 1.51 Refractive Index gel. 1 cm thickness, quartz cuvette from 240 nm – 2600 nm

Phenyl containing silicones can absorb in UV wavelengths but are essentially transparent in the regions 300nm-850nm. For example, at 289nm a 1.51 RI silicone may have ~ 16% T compared to a 1.40 RI non-phenyl containing silicone having ~ 80% T. However, at 365 nm they both have >80% T.

Thermo-Optic Performance

There is currently no standardized material level test designed to perform accelerated aging tests under UV and heat exposure, as well as no set failure criteria specific to CPV. The failure criteria should be based on industry standards that apply to the module performance, such as stated system efficiency per IEC 62108. The data presented below follows a test that was performed by NuSil Technology for relative comparison only and is not to be considered an industry standard[4].

%T was measured over time on silicones with no phenyl (PDMS at 1.40 RI) and one with the maximum amount of phenyl commercially available (1.57 RI). After they were exposed to; a) dry heat (150ºC) and b) exposing the materials to a Dymax UV Flood light.

All samples were placed 6 inches from the bulb. Radiation exposure is 190mW/cm^2 and 680 J/cm^2 total radiation. The temperature in the chamber ranged from 75-90°C. An EIT UV Power Puck was used to confirm UV intensity

TABLE 2. Spectral Bands in Dymax UV Flood Light

Spectral Bands	% Radiation	mW/cm^2
Visible (400-750 nm)	49	93
UVA (320-400nm)	34	64
UVB (280 – 320nm)	17	32
UVC (< 280nm)	0	0

%T of PDMS (1.40) after Dry Heat and UV Exposure

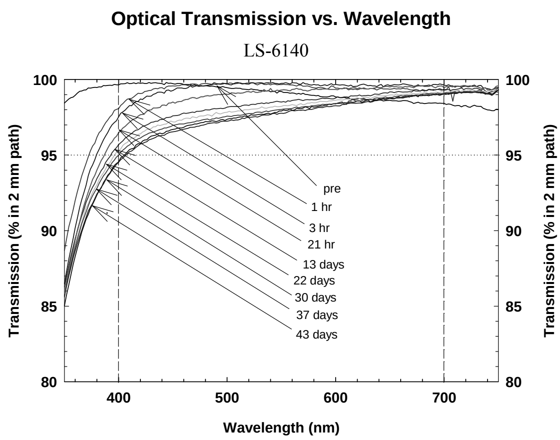

FIGURE 4. PDMS Elastomer after Exposure to Dry Heat (150˚C)

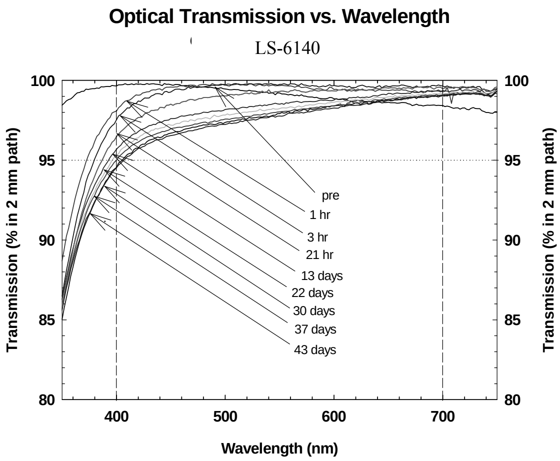

FIGURE 5. PDMS Elastomer after Exposure to UV

%T of Phenyl Silicone (1.57) after Dry Heat and UV Exposure

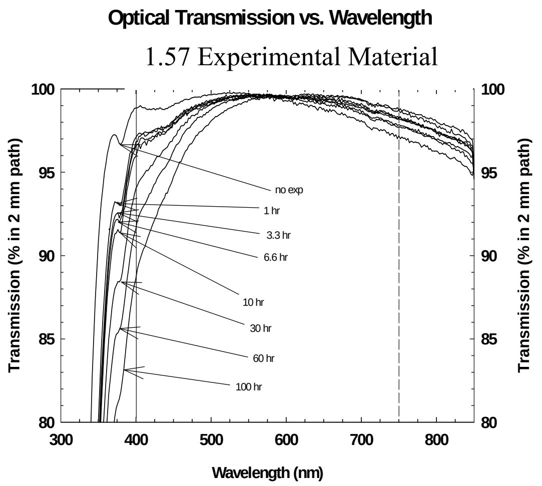

FIGURE 6. Phenyl Elastomer (1.57) Elastomer after Exposure to UV

Other factors also affected the optical performance of the silicone over time, such as heat and oxygen. Figure 6. shows the effects of oxygen on the rate of discoloration when exposed to 150˚C.

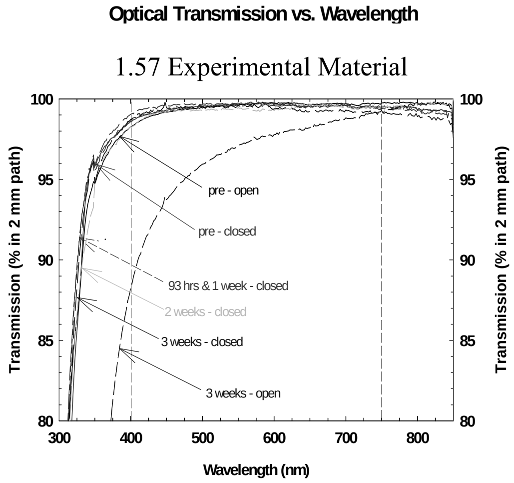

FIGURE 7. Phenyl Elastomer (1.57) after Exposure to Dry Heat (150˚C)

RESULTS

The % T of the phenyl containing silicones decreased in the visible region of the spectrum more so than the dimethyl silicone tested in the same UV conditions. These results correspond with industry concerns of phenyl containing silicones "yellowing" under UV exposure. However, the high phenyl containing silicones were exposed to UVB which is known to absorb at these wavelengths. The phenyl containing silicones also showed relatively stable %T when exposed to 150˚C after 3 weeks however when exposed to air, the %T greatly decreased in the visible region.

CONCLUSION

Phenyl containing materials may help with increasing the photon flux to the cell but their overall long term performance will be dependent on many factors where the design is the most critical. These include the material the SOE is composed of, exposure of the encapsulant to air, dirt, debris plus thermal management since chemical reactions will be accelerated with heat.

Regardless of the material selected, it is highly recommended to design and implement a reliability test that best mimics the module design and test conditions that are critical to long term silicone performance. These accelerated aging tests will help to ensure the encapsulant or adhesive gives the required performance.

With the right material selection reliability and durability can be achieved.

ACKNOWLEDGMENTS

The author would like to thank Robert Kivlin, Joan Meyer, Randall Elgin, Lori Tovias, Mustafa Al-Azzam and Aaron Lewis for their tireless efforts in testing and discussion on the results.

REFERENCES

1. W. Noll, "Chemistry and Technology of Silicones" Academic Press, New York, 1968
2. H.D. Burns, A.F. Whitaker and R.C. Linton, "Atomic Oxygen Resistant Protective Coatings for the Hubble Space Telescope Solar Array in Low Earth Orbit" in *Surface and Coatings Technology,* 39/40 (1989) 627-636.
3. J.A. Carey, W.D. Collins III and J.L. Posselt, U.S. Patent No. 6,590,235 (8 July 2003).
4. B. Riegler, R. Elgin and R. Thomaier, "A Characterization of UV Effects on Optical Silicones used in Opto-electronic Devices and New Developments in Resistant Materials", presented at SPIE Photonics West, San Jose CA, U.S.A., 23-25 January 2007,