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Abstract. Using concentrated natural sunlight at the NREL High Flux Solar Furnace, we have exposed several materials to acceleration factors of up to 400 times the normal outdoor UV exposure dose. This accelerated rate allows the exposure of materials such that a year of outdoor exposure can be simulated in about 5 hours. We have studied the solarization of cerium containing glass, the degradation of ethylene vinyl acetate laminated between borosilicate glass, and the yellowing of standard polystyrene test coupons. The first two candidates are of interest to the photovoltaics (PV) program, and the last candidate material is a widely used dosimeter for ultra violet (UV) exposure in accelerated weathering chambers.

INTRODUCTION

A major impediment to the introduction of energy efficiency and renewable energy (EERE) multilayered devices into the marketplace is the inability to predict the service lifetimes of components in a reliable way. This has been widely recognized, but comparatively little effort has been directed toward understanding the materials science stability issues for making service lifetime predictions from accelerated testing. More than 98% of the effort in EERE multilayered devices has been to develop components with increased efficiencies of conversion, typically measured in an unaged state (1-3). This is appropriate for the early stage of technology development, but in the advanced stages, accelerated testing and lifetime prediction become crucially important issues for estimating life-cycle costs for various EERE systems. Other industries (notably electronics, medical, aeronautical, and nuclear) have abandoned their dependence on long-term, in-service tests in favor of short-term (accelerated) laboratory tests coupled with a service life prediction methodology. It will be necessary to follow similar pathways as EERE components and markets mature. To spur the commercialization of renewable energy devices, such as photovoltaic modules, a critical need exists to be able to accurately predict their service lifetimes (4). One approach to this problem has been to try to correlate real-world test results with accelerated lifetime test (ALT) results. ALT usually makes use of laboratory-controlled, elevated light intensity levels from artificial light sources (typically weatherometers (WOMs), QUV chambers, and solar simulators, with a variety of different light sources). A fundamental complication of this approach arises from the spectral differences between natural sunlight and the artificial light sources used in accelerated test chambers. Because of this, various devices have been developed to provide concentrated natural sunlight for exposure durability test

purposes. The most successful concept, which uses Fresnel reflector elements, allows terrestrial sunlight acceleration factors of 5-6X (5).

If sample temperatures can be adequately controlled and reciprocity relationships (i.e., the level of acceleration does not change the failure/degradation modes) can be demonstrated, acceleration factors of up to 500X (total UV dose) may be achieved at the NREL High Flux Solar Furnace (HFSF). This would permit a year's worth of representative weathering (in terms of natural sunlight exposure) to be accumulated in just a few hours.

EXPERIMENTAL

We chose three material systems to expose in the HFSF to explore the relationship between acceleration factors of 100 or more to real-time testing at one sun (outdoor exposure), and testing at acceleration factors less than 10 in our commercial weathering chambers. These are polystyrene coupons, ethylene vinyl acetate (EVA)/borosilicate glass laminates (A9918 EVA, standard cure), and cerium containing glass. A view of the NREL HFSF is shown in Figure 1, depicting the heliostat, the concentration bank of mirror facets, and the laboratory test facility (6). In operation, direct-normal solar radiation is reflected from the heliostat and directed onto the bank of focusing mirrors that then focus the radiation into the test bay. In all of our experiments, all facets were aimed at the same point, where the target was placed. The concentration of the radiation could be varied up to 2500, which corresponds to a flux of 250 W/cm^2 when the direct normal radiation from the sun is 1 kW/m^2 . The concentration factor can be easily controlled by either changing the number of secondary reflector facets exposed to the primary solar beam or by using attenuation devices within the sample bay. In the experiments reported here, fluxes in the range of 10 W/cm^2 to 200 W/cm^2 were used. With proper thermal management techniques, accelerated testing of samples can be rapidly accomplished with this concentrated natural sunlight.



FIGURE 1. The High Flux Solar Furnace

The possibility of contamination of the spectrum by unrealistic high-energy photons, such as seen with many artificial light sources, is thus completely eliminated in the accelerated testing of materials at the HFSF.

The overall spectral quality of the concentrated light obtained with the HFSF is still an important consideration for accurate accelerated testing of materials. Many target materials are degraded primarily by the solar radiation in the ultraviolet range. Longer wavelength radiation usually does not participate in photolytic processes, but contributes to thermal loading of the target material. Spectral radiometry of the solar beam, heliostat, and concentrator facets indicates that even with first surface aluminum reflectors, a significant portion of the available solar UV spectrum under 400 nm is attenuated by the HFSF optics. The attenuation factor resulting from the two reflections at 350 nm is 2.5 (350 nm is in the middle of the UV region thought to be responsible for the changes in optical properties observed in these experiments). Therefore, when we measured a flux of 200 W/cm² with calorimeters, the radiation at 350 nm had been concentrated by a factor of only 800, instead of the nominal 2000.

Atmospheric scattering is an additional consideration in comparing the reciprocity between real-time testing and the highly accelerated testing at the HFSF. Rayleigh scattering in the atmosphere results in higher levels of UV radiation in global radiation than in the direct-normal radiation. Below 400 nm, there is twice as much global radiation measured on a sun-facing 37° tilted surface, as is measured in the direct normal-beam (7). When this factor is combined with the reduction in the UV caused by the two reflections in the solar furnace, we would expect that a 200 W/cm² beam would result in an acceleration of the photolytic degradation that is about 400 times faster than would be observed outdoors on a tilted plate. Some samples were also exposed in an Atlas weatherometer at about one sun using a filtered Xenon-arc light source at 60°C and 80% RH. All samples were optically characterized with a Perkin-Elmer UV/VIS/NIR Lambda-9 spectrophotometer before and after exposure. In the test chamber used to expose samples to concentrated light at the HFSF the sample is mounted behind a fused-quartz window. The chamber is equipped with a deionized water cooling loop to maintain a constant sample temperature during exposures.

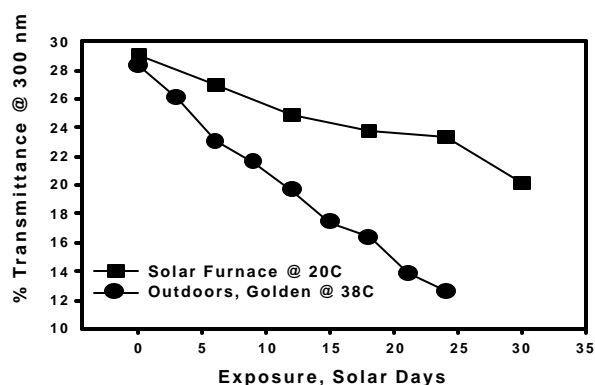


FIGURE 2. Optical changes of polystyrene coupons in the HFSF compared with outdoor exposure.

Samples are mounted between small stainless steel posts near the front of the chamber adjacent to the window.

RESULTS

The changes in the optical properties of polystyrene samples exposed to concentrated solar radiation are compared with samples weathered outdoors in Figure 2. These polystyrene reference coupons absorb in the UV/blue portion of the spectrum as a function of UV dose (8). The rate of degradation or weathering can thus easily be determined by the measured percent transmittance of the sample at 300 nm. The difference in degradation rates seen in these two samples most likely results from the difference in the temperature at which the samples were exposed. In the HFSF, the samples were exposed at 20°C, while outdoor-exposed samples were typically at about 38°C during the day.

To determine the reciprocity relationship, that is, if different intensities of solar radiation degraded samples at different rates, samples of polystyrene were exposed at different flux levels at the HFSF (Figure 3). The samples were exposed to equivalent photon doses at flux levels of 100, 500, and 1000 times one sun intensity. Note that the equivalent UV doses are 20, 100, and 200 times the global level on a tilted plate outdoors. After each 10 solar day exposure, the samples were removed from test and their absorbance spectra were measured. The data indicate that the degradation rate of the polymer is constant over the solar flux range studied. At the lowest flux level of 100 suns, the data for 10 solar days exposure can be accumulated in less than 4 minutes of beam time at the HFSF.

In Figure 4, the exposure of a sample of cerium containing glass to the equivalent of 6 years outdoors is shown. The sample was incrementally exposed at a flux of 2000 suns of concentrated sunlight. The exposure results in rapid solarization of the glass as Ce^{+3} in the glass is converted to Ce^{+4} by the UV in the concentrated radiation (6,9). After the initial solarization, the glass is stable to further solar induced changes in

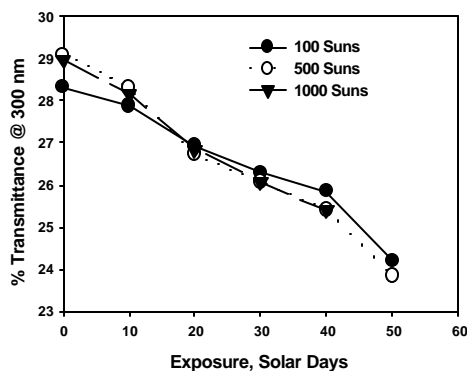


FIGURE 3. Polystyrene reference coupons exposed at different intensities at the HFSF.

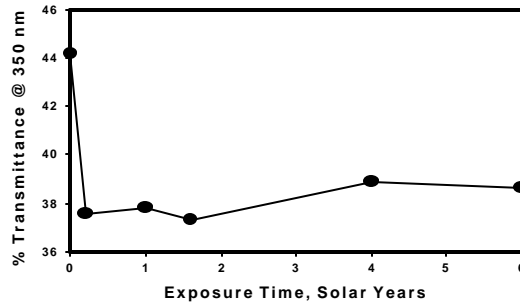


FIGURE 4. Cerium containing glass exposed to 6 years of equivalent photon dose at the HFSF.

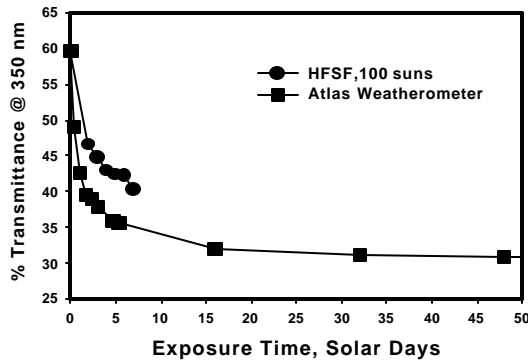


FIGURE 5. Cerium containing glass weathered in the HFSF and WOM.

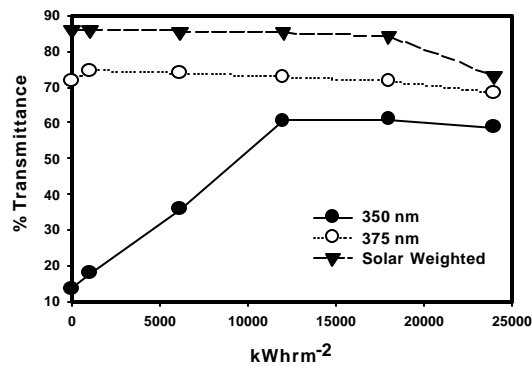


FIGURE 6. Transmittance changes of an EVA/glass laminate as a function of exposure at the HFSF.

transmission for many years. The total beam time required to simulate 6 years outdoors is only about 30 hours, which can be accomplished at the HFSF in about 1 week, under clear sky conditions.

In Figure 5, a comparison of the effect of an Atlas WOM and concentrated sunlight on the transmittance at 350 nm of cerium containing glass is shown. The exposure time in the WOM has been normalized to solar days to account for differences in the radiation intensity below 400 nm. The solarization of cerium containing glass is rapid, with the process being complete in only a few days of exposure. From the data one may also conclude that the solarization rates are slightly different in the WOM, perhaps resulting from differences in the spectral content.

The results of the accelerated exposure testing of a sample of EVA laminated between borosilicate glass plates is shown in Figure 6. After each solar exposure, the distinct odor of acetic acid was detected, indicating that the exposure to the concentrated sunlight results in the degradation of the EVA (10,11). The initial increase in transmittance of the laminate structure at 350 nm after exposure most likely results from the photon-induced degradation of UV stabilizers present in the EVA (10,11,12).

CONCLUSIONS

We have demonstrated that with careful calibration of the HFSF flux and beam spectral distribution, we can expect to provide realistic acceleration factors hundreds (up to about 400) of times faster for some materials than possible with conventional light sources. We found that temperature as well as flux can be a major consideration in the accelerated testing of some materials in the HFSF, and we demonstrated that a reciprocity exists between HFSF exposures of 100, 500, and 1000 suns for SAE standard polystyrene reference coupons.

We have also shown that cerium containing glass undergoes a rapid 20%-30% decrease in transmittance at 350 nm after a photon dose equivalent to just 5 days outdoor exposure. It then remains stable for photon doses equivalent to 6 years outdoors. The 6-year equivalent photon dose can be accumulated in just 30 hours of actual HFSF beam time. Thus, it is possible to do ultra accelerated testing of transparent PV module components and a variety of materials at the HFSF using concentrated natural sunlight.

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