Effect of Intensity and Wavelength of Spectral UV Light on Discoloration of Laminated Glass/EVA/PPE PV Module
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Introduction
Discoloration, one of major failure modes of PV modules, could result in lower efficiency of power output and cause concerns for long-term durability. Studies have indicated that ultra-violet (UV) irradiation is a predominant environmental factor for yellowing occurred in PV modules. However, the quantitative effects of light intensity and wavelength on the discoloration of modules are still unclear.

This work aims to establish a quantitative relationship between the spectral UV irradiance/wavelength and the discoloration of a laminated Glass/EVA/PPE system during UV exposure at elevated temperature. The yellowing mechanism of the model system has been investigated, and the validation of the reciprocity law has been carried out. The dependence of yellowing on wavelength (i.e., action spectrum) has also been established. This study provides foundations for developing accelerated laboratory testing and mathematical models for service life prediction.

Experiments
Sample Construction
Laminated test
Glass (~3 mm)
EVA (0.5 mm)
Glass/EVA A/PPE Backsheet

Laminate
Large samples to avoid the edge effect on yellowing rate.

Exposure conditions
NIST 2-meter SPHERE®
UV exposure direction
UV irradiance
Variable UV irr: (606 ± 14) μWcm⁻²
Extraction fixtures
Filter holder
Laminates
Sample
Fiber holder
Filters in filter holder
Neutral Density Filter
Bandpass Filter

Stability of Filters and Spectral Distribution
Neutral Density Filter
Bandpass Filter
Both neutral density filters and bandpass filters are stable during UV exposure at 85°C/Dry on the SPHERE.

Effect of UV Light Intensity (Reciprocity study)

Digital Photos
Visual yellowing of regions under 306 nm, 326 nm and 354 nm UV was observed.

UV-Visible Spectra
The exposure regions gradually became yellow, while yellowing areas basically kept constant.

Evolution in Yellowing Index (YI)
A higher light intensity led to a faster yellowing growth.
A quasi-linear relationship was observed for the YI-aging time plot.
The YI-aging plots for different light intensities superimposed in a master curve.

Validation of Reciprocity Law
Schwarzschild Law: \( \frac{dI}{dI} = \text{constant} \) or \( k = \text{constant} \)
When Schwarzschild coefficient \( k \rightarrow 1 \), Schwarzschild Law reduced to Reciprocity Law.

For YI growth
Validation of Reciprocity Law
It appeared that the needed dosage at specific damage was independent of intensity and a value was done to be 1.
It was also found that growth of YI followed the same mechanism with different light intensity, as YI-aging time curves could be superimposed to a master curve based on scaling factors.
Reciprocity Law appeared to be obeyed.

Possible Mechanisms for UVA Loss and Yellowing

Stability and spectral distribution
Neutral density filters and bandpass filters are stable during UV exposure at 85°C/Dry on the SPHERE.

Effect of UV Wavelength

UV vs. Dosage
Shorter wavelength led to a higher YI.
YI increased linearly under 306, 326 and 354 nm, while under 452 nm it slowed down at late stage.

Action Spectrum for YI
Efficiency was measured based on yellowing per dosage.

UVNA Loss vs. Dosage
Both UVA loss and yellowing growth increased with exposure time under wavelengths of 306, 326 and 354 nm.
The growth of yellowing under 452 nm slowed down at late stage, possibly due to competition between yellowing and photochemicals.

Action Spectrum for UVA Loss

Correlation between YI growth and UVA loss

Reciprocity study
A nearly linear relationship was found between YI and the loss of UV absorbers for the Glass/EVA/PPE system after UV exposure under 306, 326 and 354 nm, but not 452 nm.
Visible light and oxygen both contribute to the photo-oxidation process under 452 nm.

Possible Mechanisms for UVA Loss and Yellowing

Summary
- Quantitative relationships between light intensity/wavelength and yellowing of Glass/EVA/PPE system have been established.
- The degradation rates for the growth of YI and the loss of UV absorbers are found to be proportional to the UV irradiance. Reciprocity law appears to be obeyed both for the growth of YI and the loss of UV absorbers in the studied UV irradiance range.
- Wavelength effect is clearly seen for growth of YI and the loss of UV absorbers. The action spectrum in exponential expression is also obtained for these changes. Photochemical effect is observed at longer wavelength under 452 nm.
- The yellowing of the glass/EVA/PPE system can be resulting from degradation of encapsulant or/and backsheet. It is found that the growth of yellowing correlates well with the loss of UV absorbers.