Literature Review of the Effects of UV Exposure on PV Modules

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Abstract !

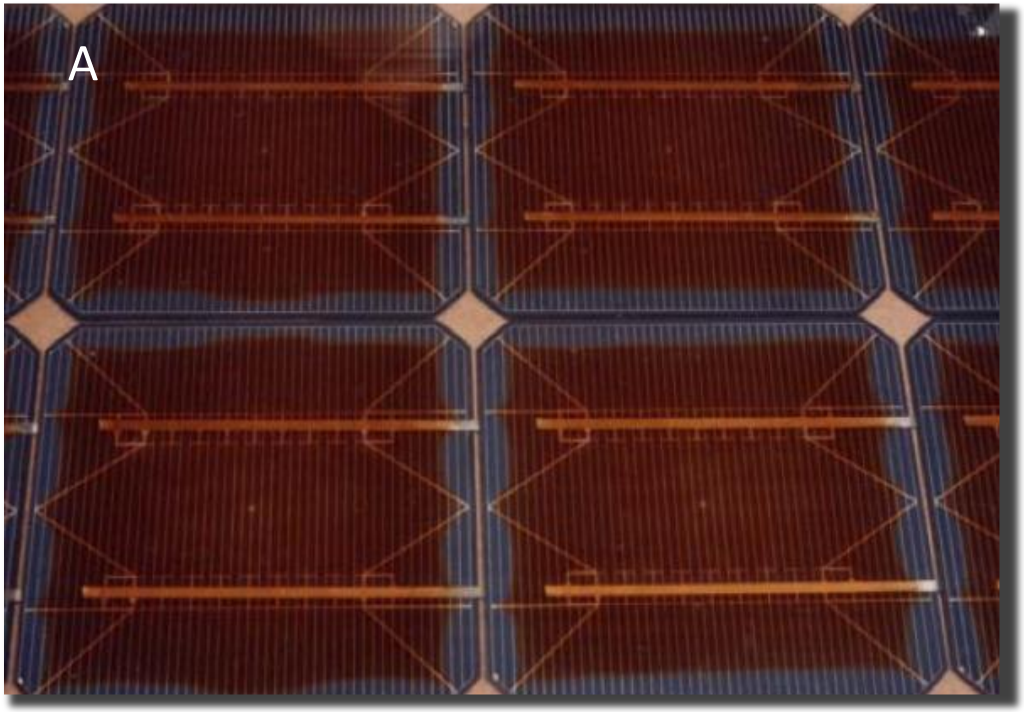
- Understanding the factors affecting the outdoor degradation and eventual failure of PV modules is crucial to the success of the PV industry. A significant factor responsible for PV module degradation is exposure to the UV component of solar radiation.
- We present here a literature review of the effects of prolonged UV exposure of PV modules, with a particular emphasis on UV exposure testing using artificial light sources, including fluorescent, Xenon, and metal halide lamps.
- We review known degradation mechanisms which have been shown to arise from UV exposure of PV modules, and examine the dependence of those degradation mechanisms on UV exposure.

UV Exposure and IEC Preconditioning Tests !

- The PV module qualification tests (*e.g.*, IEC 61215 [1] and IEC 61646 [2]) are not meant to simulate outdoor UV exposure for extended periods of time.
- The "UV Preconditioning" sections of the IEC standards mentioned above typically require 15 kWh/m^2 of total UVA+UVB exposure (280 nm - 400 nm), and at least 5 kWh/m^2 of UVB exposure (280 nm – 320 nm). The IEC standards require that the UV light source used emit light with a UVB content between 3% and 10%.
- The standard AM 1.5 spectrum [3] contains 46.1 W/m^2 between 280 nm and 400 nm, and 1.52 W/m^2 between 280 nm and 320 nm.
  - ~5% of the AM 1.5 Spectrum is UVA+UVB, and ~0.15% is UVB.
  - **15 kWh/m^2 (between 280 nm and 400 nm) corresponds to 13.5 days under the AM 1.5 spectrum.**
  - **5 kWh/m^2 (between 280 nm and 400 nm) corresponds to 137 days (~4.5 months) under the AM 1.5 spectrum**
- Annual total UV exposure in the Negev Desert is on the order of 120 kWh/m^2 [4]. 25 years of outdoor exposure in this environment is equivalent to approximately 3000 kWh/m^2.
  - The proscribed total UV dose in the IEC preconditioning tests of **15 kWh/m^2 simulates 2-4 months (conservatively) of real world operation** [5].
- **IEC UV Preconditioning tests provide no information on module lifetime.**

Encapsulant Issues !

EVA Browning !

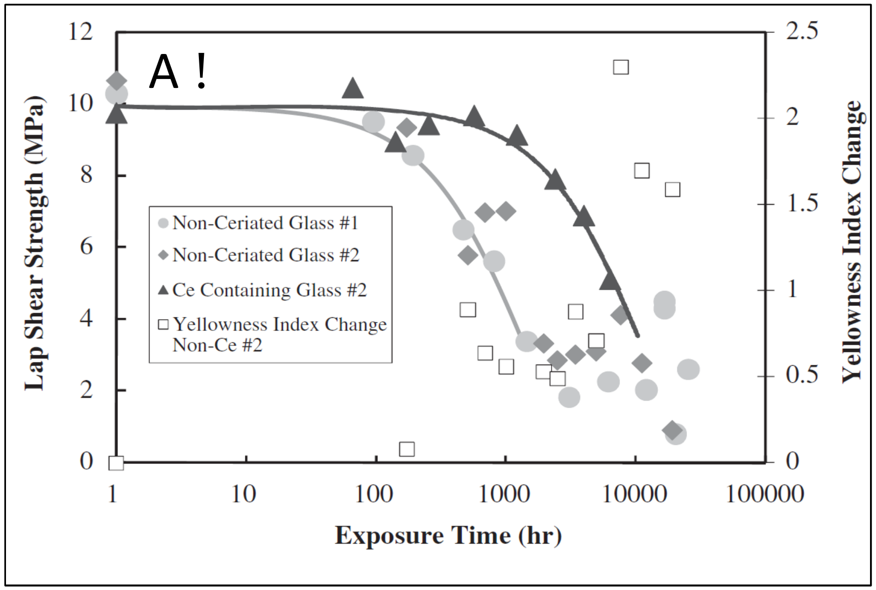


- The browning of EVA ! encapsulant used in PV modules with outdoor exposure has been observed ! since at least the late 1980s at the Carrisa Planes PV installation [6]–[9]. !
- Later observations and studies appeared in the mid-1990s [10], [11], although at this time the agent responsible for EVA browning had not been identified. It is interesting that even in 1994 the authors of Ref. [10] noted that Cerium Oxide-containing glass (which blocks UV radiation below 350 nm) prevented EVA discoloration in indoor tests.

Figure A taken from Ref. [8].

EVA Browning !

- Formulations of EVA that undergo yellowing/browning has also been shown to produce acetic acid, with UV exposure which corrodes solder bonds and electrical contacts [12]–[14]. This also corresponds to increased leakage current through the encapsulant [15].
- EVA adhesion and shear strength also studied, both shown to decrease significantly with EVA degradation [12], [16];
- By 1996-1997 it had been found that that EVA discoloration could be mediated through different EVA formulations (*i.e.*, the use of different additives), and by UV blocking glass [6], [13], [16]–[18].



Lap Shear Strength and Yellowness Index of EVA after exposure to 60 °C/60% Relative Humiditiy, and 2.5 UV Suns. !

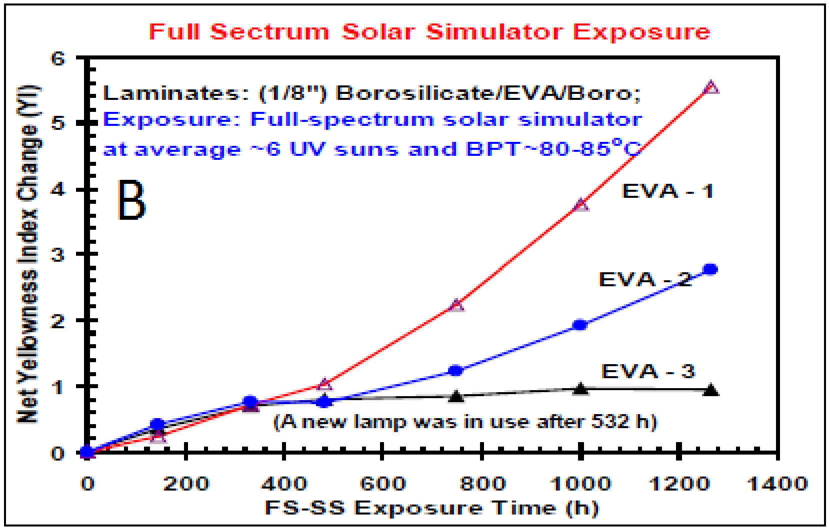
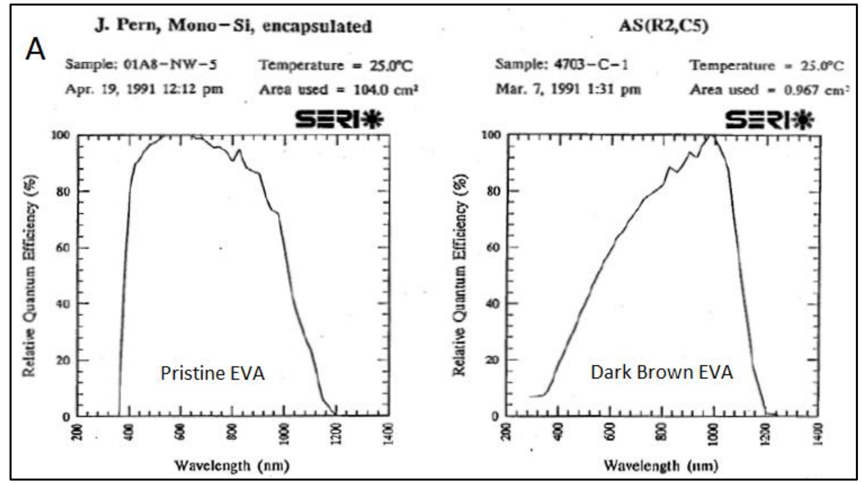
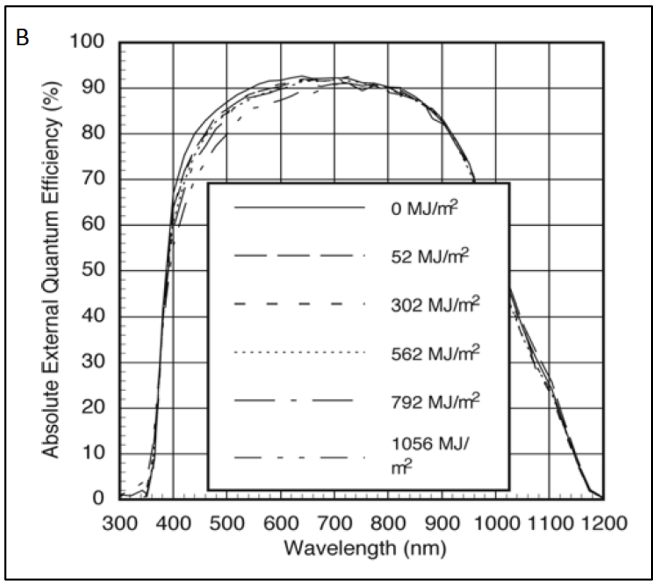


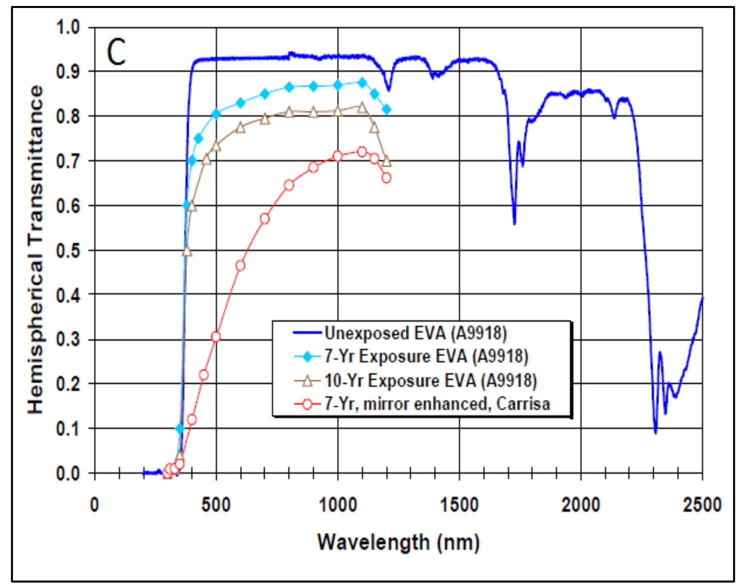
Fig. A taken from Ref [16]. *Fig. B taken from Ref. [8].*

Optical Losses due to EVA Browning

- Browning of EVA can cause a significant change in the perceived optical transmission of c-Si cells [8], [19], [20].
- Performance Losses initially attributed optical losses at the from EVA browning at the Carrisa Planes Site have later attributed to Fill Factor Losses due to solder-bond degradation and inadequate use of bypass diodes [21].
- Fig. A taken from Ref. [8], Fig. B taken from Ref. [22], and Fig. C taken from Ref. [19].







Encapsulant Adhesion & Delamination !

- Encapsulant delamination with prolonged outdoor exposure of PV modules is a well-known phenomenon [19], [23]–[26]. However, separating the effects of UV exposure and moisture on encapsulant delamination is not trivial.
- In 2003 Jorgensen *et al.* measured the "Peel Strength" of EVA layers vacuum laminated to various backsheet materials after exposure to a Xenon UV source at intensities of ~1 sun [27]. The results of the study are shown in the table below.
- Kempe has also quantified the effect of UV exposure on EVA adhesion via Lap Shear studies. See, *e.g.*, Ref. [16], and Fig. A on Slide 6.

Peel strength (N/mm) at the EVA/coating interface as a function of exposure time in an Atlas Ci4000 Xenon Weather-Ometer (light intensity ~1 sun, 65°C, and 10% RH).

	Time of Ci4000 Exposure (h)			
Backsheet	**0**	**400**	**800**	**1200**
AKT Coated PET	11.4	13.0	7.2	6.4
NREL Coated PET	11.4	12.1	6.9	4.2
Uncoated PET	0.5	0.5	0.5	
TPE	7.5	7.0	0.5	
TAT	0.5	0.6	1.5	

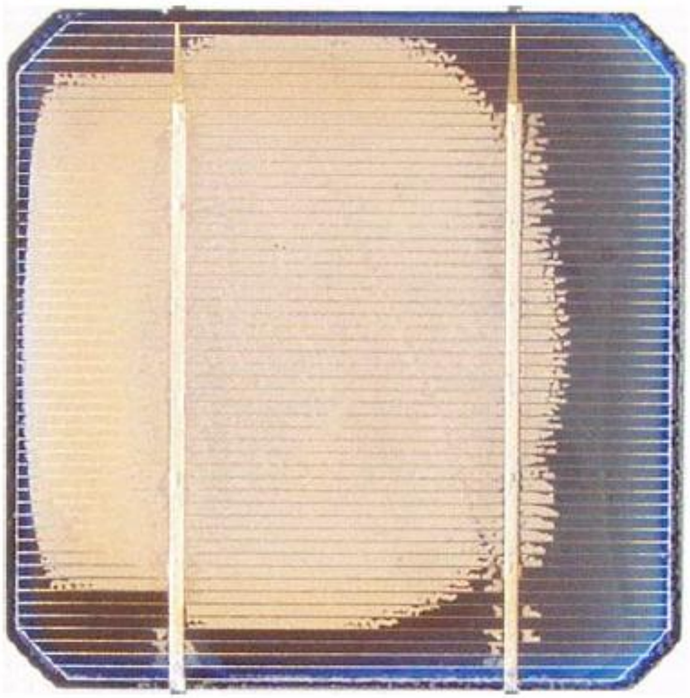
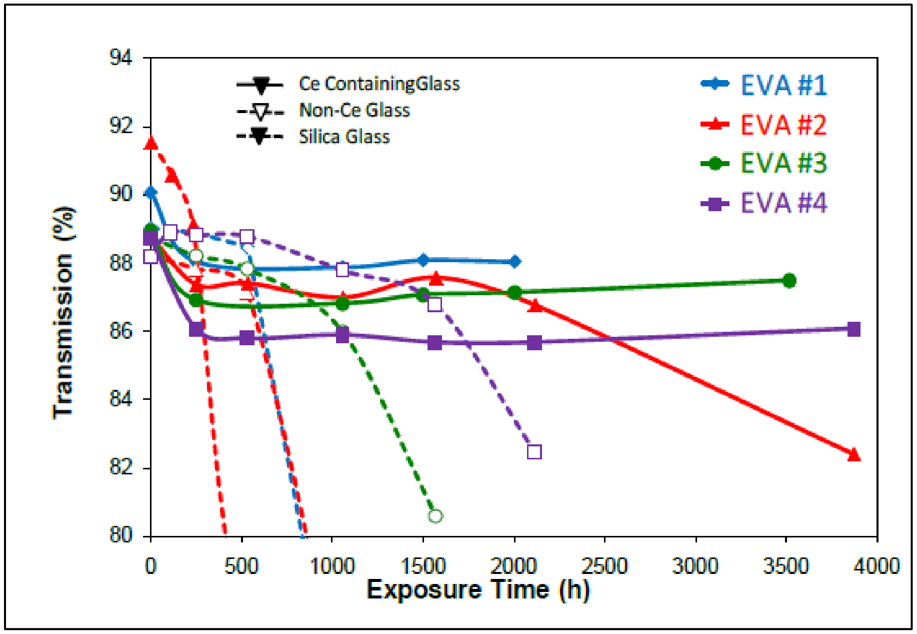
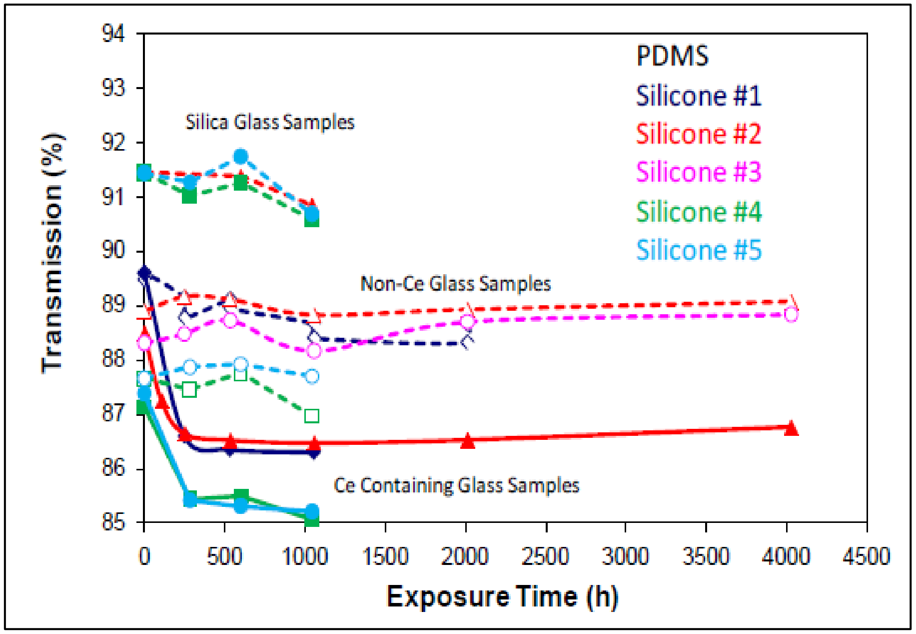


Image of cell with delaminated encapsulant taken from Ref. [26]

EVA Alternatives

- Silicone has been shown to be more stable with UV exposure than EVA [15], [16], [28]
- Silicone encapsulants has been shown to have better optical transmission than EVA encapsulants. [29]–[31], resulting in one study in a 0.5% to 1.5% relative increase in PV module efficiency, mostly due to an increase in transmission below 400 nm [31].
- At least one study has examined the decrease in light transmittance and PV module efficiency for silicone-encapsulated PV modules with UV light exposure under an AM0 spectrum [32]. The authors found a ~15% decrease in PV module efficiency after a ~15 year UV dose.





Figures taken from Ref. [28].

Intrinsic c-Si Degradation with UV Exposure !

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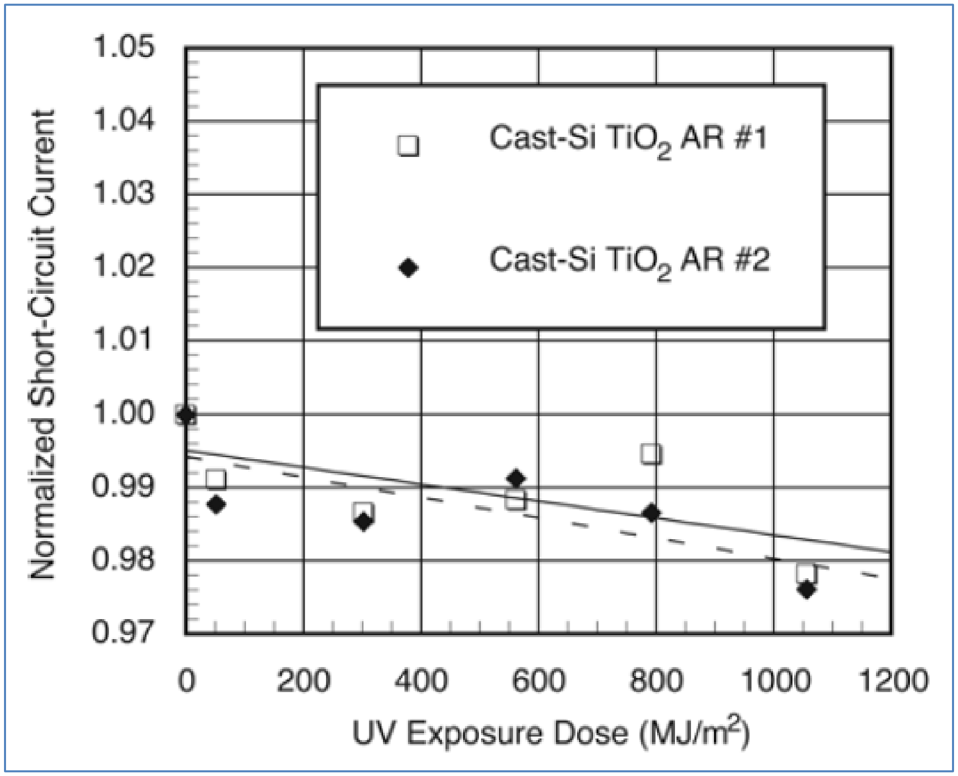
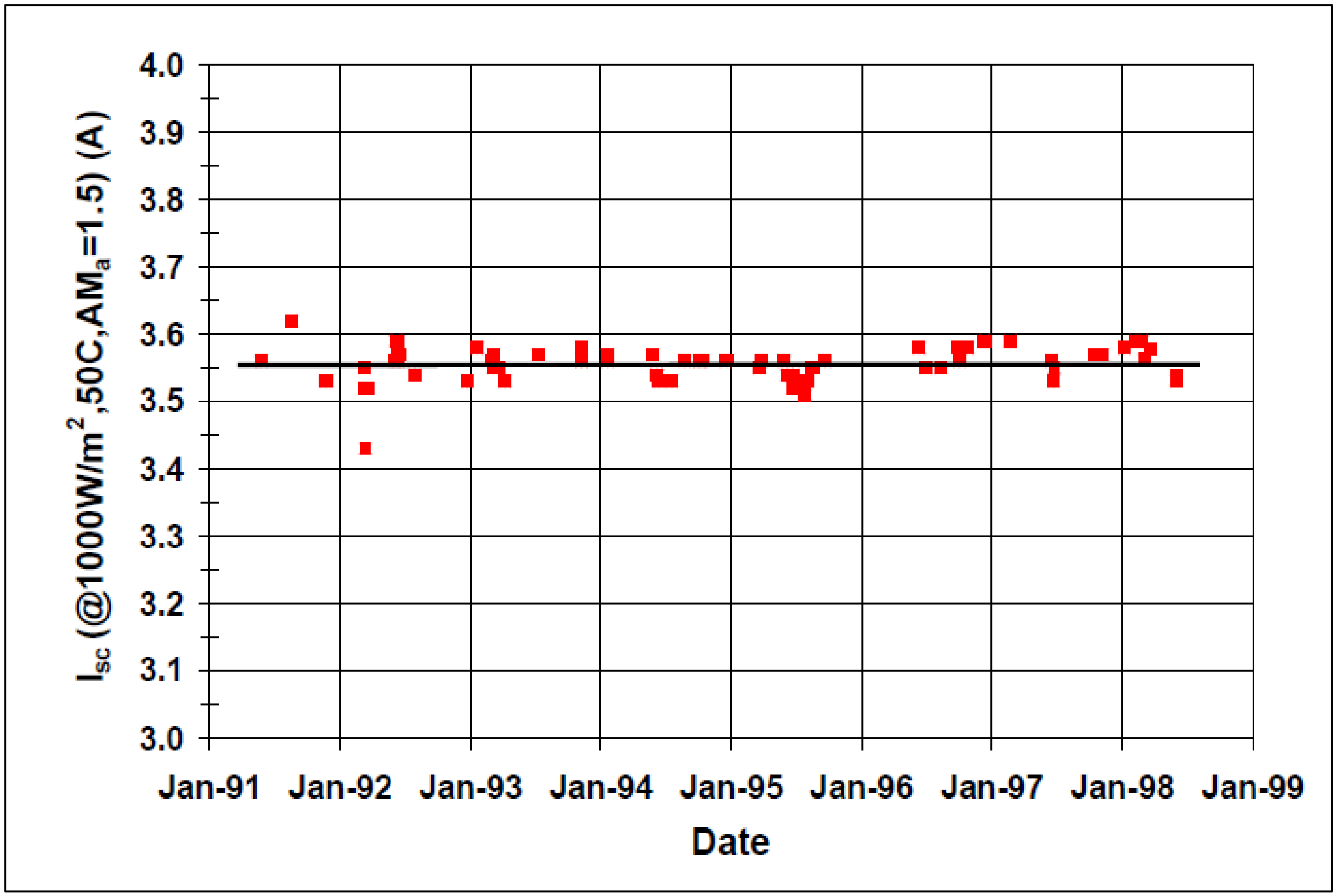
Intrinsic c-Si Isc Degradation with UV Exposure

- In 2003, Osterwald *et al.* published the results of a 5-year study of commercial c-Si PV modules in which the authors found a linear relationship between slow Isc degradation rates (-0.2%/year tob-0.5% year) and UV radiation dose [33]. The authors did not attribute the decrease in Isc to EVA browning, noting an example of one module with an 8% drop in Isc and no obvious change in encapsulant appearance.
- Osterwald *et al.*'s initial 2003 study was followed up by a 2005 study of EVA encapsulated and unencapsulated Si cell Isc degradation rates with UV exposure [22].
- The authors observed a 2% drop in Isc with a UV dose of 1056 MJ/m^2 (~3.8 years of outdoor exposure) in unencapsulated cells [22].
- The degradation rate with UV exposure of unencapsulated cells of varying types (*e.g.*, cast c-Si vs. Cz c-Si, with and without $TiO_{2,}$ etc.) varied by a factor of ~2.7X [22].
- Unencapsulated cells kept in an oven as a control showed no change in Isc.
- Fig. shown from Ref. [22] for unencapsulated cells.



Intrinsic c-Si Isc Degradation with UV Exposure !

- King *et al.*, were able to show the use of Ce-Doped glass and a browning-resistant EVA formulation resulted in a stable PV module Isc after 7 years of outdoor exposure in Albuquerque [19]. Figure shown below taken from Ref. [19].



Simulating Outdoor UV Exposure !

Artificial Light Sources !

- Several artificial light sources that have been used for indoor UV exposure, including Xenon Arc Lamps [10], [12]–[14], [16]–[18], [28], [30], [34]–[37], [27], [38]–[40], Metal Halide Arc-Lamps [22], [34], [35], [41], and UV fluorescent lamps [4], [29], [35], [37], [39], [42]–[45].
- At least one study found differences in transmission spectra of EVA encapsulant aged in natural sunlight for 17 years and EVA encapsulant aged at high UV irradiances [34]. Another study used Raman Spectroscopy to compare outdoor aging of PV Modules with indoor exposure from fluorescent lamps [42].
- One major challenge is accurate spectral and irradiance measurements of UV irradiance.
- Fraunhofer ISE has performed an inter-comparison of UV sources and irradiance measurement sensors from accredited laboratories and major PV module manufacturer test centers, and errors as large as 120% in the calibrations of irradiance sensors [41].

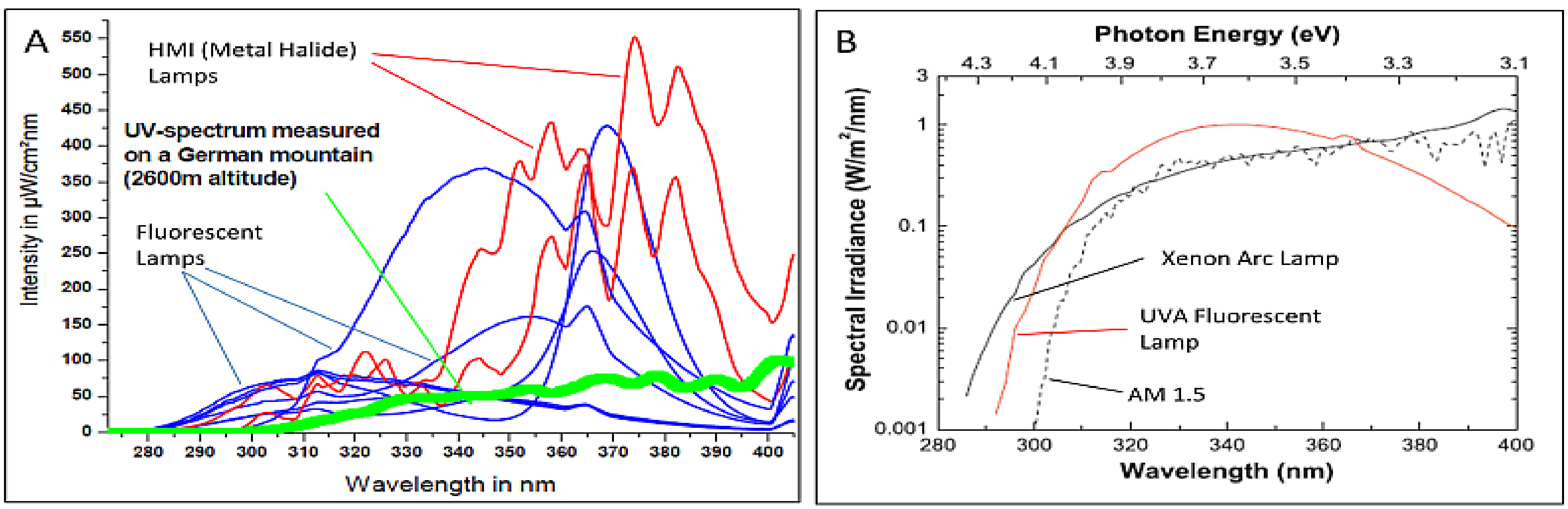


Fig. A taken from Ref. [41]. *Fig. B taken from Ref.* [29].

Atonometrics UV Exposure System !

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