The Principles of Weathering and How They Apply to Environmental Durability Testing of PV Backsheets

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Content

Atlas - Introduction

Part 1

- Accelerated Weathering
- The Principles of Weathering

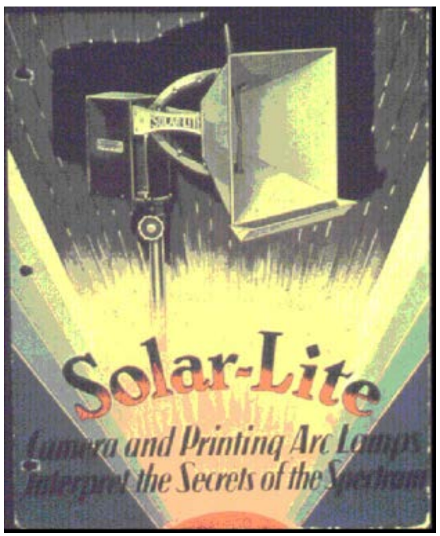
Part 2

- Solar Radiation on PV Backsheets
- Accelerated Weathering of PV Backsheet
- Recommendations for a Test Considerations

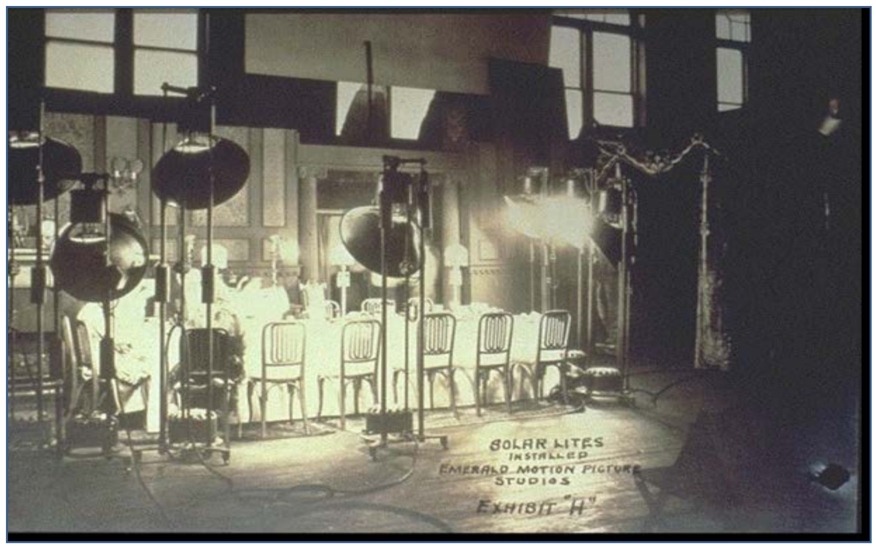
Summary and Conclusion

Atlas – The Beginnings 1915-1918

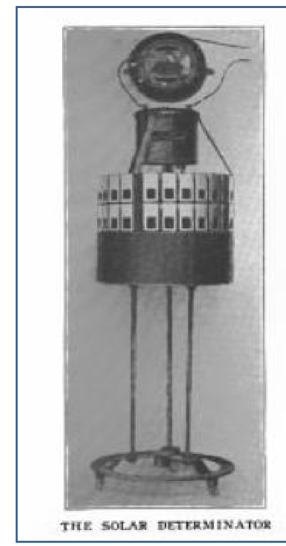
The history of Atlas' predecessor goes back to the early 1900's, however the current Atlas began in 1915 when the core carbon arc lamp lighting business was threatened by new high-power tungsten lamps. This led to textile dye fading experiments in 1915 in the back room and the development of the Solar Determinator in February 1918 as a result of the loss of German aniline dyes with the beginning of World War I and the switch back to less-lightfast natural plant dyes and the beginning of laboratory artificial sunlight testing.



Carbon arc lamps for lithographic plates.



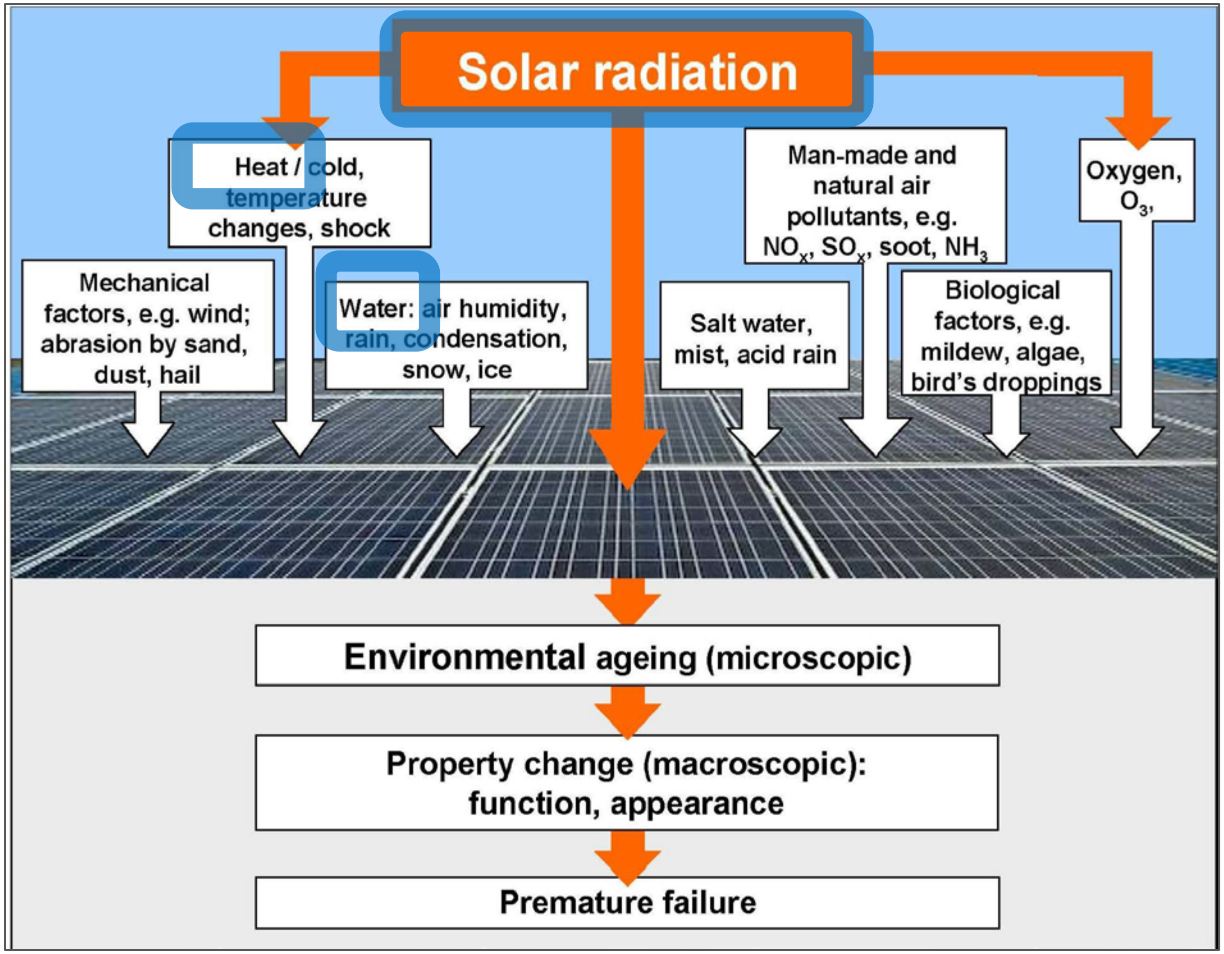
Photographic and motion picture lighting.



Press release February 1918

- Concluding our 100th anniversary year in lightfastness and weathering testing equipment and services innovation and leadership.

Part 1: Primary and Secondary Weather Stress Factors

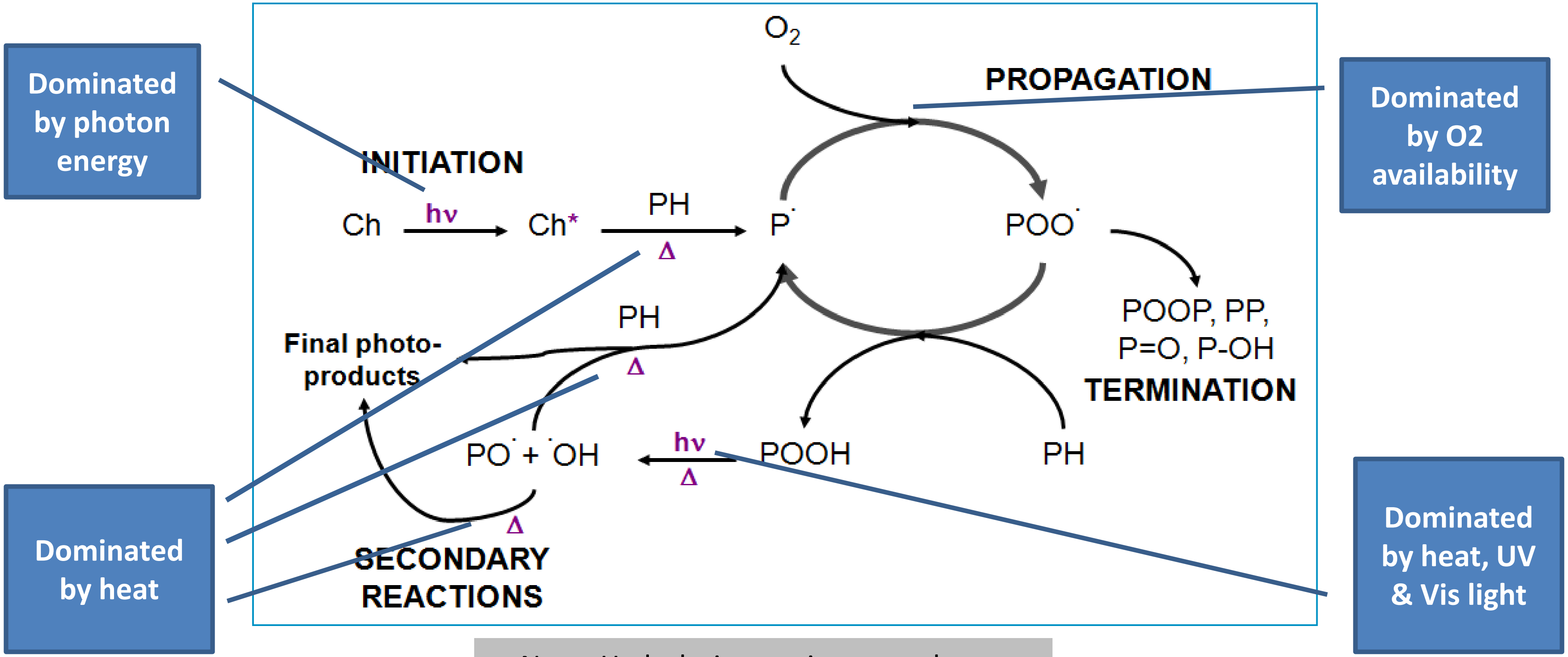


Weathering Test - Climatic Test

Weathering Test	Climatic Test
Weathering Instrument, chamber, etc.	Climatic Chamber, Oven, Damp Heat Chamber, etc.
Light + Temperature + Water (Relative Humidity and Spray)	**Temperature + Relative Humidity** (no light)
	 *Source: heckertsolar.com*
Caution: Parameters from climatic tests usually have to be changed when adding light to account for full-spectrum solar heating of test specimens. (Example: Damp Heat + 1 Sun)	

General Polymer Degradation Mechanism

Polymer Autocatalytic Photo-oxidation Cycle



Note: Hydrolysis reactions not shown

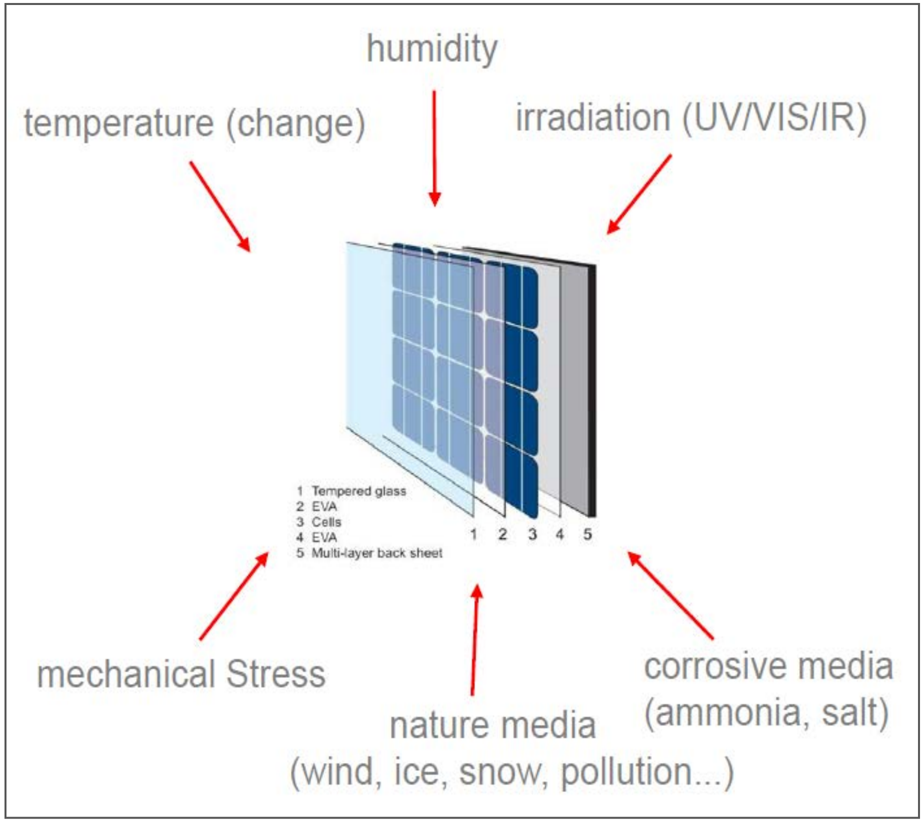
Photons, especially UV ***photoinitiate*** degradation, however much of the subsequent 2◦ free radical reactions primarily responsible for property degradation are ***thermally*** driven processes.

6 Basic Principles of Weathering Tests

Details follow

1. **Primary weather factors should be applied simultaneously to the specimens.**
   - As in real life
   - Synergistic and interaction effects
2. **Test parameters should include cyclic change and not steady state**
   - As in real life
   - To induce mechanical stresses
3. **Maximum stress levels should not be exceeded.**
   - As in real life
   - Unless supported by data and knowledge.
4. **The (laboratory) light source should resemble global solar radiation (”daylight“) as closely as possible in the UV and VIS (and NIR) wavelength regions.**
   - Especially in the UV cut-on region
5. **The acceleration of a laboratory test should be limited to avoid distortion of the degradation mechanism(s).**
   - Requires time and compromises
   - Rule of thumb **< 10 x**
6. **”Black box“ approach has proven to be useful because most environmental ageing processes are complex and usually not known in detail.**
   - i.e. simulating the worst-case in-use conditions

No 1: Apply Primary Weather Factors Simultaneously



+ Liquid water (rain, condensation)

+ Abrasion (sand)

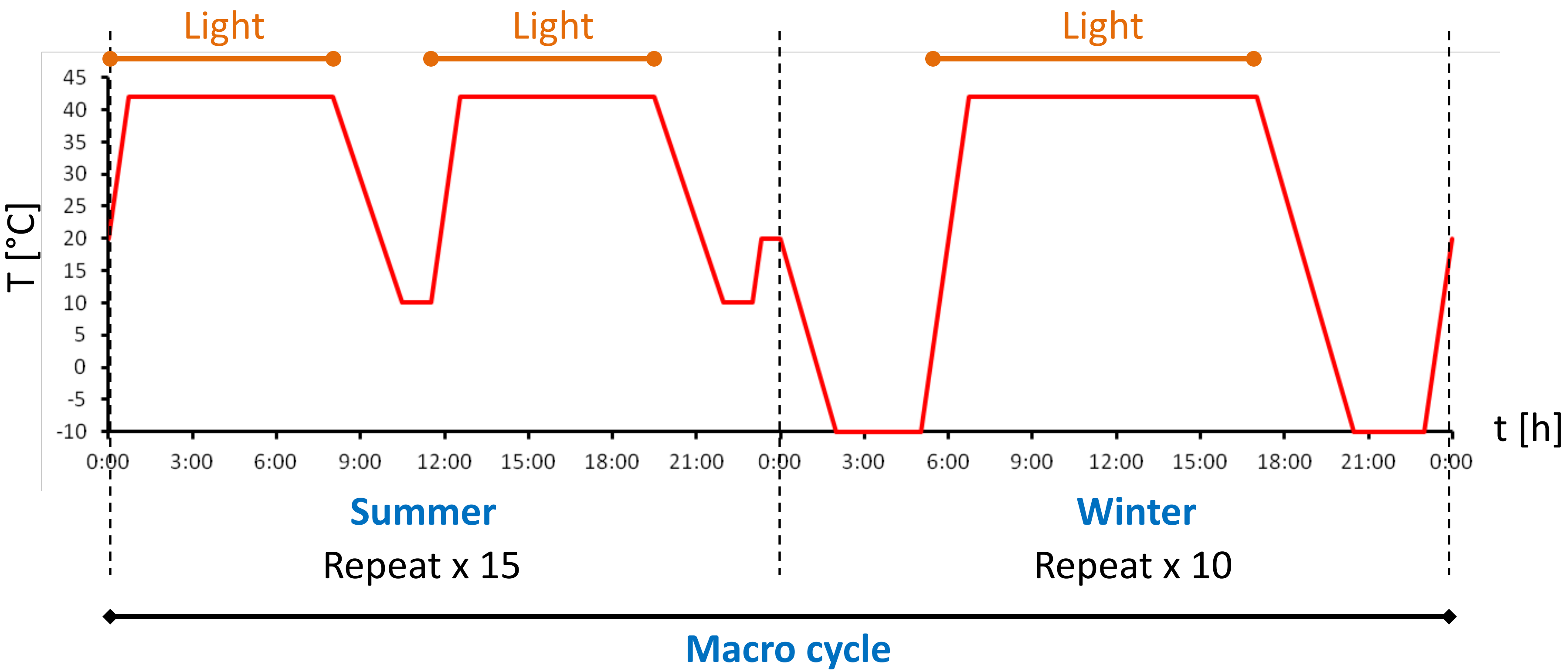
Weathering degradation often involves synergistic and interaction effects.

Source: *Gabriele Eder, Yulia Voronko et. al. Influence of environmental factors on the ageing behaviour of photovoltaic backsheets. 6th European Weathering Symposium EWS. 11 – 13 September 2013. Bratislava, Slovak Republic.*

No 2: Change Test Parameters Cyclically

E.g., Test sequence according to automotive component testing standard DIN 75220

Steady-state conditions never exist in the real world



Source: *Florian Feil, David Dumbleton: OPTIMIZING WEATHERING EXPERIMENTS FOR THE REPRODUCTION OF SIMULTANEOUS PHOTOCHEMICAL AND PHYSICAL DEGRADATION PATHWAYS, 6th European Weathering Symposium EWS. 11 – 13 September 2013. Bratislava, Slovak Republic.*
DIN 75220:1992-11 Ageing of automotive components in solar simulation units

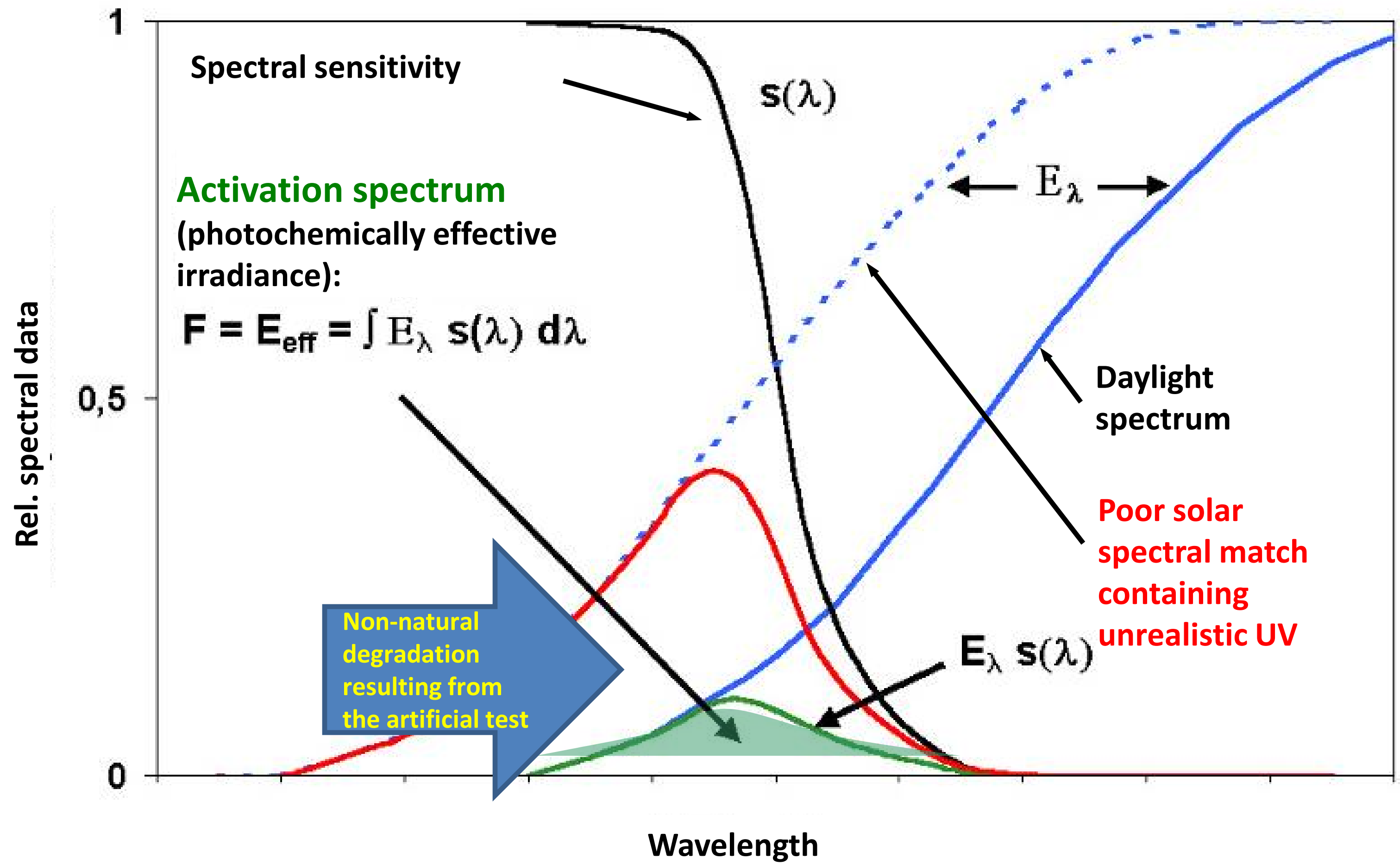
No. 3: Do not Exceed Maximum Stress Levels

Example: Glass Transition Temperatures	T_g (°C)
Polypropylene (atactic)	-20
Polypropylene (isotactic)	0
Poly-3-hydroxybutyrate (PHB)	15
Poly(vinyl acetate) (PVAc)	30
Polyethylene terephthalate (PET)	70
Poly(vinyl chloride) (PVC)	80
Poly(vinyl alcohol) (PVA)	85
Polystyrene	95
Poly(methylmethacrylate) (atactic)	105
Poly(carbonate)	145
Polynorbornene	215

The apparent rate of weathering often increases >T_g in laboratory tests

Source: *C. E. Wilkes et al, PVC Handbook (2005), Hanser Verlag, ISBN 1569903794.*

No. 4: Laboratory Light Must Match the Sun



No. 5: Acceleration is Limited

- When there is not a simple single photolytic, hydrolytic or thermal degradation mechanism.
- When there are stress-interaction effects.
- Not all weathering stress factors can be accelerated at the same rate in tests.

No. 6: Use Black-Box Approach

- All organic materials undergo weathering due to combined effects of **light, heat, and moisture** in the presence of **oxygen.**
- Degradation mechanisms of polymers are **complex** and not fully understood

→ Use "black box approach" or – in other words – "agnostic testing"

For Standards:

C. "Agnostic Testing"
- Materials Independent
- Gives some confidence that a new product will work during its service life
- Example: encapsulants
  - EVA, polyolefins, silicones, new ideas
  - Anything that will work in the field should pass the test

- Philosophy: run at or near typical maximum values observed in the application
  - Rule of thumb: limit acceleration to 10X
    - 25 years → 2.5 years!
      - Delta testing: Up to 10x: look for change, as opposed to a failure
    - Accelerating >10x, expect errors; may see failures that don't occur in real world

Source: *Nancy Phillips, Kurt Scott, David Burns. Quantifying PV module microclimates, and translation into accelerated weathering protocols. 2nd Atlas/NIST PV Durability Workshop, 14 November 2013. NIST, Gaithersburg, MD, USA.*

Summary: 6 Basic Principles of Weathering Tests

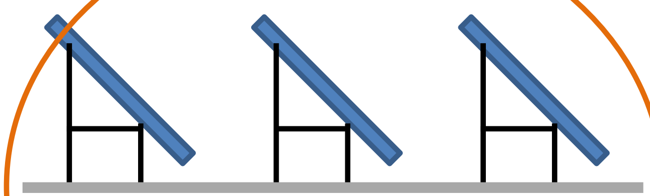
1. Simultaneous application of primary weather stress factors
2. Change test parameters cyclically as in nature
3. Do not exceed maximum stress levels.
4. Laboratory light must match global solar radiation in UV and VIS and usually NIR.
5. Acceleration of a laboratory test is limited.
6. Use ”Black box“ agnostic approach to avoid altering mechanisms or skewing tests to what you *think* you know.

See ISO 4892-1 / ASTM G151 for a good explanation of factors that decrease laboratory test correlation to outdoor weathering for polymers.

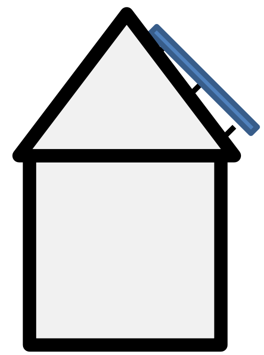
Part 2: Environmental Stresses on Backsheets

Weather exposed side of Backsheet	Encapsulated side of Backsheet
Global Solar Radiation • E reflected from Ground - Albedo • E reflected from next PV modules • Irradiance, radiant exposure? • Spectral Power Distribution (SPD)?	**Global Solar Radiation** • Transmitted through glass and encapsulant • Irradiance, radiant exposure? • Spectral Power Distribution (SPD)?
Temperature • Dark: Ambient temperature • Light: between module operating T and ambient T • Day-night cycles • Diurnal variations (rain, etc.)	**Temperature** • Dark: Ambient temperature • Light: module operating temperature • Day-night cycles • Diurnal variations (rain, etc.)
Water • Condensation • Heavy rain / spray •Atmospheric humidity	**Water** • Relatively negligible
Secondary factors • Sand abrasion in deserts • Salt in marine environments • Ammonia in agricultural installations • Air pollutants in industrial areas • Biological agents, e.g. mildew, algae, fungi etc. • *...others*	

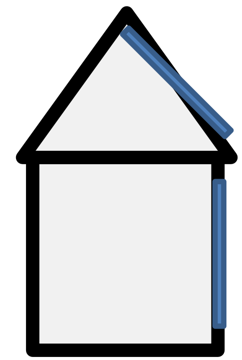
Mounting Geometry - Three Cases



On-rack –
Ground or flat roof
Utility Scale



On-roof
Residential, Commercial



BIPV
Residential, **Commercial**

Typical Geometry - On-Rack Installation

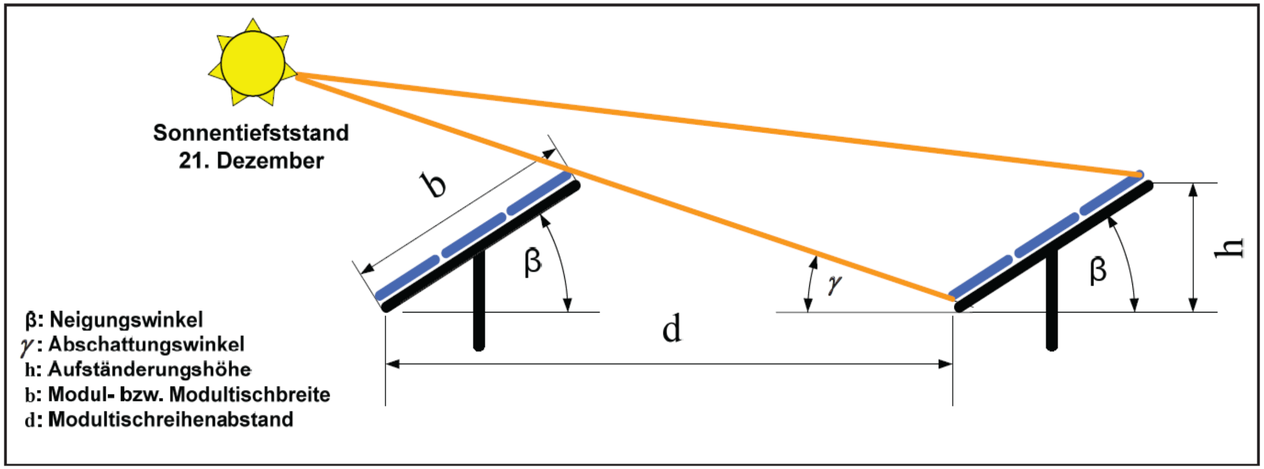


Bild 2.9: Verschattung bei aufgeständerten Photovoltaikanlagen; Quelle: Eigene Darstellung

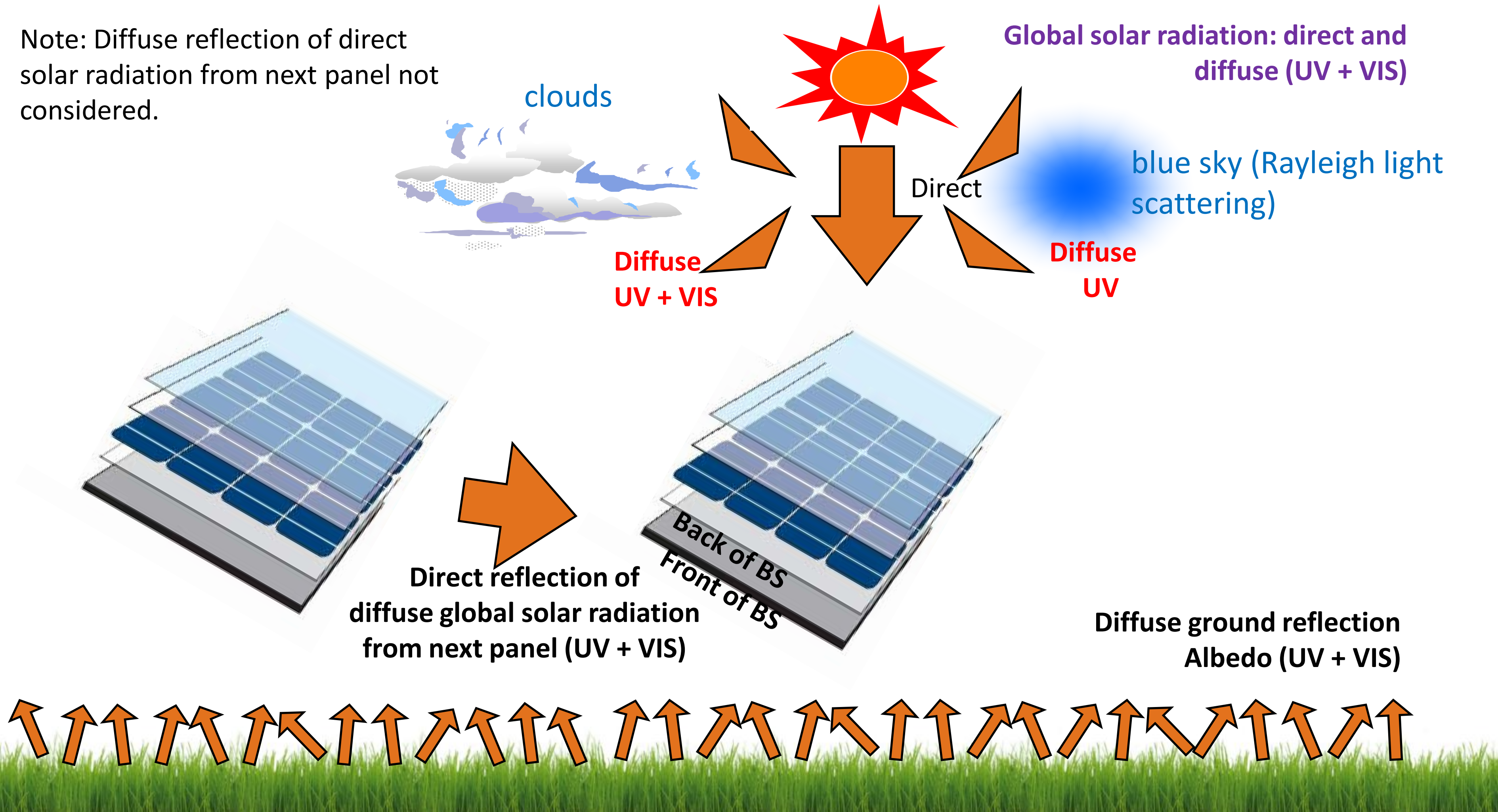
Example for Germany:
Beta = 30°,
Module area / ground area = ca. 1/3

Source: *Ahmadreza Yegani. Systemorientierte Optimierung von PV-Freiflächenanlagen. Master Thesis. University of Kassel, Germany, December 2009, page 14/15.*

Pictures: *Solar Park Lieberose*

Solar Radiation on Front and Back of Backsheet

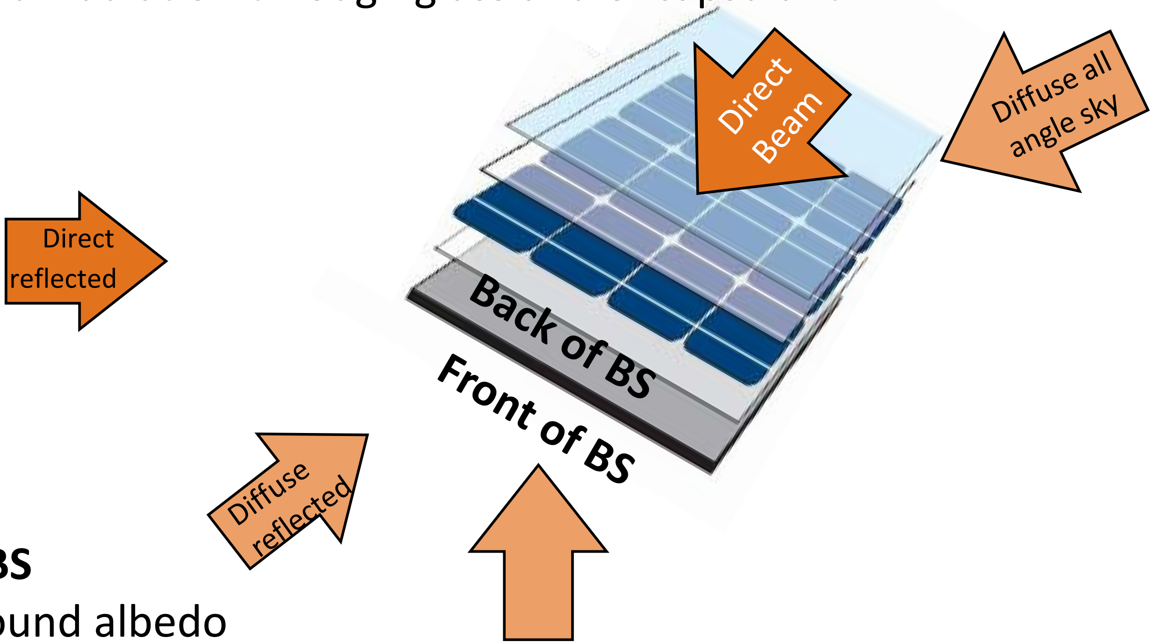
Note: Diffuse reflection of direct solar radiation from next panel not considered.



Solar Radiation on Front and Back of Backsheet

On Back of BS

- Direct solar radiation through glass and encapsulant
- + Diffuse solar radiation through glass and encapsulant
- = Global solar radiation through glass and encapsulant

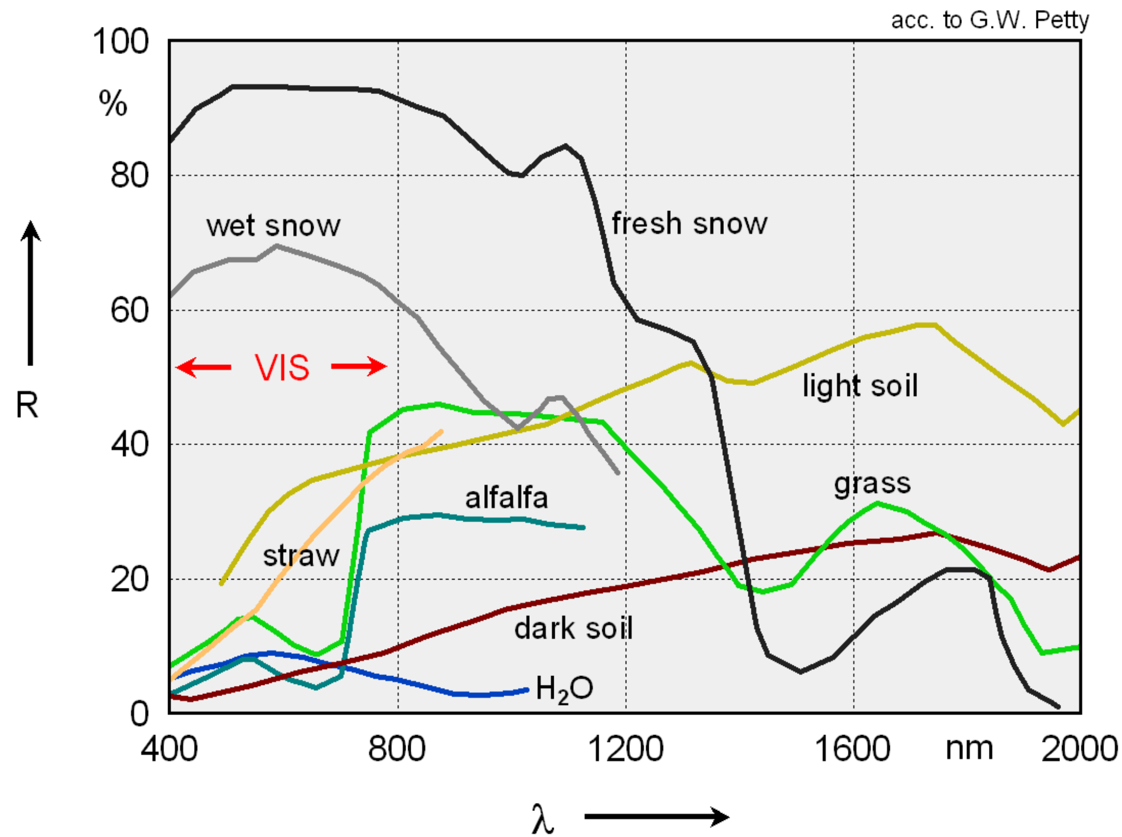


On Front of BS

- Diffuse ground albedo
- + Direct reflected radiation of diffuse global solar radiation by next panel row

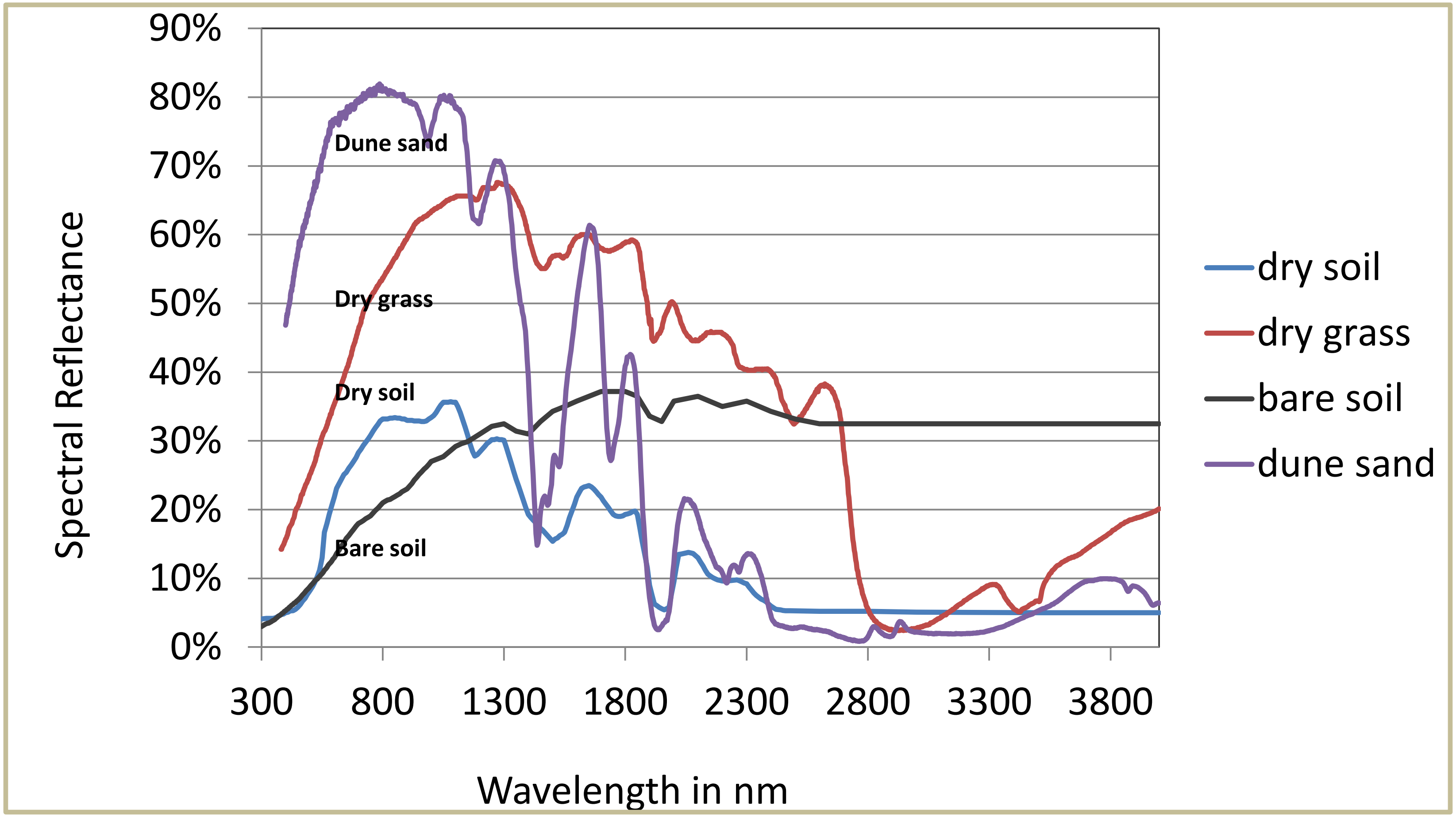
Terrestrial Albedo of Ground Surfaces in VIS, IR

Surface	Typical albedo	
Fresh asphalt	0.04	(1)
Worn asphalt	0.12	(1)
Bare soil	0.17	(2)
Green grass	0.25	(2)
Desert sand	0.40	(3)
New concrete	0.55	(2)
Fresh snow	0.80 – 0.90	(2)



Sources: *(1)* Brian Pon (30 June 1999). Pavement Albedo. http://web.archive.org/web/20070829153207/http://eetd.lbl.gov/HeatIsland/Pavements/Albedo/ Heat Island Group. Retrieved 2007-08-27; (2) T*om Markvart, Luis Castałżer (2003). Practical Handbook of Photovoltaics: Fundamentals and Applications. Elsevier.* *ISBN* *1-85617-390-9. (3)* Tetzlaff, G. (1983). "Albedo of the Sahara". *Cologne University Satellite Measurement of Radiation Budget Parameters*. pp. 60–63. (4) Grant W. Petty, *Atmospheric and Oceanic Sciences, University of Wisconsin-Madison*

Terrestrial Albedo of Ground Surfaces in UV, VIS, IR



Reflected Solar Radiation on Front of BS Includes Considerable UV

Shown sun to the north of a south-facing module for worst-case sun shining on back of module.

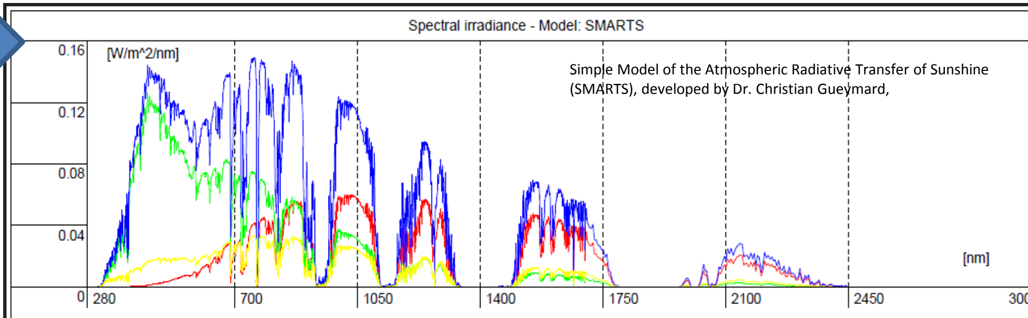
0.16 W/m2 nm

Calculation on the right →:

- Spectral irradiance on Front of BS
- **Low morning sun**
- Ground cover: dry grass

→ **Very low direct E**

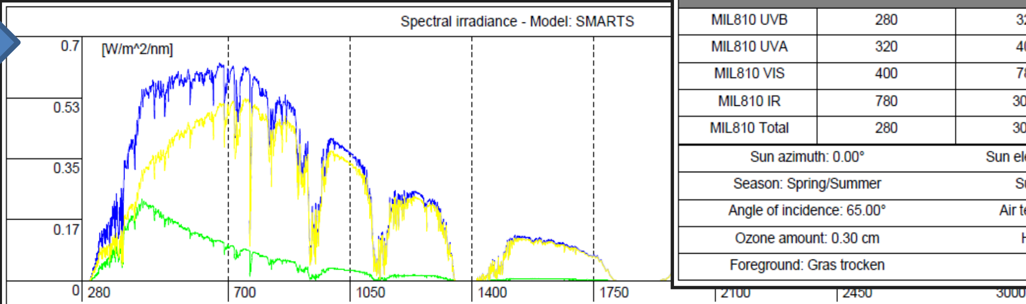
→ **Considerable diffuse and reflected E**



Spectral range [nm]			Broadband irradiance value [W/m^2]			
Name	from	to	direct	diffuse	global	reflected
MIL810 UVB	280	320	0.00	0.00	0.01	0.00
MIL810 UVA	320	400	0.00	1.74	2.14	0.40
MIL810 VIS	400	780	4.70	30.19	42.22	7.32
MIL810 IR	780	3000	29.28	13.94	54.35	11.12
MIL810 Total	280	3000	33.98	45.87	98.71	18.85

Sun azimuth: 0.00°	Sun elevation angle: 5.00°	Height: 0 m	Climate: rural
Season: Spring/Summer	Surface tilt: 150°	Surface azimuth: 0°	Object height: 0.00 km
Angle of incidence: 65.00°	Air temperature: 25°C	Pollution (/4): 2	Average temp.: 15°C
Ozone amount: 0.30 cm	Humidity: 50%	Precipitable water: 2.51 cm	Turbidity coefficient: .14
Foreground: Gras trocken			

0.7 W/m2 nm



Spectral range [nm]			Broadband irradiance value [W/m^2]			
Name	from	to	direct	diffuse	global	reflected
MIL810 UVB	280	320	0.00	0.15	0.55	0.41
MIL810 UVA	320	400	0.00	5.13	12.54	7.41
MIL810 VIS	400	780	0.00	53.90	205.44	151.54
MIL810 IR	780	3000	0.00	17.08	209.23	192.16
MIL810 Total	280	3000	0.00	76.25	427.77	351.52

Sun azimuth: 180.00°	Sun elevation angle: 60.00°	Height: 0 m	Climate: rural
Season: Spring/Summer	Surface tilt: 150°	Surface azimuth: 0°	Object height: 0.00 km
Angle of incidence: 180.00°	Air temperature: 25°C	Pollution (/4): 2	Average temp.: 15°C
Ozone amount: 0.30 cm	Humidity: 50%	Precipitable water: 2.51 cm	Turbidity coefficient: .14
Foreground: Gras trocken			

←Calculation on the left:

- Spectral irradiance on Front of BS
- **High sun at local solar noon**
- Ground cover: dry grass

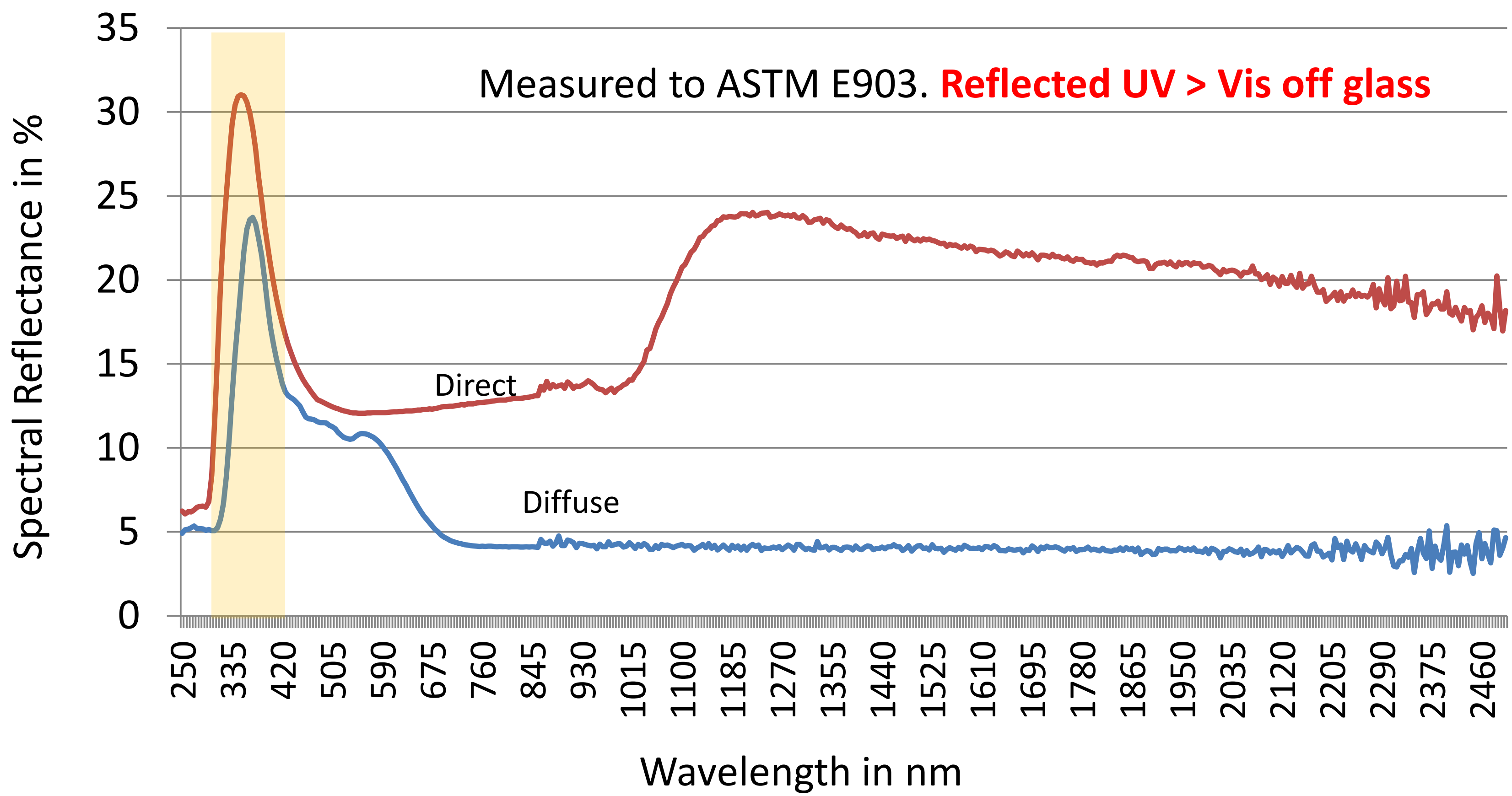
→ **No direct E (sun to the north)**

→ **Considerable diffuse and reflected E**

→ **UV 6 x higher than at morning**

PV Modules Reflect Considerable Amounts of Solar UV Radiation

Total (brown) and **diffuse** (blue) reflection of a CIGS solar reference cell with Schott BK7 glass



Solar Radiant Exposure on Front of BS v. Module Surface

Arizona
Radiant Exposure
Model **Year 2006**
Albedo: bare soil

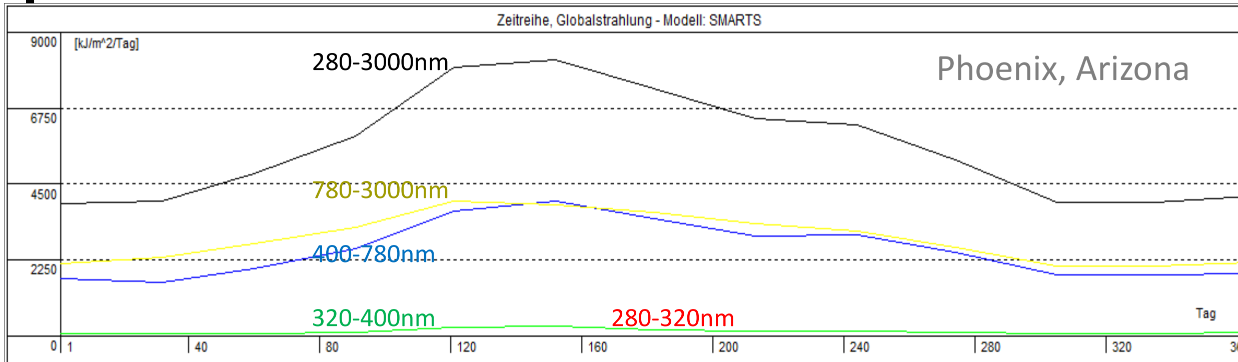
Front side of BS
- 53 MJ/m² (UV)

Incident Module Surface
- 457 MJ/m² (UV)

Relation: 11.6 %

→ The Front of BS receives only 11.6 % of Incident radiant Exposure (factor of 8.6)

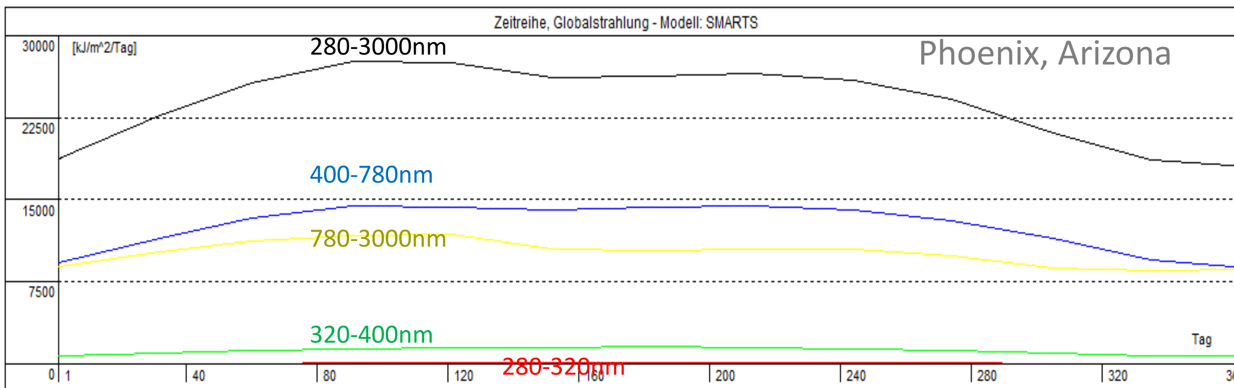
Dry grass albedo = 22%, ~2X bare soil.



Energie der Strahlungsart von 0h - 23h [kJ/m^2]

MIL810 UVB (280nm - 320nm)	MIL810 UVA (320nm - 400nm)	MIL810 VIS (400nm - 780nm)	MIL810 IR (780nm - 3000nm)	MIL810 Total (280nm - 3000nm)
1636,59	51038,89	947753,79	1069622,83	2070052,09

Ort: US/Central Arizona AWSG	Geogr. Länge: -112° 8'	Geogr. Breite: 33° 54'	Höhe: 610 m	Lokale Zeit: Wahre Ortszeit	Klima: Wüste
Flächenneigung: 150°	Flächenazimut: 0°	Objekthöhe: 0,00 km	Zeitraum: 1.1. - 31.12.2006		



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MIL810 UVB (280nm - 320nm)	MIL810 UVA (320nm - 400nm)	MIL810 VIS (400nm - 780nm)	MIL810 IR (780nm - 3000nm)	MIL810 Total (280nm - 3000nm)
19049,86	437586,50	4658436,46	3724525,94	8839598,72

Ort: US/Central Arizona AWSG	Geogr. Länge: -112° 8'	Geogr. Breite: 33° 54'	Höhe: 610 m	Lokale Zeit: Wahre Ortszeit	Klima: Wüste
Flächenneigung: 30°	Flächenazimut: 180°	Objekthöhe: 0,00 km	Zeitraum: 1.1. - 31.12.2006		

Summary for Solar Radiation on Front of BS

- Reflected and diffuse solar irradiance on the Front of BS contains considerable UV, as well as VIS and IR.
- ”Xenon-arc with daylight filters“ per ISO and ASTM standards should be an appropriate laboratory light source for testing the total effects of sunlight (UV, Visible, and NIR for heating)*
- Yearly radiant exposure on the Front of BS can be assumed as 10 – 20 % of solar radiation incident on front of PV module (in AZ for different ground covers; excluding effect of module row spacing).

* Note that all standards compliant implementations of spectral power distributions are equivalent; consult manufacturer for specifications.

Solar Radiation on Back of BS

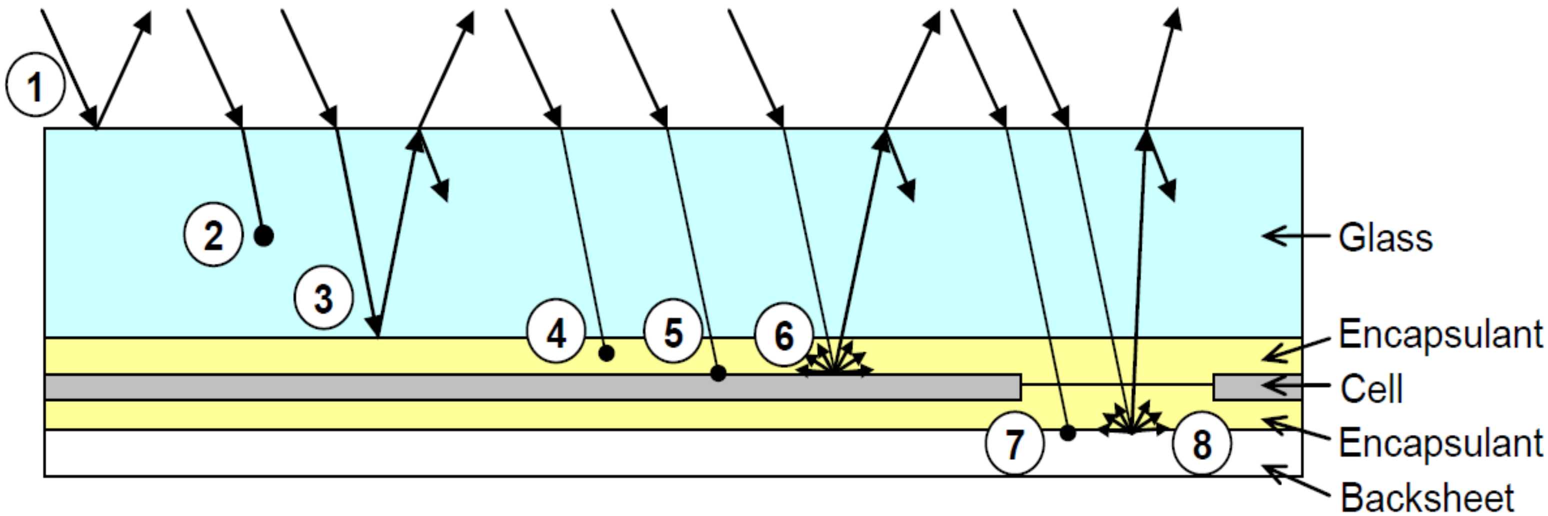
"Light Window Pane Effects"

Poly-crystalline

Mono-crystalline

Thin-film

Solar Radiation on Back of BS Through Glass and Encapsulant



An accurate optical assessment of a PV module is not trivial.

Source: *Keith R. McIntosh et al. An optical comparison of silicone and EVA encapsulants for conventional silicon PV modules : a ray-tracing study. Dow Corning Technical Paper. Form No. 06-1045-01. 10 November 2009.*

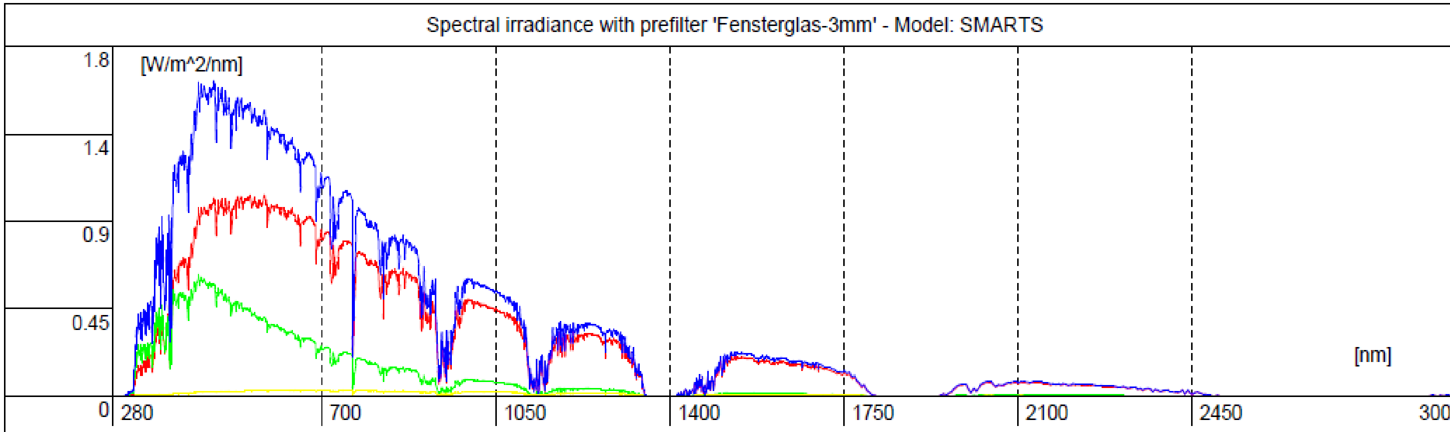
Glass Shifts Cut-on λ of Transmitted Solar from 300 → 320 nm

Spectral irradiance through 3 mm window glass; individual glasses vary.

High sun at noon

Perpendicular incident light (DNI)

→ direct E dominates

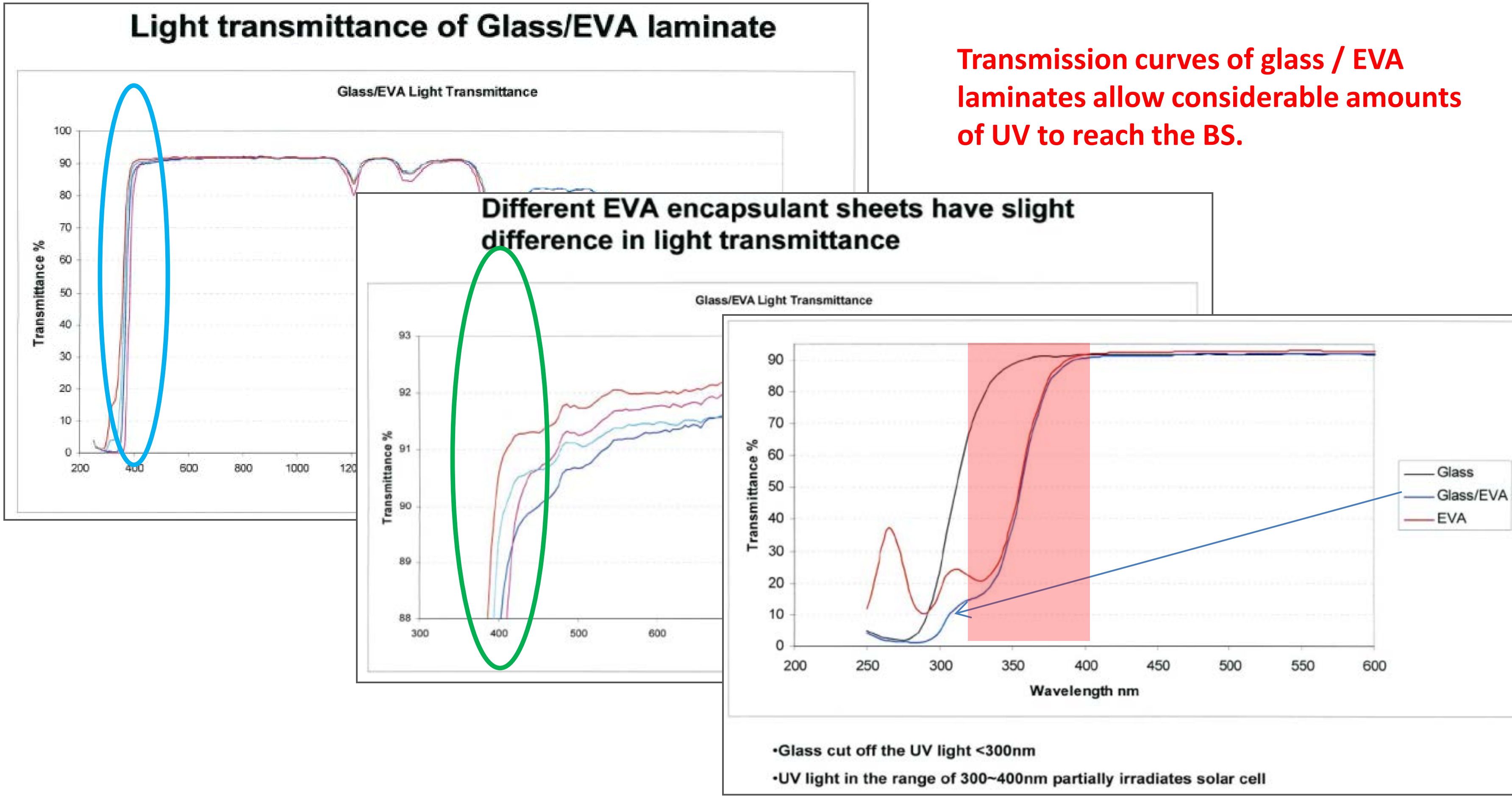


Spectral range [nm]			Broadband irradiance value [W/m^2]			
Name	from	to	direct	diffuse	global	reflected
MIL810 UVB	280	320	0.10	0.18	0.28	0.00
MIL810 UVA	320	400	19.10	22.44	41.95	0.41
MIL810 VIS	400	780	330.11	143.68	483.24	9.45
MIL810 IR	780	3000	281.21	40.80	333.05	11.03
MIL810 Total	280	3000	630.51	207.11	858.52	20.90

Sun azimuth: 180.00°	Sun elevation angle: 60.00°	Height: 0 m	Climate: rural
Season: Spring/Summer	Surface tilt: 30°	Surface azimuth: 180°	Object height: 0.00 km
Angle of incidence: 0.00°	Air temperature: 25°C	Pollution (/4): 2	Average temp.: 15°C
Ozone amount: 0.30 cm	Humidity: 50%	Precipitable water: 2.51 cm	Turbidity coefficient: .14
Foreground: Gras trocken			

ATLAS
MATERIAL TESTING SOLUTIONS

Solar Through Glass and Encapsulant Still Contains UV



Transmission curves of glass / EVA laminates allow considerable amounts of UV to reach the BS.

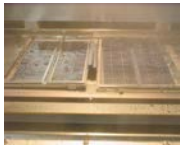
***Source**: Zhao Ruo Fei, DuPont China R&D Center. Photovoltaic Encapsulant Optical Property Study. 9 May 2009.*
http://www2.dupont.com/Photovoltaics/en_US/assets/downloads/presentations/PVEncapsulants_OpticalStudy.pdf. Retrieved 30 December 2013

Summary for Solar Radiation on Back of BS

- For crystalline Si modules, there is light passing through glass and encapsulant onto the back of BS.
- Solar radiation through glass and encapsulant still contains UV; the effect adds up over time.
- For realistic testing, it is recommended to use either test coupons made from glass / encapsulant / backsheet or representative mini modules.

Recommendations for Laboraotry Testing Methods

	Front of BS	Back of BS
Specimen	Backsheet only or Coupon	Coupon or (oper.) mini-module
Geometry	Light on BS	Light through glass/encapsulant
Light Source	Daylight spectrum (UV + VIS)	Daylight spectrum (UV + VIS)
Irradiance	1 sun (60 W/m^2 in UV)	1 sun (60 W/m^2 in UV)
Relative Humidity	Per ISO, ASTM: e.g. 50 % or as appro.	Per ISO, ASTM or as appropriate
Rain / Water Spray	Per ISO, ASTM stsandards: e.g. 102 min Light / 18 min Light + H_20 Spray	none
Test Accel. over AZ real time	Lab: ~5X – 10X faster than real time exposure (@ 10-20% of incident E)	~4 - 5 times faster than real time



Summary and Conclusions

- Stress by solar radiation on Front of BS:
  - Reflected and diffuse solar irradiance on the Front of BS contains considerable UV, as well as VIS and IR.
  - ”Xenon-arc with daylight filters“ acc. to ISO and ASTM standards should be an appropriate laboratory light source for testing.
  - Yearly radiant exposure on the Front of BS can be assumed as 10 – 20 % of solar radiation incident on front of PV module (in AZ for different ground covers).
- Stress by solar radiation on Back of BS:
  - For crystalline Si modules, there is light Passing through glass and encapsulant on the back of BS.
  - Solar radiation through glass and encapsulant still contains UV.
  - For realistic testing, it is recommended to use either test coupons made from glass / encapsulant / backsheet or representative mini modules.
- Weathering Test on the Front of BS may be up to 10-50 times faster than in real life (with regard to E only)
- Recommendation for weathering tests parameters are made for testing both sides of BS.

Thank you very much! Your questions?

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