“Examination of an Optical Transmittance Test for Photovoltaic Encapsulation Materials” (8825-8)

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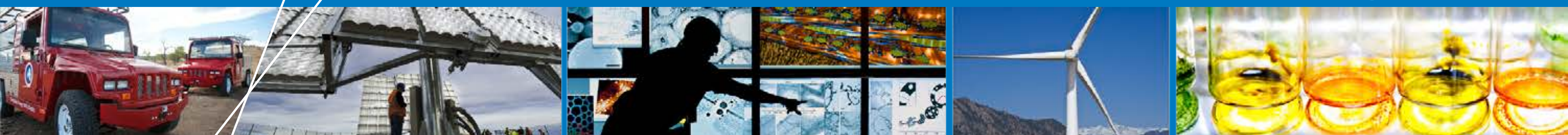

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(Rm 16B, Convention Center, San Diego, CA)

2013/8/28 (Wednesday), 14:00 – 14:20

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-this presentation contains no proprietary information-

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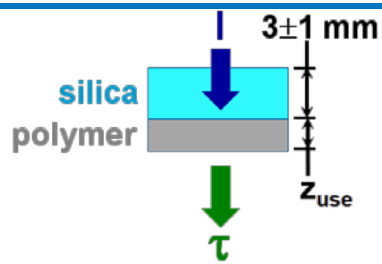
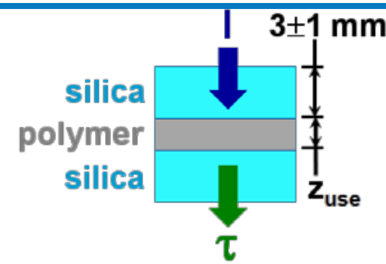
Motivation for the "Transmittance" Standard





Schematics (in cross-section) of specimen configurations for the "transmittance" standard.

- Optical transmittance (τ) is a key performance characteristic for encapsulation.
- Encapsulation discoloration continues to be correlated to performance degradation in recently fielded PV modules.

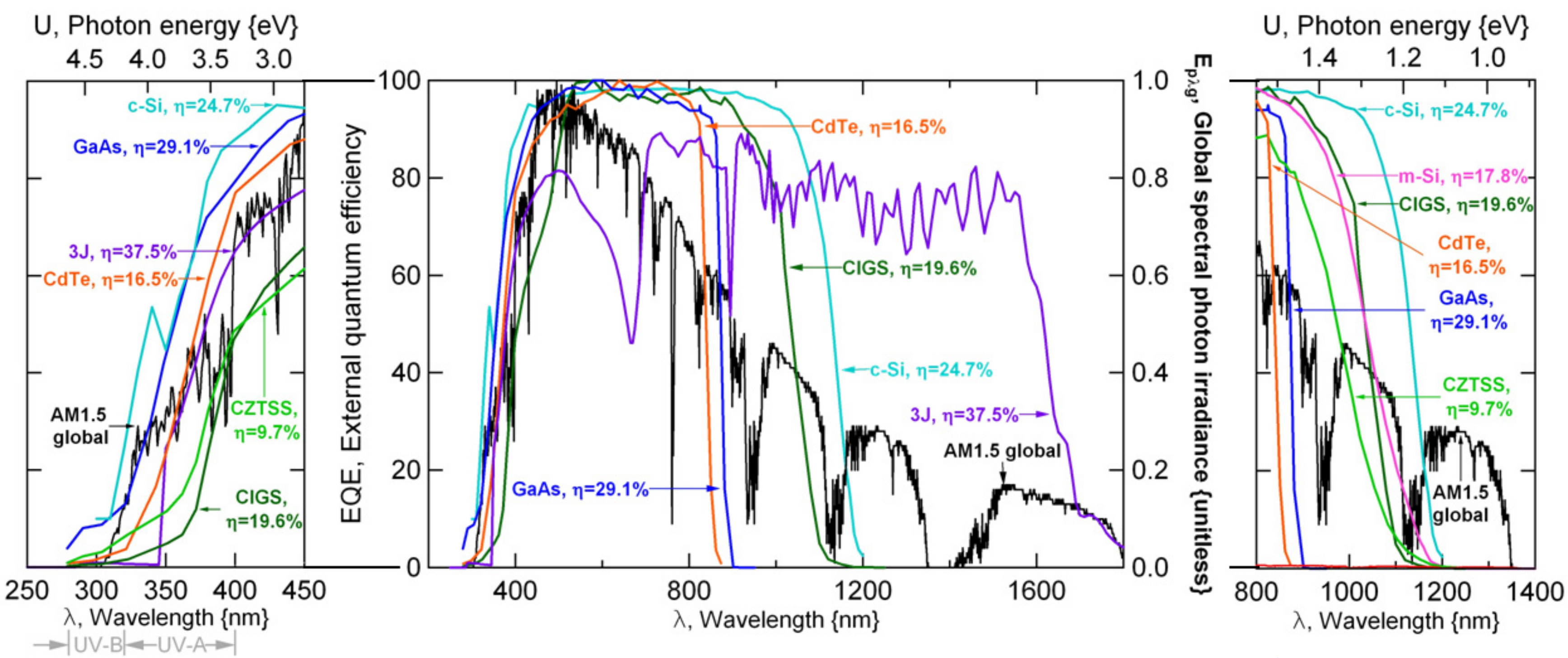
- Existing optical standards (ISO 13468, ASTM E903, ASTM E1175, ASTM E424) were found insufficient for the study of unaged or aged PV encapsulation.

- The encapsulation work-group within IEC TC82 WG2 has proposed a new test standard that may be used to assess the transmittance of encapsulation.
- Protocol for spectral transmittance measurement, with subsequent calculation of weighted transmittance ($E_{p\lambda}$), yellowness index (*YI*), UV cut-off λ (λ_c).

- No pass/fail. Test aids material and module manufacturers in material acceptance, material/process development, design analysis, or failure analysis.

Details of the Solar-Weighted Transmittance

- The photon irradiance ($E_{p\lambda}[\lambda]=\frac{\lambda}{hc}E_{\lambda}[\lambda]$) considers the photon energy, the correct unit of measure,immediately relevant to bandgap operant PV devices.
- The solar weighted transmittance of photon irradiance ($\tau_w = \frac{\int \tau[\lambda]E_{p\lambda}[\lambda]d\lambda}{\int E_{p\lambda}[\lambda]d\lambda}$) considers τ relative to the $E_{p\lambda}$ of the terrestrial sun.
- τ_{sw}: the "solar-weighted" τ is defined for $300 \leq \lambda \leq 2500$ nm, 1 nm increment.
- τ_{rsw}: the "representative solar-weighted" τ is defined for $300 \leq \lambda \leq 1250$ nm.

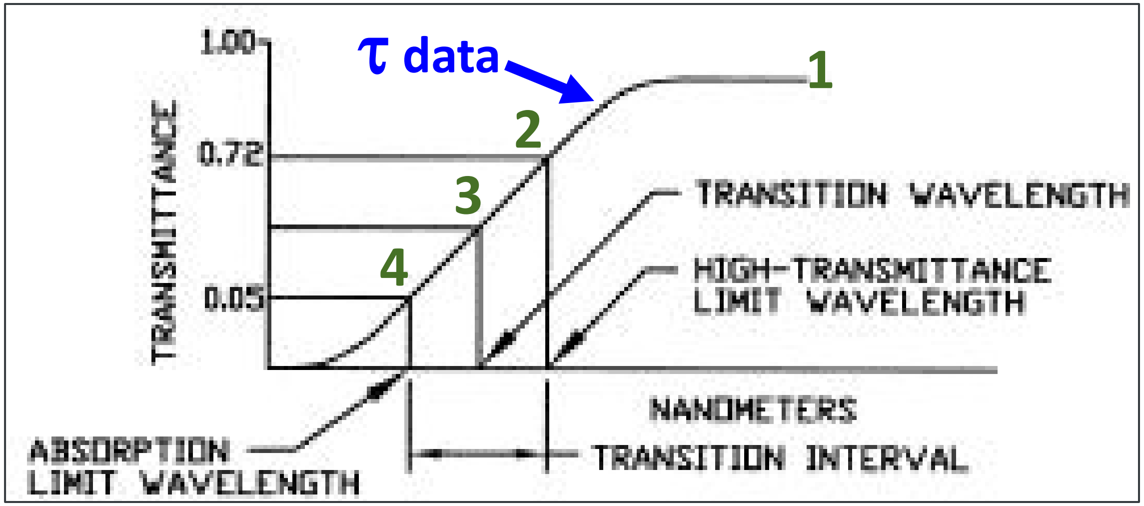


EQE of popular PV cell technologies, shown relative to the terrestrial global solar spectrum (AM1.5 in IEC 60904-3).

Details of the Yellowness Index and UV Cut-Off λ

•Consider a D65 illuminant (mid-day outdoor sun, as in ISO 11664-2) for a human observer (CIE 1964 XYZ color space with 10° field of view, as in ISO 11664-1).
•Calculation defined in ISO 11664-1.
•$YI \propto$ (measured transmittance · D65 source · the "EQE" of the human eye).
•Interpretation: 0.00 = perfectly neutral, increasing values ⇒ more "yellow".

•Like *YI*, λ_{cUV} may be used to assess effects of aging.
•High threshold (τ>90%) overlaps with chromophore species (as in *YI*).
•Low threshold (τ>10%) queries UV absorber(s) or polymer additives.
•Ametek recommends an extrapolation method, found to improve repeatability between customers using different spectrophotometers.



Schematic for the Atlas λ_{cUV} determination scheme (courtesy Ametek, Inc.)

Choosing The Appropriate Glass for Measurements

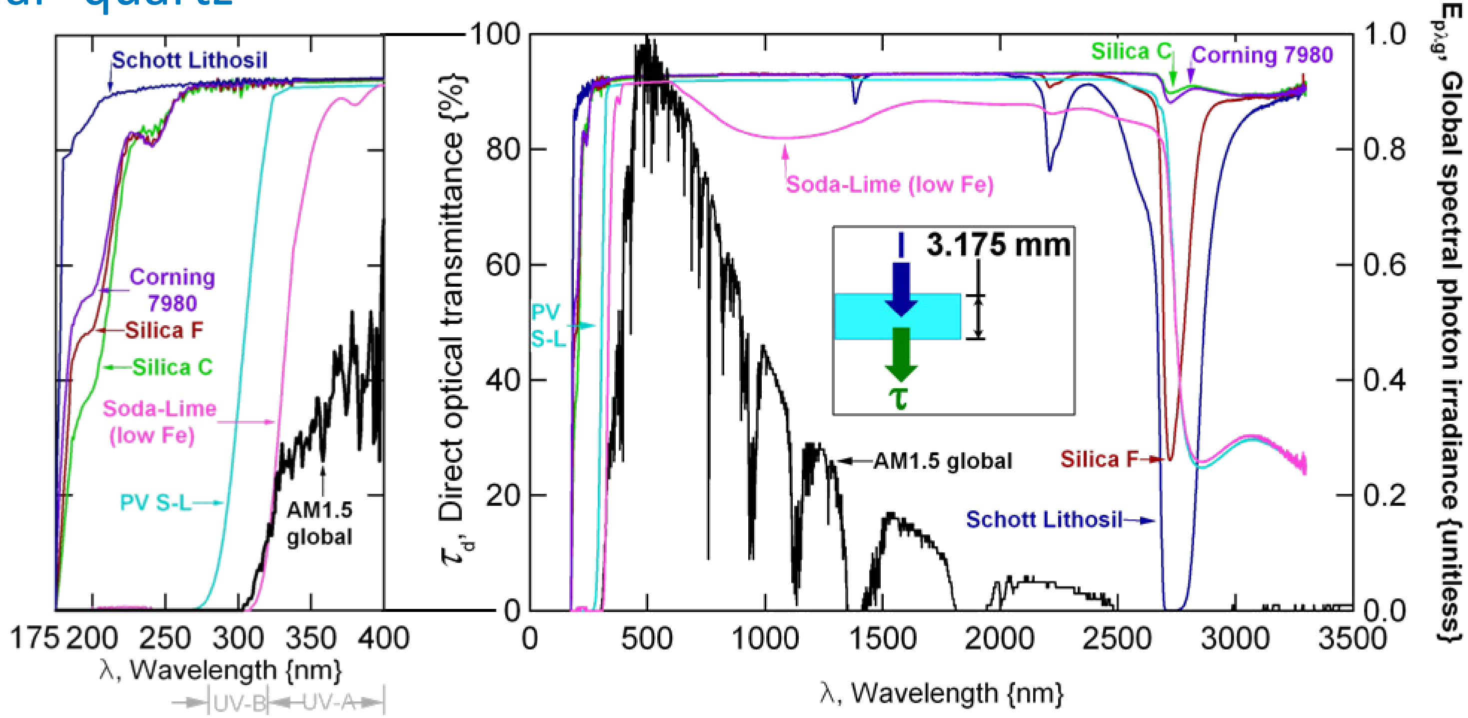
- Standard specifies silica/polymer or silica/polymer/silica specimens.
- Glass z=3±1mm. In datasheets, use no texture, coatings, or AR layer(s).

"Silica"- what does that mean? Examples of glass for comparison, including:

Silica in round-robin

Soda-lime glass (low Fe and PV specific)

Commercial "quartz"



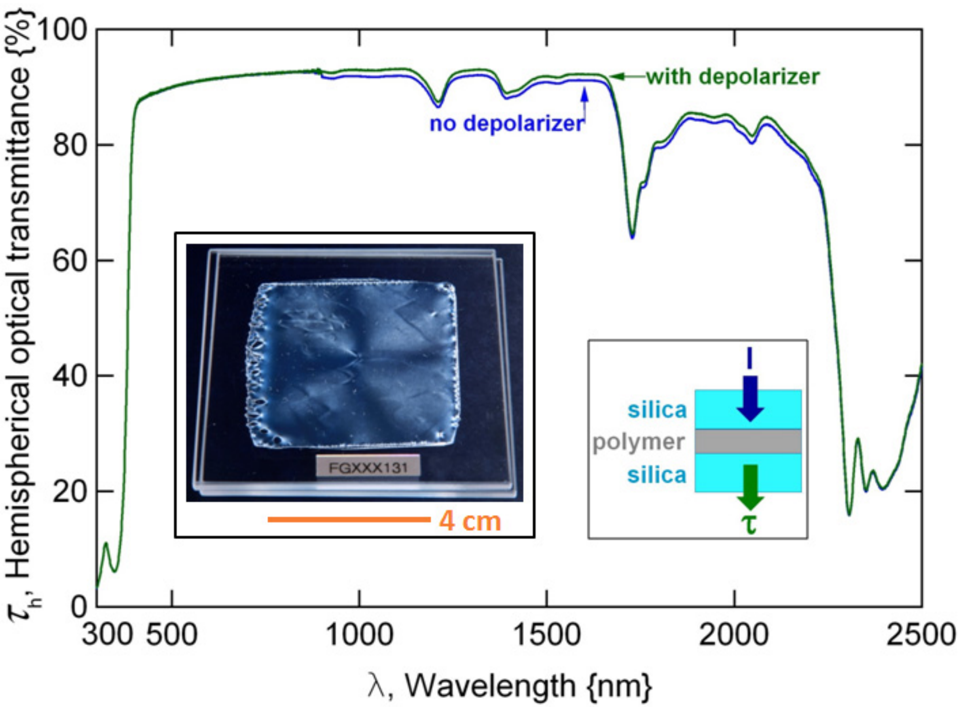
Measured τ for (2) silica glass specimens relative to commercial "quartz" and soda-lime glass products.

- τ_{sw}~93%; τ>90% at λ=300 nm. *YI*~0.2, λ_{cUV}<250nm. Few absorbance peaks.

A depolarizer Minimizes the Effects of Birefringence

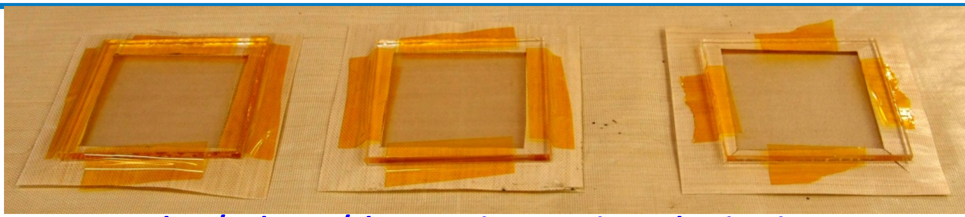
- Materials (*e.g.*, EVA and polyolefin) are birefringent (polarization sensitive).
- The effect may be used to visualize/quantify stress within specimens.
- Birefringence can render discontinuities during measurements at grating or source changes.
- Effect may be minimized by using a depolarizer with your spectrophotometer.

- Also be aware of the effect of residual moisture (remaining in a specimen after aging in humidity)!



Measured τ for a g/p/g specimen, measured on the same spectrophotometer, with and without a depolarizer.

Details of the Round-Robin Experiment



Glass/polymer/glass specimens prior to lamination, including Teflon coated fiberglass release liners at the specimen's periphery, and Kapton tape used to hold the components in place.

Goals:

- Determine within laboratory repeatability and interlaboratory reproducibility for the test standard.
- Develop the test standard (λ_{cUV}).

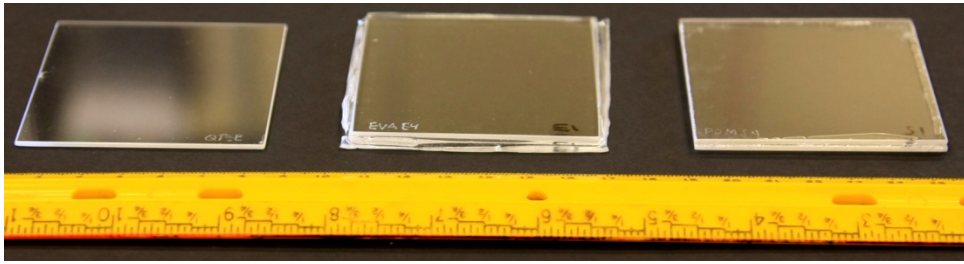
Discovery experiments:

- Variability of representative silica glass.
- Single-beam vs. double-beam spectrophotometers.
- Interlaboratory variability of specimen fabrication.

Round-Robin:

- 7 participating laboratories, w/ (6) different instrument models (2 replicates).
- 4 material types: EVA, ionomer, PDMS, & TPO. Hazy and non-hazy version of (1).
- Both glass/polymer and glass/polymer/glass specimen geometries examined.

- NREL data treatment: for $0\%<\tau$ or $\tau>100\%$, use $\tau=0.0001\%$ or $\tau=99.9999\%$



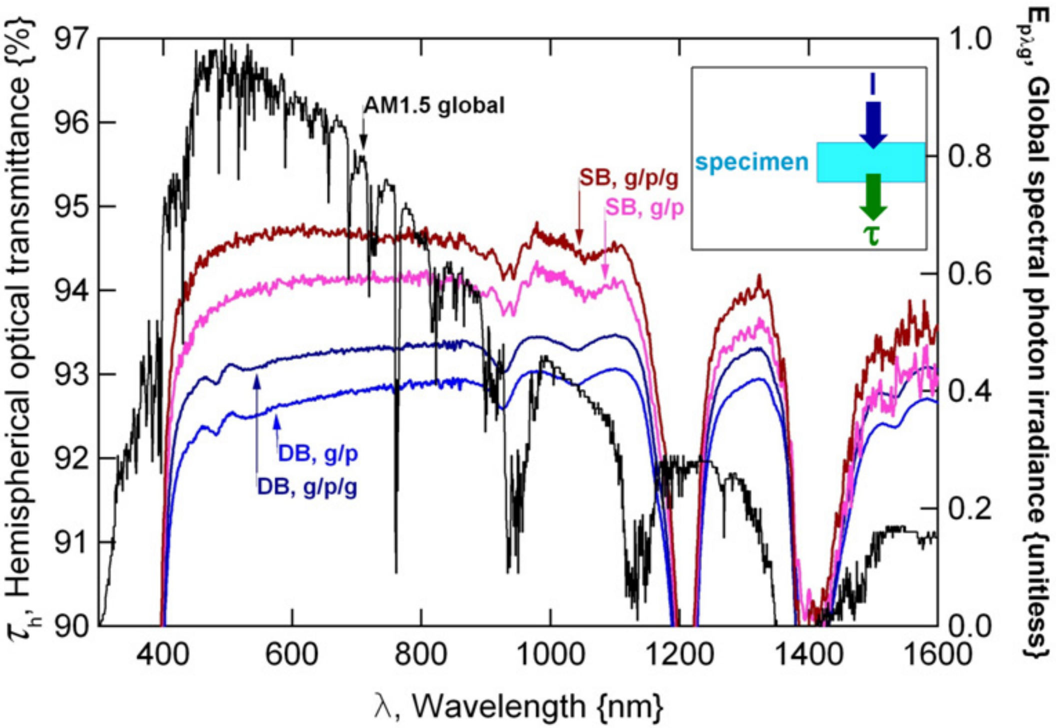
Representative silica, and silica/polymer/silica specimens ready for examination (EVA and PDMS shown)

Single- Found Comparable to Double-Beam Instrument (1)

- Substantial (1.3% difference) between SB (without measurement correction) and DB instruments.
- Solution: first baseline with specimen on exit port then measure with specimen on entrance port for automatic measurement compensation.

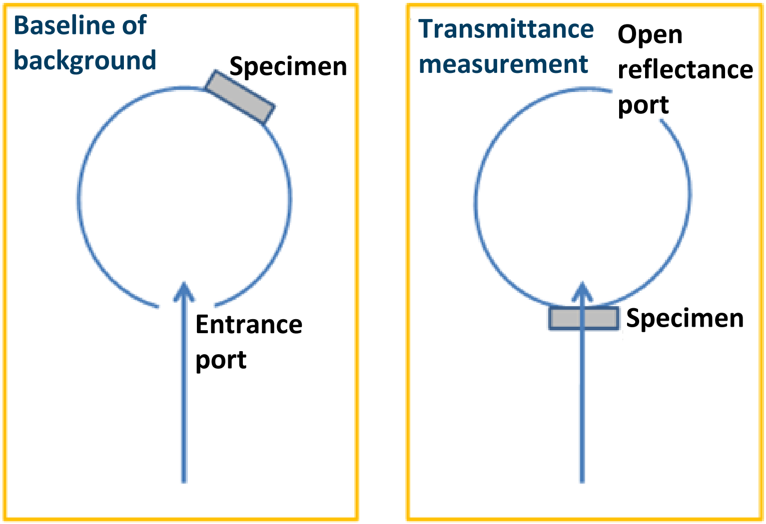
- ~0.6% difference between g/p/g and g/p measurements.
- $\tau_{g/p/g} > \tau_{g/p}$ (typically).
- Δ comes from refractive index at polymer/air or glass/air.

- *n* mismatch in air is different for the measurement than at the polymer/cell interface.



Comparison of single-beam (uncorrected) and double-beam instrument measurements for glass/polymer and glass/polymer/glass specimens.

Single- Found Comparable to Double-Beam Instrument (2)

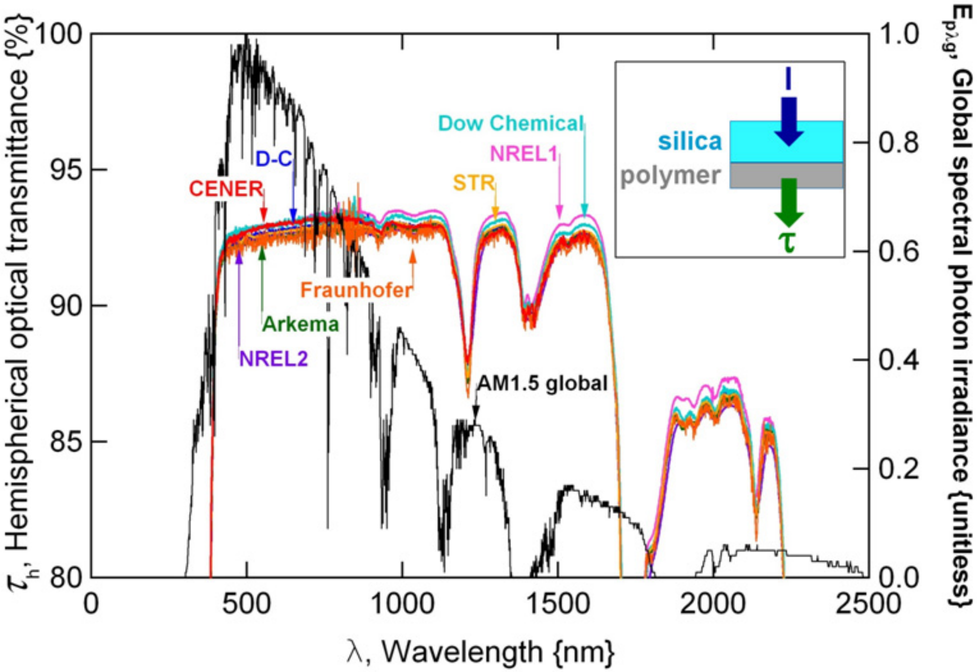


Schematic showing the procedure to baseline then measure using a SB instrument.

- Baselining procedure (with light first striking the sphere) more accurately accounts for reflectance at the entrance port and light trapping within the sphere.
- Requires a double-beam or off-axis sphere.

See also: "RSA-PE-20, AQ-00073-000, Rev. 7", Labsphere Inc., 2001, 1-34.

- With compensation, the SB measurements were within the range of error for the different laboratories.
- Discontinuity at detector & grating changeover (~800 nm) as well as greater noise evident in the UV-vis profiles.
- Noise from technology (detector) limitations as well as airborne moisture.



Comparison of single-beam (corrected) and double-beam instrument measurements (representative profiles) for glass/polymer specimens.

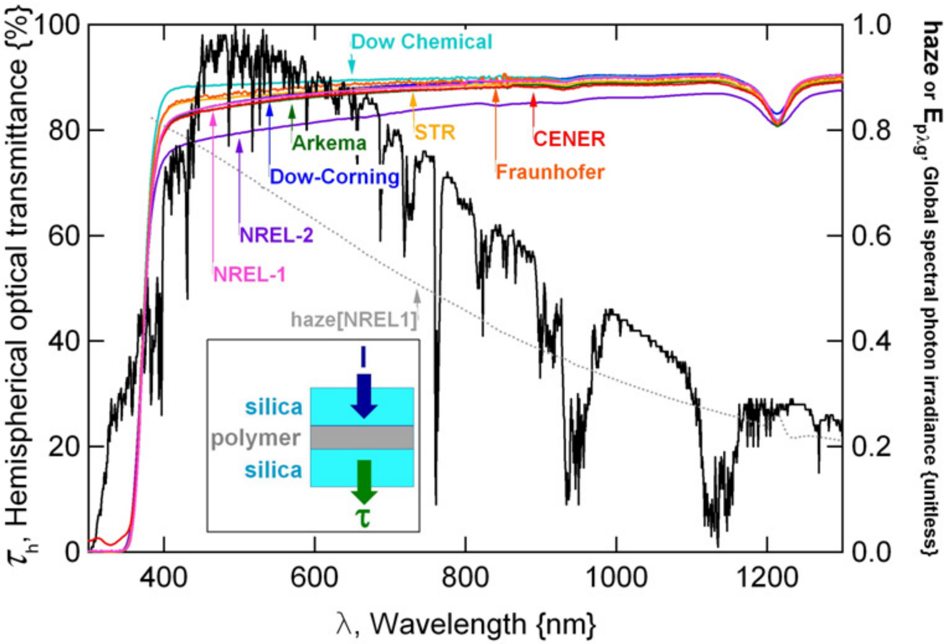
Haze-Prone Material Limited by Instrument Make

- Typically very strong correlation (overlap) for τ at all λ's between the labs.
- Considerable variation for the (1) hazy material intentionally chosen for R-R.
- Correlates with optical *haze,* $(\tau_h-\tau_d)\bullet \tau_h^{-1}$, particularly for NREL2 instrument.
- Some correlation between same instrument model, *e.g.*, D-C and NREL1.

- Variation could result from the different acceptance angles for each instrument make & model.
- θ_{HFOV} not specified in product literature.

- Variation could also result from discoloration of the sphere wall or reflectors at the ports.

- Unclear if same trend would emerge for discolored aged specimens.



Measured τ for the haze-prone material.
The *haze* (calculated from NREL 1) is also shown, relative to the normalized terrestrial solar spectrum.

Measurement Thresholds

(From labs' 10x repeated measurements of the same EVA specimen without replacement).

• Minimum thresholds of ±0.03%, ±0.01, and ±0.5nm for τ, *YI*, and λ_{cUV} for the instruments.

(From labs' 10x repeated measurements of the same EVA specimen with replacement).

• Practical threshold values of ±0.06%, ±0.02, and ±0.5nm for τ, *YI*, and λ_{cUV} for the specimens.

"Statistical" Terminology

• Repeatability, s_r: "What is the average of the variance for the laboratories – how tightly clustered are the data within each laboratory?" If each lab had a small variation, then s_r would be minimal, even if the variation between the different labs was substantial.

• Reproducibility, s_R: Deviation of the laboratory averages from the average of the experiment as well as the term s_r weighted by the number of samples How well do the data sets overlap and how tightly clustered are the data within each laboratory (s_r)?"

Specimen Manufacture Experiment

• What is the s_r and s_R associated with the making of specimens of the same test material?

• Each lab in the R-R was tasked with creating (3) g/p and (3) g/p/g specimens.

• EVA sent to each lab with the standard document. Purchase silica and build specimens.

• All specimens measured on the same NREL instrument.

The Variability for the Make of (EVA) Specimens

• s_r and s_R both apply to specimens (not measurements) made in different laboratories.

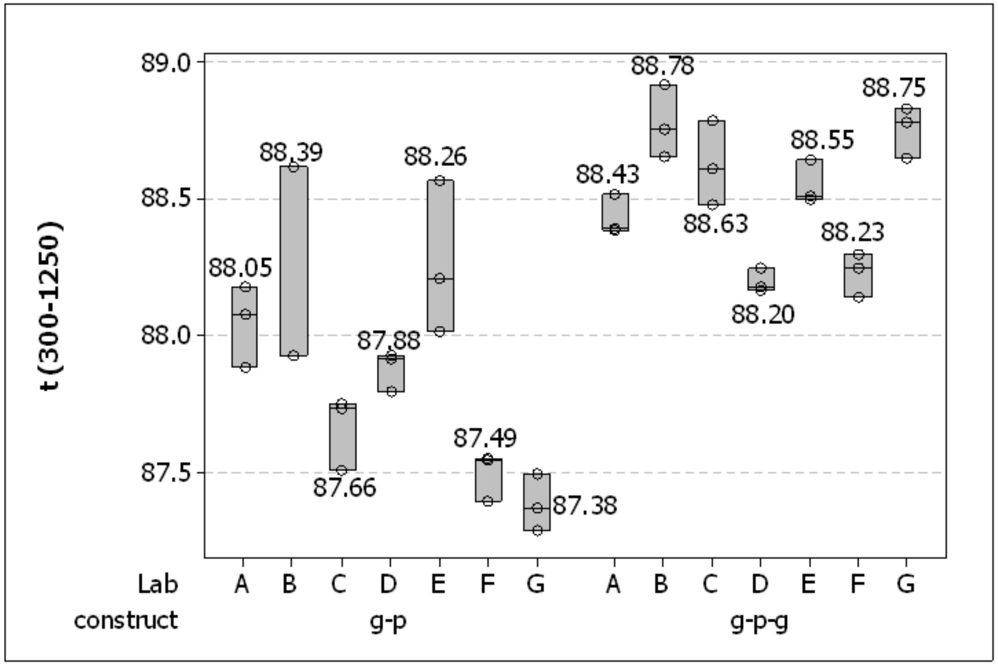
• g/p EVA-B, g/p EVA-E, g/p/g EVA-B, g/p/g EVA-C showed greatest variability

•$\tau_{g/p/g} > \tau_{g/p}$ (by 0.6%); $YI_{g/p/g} < YI_{g/p}$ (by 0.1); $\lambda_{cUV\ g/p/g} < \lambda_{cUV\ g/p}$ (by 1nm)
Attributed to reflection loss, typically: $n_{air} < n_{silica} < n_{polymer}$.

•Maximum s_r and s_R of τ_{sw}=±0.29%, τ_{rsw}=±0.29%, YI=±0.09, and λ_{cUV}=±1.3nm.

•Maximum s_r and s_R both observed for the g/p specimens.

• s_r and s_R for different makes of EVA ~3x measurement minimum threshold but ~1/3x that observed for the different materials and instruments used in the R-R.



Box plot for τ_{rsw} of g/p EVA specimens.

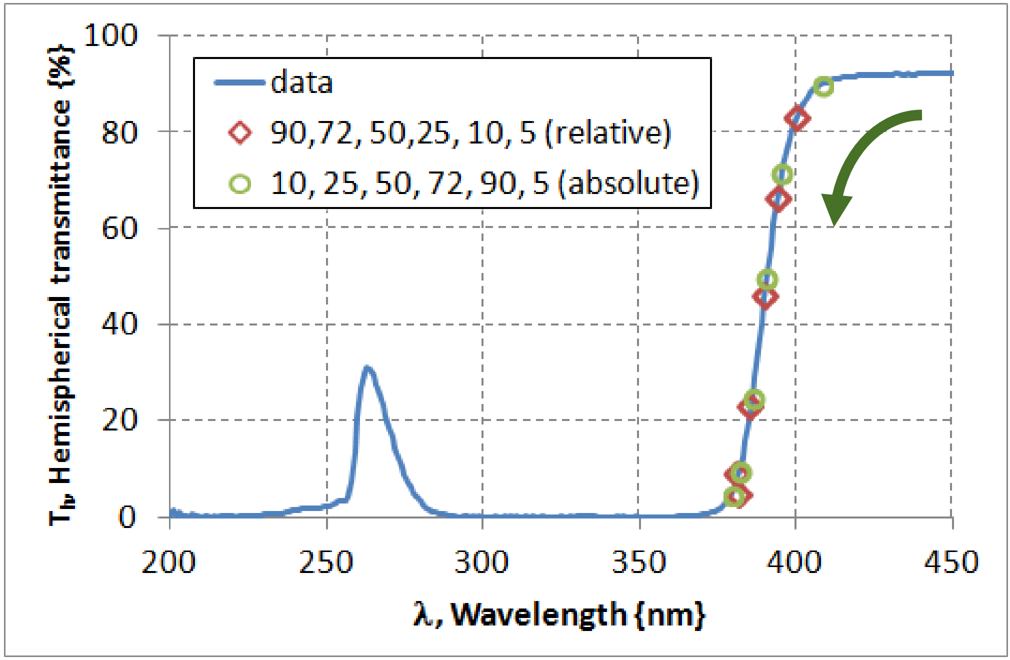
How to Determine the UV Cut-off Wavelength (λ_{cUV})?

- Candidate criteria:

10% absolute τ (absorbance of 1, common in biological- and nano-sciences).
ATLAS/Ametek (extrapolate to 5% relative to τ_{max}).
1% absolute τ ("physics approach" for biologically affecting radiation).
50% absolute τ (photographic filters).

- Is a low, medium, or high threshold preferred (τ=10, 25, 50, 72, or 90%)?
- Use an absolute or relative τ?

- Potential pitfall: spectra with UV transmitting regions.

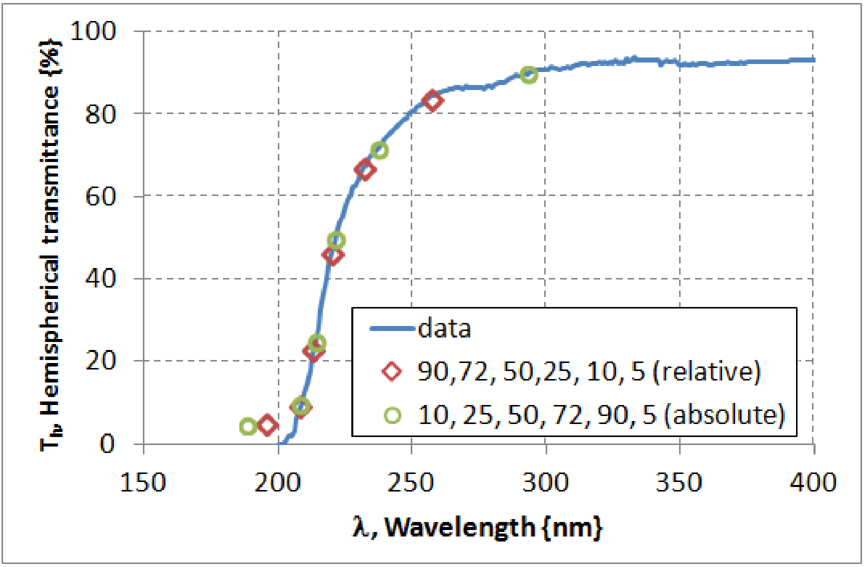


The λ_{cUV} determination algorithm must allow for UV transmitting regions.

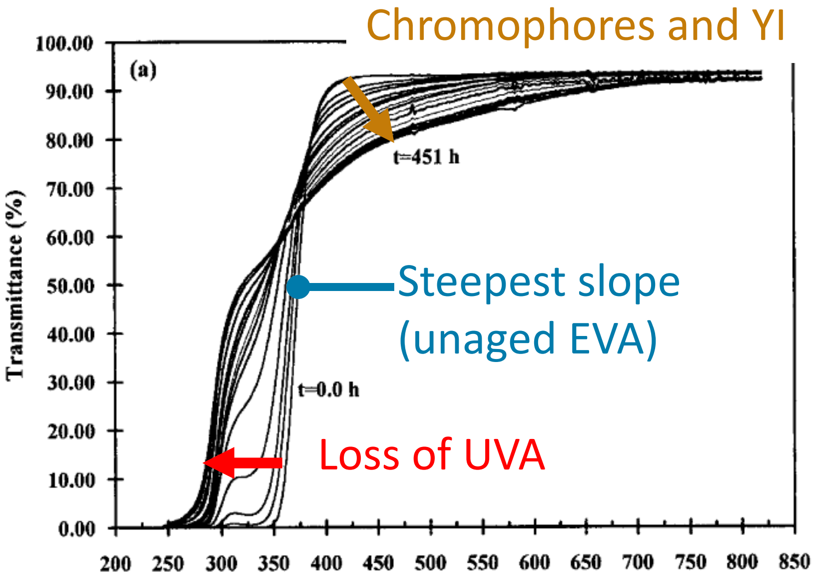
The 10% Absolute Criteria Was Selected for λ_{cUV}

- Several criteria approached/exceeded the ±0.5 nm resolution for Δ=1nm.
- Best s_r, s_R near steepest slope in τ profile (50% for unaged encapsulation)
- R-R: ATLAS/Ametek criteria was less repeatable & reproducible (>1 nm).
- Ametek method could render results off of the data profile.

- A low (τ≥10%) absolute (immediately defined) threshold was selected to discern between chromophore species formation (as in *YI*) and loss of the UV absorber or stabilizer additives (separate from *YI*).



Extrapolated λ_{cUV} criteria may fall off of the measured data profile.



Example: aging of EVA in Pern, SOLMAT, 41/42, 1996, 587-615.

The General Results of the Round-Robin Experiment

- s_r now emphasizes repeatability within the same lab.
- s_R now emphasizes reproducibility between labs.

- Maximum ($\geq 2\sigma$) s_r values of $\pm$0.78%, $\pm$0.63%, $\pm$0.27, and $\pm$2.4nm for τ_{sw}, τ_{rsw}, *YI*, and λ_{cUV}, respectively.
- Maximum ($\geq 2\sigma$) s_R values of $\pm$0.88%, $\pm$0.90%, $\pm$0.46, and $\pm$2.4nm for τ_{sw}, τ_{rsw}, *YI*, and λ_{cUV}.

- The maximum s_r and s_R values R-R exceed the minimum threshold (no replacement) and practical threshold (with replacement) τ values $\rightarrow$ increased variability for measurements of different materials.
- s_r was generally less than the s_R.

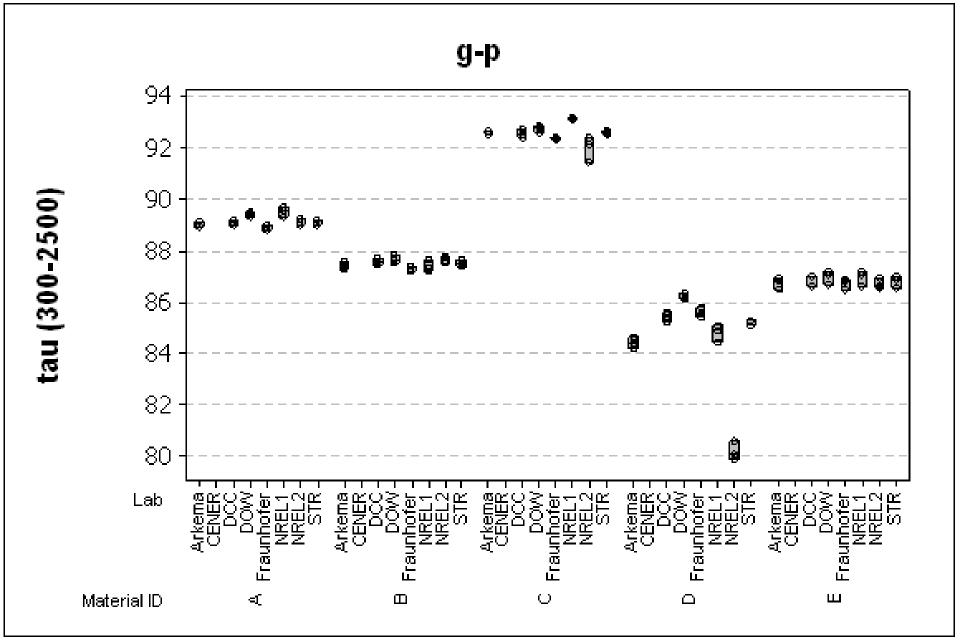
Consistent with replacement experiment for the g/p/g EVA specimen.

The τ Results of the Round-Robin Experiment

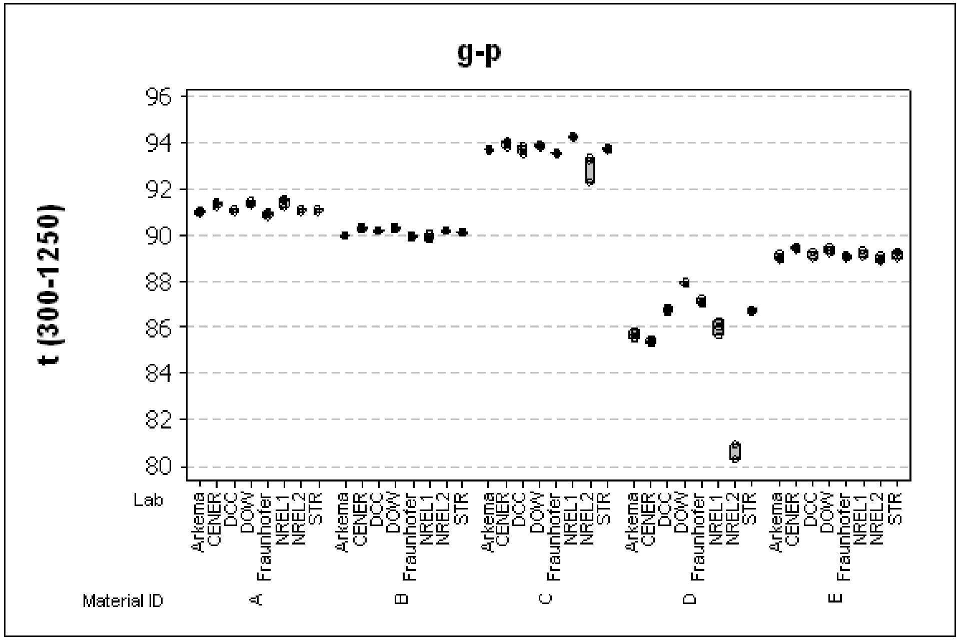
- 5% range of optical performance, exceeding s_r or s_R, for similar *h*. Attributed to the materials (or formulations).

- τ_{sw} is typically less than τ_{rsw}.
- Polymers' absorbing IR bands do not affect τ_{rsw} ($300<\lambda<1250$ nm).

- τ for the g/p/g specimens typically greater than g/p specimens.
- *n* mismatch (reflectance loss). $n_{polymer} > n_{silica}$, except for material C.



Box plot summarizing the τ_{sw} results from the R-R experiment.

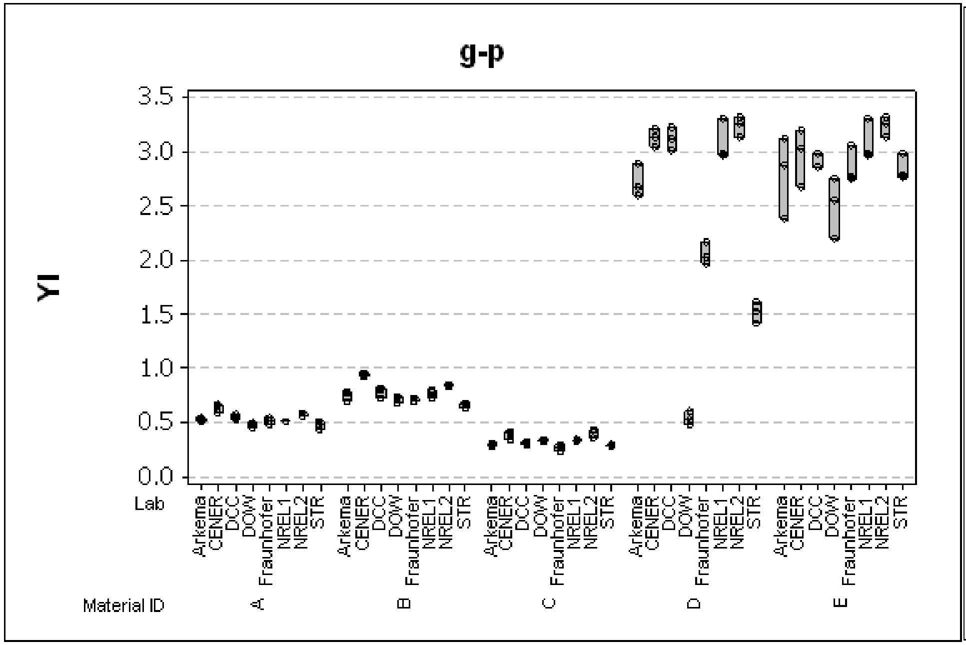


Box plot summarizing the τ_{rsw} results from the R-R experiment.

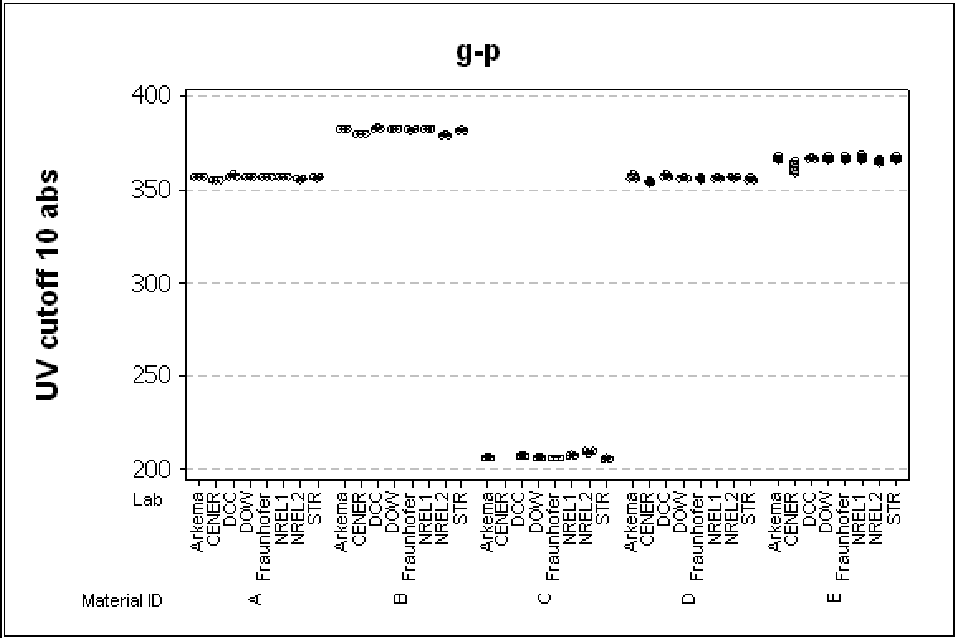
The *YI* and λ_{cUV} Results of the R-R Experiment

- s_r and s_R of the hazy material D $\rightarrow$10x the τ and YI of other materials.
- Consistent with instrument dependent data profiles (θ_{HFOV}, sphere).

- Material C: greatest s_r and s_R values for λ_{cUV}, with lowest λ_{cUV}.
- Results from detector and atmospheric (H_2O scatters UV) limitations.



Box plot summarizing the *YI* results from the R-R experiment.



Box plot summarizing the λ_{cUV} results from the R-R experiment.

Summary

•Measurement capability:
Minimum threshold of τ=±0.03%, *YI*=±0.01, and λ_{cUV} =±0.5nm for contemporary spectrophotometer instruments.
Practical threshold of τ=±0.06%, *YI*=±0.02, and λ_{cUV} = ±0.5 nm for a particular specimen using a trusted instrument.
•The criterion 10% of absolute τ provides a reasonable s_r and s_R for λ_{cUV} and helps to distinguish between the formation of chromophores and loss of UV absorpber(s).
•Maximum s_r of τ_{sw}=±0.78%, τ_{rsw}=±0.63%, *YI*=±0.27, and λ_{cUV}=±2.4nm.
•Maximum s_R of τ_{sw}=±0.88%, τ_{rsw}=±0.90%, *YI*=±0.46, and λ_{cUV}=±2.4nm.
• s_r and s_R for different makes of EVA ~3x that which can be measured for a particular specimen but ~1/3x that observed for the different materials and instruments used in the R-R.

•Use of a depolarizer for measurements of birefringent materials.
•Representative τ profiles provided for silica glass
(the substrates and superstrates in the test procedure).
•Proper baselining will compensate a single-beam spectrophotometer.
•Haze-prone materials were found to limit τ and YI.
(Unclear if this extends to discolored aged specimens).

Acknowledgements

- NREL: Dr. Michael Kempe, Scott Deibert

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NREL STM campus, Dennis Schroeder

See also the manuscript: “Examination of an Optical Transmittance Test for PV Encapsulation Materials”, Proc. SPIE 2013, 8825-8.

Calculation of the YI

1. The three tristimulus values

$$X = k\int \tau[\lambda]S_{D65}[\lambda]\overline{x}[\lambda]d\lambda$$

$$Y = k\int \tau[\lambda]S_{D65}[\lambda]\overline{y}[\lambda]d\lambda$$

$$Z = k\int \tau[\lambda]S_{D65}[\lambda]\overline{z}[\lambda]d\lambda$$

2. The normalizing factor (k= 8.606•10^{-3} for 1nm increment)

$$k = \int S_{D65}[\lambda]\overline{y}[\lambda]d\lambda$$

3. The yellowness index (YI)

C_X=1.3013

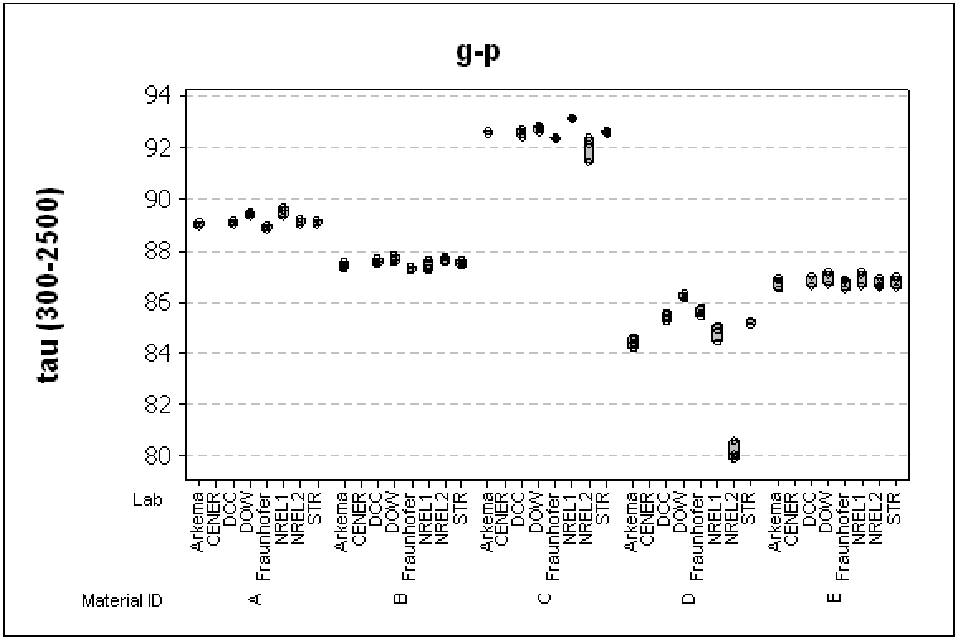
C_Z=1.1498.

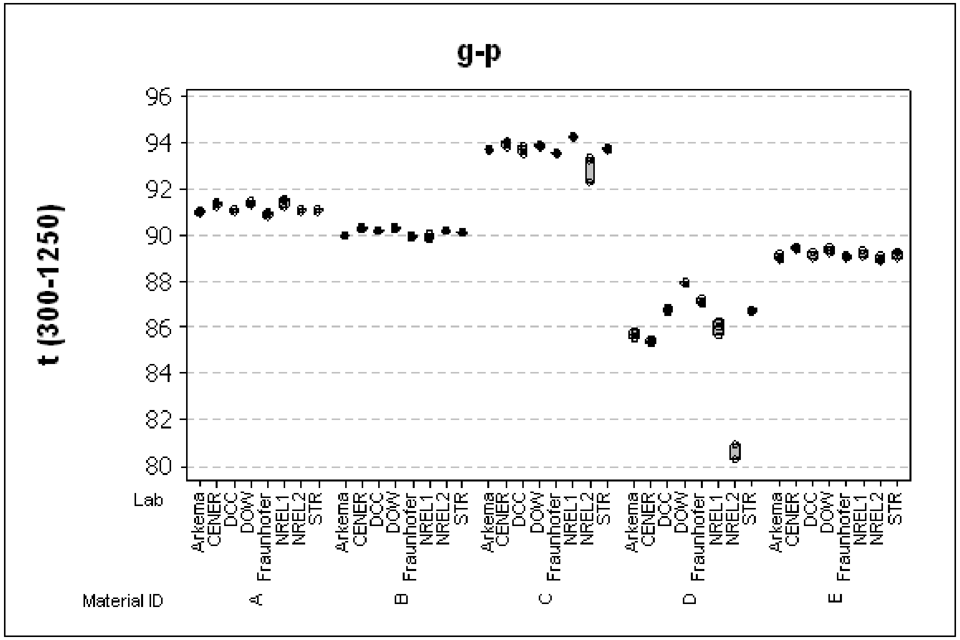
$$YI = 100\frac{C_X X - C_Z Z}{Y}$$

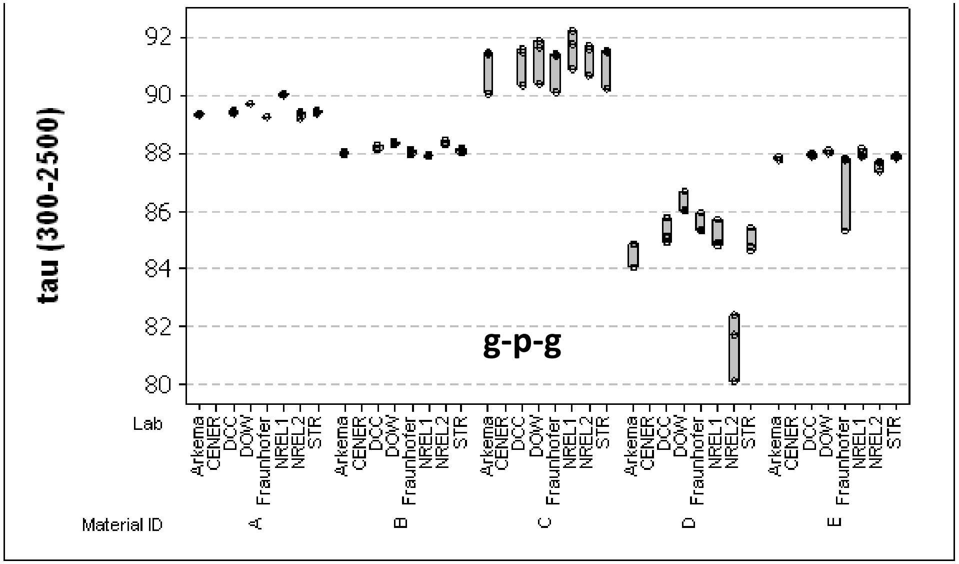
The steps for calculating *YI*.

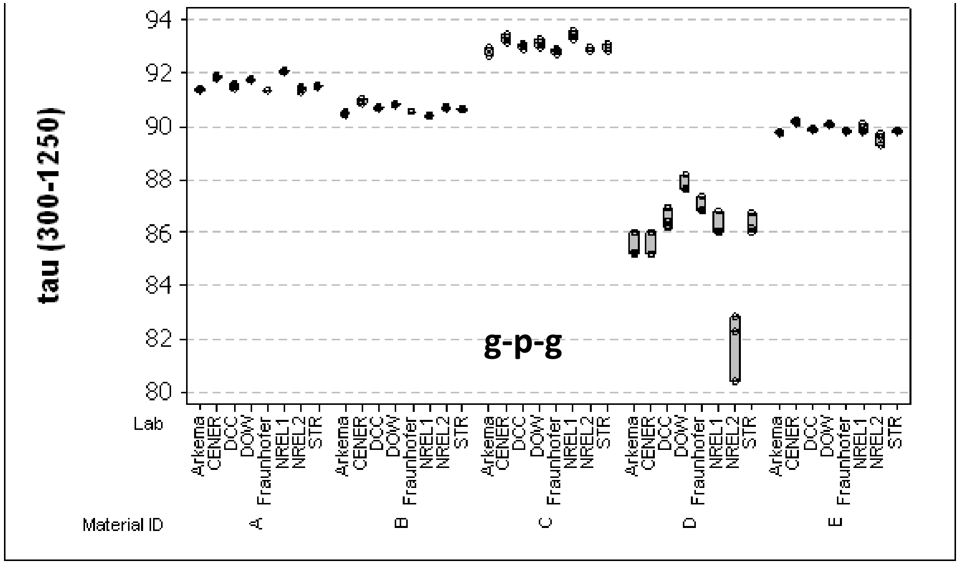
The τ Results of the Round-Robin Experiment

- g/p/g results compared to g/p here for reference. (Only g/p shown in formal presentation).







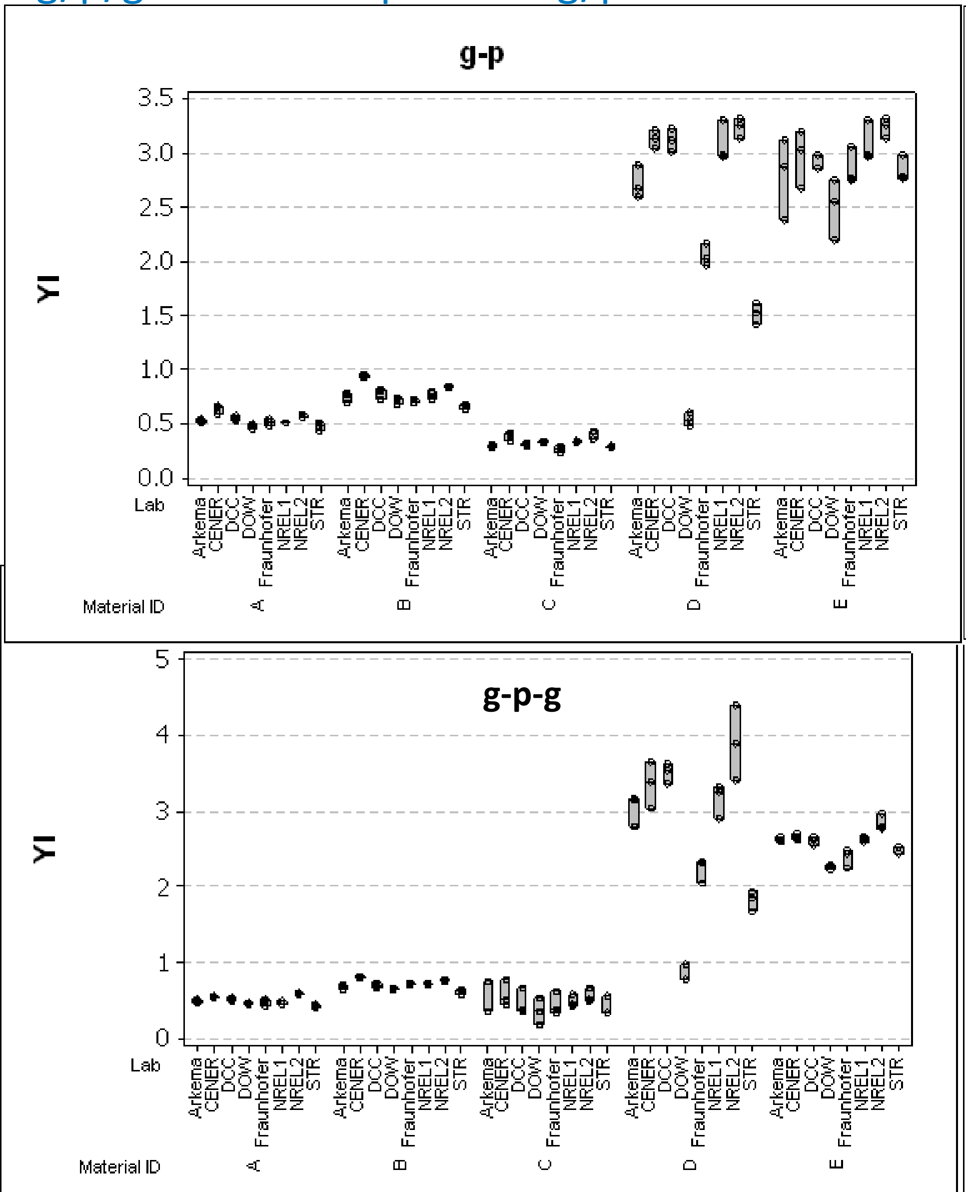


Box plot summarizing the τ_{sw} results from the R-R experiment.

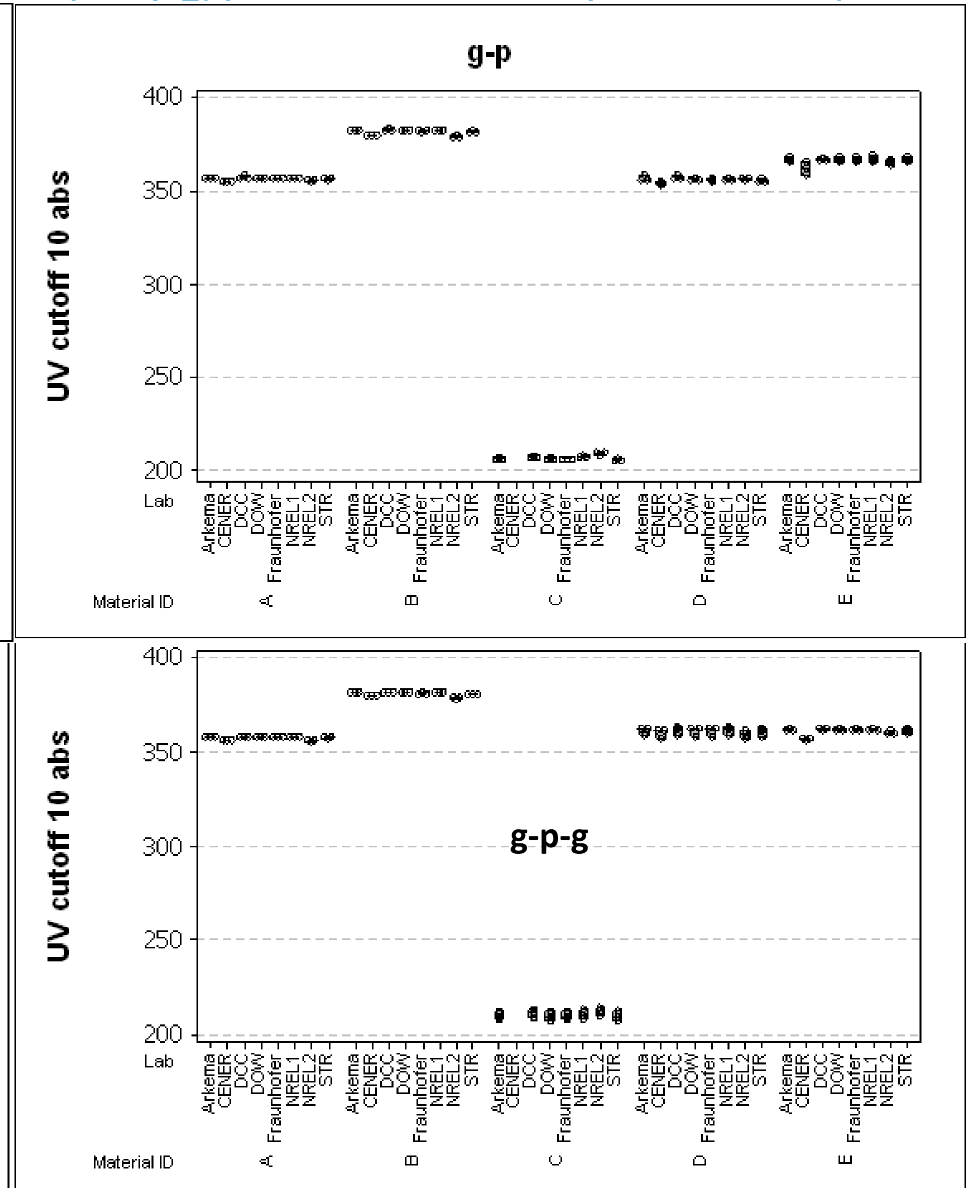
Box plot summarizing the τ_{rsw} results from the R-R experiment.

The *YI* and λ_{cUV} Results of the R-R Experiment

- g/p/g results compared to g/p here for reference. (Only g/p shown in formal presentation).



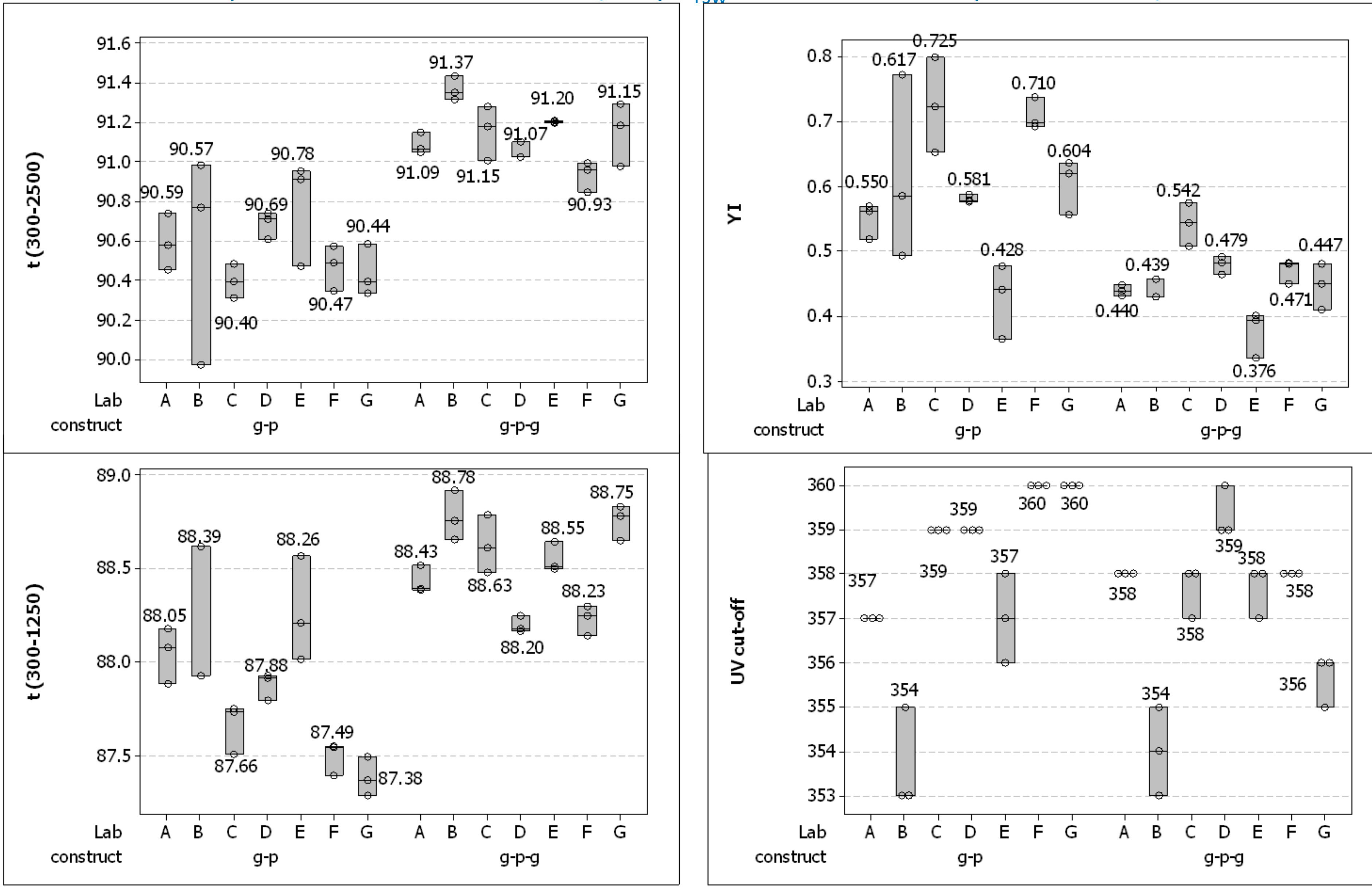
Box plot summarizing the *YI* results from the R-R experiment.



Box plot summarizing the λ_{cUV} results from the R-R experiment.

The τ , *YI*, and λ_{cUV} Results of the EVA Specimen Make Experiment

- All results compared here for reference. (Only τ_{rsw} shown in formal presentation).



Box plots summarizing the τ_{sw} , τ_{rsw} , YI, and λ_{cUV} results from the EVA specimen make experiment.

The τ , *YI*, and λ_{cUV} Results of the EVA Specimen Make Experiment

- All results compared here for reference. (Only τ_{rsw} figure appears in the formal presentation).

		τ_{sw} {%}		τ_{rsw} {%}		*YI* {unitless}		λ_{cUV} {nm}	
MATERIAL	CONSTRUCTION	*x*	*DIFF*	*x*	*DIFF*	*x*	*DIFF*	*x*	*DIFF*
EVA-A	g/p	88.05	0.15	90.59	0.14	0.55	0.03	357.0	0.5
EVA-B	g/p	88.39	0.35	90.57	0.51	0.62	0.14	353.7	1.0
EVA-C	g/p	87.66	0.12	90.40	0.08	0.72	0.07	359.0	0.5
EVA-D	g/p	87.88	0.07	90.69	0.07	0.58	0.01	359.0	0.5
EVA-E	g/p	88.26	0.28	90.78	0.24	0.43	0.06	357.0	1.0
EVA-F	g/p	87.49	0.08	90.47	0.11	0.71	0.02	360.0	0.5
EVA-G	g/p	87.38	0.10	90.44	0.13	0.60	0.04	360.0	0.5
***x* , AVG**	g/p	**87.87**	N/A	**90.56**	N/A	**0.60**	N/A	**358.0**	N/A
DIFF	g/p	**1.01**	N/A	**0.38**	N/A	**0.29**	N/A	**6.3**	N/A
EVA-A	g/p/g	88.43	0.07	91.09	0.05	0.44	0.01	358.0	0.5
EVA-B	g/p/g	88.78	0.13	91.37	0.06	0.44	0.01	354.0	1.0
EVA-C	g/p/g	88.63	0.15	91.15	0.14	0.54	0.03	357.7	0.5
EVA-D	g/p/g	88.20	0.04	91.07	0.04	0.48	0.01	359.3	0.5
EVA-E	g/p/g	88.55	0.07	91.20	0.01	0.38	0.03	357.7	0.5
EVA-F	g/p/g	88.23	0.08	90.93	0.07	0.47	0.02	358.0	0.5
EVA-G	g/p/g	88.75	0.09	91.15	0.16	0.45	0.04	355.7	0.5
***x* , AVG**	g/p/g	**88.51**	N/A	**91.14**	N/A	**0.46**	N/A	**357.2**	N/A
DIFF	g/p	**0.58**	N/A	**0.44**	N/A	**0.16**	N/A	**5.3**	N/A

Table summarizing the τ_{sw} , τ_{srsw} , YI, and λ_{cUV} results from the EVA specimen make experiment.