SolarPACES
Solar Power & Chemical Energy Systems

Round Robin Test of Absorptance and Emittance of Particles for CSP

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2. ENEA , Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile, Centro Ricerche Casaccia (Roma, Italy)
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6. NREL, National Renewable Energy Laboratory (Golden, Colorado, United States)
7. SNL, Sandia National Laboratories (Albuquerque, New Mexico, United States)

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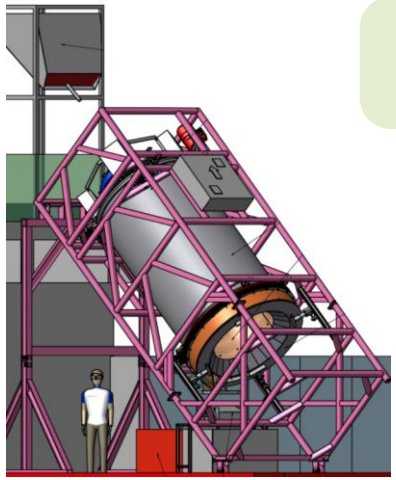
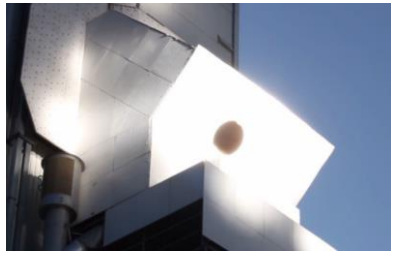
Background

- SolarPACES Task III: *Solar Technology and Advanced Applications*
  - Optical Properties Working Group, coordinated by Aránzazu Fernández-García.
- Working Group Objective
  - *“Define and improve the measurement methods and protocols of optical properties of solar materials (including reflectors -clean and soiled-, receiver particles, etc.), both in laboratory conditions and in solar fields, and translate the results into official standardization bodies.”*
- Motivation for Current Work
  - General absorber efficiency [1]: $\eta = (\alpha \cdot Q" - \varepsilon \cdot \sigma \cdot T^4)/Q"$
  - Establish a guideline for evaluating the optical properties of particles.
    - Special focus on instruments/configurations that require windows.
  - Assess the guideline and proposed window-correction method via a round robin test (RRT) among various institutes.

Directly-irradiated Particle Receivers



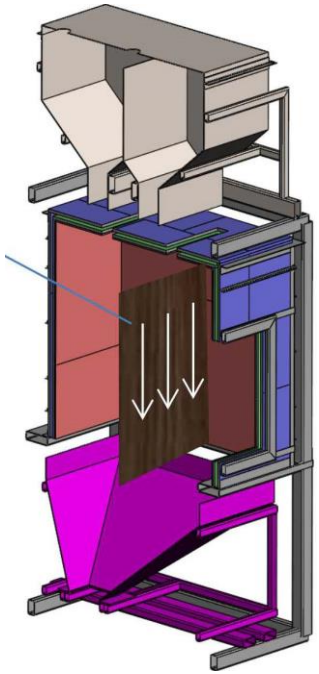


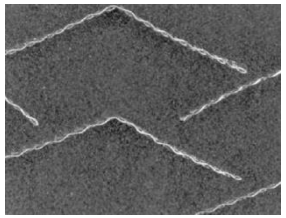
Centrifugal (DLR)

DOI: 10.1063/1.5067040
DOI: 10.1063/1.5117530

Free-Falling (SNL)

SAND2018-9997C



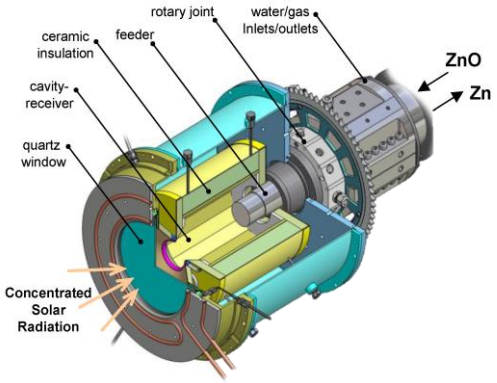


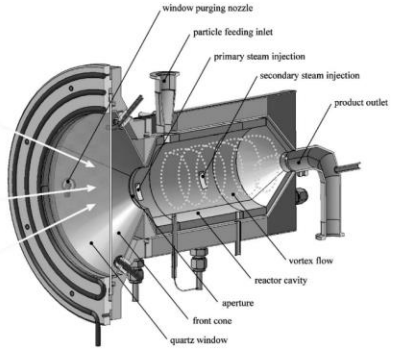
Obstructed Flow (GT, KSU)

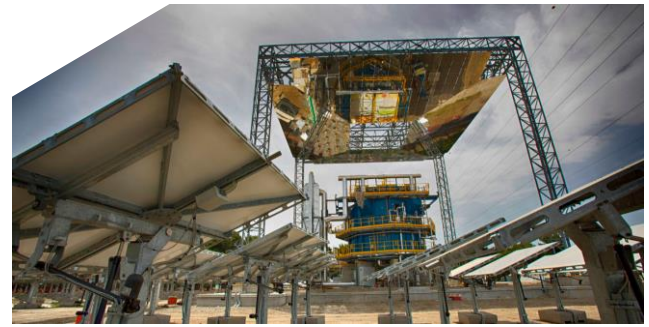
DOI: 10.1016/j.solener.2017.03.048

Solar Thermochemical

DOI: 10.1115/1.1349717





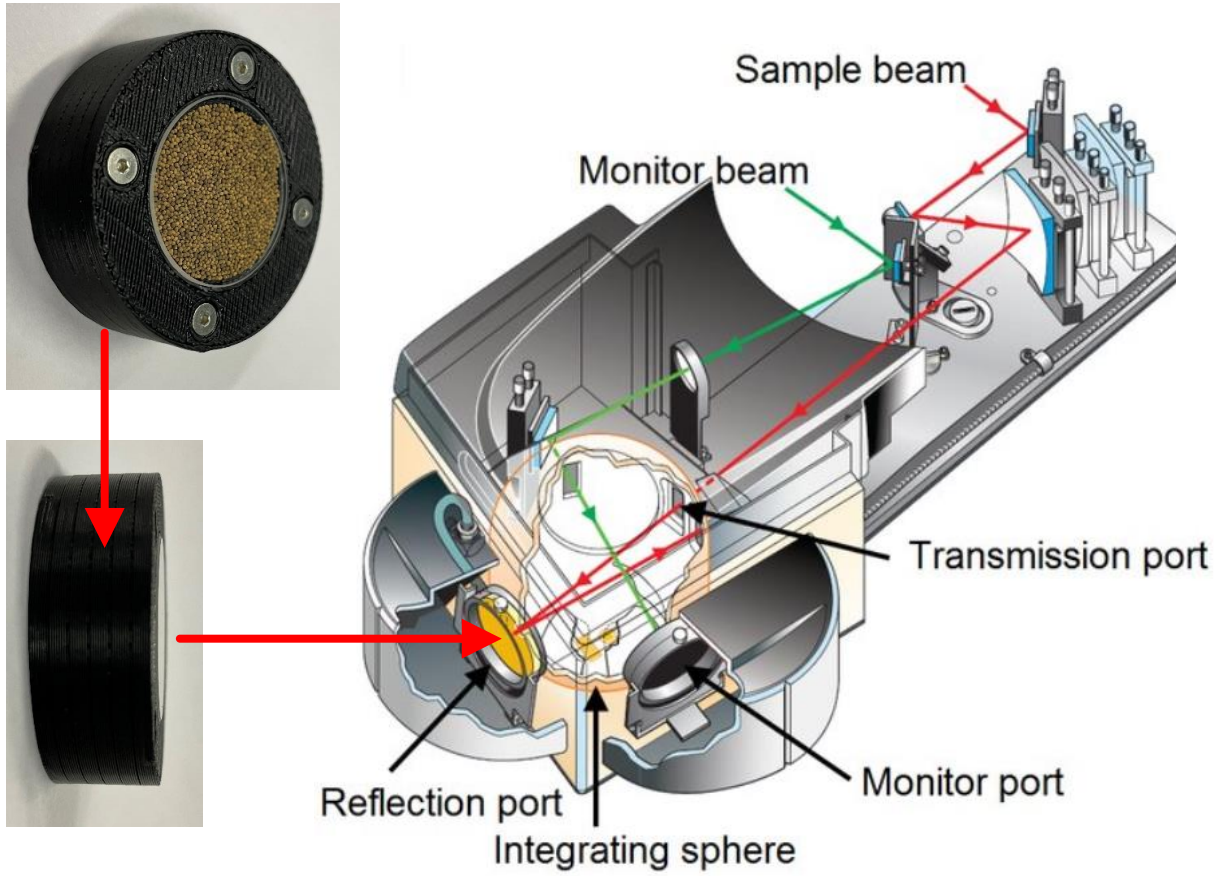


Fluidized Bed (Magaldi)

STEM – Solar Thermo-Electric Magaldi

The Measurement Challenge

Windowed Spectrophotometers



Windowless Reflectometers

Methodology

Sample ID	Trade Name / Description	Manufacturer	Diameter range
BL 1630	BauxLite	Saint-Gobain	297-590 µm
BL 3050	BauxLite	Saint-Gobain	590-1190 µm
SB 3050	Sintered bauxite	Saint-Gobain	297-590 µm
IP 3050	Interprop	Saint-Gobain	297-590 µm
Coated	BauxLite + black spinel	CIEMAT coating	297-590 µm

Note: Diameter range presented as min. and max. mesh sizes.

		Evaluator 1	Evaluator 2	Evaluator 3	Evaluator 4	Evaluator 5	Evaluator 6	Evaluator 1 / 6 / 7
α	Brand	PE1050	PE950	PE950	PE950	PE950	PE1050	Surface Optics 410
	Window	1mm quartz	4mm glass	2 mm SF4 glass	1mm sapphire	2mm quartz	1mm quartz	N/A
	Reference	Calibrated grey, diffuse refl. target, 10%R	Calibrated black, diffuse refl. target, 5-9%R	Certified spectralon, 99%R	Certified spectralon, 99%R	Calibrated grey, diffuse refl. target, 10%R	Certified spectralon, 99%R	Specular and diffuse calibration coupons provided by Surface Optics
ε	Brand	PE Frontier & Pike Mid-IR IntegratIR 76mm IS	-	PE FTIR 100 & 76mm Pike IS	-	PE Frontier & Pike Mid-IR IntegratIR 76mm IS	Thermo Nicolet 6700 FTIR & SOC-100	Surface Optics ET100
	Window	2mm ZnSe with AR-coating	-	2mm ZnSe with AR-coating	-	2mm ZnSe with AR-coating	None (beam-done)	N/A
	Reference	Diffuse gold reference RS-Au-02c	-	Diffuse gold reference	-	Diffuse gold reference	Diffuse gold reference, Avian Tech.	Specular gold calibration coupon provided by Surface Optics

Note: PE stands for PerkinElmer Lambda, IS stands for integrating sphere, and AR stands for anti-reflective.

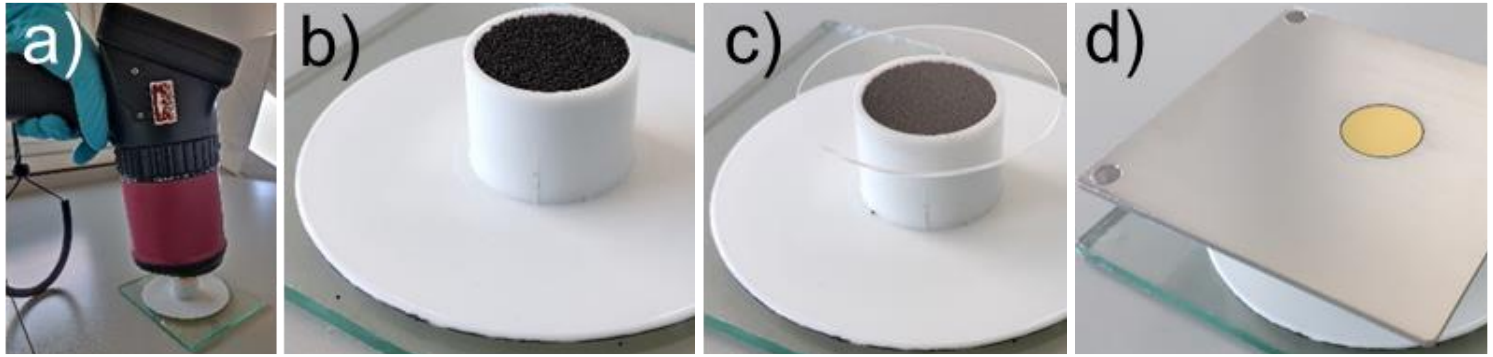
1. Window Correction Validation

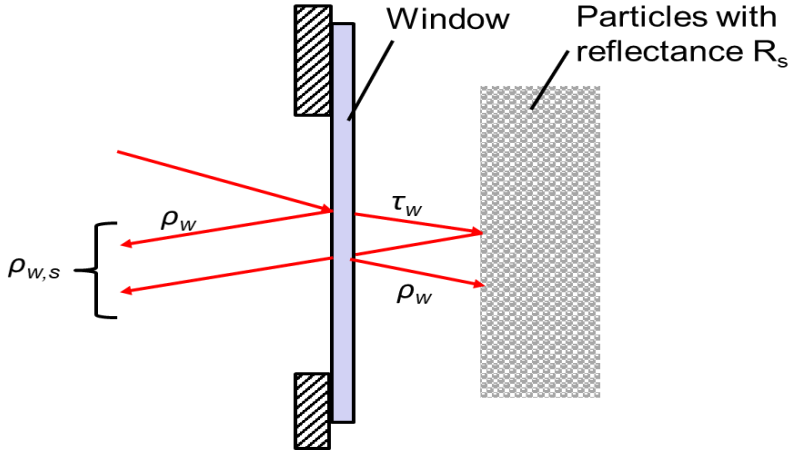
2. RRT: 5 particle types → 7 evaluating institutes → measure + correction → result comparison

WINDOW CORRECTION

Selected Window Correction

- Selected ***Method #0: Flat angular behavior***
  - Assumes negligible angular behavior of window.
  - Easiest to apply, good agreement with windowless measurements.
- Comprehensive descriptions of the 6 methods explored:
  - *SolarPACES Guideline, Method to evaluate the reflectance, absorptance and emittance of particles for concentrating solar power technology* and [2-4].
- Correction Method Evaluation:

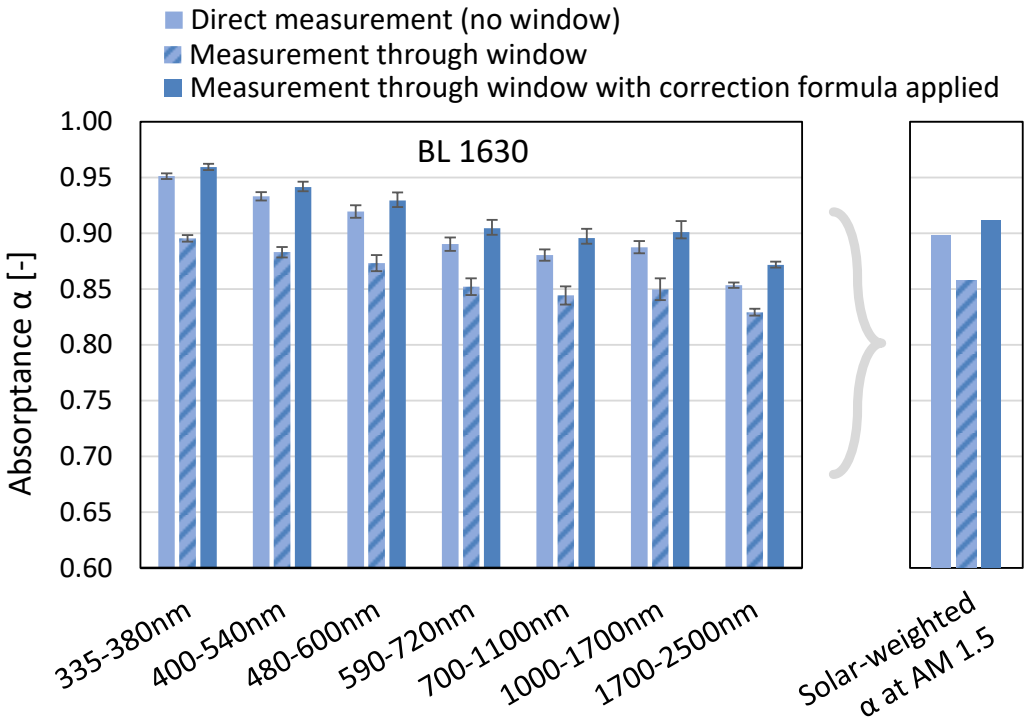


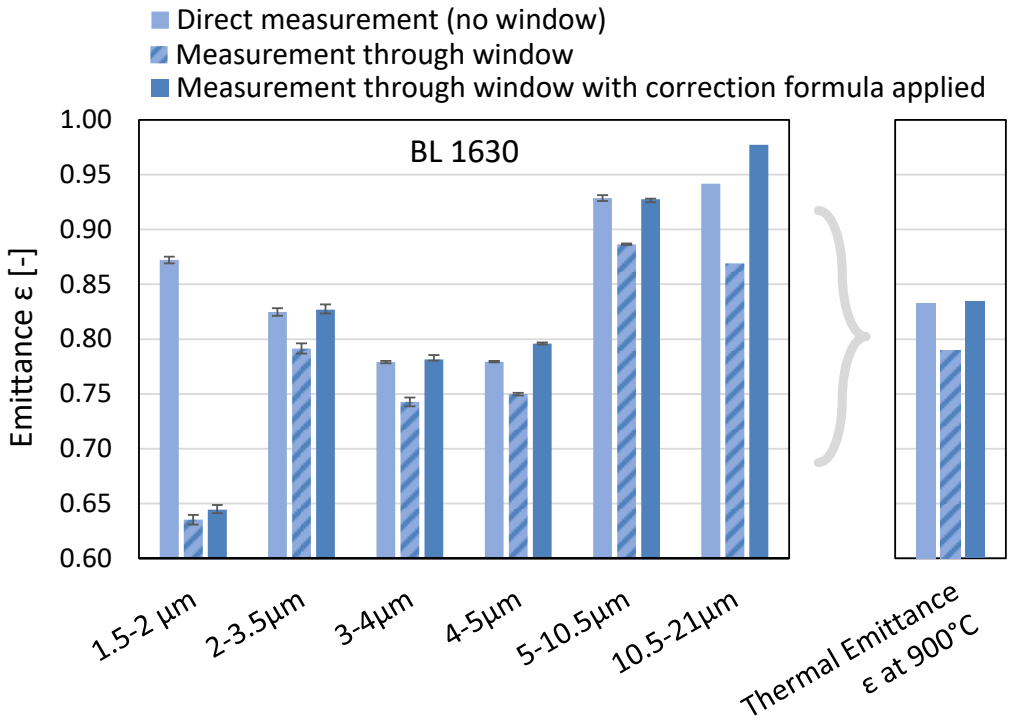


$$R_s = \frac{\rho_{w,s} - \rho_w}{\tau_w^2 + \rho_w(\rho_{w,s} - \rho_w)}$$

R_s = particle spectral reflectance
$\rho_{w,s}$ = particle spectr. refl. through window
ρ_w = spectral reflectance of the window
τ_w = spectral transmittance of the window

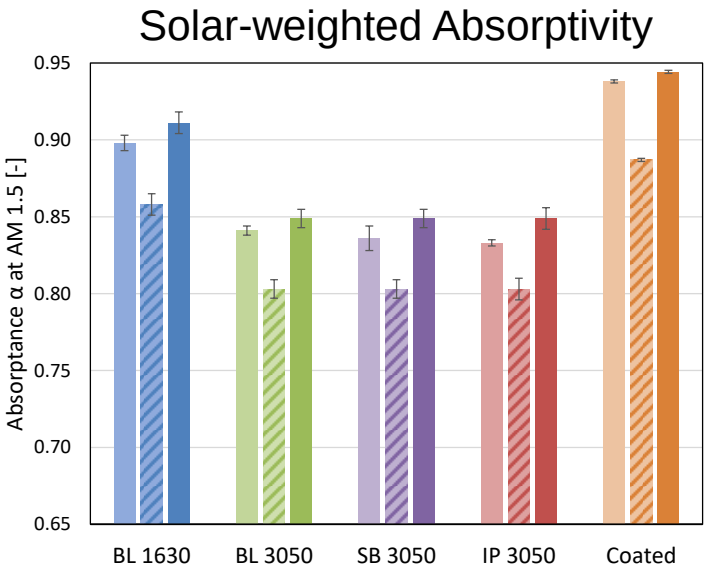
Example of Absorptance/Emmitance (BL 1630)

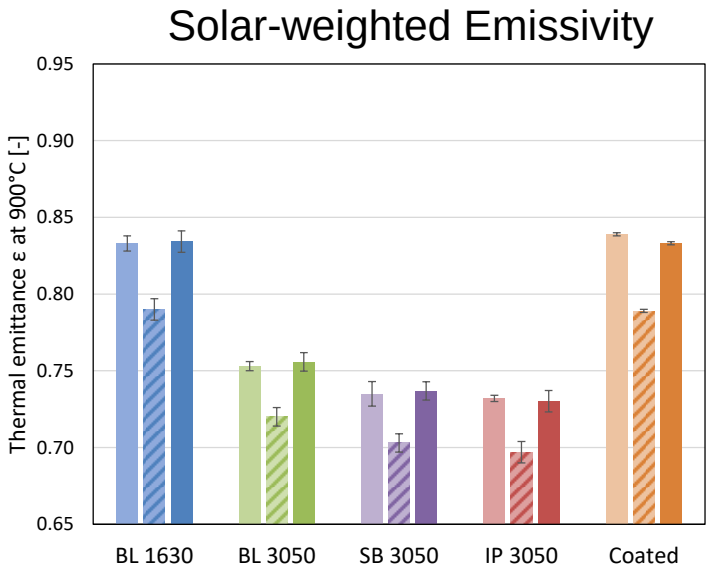


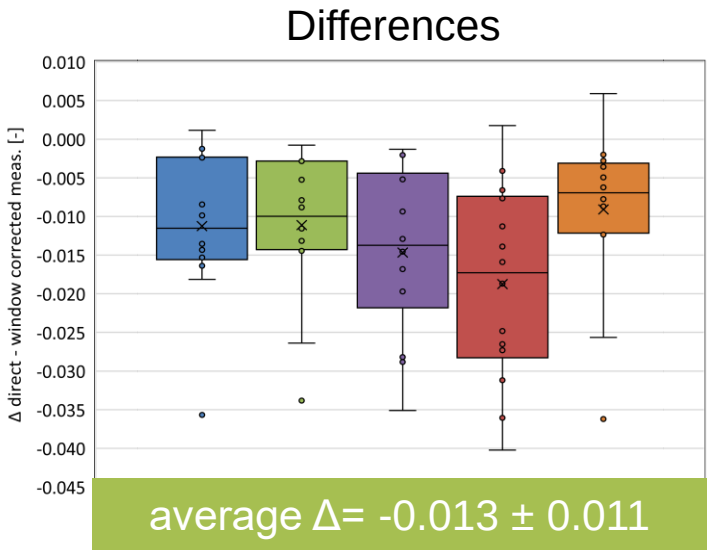


Comparison of direct (windowless) measurements with measurements through quartz (used from 250 - 2500nm) and ZnSe (used from 1.5 - 21µm) windows with and without the window correction method for BL 1630 particles in the absorptance spectral bands of the (left) SOC 410 and emittance bands of the (right) ET100.

Summary of Absorptance/Emmitance (all particles)





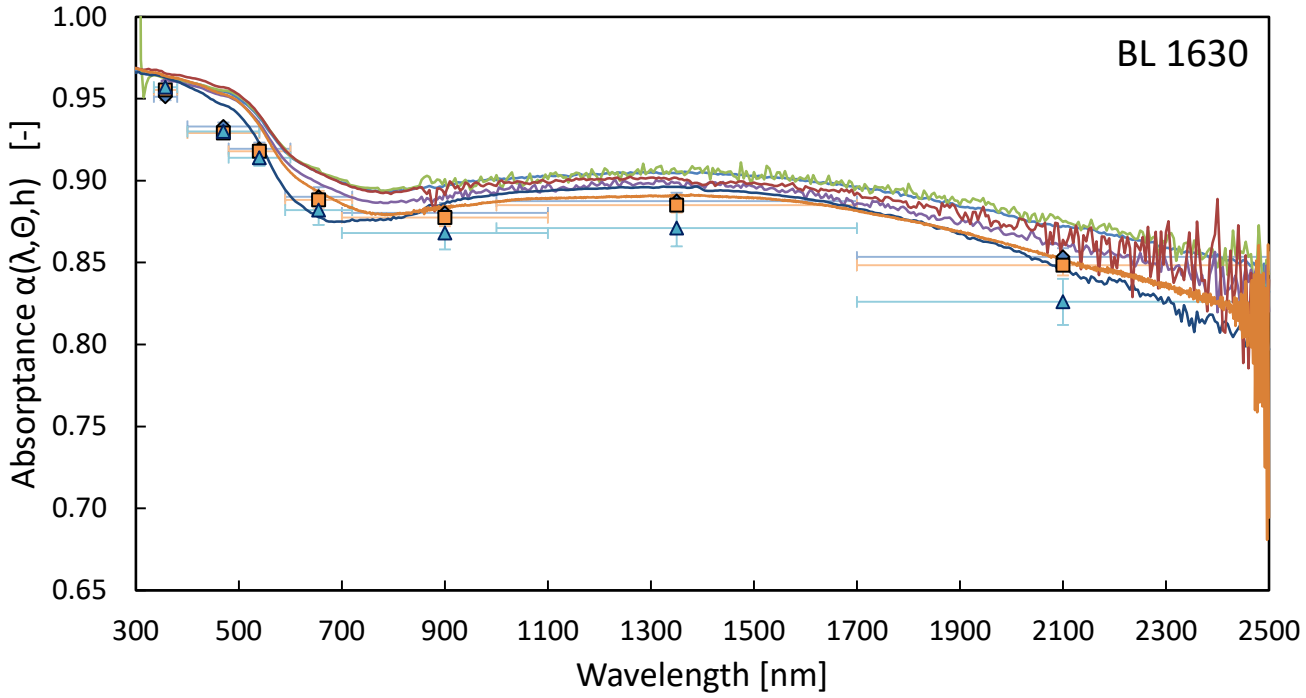


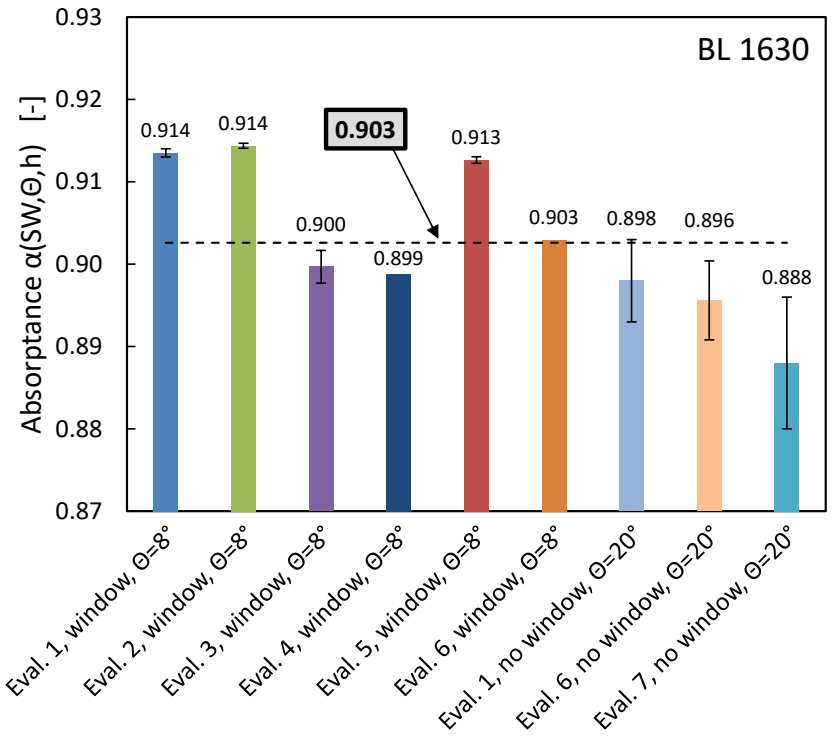
Summary of solar absorptance (left) and emittance (middle) for all five particle types with thermal emittance calculated at 900°C. Box-and-whisker plot (right) represents the difference between direct (windowless) measurements and measurements through the quartz and ZnSe windows after applying the correction method and omitting data from band 1.5 - 2 µm.

Comparison of direct (windowless) and indirect measurements validates Method #0

ROUND ROBIN TEST

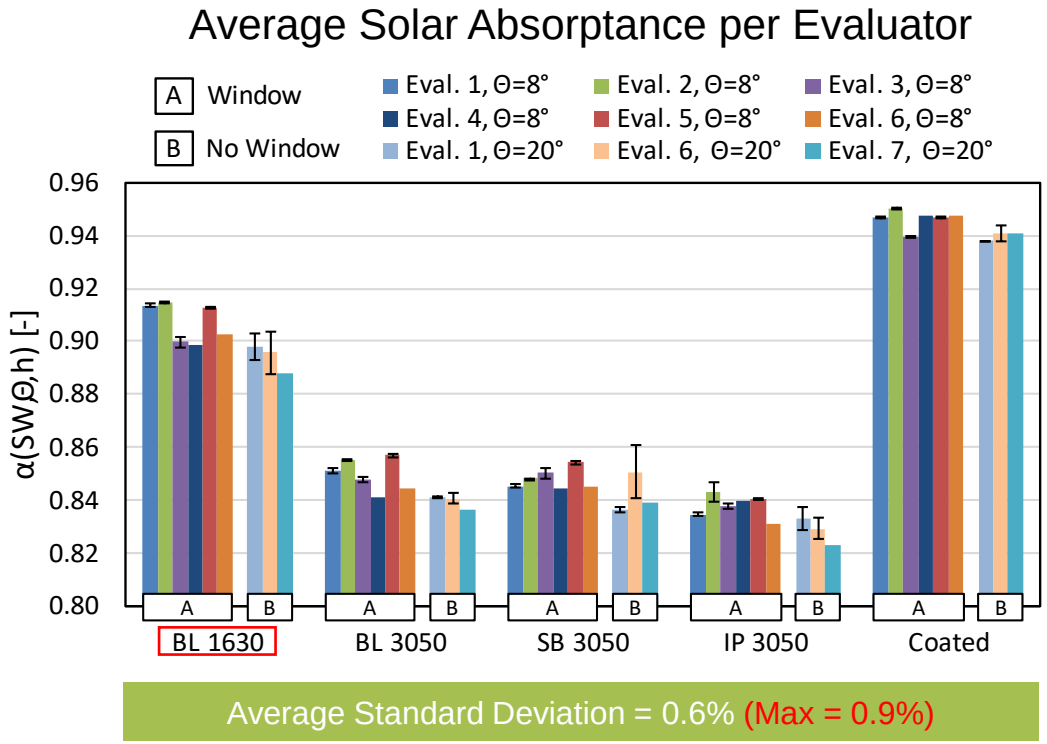
Example of RRT Results (BL 1630, α)



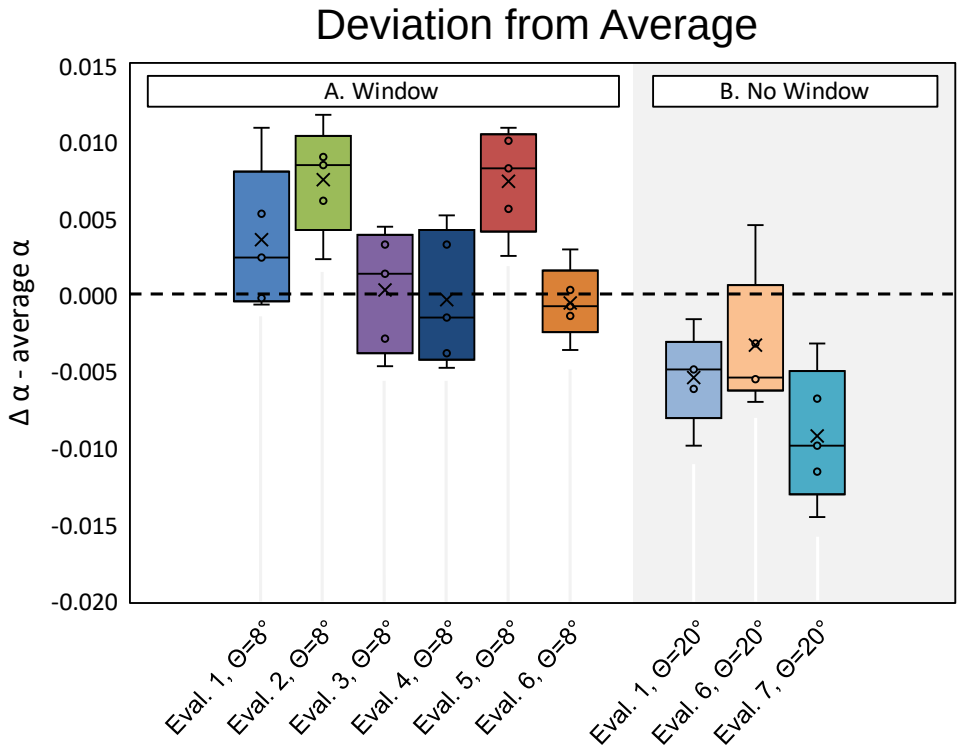


Spectral (left) and solar-weighted absorptance with ASTM G173 direct AM1.5 solar spectrum (right) per evaluator for particle type BL 1630 (Θ is the incidence angle of the measurement).

Summary of Round Robin Results (α)



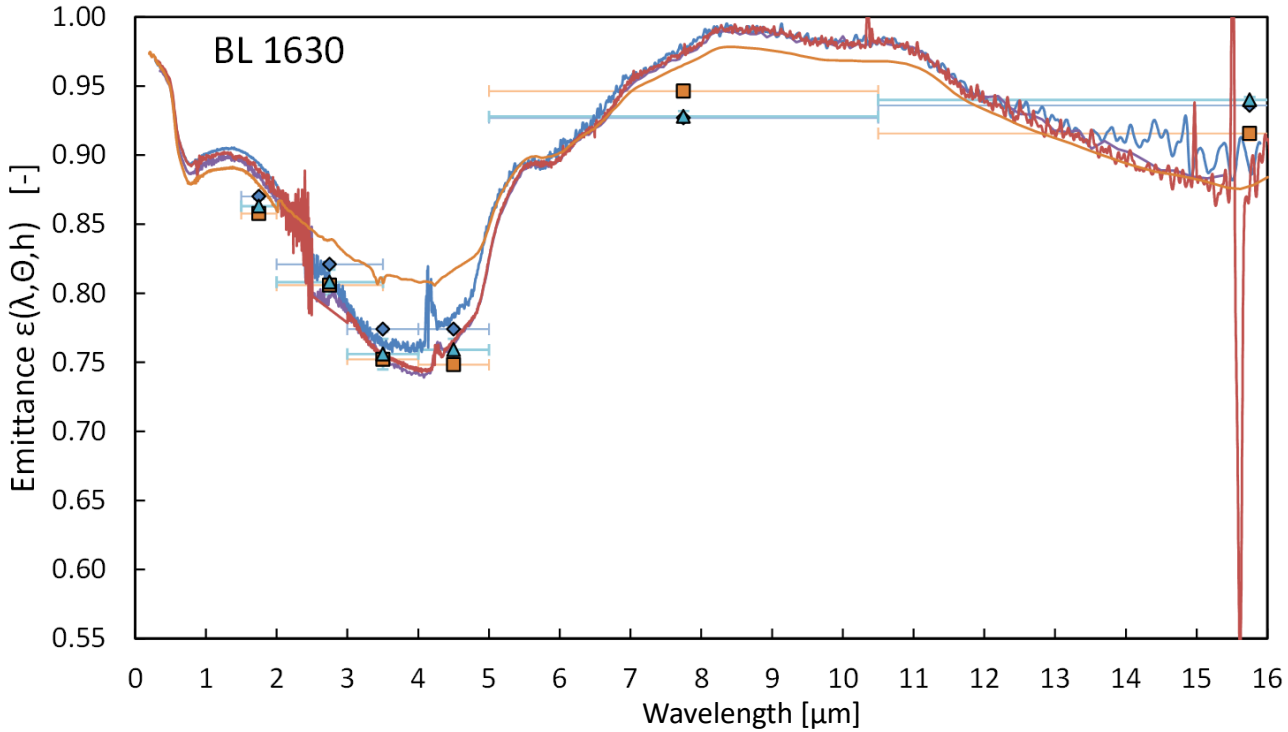
Average Standard Deviation = 0.6% (Max = 0.9%)

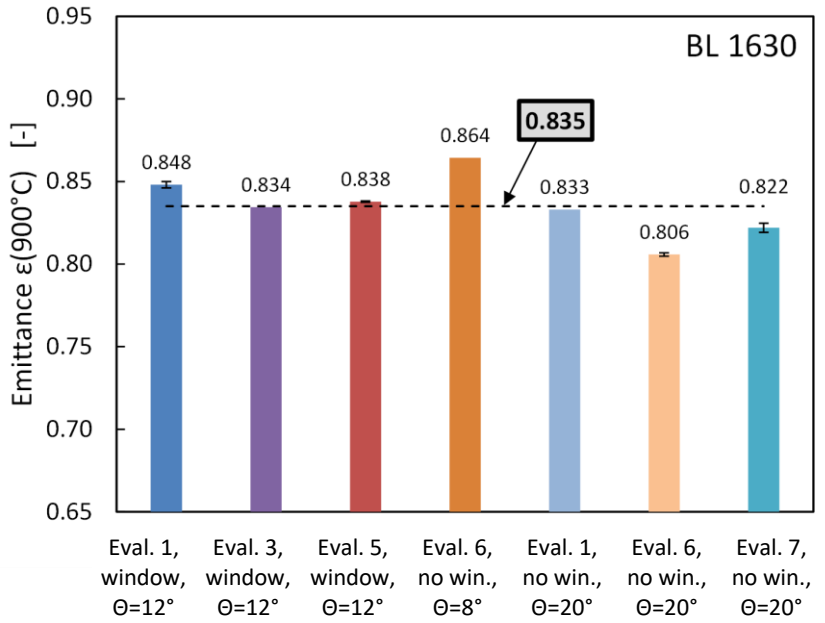


Solar-weighted absorptance with ASTM G173 direct AM1.5 solar spectrum per evaluator and particle type (left) and deviation from average solar-weighted absorptance of the RRT per evaluator (right).

High agreement for solar-weighted absorptivity (α)

Example of RRT Results (BL 1630, ε)

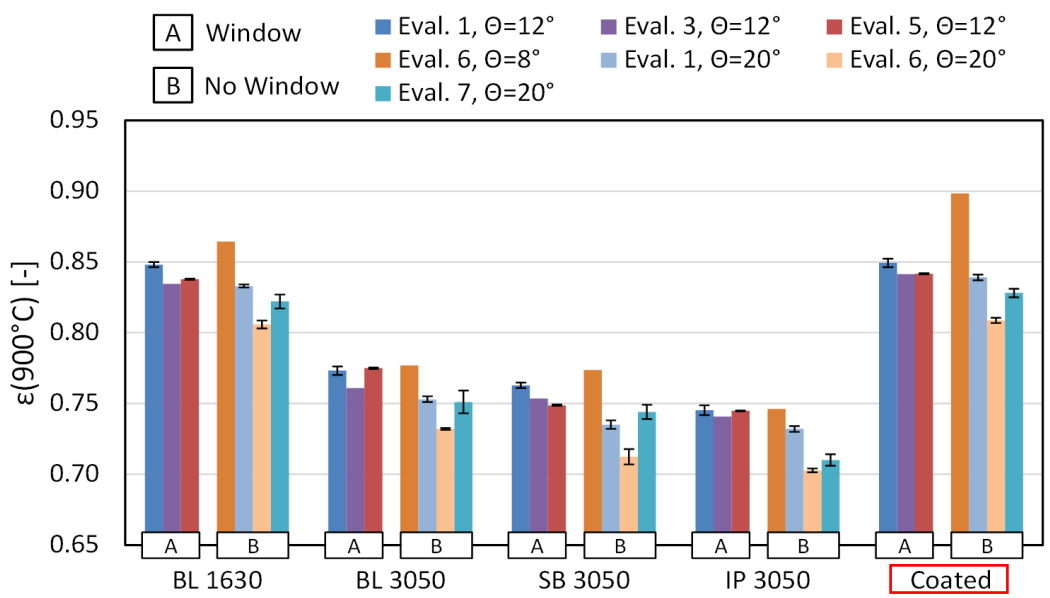




Spectral emittance (left) and computed thermal emittance at 900°C (right) per evaluator for particle type BL 1630.

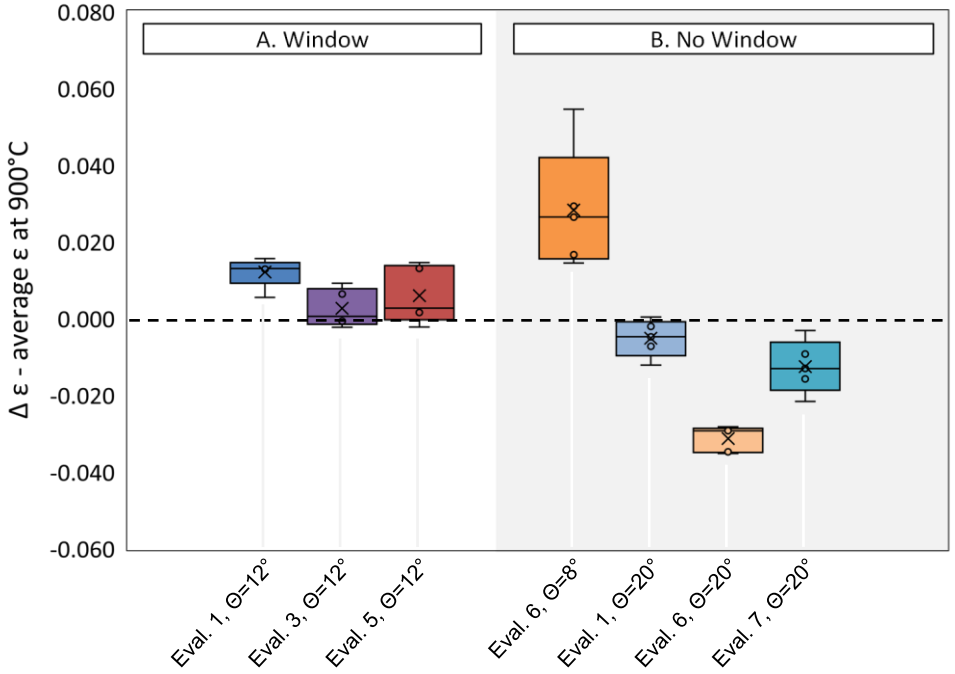
Summary of Round Robin Results (ε)

Thermal Emittance at 900°C per Evaluator



Average Standard Deviation = 1.9% (Max = 2.5%)

Deviation from Average



Overview of thermal emittance at 900°C per evaluator and particle type (left) and deviation from average thermal emittance at 900°C of the RRT per evaluator (right).

Lower agreement for of thermal emittance at 900°C (ε)

Conclusions

Correction Method

- Validation of a window correction method to correct for optical reflectance measurements of particles through windows.
  - Allows instrument users to collect measurements in spectrophotometers/spectrometers with typical vertical sample port configurations.
- Correction slightly overestimates the absorpt./emittance by Δ= 0.013
  - Difference is close to the uncertainty among different laboratories, so we consider the correction method a useful tool, capable of predicting direct (windowless) measurements.

RRT

- RRT including 5 particle types, 7 institutes,16 different instruments.
  - High agreement for solar-weighted absorptivity (α), Avg. Std. Dev. = 0.6%
  - Lower agreement for of thermal emittance at 900°C (ε), Avg. Std. Dev. = 1.9%

References

1. C. Ho et al., *Technology Advancements for Next Generation Falling Particle Receivers*, Energy Procedia, vol. 49, pp. 398–407, Jan. 2014.
2. A. Palacios, A. Calderón, C. Barreneche, J. Bertomeu, M. Segarra, A. I. Fernández: *Study on solar absorptance and thermal stability of solid particles materials used as TES at high temperature on different aging stages for CSP applications.* Solar Energy Materials and Solar Cells 201 (2019) 110088.
3. B. Gobereit, L. Amsbeck, C. Happich, M. Schmücker, M. Wolff, *Assessment and improvement of optical properties of particles for solid particle receiver.* Proceedings of the 11th International Conference on Energy Sustainability ES2017, Charlotte, 2017.
4. SolarPACES Guideline, *Method to evaluate the reflectance, absorptance and emittance of particles for concentrating solar power technology,* Version 1, May 2022. Available online: https://www.solarpaces.org/csp-research-tasks/task-annexes-iea/task-iii-solar-technology-and-advanced-applications/.

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Questions & Comments?

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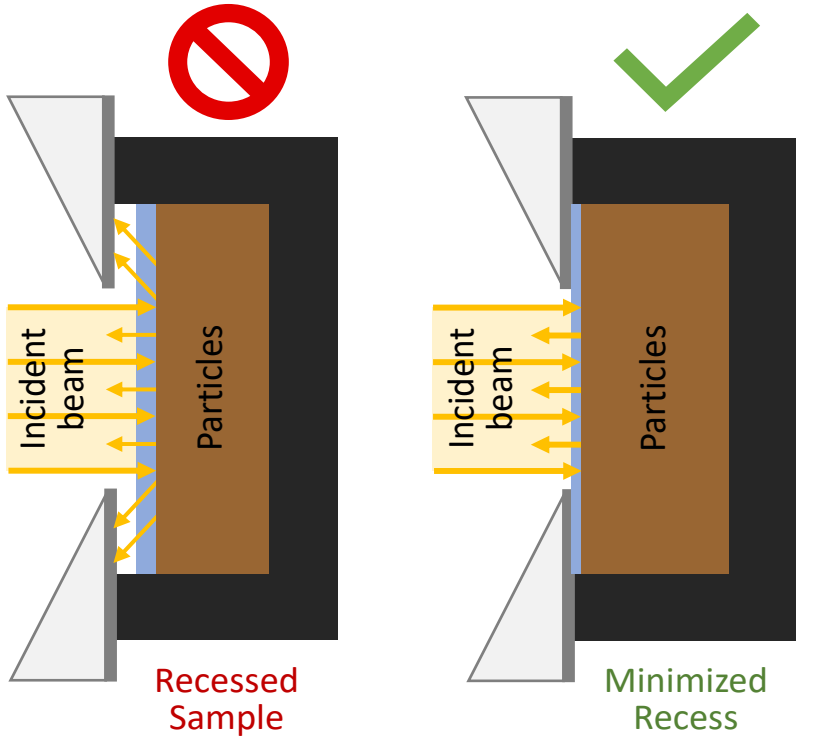
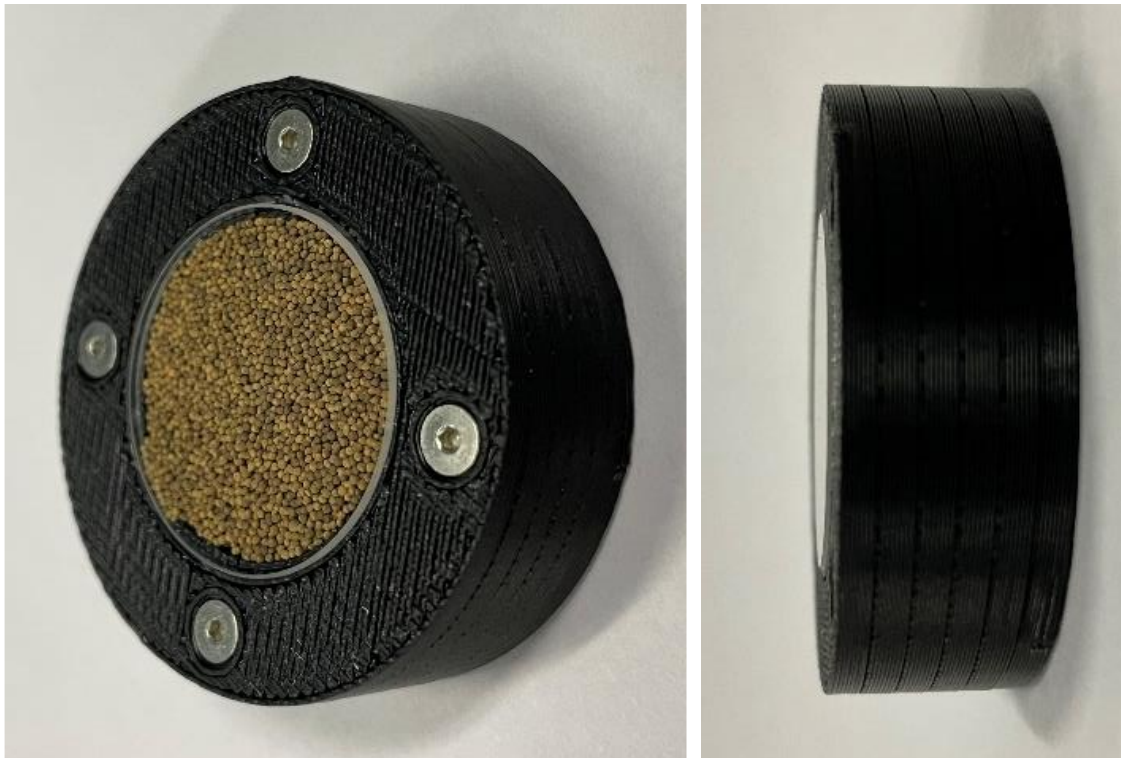
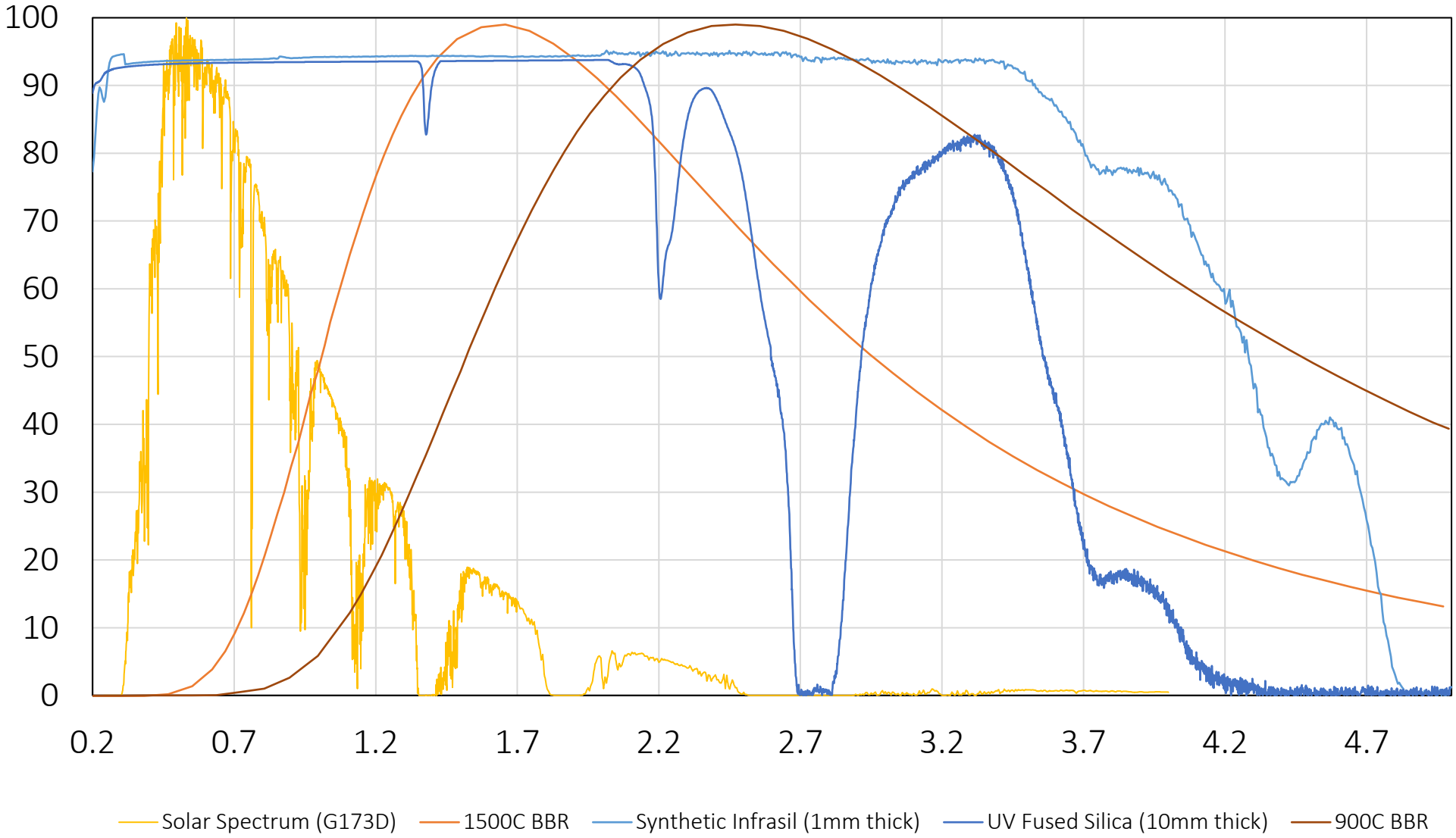

Incident beam
Particles
Recessed Sample
Incident beam
Particles
Minimized Recess

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1.2
1.7
2.2
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3.2
3.7
4.2
4.7
Solar Spectrum (G173D)
1500C BBR
Synthetic Infrasil (1mm thick)
UV Fused Silica (10mm thick)
900C BBR