Accelerated Ageing of Solar Receiver Coatings: Experimental Results for T91 and VM12 Steel Substrates

Simon Caron, F. Sutter, N. Algner, M. Esteller (DLR),
Y. Binyamin, M. Baidosi, A. Kenigsberg (Brightsource Industries),
A.Agüero (INTA), D. Fähsing (DECHEMA), C. Hildebrandt (Fraunhofer ISE)

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Outline

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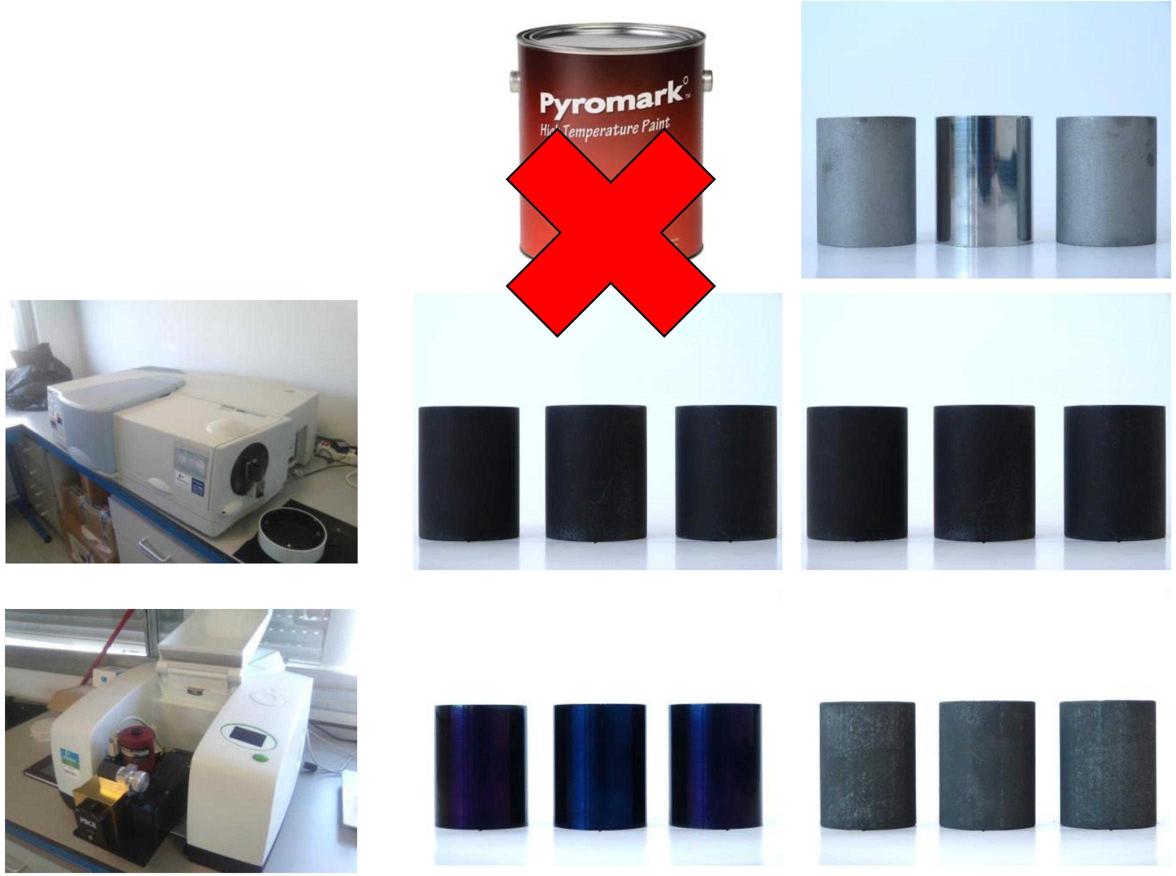
  - Degradation mechanisms
- **Optical Characterization**
  - Solar absorptance
  - Thermal emittance
- **Experimental setups**
  - Solar cycling tests
  - Climate test chambers
- **Results and discussion**
- **Conclusion & Outlook**



Introduction

Solar receiver coatings (1)

- **State of the art:**
  - **Pyromark 2500** (Tempil)
    - “Silicon based coating for metals”
    - “Long lasting vs. **oxidation** and **corrosion**”
    - “Withstands high temperature, 1093 °C”
    - High nominal solar absorptivity of 0.95
    - **High thermal emittance**
      - ~ 0.8 at 100 °C to 0.9 at ~1000 °C
  - **Reality:**
    - Poor durability
    - Max. temp. ~ 750 °C
    - High thermal emittance

- **New coating formulations:**
- Coating A:
  - ceramic paint, spray
- Coating B:
  - protective slurry aluminide + coat. A (top)
- Coating C:
  - sputtered on polished substrate
  - selective coating (low thermal emittance)
- Coating D:
  - multi-metallic diffusion coating
  - based on Chromium (Cr) and Manganese (Mn)

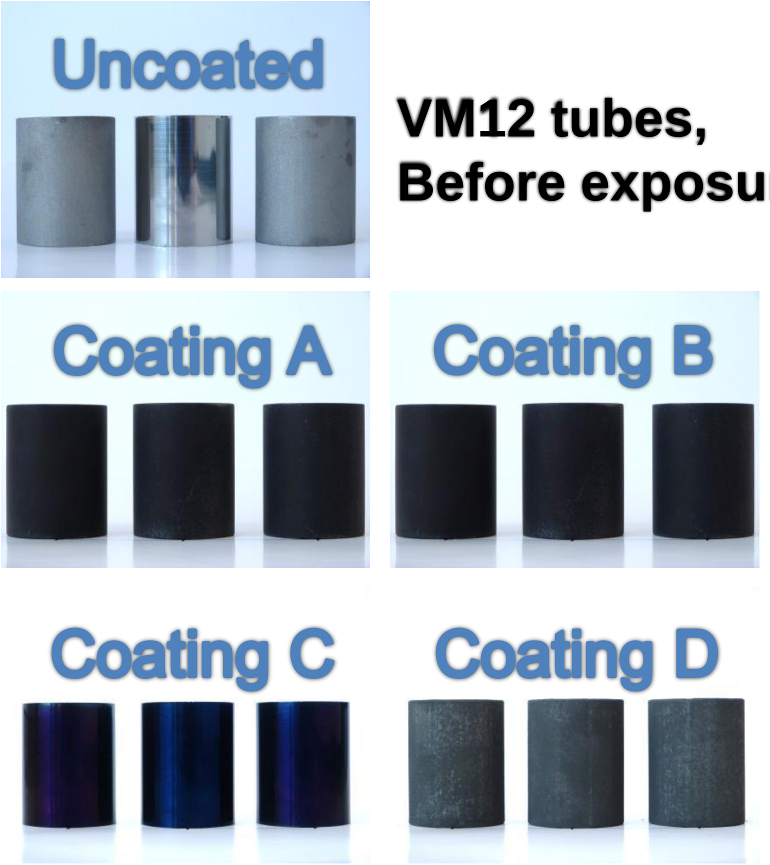
Introduction

Solar receiver coatings (2)

- **Four different metal substrates**
  - **End Applications**:
    - Solar Receiver Steam Generator (SRSG)
    - Molten Salt Receiver (MSR)

Substrate	Solar cycling (Tube samples)	Climate chambers (Flat samples)
T91/P91 (max. 650 °C)	Overheated ✗	Completed ✓
VM12 (max. 650 °C)	100+ cycles ✓	In progress ⚠
T22 (max. 600 °C)	Start: Mid-October 2017	Start: Mid-October 2017
Inc-617 (max. 750 °C)	Schedule: Early 2018	Schedule: Early 2018

- **Flat and tubular sample geometries**



VM12 tubes, Before exposure

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Introduction

Solar receiver coatings (3)

- **Identified degradation mechanisms**

  - **Effects:**
    - Optical fading
      - Loss of solar absorptance
      - Gain of thermal emittance
  - **Causes:**
    - Corrosion (“red dots”)
    - Hot oxidation (“white dots”)
    - Flaking / delamination / cracks

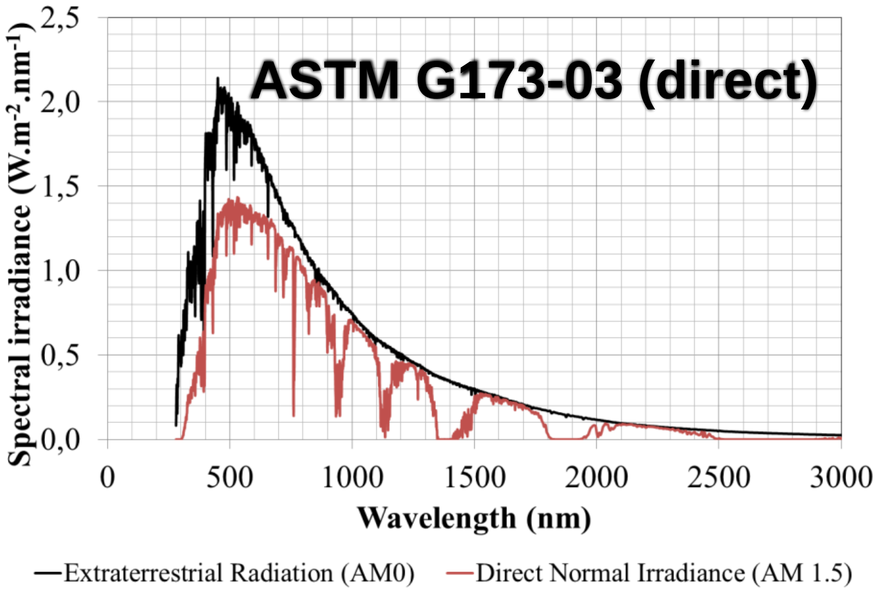
  - **Goal**: Reproduce mechanisms
    - Outdoor: Dish test facility
    - Indoor: Climate test chambers

Optical Characterization

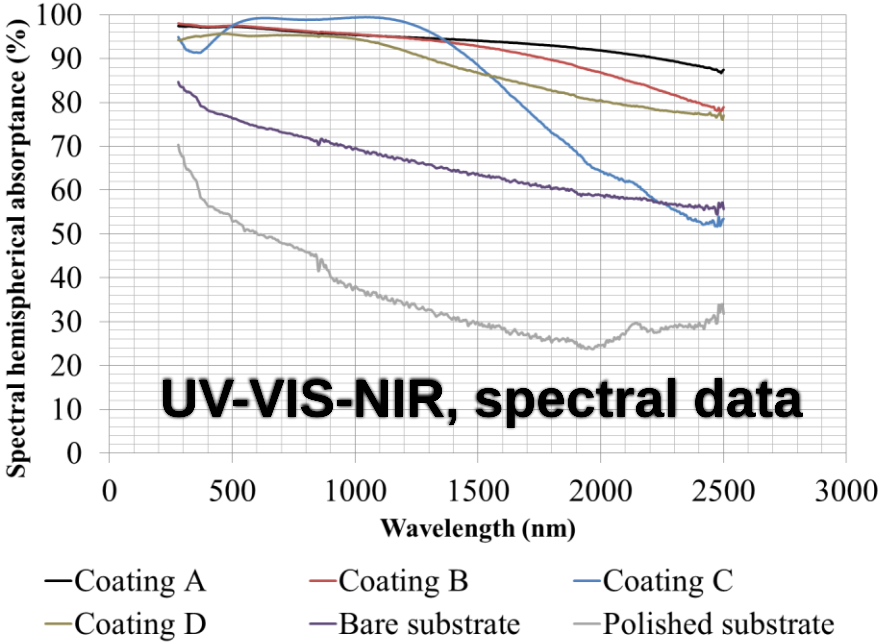
Solar weighted absorptance

- **Weighting formula:**

$$\alpha_s = \frac{\int_{\lambda 1}^{\lambda 2} [1 - R(\lambda)] \cdot G_{sol}(\lambda) \cdot d\lambda}{\int_{\lambda 1}^{\lambda 2} G_{sol}(\lambda) \cdot d\lambda}$$



- **Spectrophotometer:**
  - Perkin Elmer Lambda1050
  - UV-VIS-NIR; 0.28 to 2.5 µm
  - Incidence angle: 8°
  - Integration sphere Ø: 150 mm



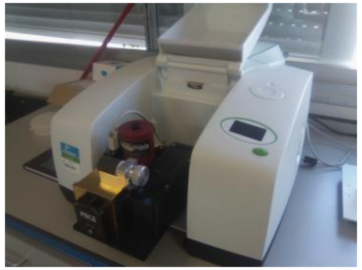
Optical Characterization

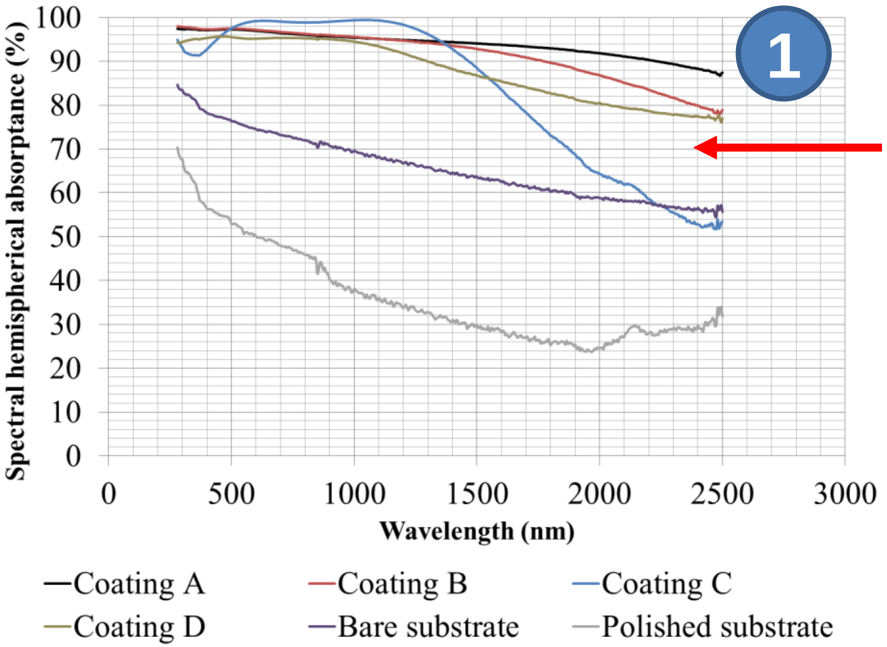
Thermal emittance (1)

Weighting formula:

$$L_{BB}(\lambda,T) = \frac{2\pi hc^2}{\lambda^5 \cdot \left[\exp\left(\frac{hc}{\lambda kT}\right) - 1\right]} \qquad \varepsilon_{th}(T) = \frac{\int_{\lambda 1}^{\lambda 3} [1 - R(\lambda)] \cdot L_{BB}(\lambda,T) \cdot d\lambda}{\int_{\lambda 1}^{\lambda 3} L_{BB}(\lambda,T) \cdot d\lambda}$$

- **Spectrophotometer:**
  - Frontier FTIR, Pike int. sphere
  - NIR-MIR; 2 to 16 µm
  - Incidence angle: 12°
  - Integration sphere Ø: 76.2 mm

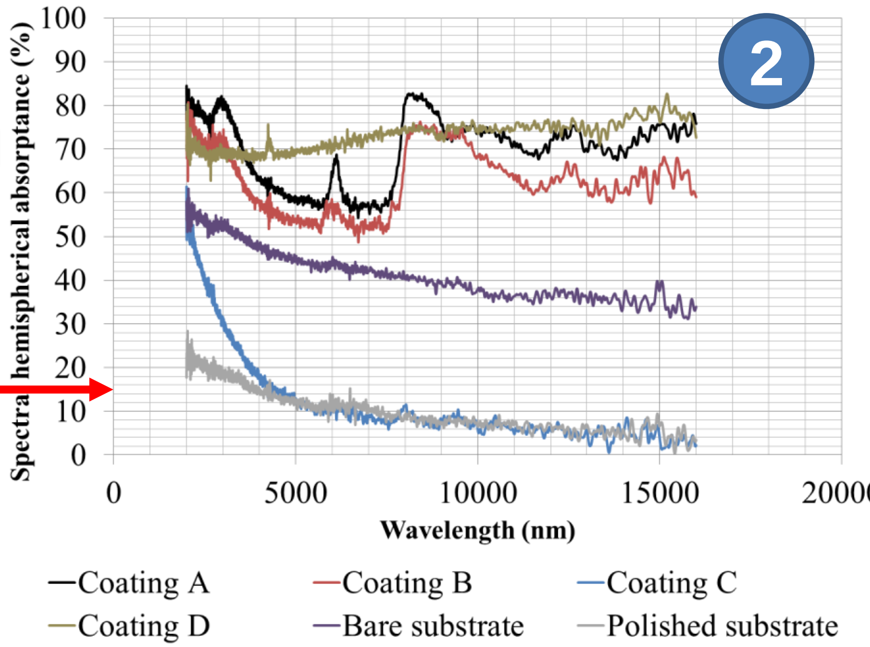




UV-VIS-NIR, calibrated

+

NIR-MIR, raw data

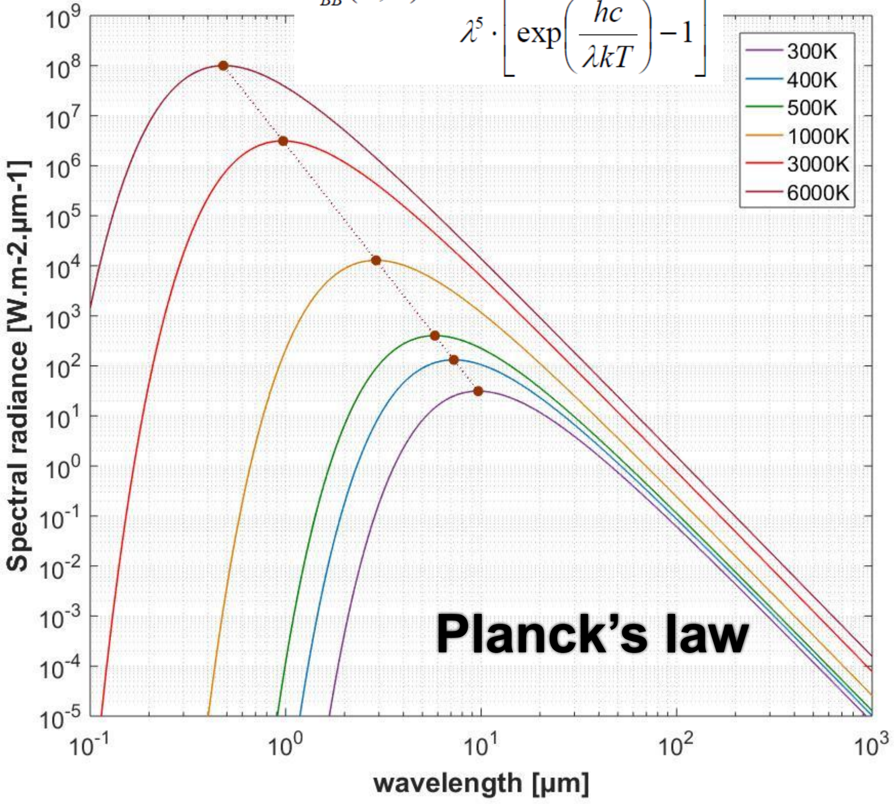


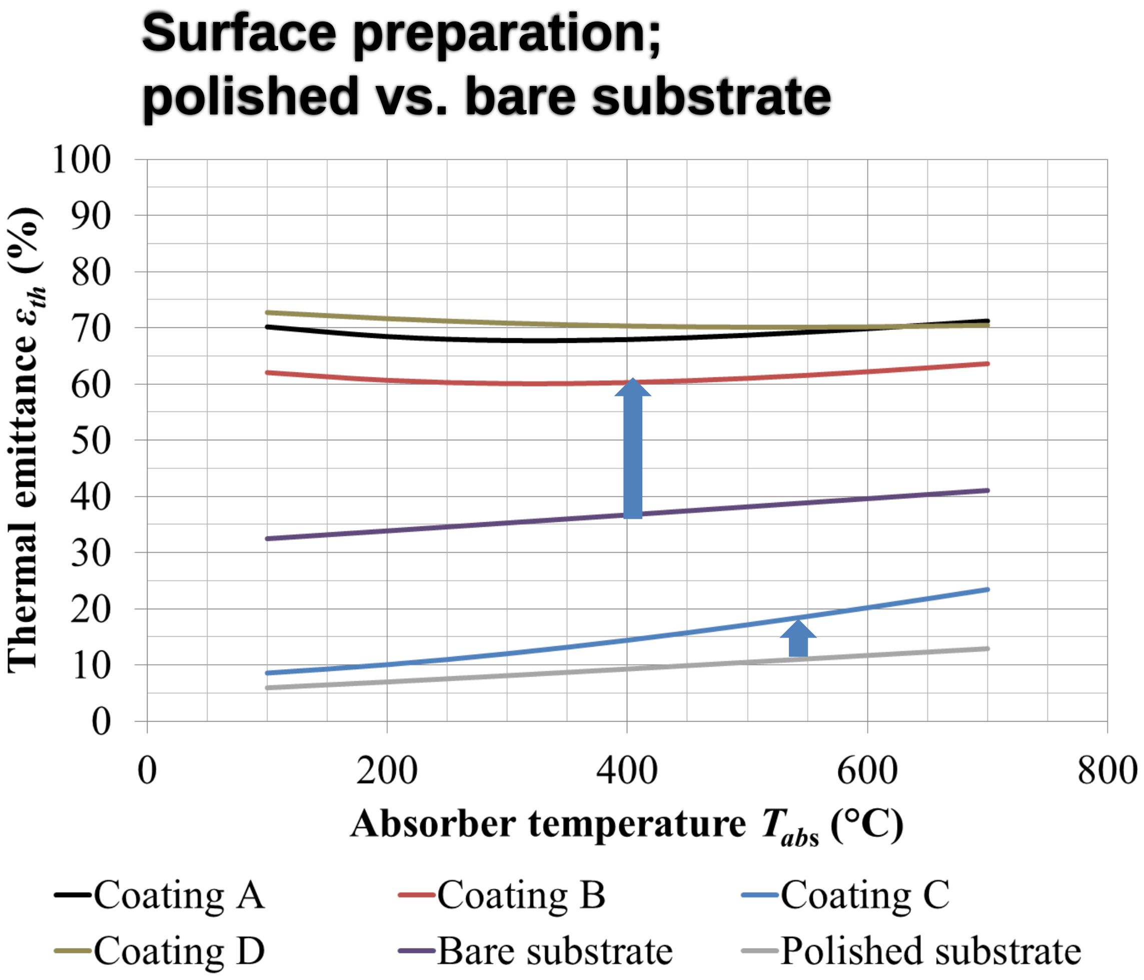
Spectral range:
0.28 to 16 µm
(~97% σ at 650 °C)

Optical Characterization

Thermal emittance (2)

$$L_{BB}(\lambda,T) = \frac{2\pi hc^2}{\lambda^5 \cdot \left[\exp\left(\frac{hc}{\lambda kT}\right) - 1\right]}$$





Optical Characterization

Performance criterion & initial values

- **Thermal efficiency**

$$\eta_{coating} = \frac{\alpha_s \cdot Q_{sol} - \varepsilon_{th} \cdot \sigma \cdot T_{abs}^{\ 4}}{Q_{sol}}$$

$$\frac{d\eta_{coating}}{d\alpha_{sol}} = 1; \frac{d\eta_{coating}}{d\varepsilon_{th}} = \frac{-\sigma \cdot T_{abs}^{\ 4}}{Q_{sol}}$$

- **Default values:**
  - Q_{sol} = 250 kW/m^{2}; T_{skin} = 650 °C
  - Trade-off: +1% α_s ~ -16.5 % ε_{th}
- **Goals:**
  - Solar absorptance ~ 96 %
  - Max. acceptable loss: - 0.5 %
  - Maximize thermal efficiency

- **Initial values**

Substrate	VM12 – Tubular samples		
Coating	α_s (%)	$\varepsilon_{th,650°C}$ (%)	$\eta_{coating}$ (%)
Coating A	96.2 ± 0.3 %	71.7 ± 1.2 %	85.4 ± 0.0 %
Coating B	95.3 ± 0.3 %	63.0 ± 0.7 %	84.4 ± 0.1 %
Coating C	95.1 ± 0.4 %	22.4 ± 0.6 %	91.4 ± 0.6 %
Coating D	93.2 ± 0.3 %	70.6 ± 1.8 %	81.6 ± 0.3 %
Bare substrate	71.7%	40.3%	65.1%
Polished substrate	44.7%	12.3%	42.7%

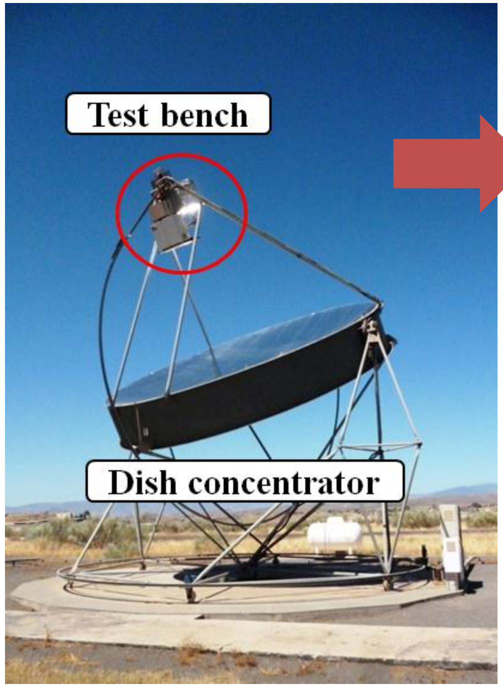
Substrate	T91 – Flat samples		
Coating	α_s (%)	$\varepsilon_{th,650°C}$ (%)	$\eta_{coating}$ (%)
Coating A	96.4 ± 0.0 %	71.4 ± 0.8 %	84.6 ± 0.1 %
Coating B	96.7 ± 0.1 %	76.5 ± 1.1 %	84.0 ± 0.2 %
Coating C	94.8 ± 0.2 %	22.2 ± 0.2 %	91.0 ± 0.2 %
Coating D	91.7 ± 0.6 %	65.0 ± 0.3 %	80.6 ± 0.6 %
Bare substrate	N.A.	N.A.	N.A.
Polished substrate	N.A.	N.A.	N.A.

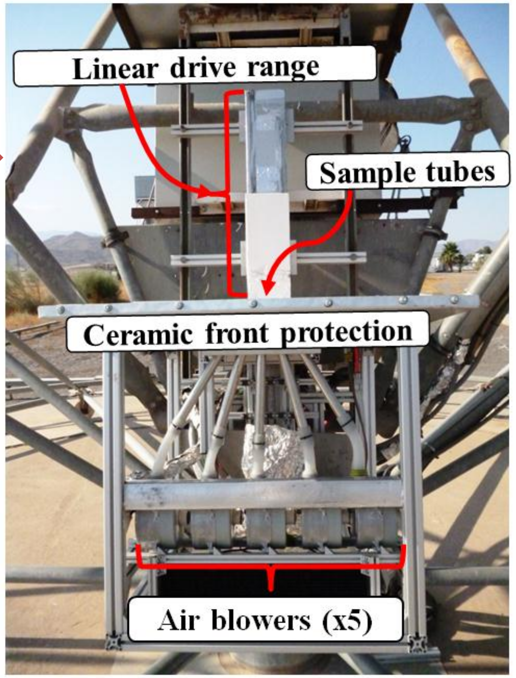
Solar Cycling Tests
Experimental test bench

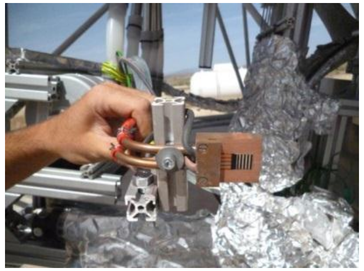
- **Dish test facility** (Distal II, PSA)
- 15 tubular samples at a time
- 5 parallel strings of 3 probes

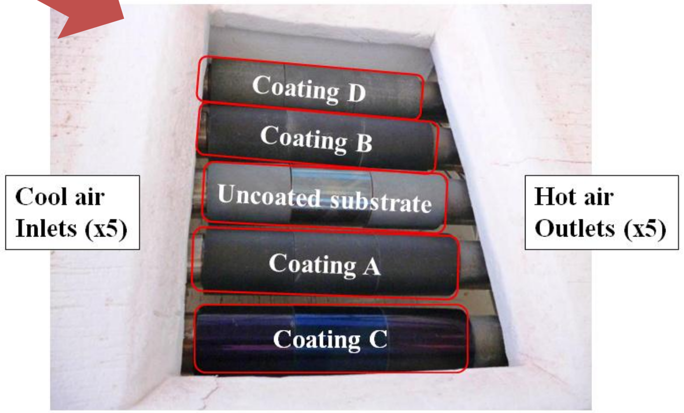
- **Flux control:**
- Linear drive (master)
- **Temp. control:**
- Air blowers (slaves)

- **Sensors:**
- Water cooled radiometer
- Thermocouples type K





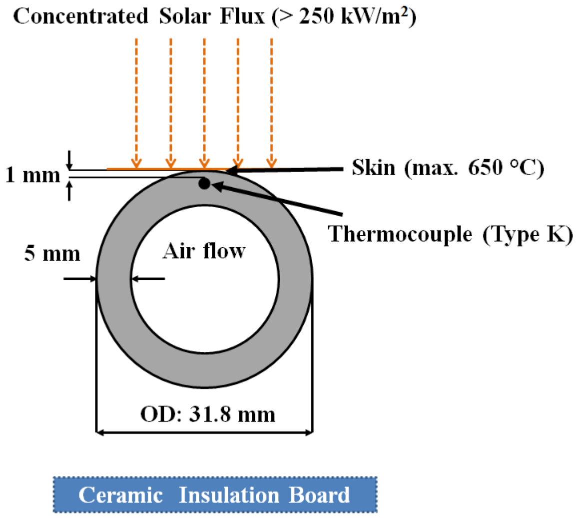


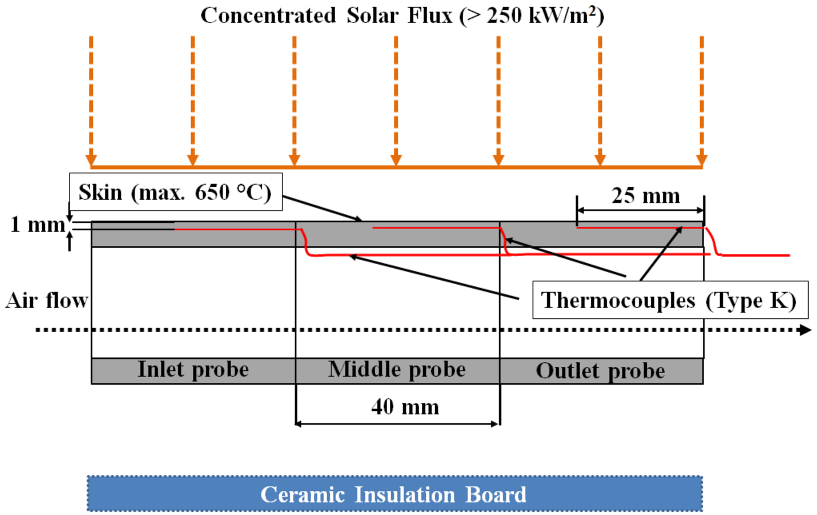


Solar Cycling Tests

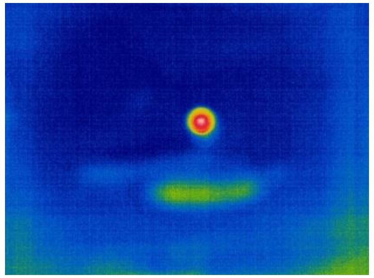
Temperature measurement

- **Embedded thermocouples** (Type K)





Coming soon



- **Solar blind infrared camera**:
- Optris PI640 G7, 7.9+/- 0.3 µm
- To be implemented end of 2017

- ΔT along wall thickness (1.9 +/- 0.1 mm)
- - 30 K for coatings A,B and D
- - 18 K for coating C (thinner coating)

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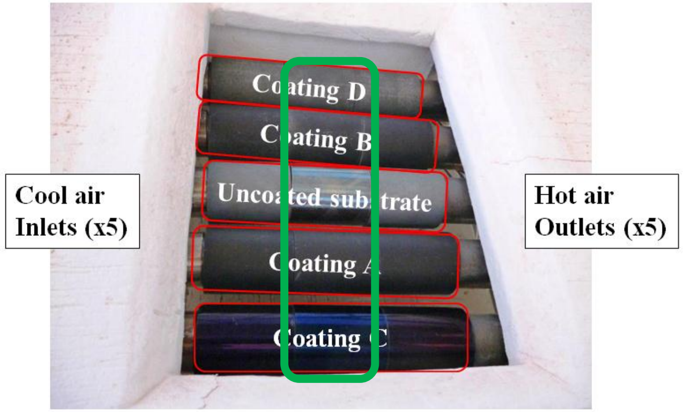
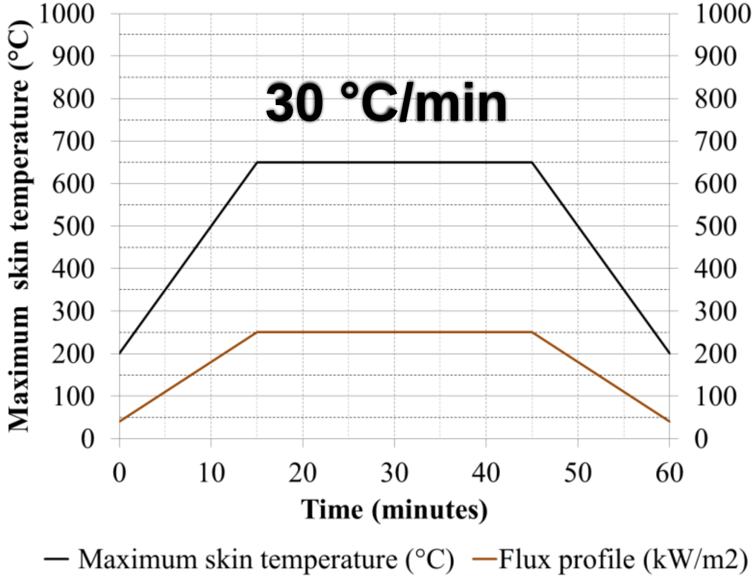
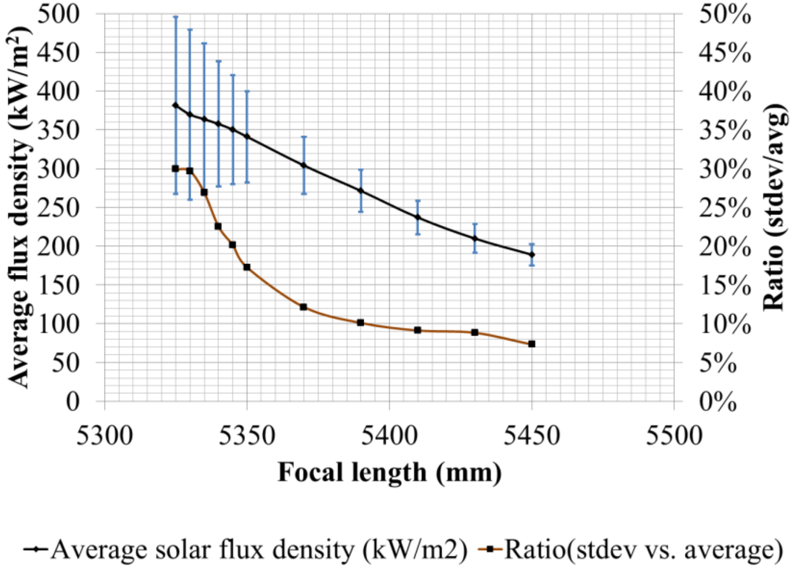
Solar Cycling Tests

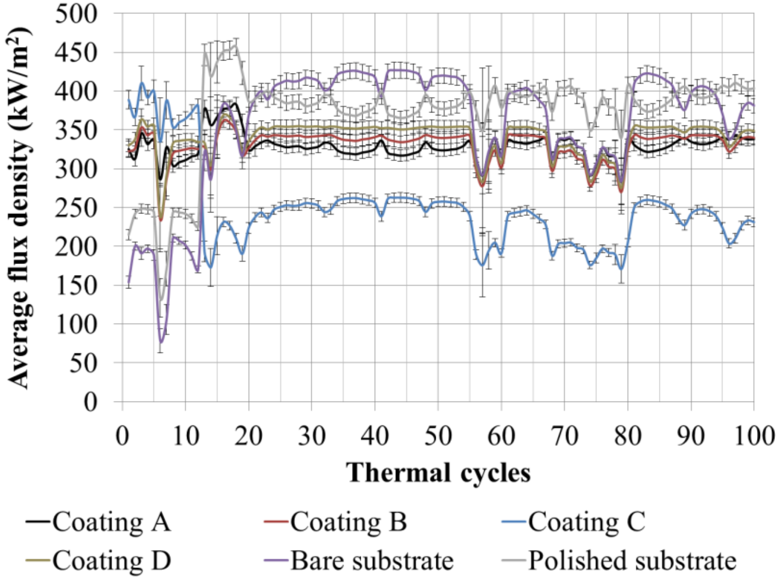
Test conditions

- **Test profiles:**
  - 650 °C max. skin temperature
  - Min. 250 kW/m^2 on samples
- **Total # cycles**:
  - 100 cycles (paper)
  - 150 cycles (Mid-September)





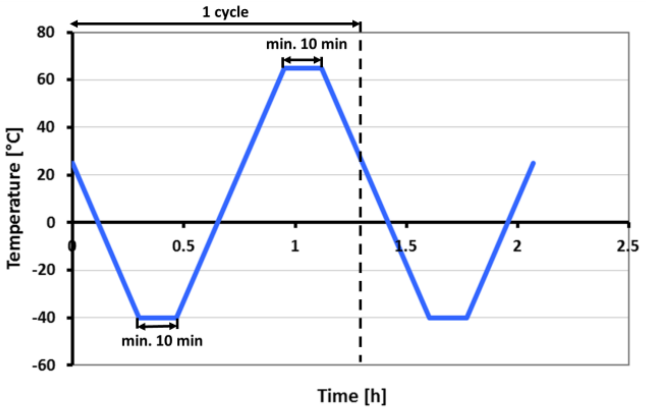




Environmental Test Chambers

Test conditions

- **Four independent tests on flat samples:**
  - Damp Heat (DH)
  - Condensation (Cond.)
  - Humidity Freeze (HF)
  - Neutral Salt Spray (NSS)



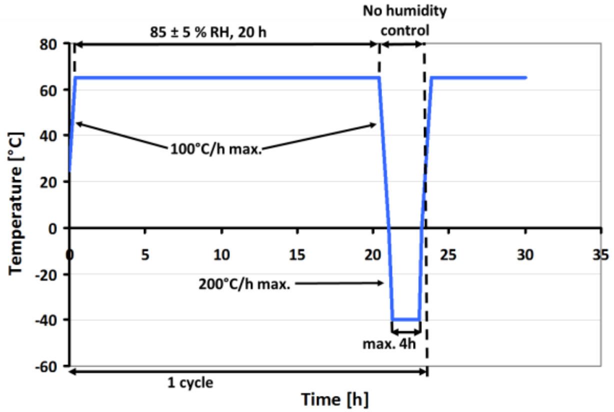


TABLE 2. Summary of climate chamber test conditions for Condensation, Damp Heat (DH), Humidity Freeze (HF) and Neutral Salt Spray (NSS). For each coating, 3 flat samples are exposed in the corresponding climate test chamber.

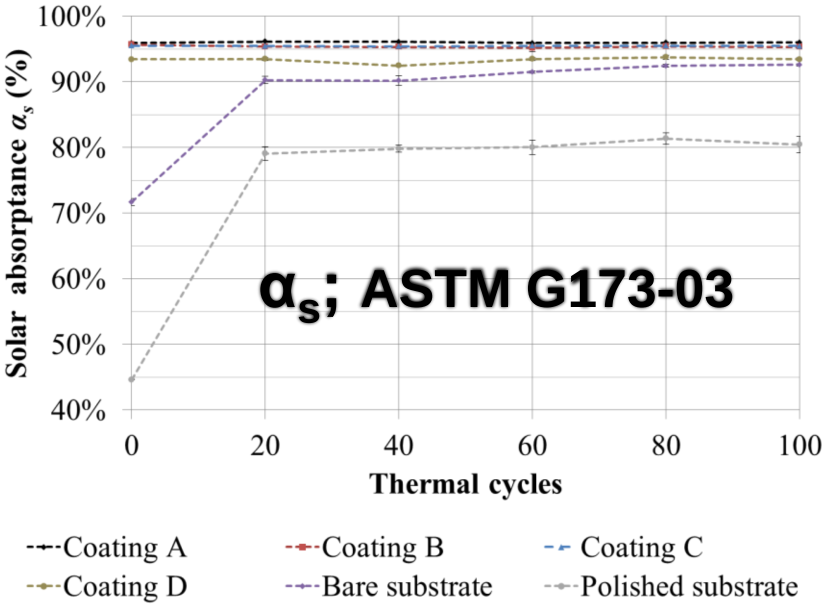
Test	Condensation	Damp Heat (DH)	Humidity Freeze (HF)	Neutral Salt Spray (NSS)
Standard	ISO 6270 [9]	IEC 62108, Test 10.7b [10]	IEC 62108, Test 10.8 [11]	ISO 92237 [12]
Duration	480 hours	1000 hours	1500 hours	480 hours
Conditions	T_{amb}: 40 °C RH: 100 %	T_{amb}: 65 °C RH: 85 %	T_{amb}: -40 to 65 °C RH: max. 85%	T_{amb}: 35 °C pH 6.5 to 7.2 at 25 °C

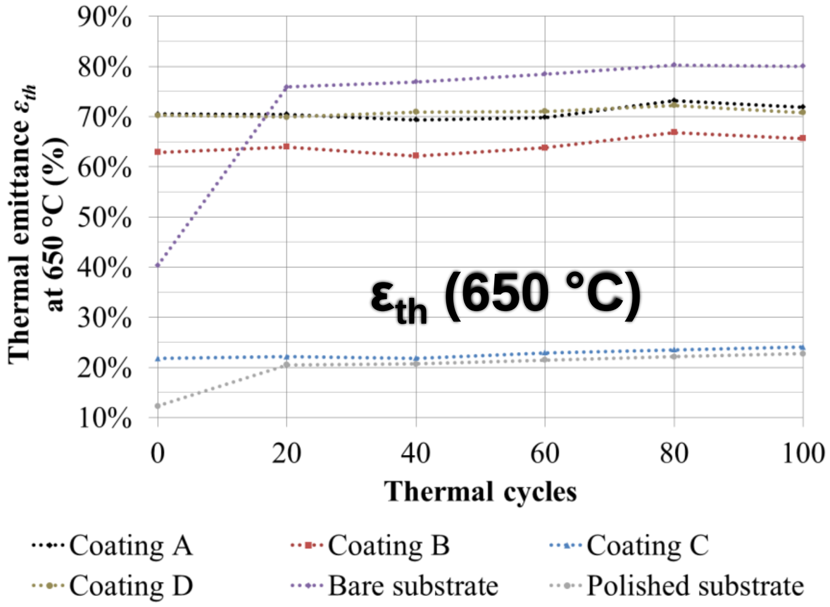
Experimental results

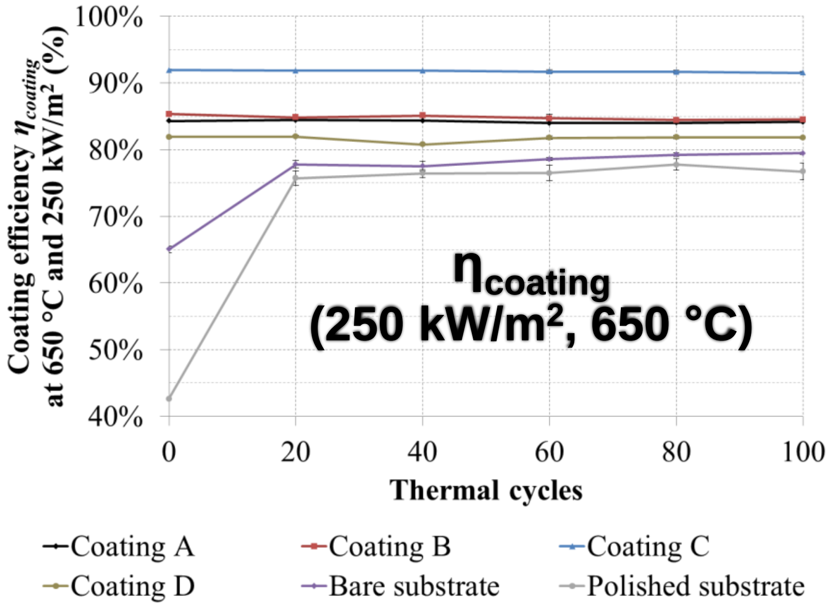
Solar cycling tests

- **Observations:**
  - No significant optical degradation observed after 100 cycles for A,B,C,D
  - Early oxidation of ref. uncoated samples

- **Ranking:**
  - Highest solar absorptance: Coatings A,B,C (> 95%)
  - Highest thermal efficiency: Coating C (91 %)
  - Coatings A and B have similar efficiencies (~ 85%)
  - Coating D performance had to be improved







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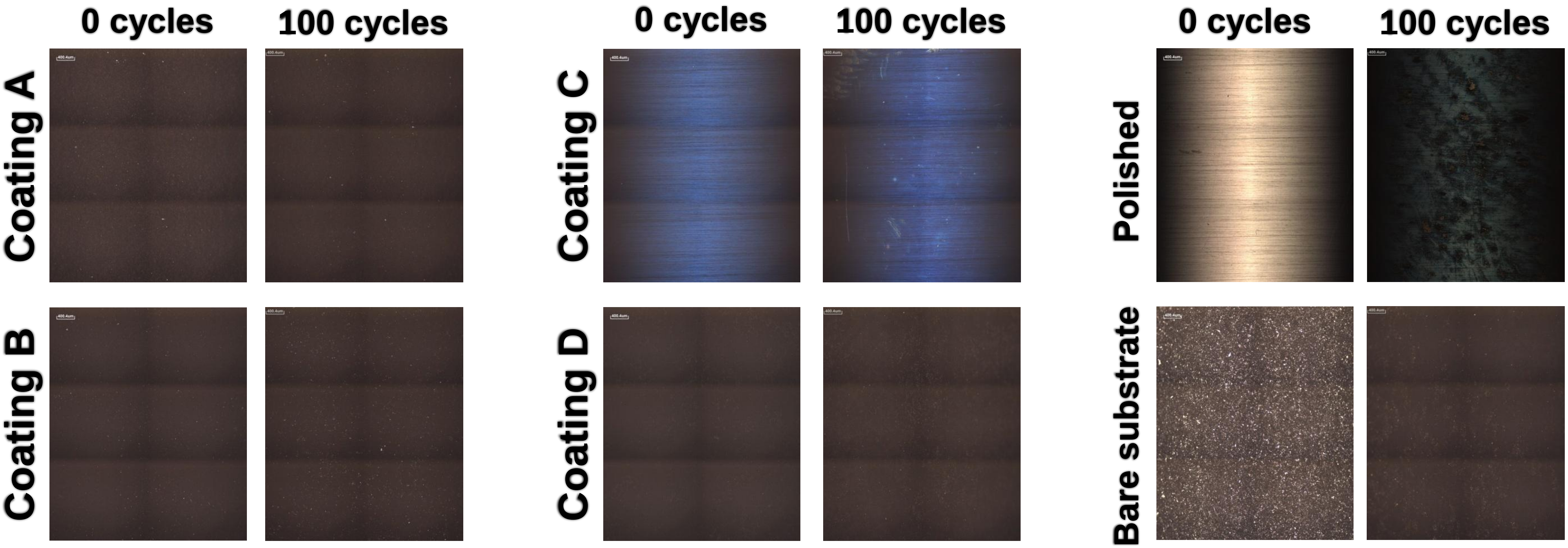
Experimental results

Solar cycling tests

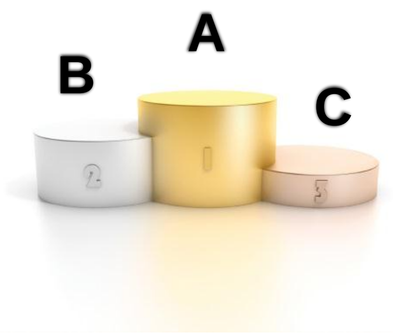


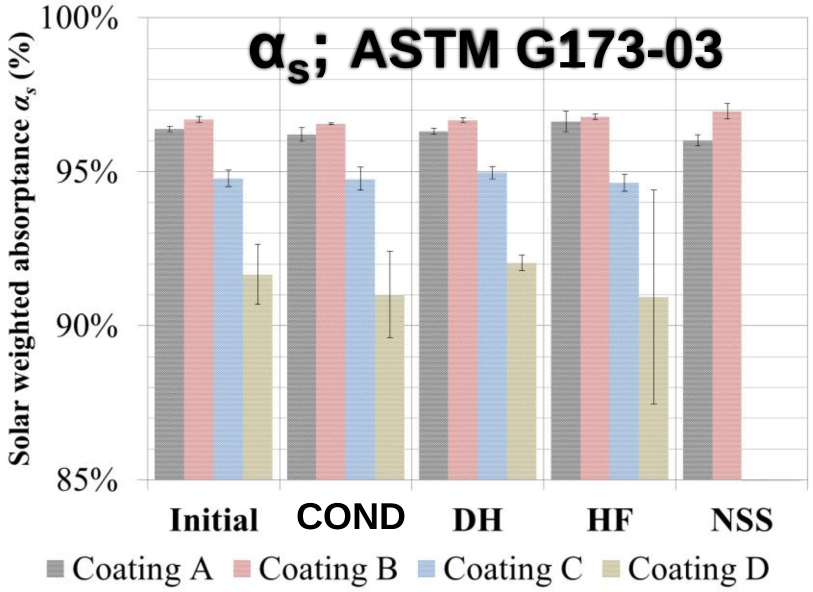
Experimental results

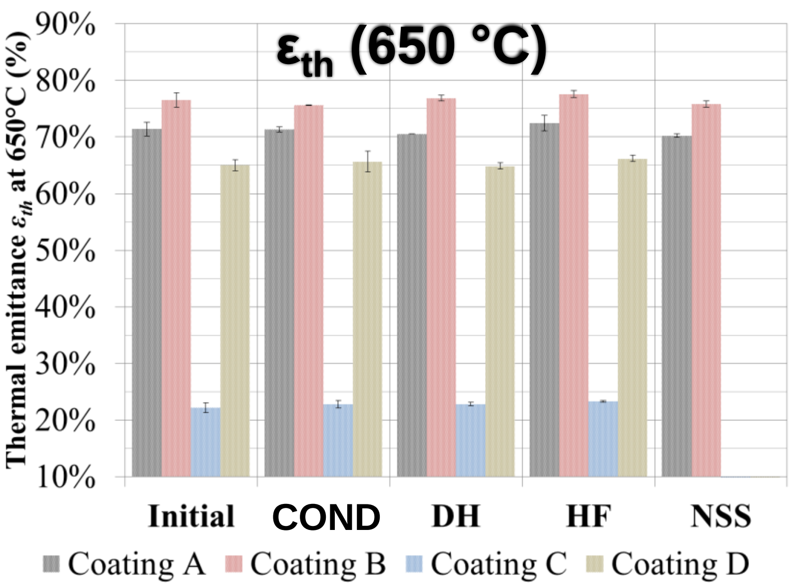
Climate chamber tests

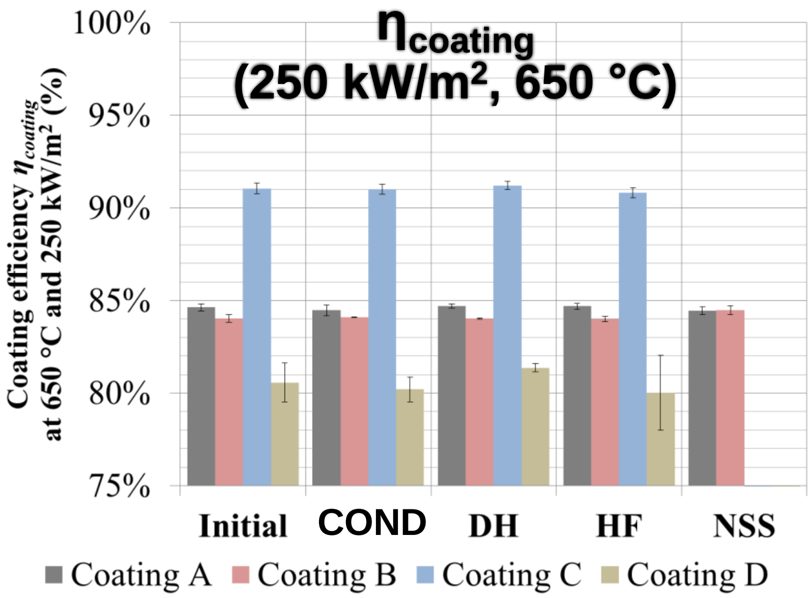
- **Observations:**
  - Coatings A, B passed all tests
    - *Par efficiency (85 %)*
  - Coating C still ranks 1st in efficiency
    - … *but it failed NSS test*
  - Coating D only passed DH test

T91	COND	DH	HF	NSS
Coating A	✓	✓	✓	✓
Coating B	✓	✓	✓	✓
Coating C	✓	✓	✓	✗
Coating D	✗	✓	✗	✗









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Conclusion

- **Solar cycling test (VM12):**
  - No significant degradation after 100 cycles
  - First signs of degradation started to show up after 150 cycles and "dust rain" event
- **Climate chamber tests (T91):**
  - Coatings A,B passed all tests
  - Coatings C,D did not pass NSS
- **Coating comparison:**
  - Performance: Coatings A,B,C
  - Durability: Coatings A and B
  - LCOC: Coating A (spray)
  - Coating C has the highest efficiency (selective)
  - Coating D performance had to be improved

Substrate	VM12 – Tubular samples		
Coating	α_s (%)	$\varepsilon_{th,650°C}$ (%)	$\eta_{coating}$ (%)
Coating A	96.2 ± 0.3 %	71.7 ± 1.2 %	85.4 ± 0.0 %
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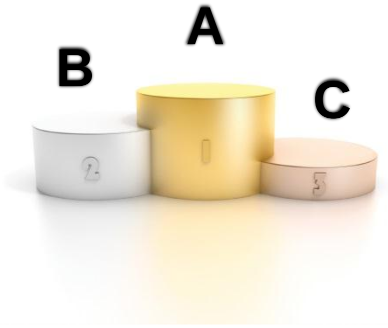
Coating C	95.1 ± 0.4 %	22.4 ± 0.6 %	91.4 ± 0.6 %
Coating D	93.2 ± 0.3 %	70.6 ± 1.8 %	81.6 ± 0.3 %
Bare substrate	71.7%	40.3%	65.1%
Polished substrate	44.7%	12.3%	42.7%

Dish – After 100 cycles

T91	COND	DH	HF	NSS
Coating A	✓	✓	✓	✓
Coating B	✓	✓	✓	✓
Coating C	✓	✓	✓	✗
Coating D	✗	✓	✗	✗



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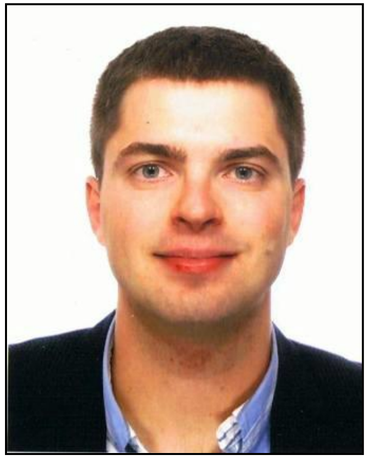
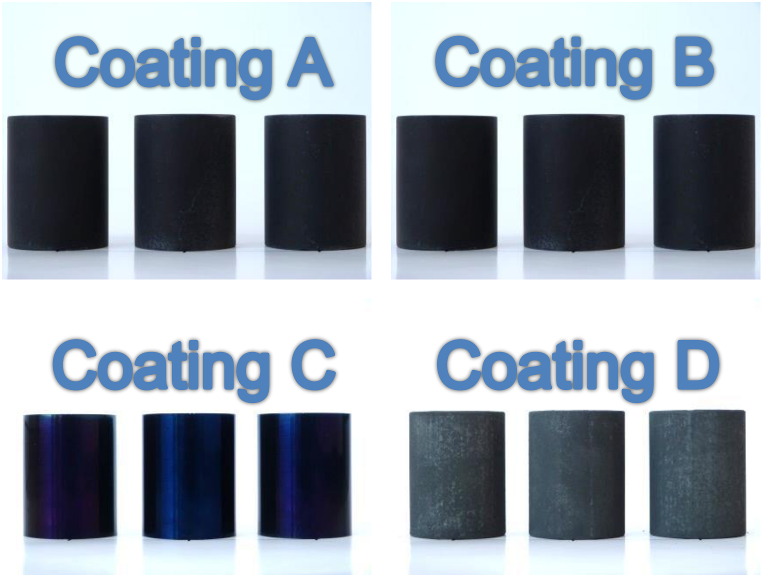


M.Sc. Simon Caron
simon.caron@dlr.de
German Aerospace Center (DLR e.V.)
Institute for Solar Research, Almeria, Spain



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