SFERA-III
Solar Facilities for the European Research Area

On-site training for industries on "Testing the durability of solar materials and systems“
08.06.2022 – 10.06.2022

WP 1.3 – NA1- 3rd FREE training course about CST materials and systems

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Solar Facilities for the European Research Area

NETWORKING

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SFERA-III

Solar Facilities for the European Research Area

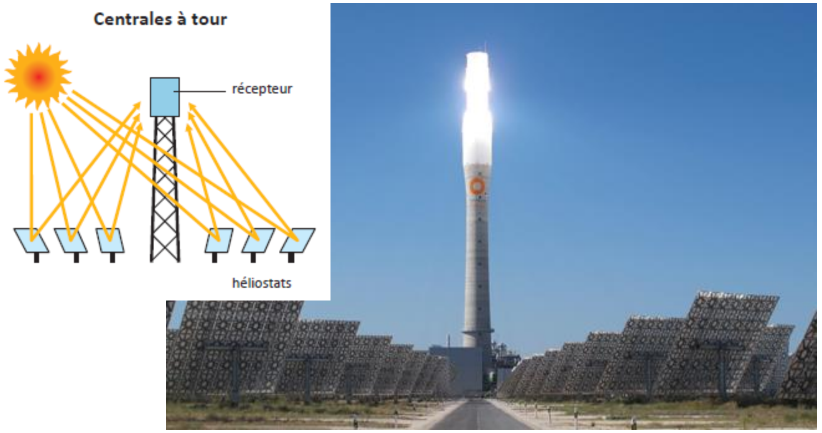
Wednesday, June 8, 2022

09:15 – 09:30	Introduction and Goals	CEA	15 min
09:30 – 9:45	Generality on durability method studies	CEA	15 min
9:45 – 11:45	Visit and discussion on CEA INDOOR/OUTDOOR facilities and Optical laboratory	CEA	120 min
11:45 – 12:00	- Coffee break -		15 min
12:00– 13:00	CEA INDOOR and OUTDOOR aging tests	CEA	60 min
13:00 – 14:00	- Lunch break -		60 min
14:00 –14:30	Standardized tests for reflectors	DLR	30 min
14:30 -15:00	Advanced tests for reflectors	CEA	30 min
15:00 –15:30	Erosion of reflectors and sandstorm simulation	DLR	30 min
15:30 -16:00	Characterization and accelerated aging of parabolic trough receiver materials	DLR	30 min
16:00– 16:30	Characterization and accelerated aging of solar absorber materials	DLR	30 min
16:30 –17:00	Sample and data management	CEA	30 min

Generality on durability studies

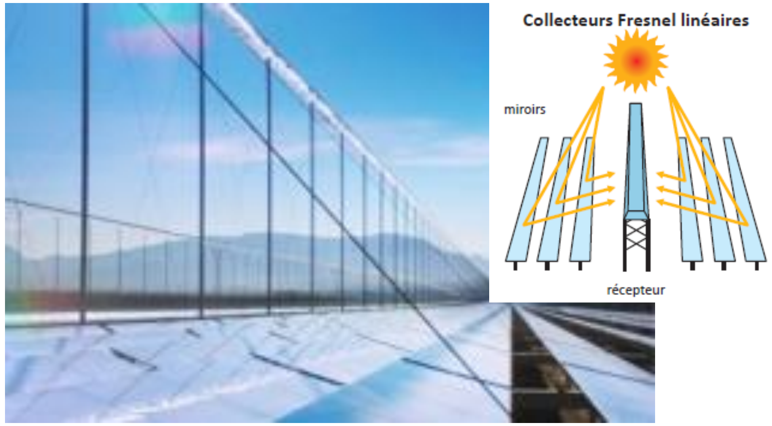
Technologies CSP/CST :

Fluid temperature : 450-1000°C
Concentration factor : ~500



Gemasolar

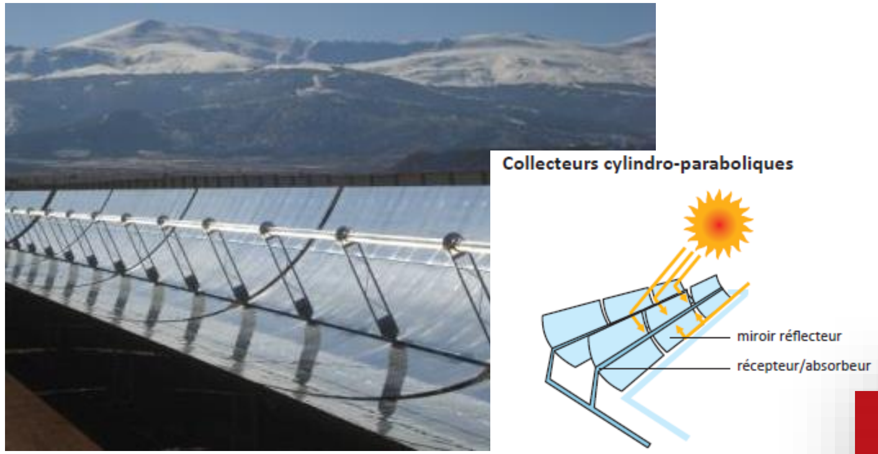
Fluid temperature : 100-450°C
Concentration factor : ~ 50



Puerto Errado Novatec

Villarrobledo

Fluid temperature : 600-1200°C
Concentration factor : ~2000

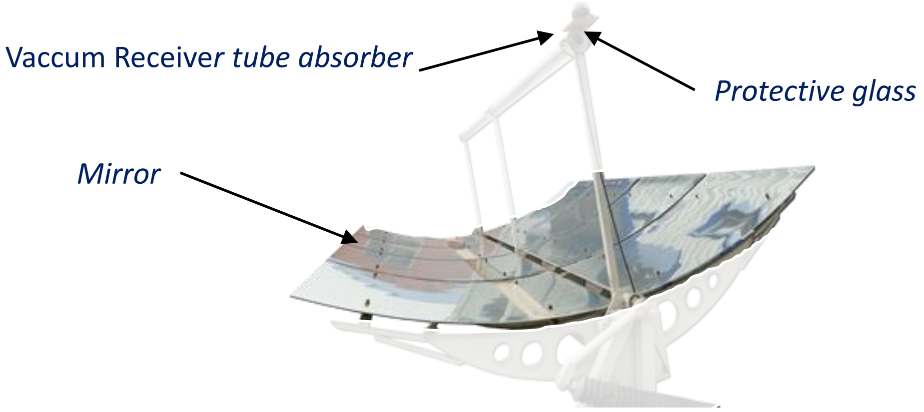


Andasol

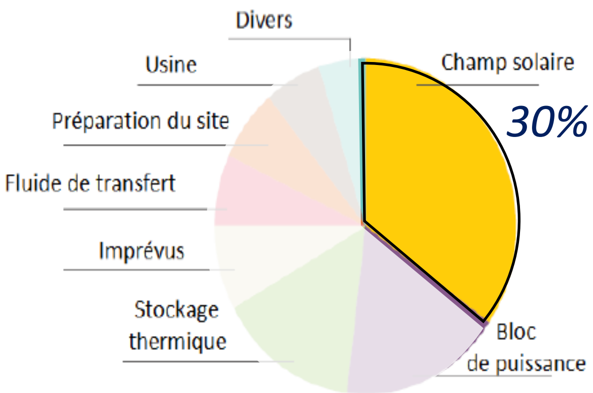
Fluid temperature : 100-450°C
Concentration factor : ~ 100

Durability :

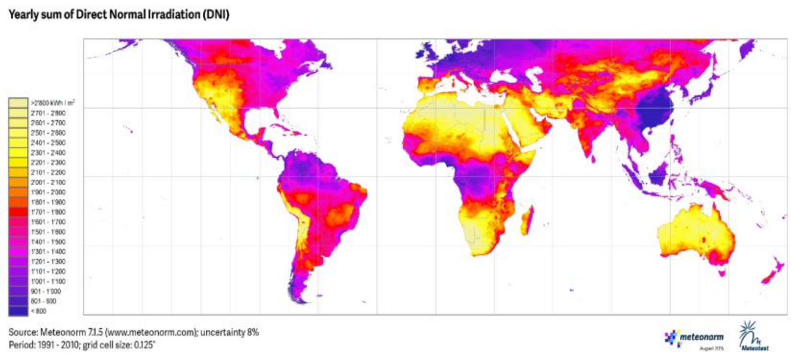
Parabolic trough Solar plant



Cost of CSP plant



Potential CSP sites



➔ Thousands of mirrors and receivers (≈ **30 % initial investment**)
➔ Best locations : Arid region or coastal area
➔ Solar mirrors and receivers lifetime of **25 years**
➔ Reflectance or absorptance **> 90%**

Being able to predict the aging and the degradation rate of solar mirrors and receivers can be profitable :

- To correctly calculate the energy produced over time and to deduce the plant LCOE
- To help scientific and industrial companies to produce best quality of components by identifying the key factors of degradation
- To reassure banks and investors by predicting more accurately future events such as the replacement of components

Durability definition:

- *<u>Durability:</u>* the ability of a material to resist deterioration caused by external factors and to maintain its performance under conditions of use. [1]

- *<u>Lifespan:</u>* time between the installation of the material and when its performance drops below the minimum required. It therefore depends on the properties of the material, but also on the performance criteria of the application and the stress factors present in the environment.

- *<u>Performance:</u>* measure of the ability to perform as desired or to exhibit properties useful for the application. [1]

- *<u>Aging :</u>* degradation of the material's properties over time. It can be natural or accelerated. Aging is said to be natural when the material is used under normal conditions for the application for which it is intended. It is said to be accelerated when the life of the material is shorter or its performance decreases faster than under normal application conditions. For this, it is subjected to greater constraints and its performance is measured over time. [2]

[1] Michael Kohl, Bo Carlsson, Gary Jorgensen, and A. W. Czanderna. Performance and durability assessment: Optical Materials for Solar Thermal systems. Elsevier Science, 2004.
[2] Wayne Nelson. Accelerated Testing: Statistical models, tests plans, and data analyses. John Wiley & Sons, Inc, 1990 edition, 1990.

Durability studies:

Platform for durability study of solar materials and systems with a network of expertise and multisite for outdoor and indoor test

Outdoor
- Characterizations
- Stress factor evaluation : environmental condition measurement
- Degradation mechanism analysis

Correlation
Ageing law
Accelerated factor
Lifetime prediction

Indoor
- Accelerate test
- Reproduction of degradation
- Characterization and analysis

Tools
+ Methodologies
= Durability test through the standards

Photovoltaic (PV)

Thermal Solar (ST)

Concentrated solar power (CSP)

Solar Heat, Solar Fuels

Component Technologies:

Reflectors:

a) Monolithic glass
b) Laminated glass
c) Aluminum
d) Polymer film

Low iron glass	1 – 4 mm
Silver	70 – 150 nm
Copper	30 – 150 nm
Prime paint	20 – 30 µm
Intermediate paint	20 – 30 µm
Top paint	30 – 40 µm

a)

Low iron glass	1 mm
Silver	70 – 150 nm
Copper	30 – 150 nm
Adhesive (PVB)	< 1 mm
Float glass substrate	1.5 mm

b)

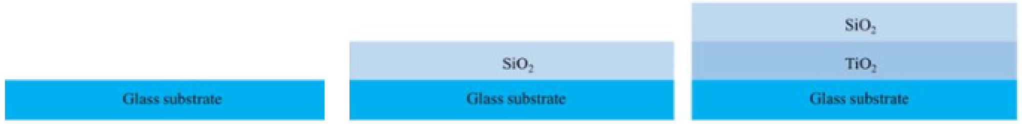
SiO_2	3 µm
TiO_2	55 – 60 nm
SiO_2	75 – 95 nm
Al pure	65 nm
Al_2O_3	0.1 – 3 µm
Al substrate	500 µm

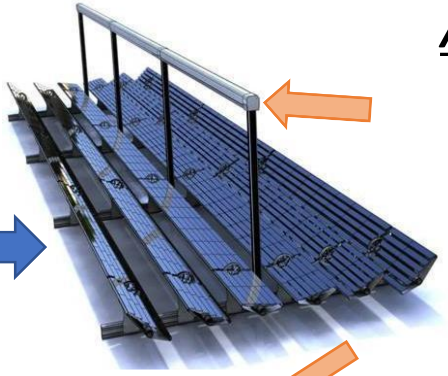
c)

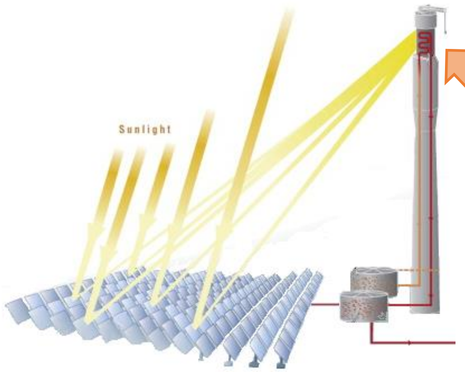
Transparent polymer	100 µm
Silver	70 – 150 nm
Copper	30 – 150 nm
Polymer substrate	100 µm

d)

Glasses:





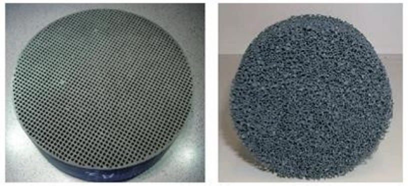


Absorbers:

Alloys with
Selective coatings

Alloys with Black Paints

Porous ceramic Silicon Carbide



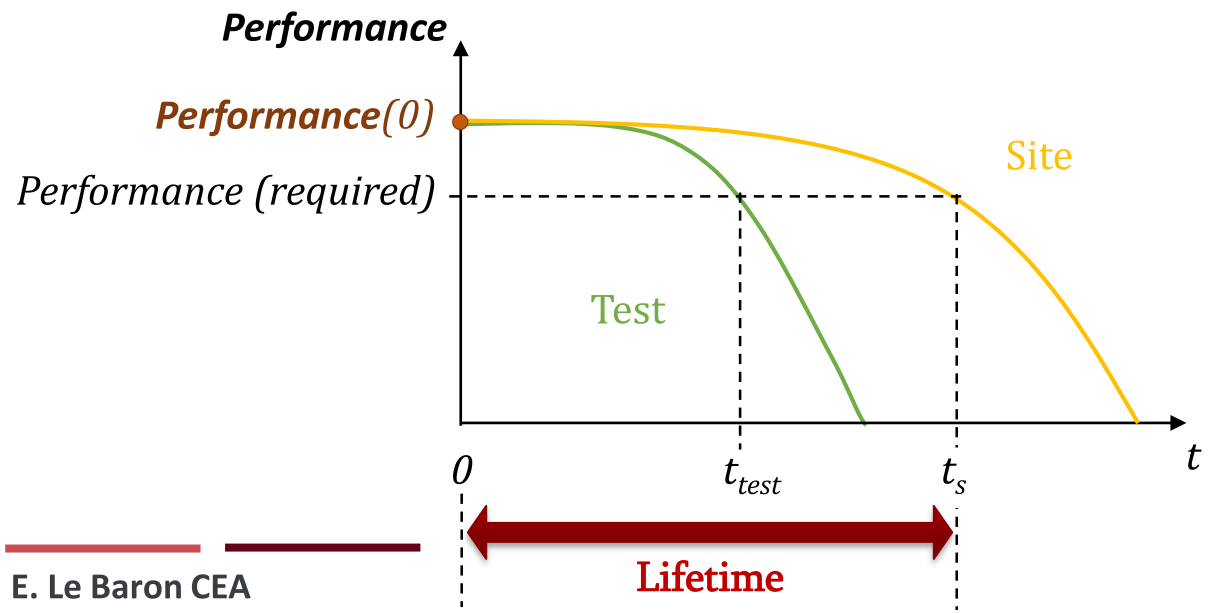
Introduction to the Durability method :

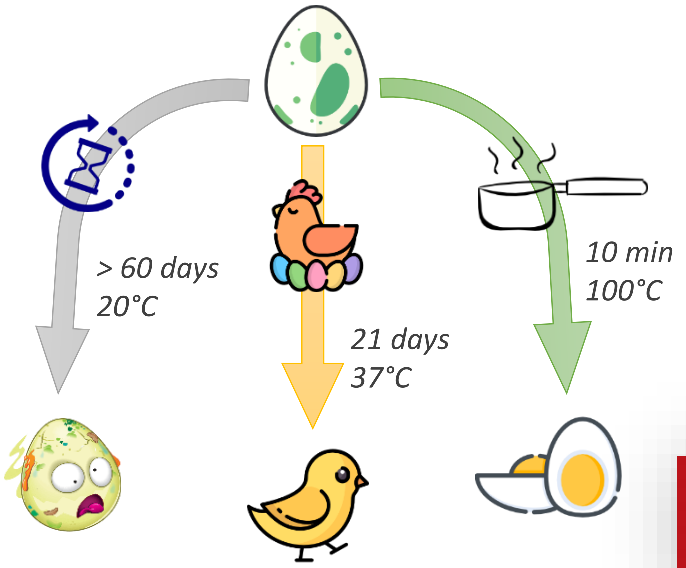
Durability = performance ≠ **Aging** ↘ performance

Natural site

Accelerated test: ↗ level of stress ⟷ ↗ degradation rate

⚠ Representativeness of aging





Visit and discussion on CEA INDOOR/OUTDOOR facilities and Optical laboratory

E. Le Baron CEA

Example of INDOOR and OUTDOOR aging facilities

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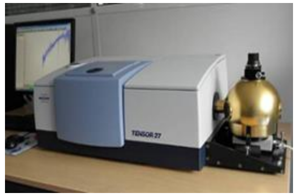
Characterization

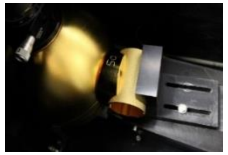
Optical, physical and chemical measurements
- Specular reflectance
- Absorption (plane, tube) at ambient and up to 1000°C
- Microscope and MEB
- FTIR …

High temperature emissivity

FTIR



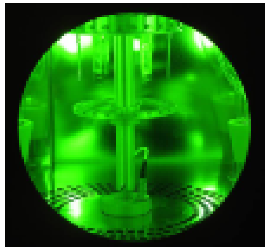
Colorimeter



Pipes

Indoor Testing

Accelerated ageing
- Temperature, humidity
- Irradiation, UV
- Abrasion (sand, cleaning)
- Salt Mist



Outdoor Testing

Mirror soiling
- France (INES, Cadarache, Reunion)
- Morocco (Ouarzazate)

CEA INDOOR aging facilities

INDOOR aging facilities : NSS

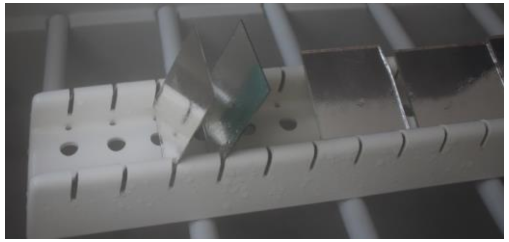
According to the standard ISO 9227:2017 (Corrosion testing in artificial atmospheres : Salt spray tests) and IEC 600068-2-52 (PV)

- Constant conditions of 35 ± 2°C with [NaCl]=(50±5) g/l; pH=6.5-7.2
- Tilt angle of 20 ± 5° respect to the vertical
- Condensation rate of 1,5 ± 0,5 mL/h on a surface of 80 cm²
- Testing time : 480 hours

Weiss SC450

Mini 3 samples positioned inside the chamber :

- By the front side (glass) facing upwards x 3
- By the back side (coating) facing upwards x 3



ISO 9227 : Corrosion tests in artificial atmospheres – salt spray tests

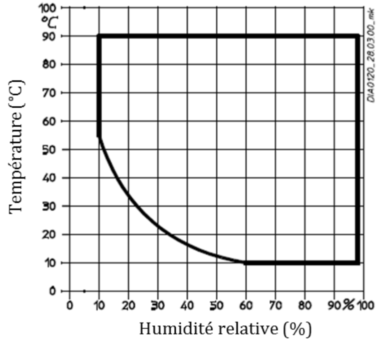
INDOOR aging facilities : CONDENSATION

According to the standard ISO 6270-2 (test CH), ISO 22975-3 and UNE 206016

- Constant conditions of samples of 40 ± 3°C with 100% relative humidity,
- T°chamber : T°sample + 5°C = 45°C
- Tilt angle of 20 ± 5° respect to the vertical, front side up
- Testing time : 480 hours

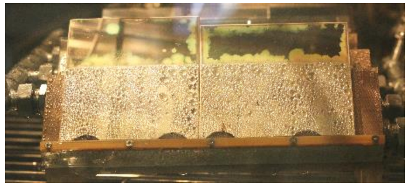
Mini 3 samples positioned inside the chamber :

- By the front side (glass) facing upwards x 3



Vötsch VC0018

T°=-10 to 90°C
RH = 10 to 98%



ISO 6270-2: Paints and varnishes – Determination of resistance to humidity
ISO 22975-3: Solar energy - Collector components and materials - Part 3: Absorber surface durability

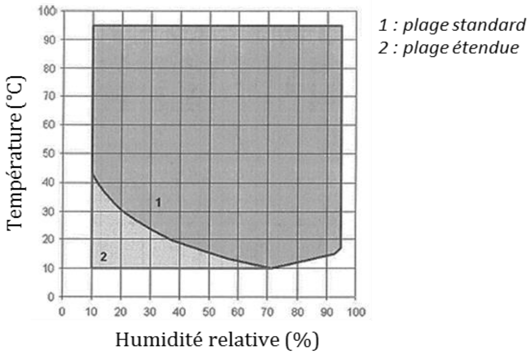
INDOOR aging facilities : CYCLICAL TEMPERATURE AND HUMIDITY

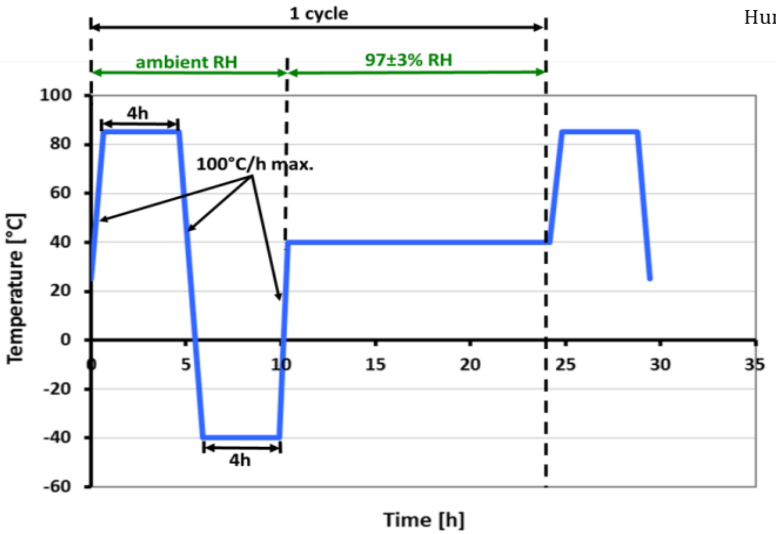
According to the standard IEC 61215 10.11 and UNE 206016

- 4 hours phase at 85°C ± 2°C
- 4 hours phase at -40°C ± 2°C
- 16 hours humidity cycle : Method A / ISO 6270-2 Constant conditions of 40°C ± 2°C with 97 ± 3 % relative humidity
- Tilt angle of 20 ± 5° respect to the vertical, front side up
- Testing time : 10 cycles ~ 240 hours

Mini 3 samples positioned inside the chamber :

- By the front side (glass) facing upwards
- By the back side (coating) facing upwards





Weiss WKL 100/40

T°=-40 to 95°C
RH = 10 to 95%

IEC 61215: Crystalline silicon terrestrial photovoltaic (PV) modules - Design qualification and type approval

INDOOR aging facilities : DAMP HEAT (DH)

According to the standard IEC 62108 (test number prefered 10.7b 65/85 or 10.7a: Damp heat test 85/85)

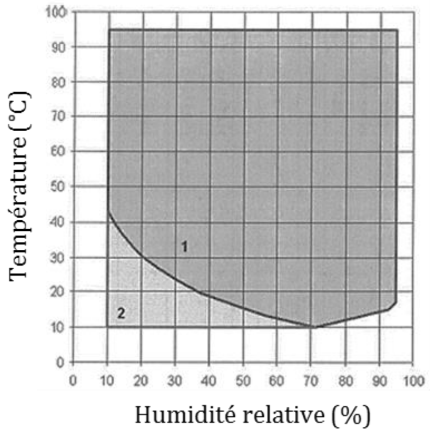
- Constant conditions of **65** ± 2°C with 85 ± 5 % relative humidity
- Tilt angle of around 25° respect to the vertical
- Testing time : 2000 hours (10.7a T = 85°C/1000 hours)

Mini 3 samples positioned inside the chamber :

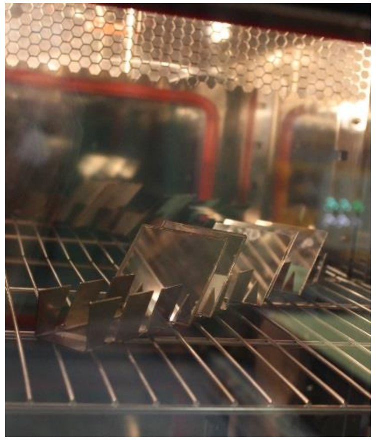
- By the front side (glass) facing upwards
- By the back side (coating) facing upwards

Weiss WKL 100/40

T°=-40 to 95°C
RH = 10 to 95%



1 : plage standard
2 : plage étendue



IEC 62108: Concentrator photovoltaic (CPV) modules and assemblies - Design qualification and type approval

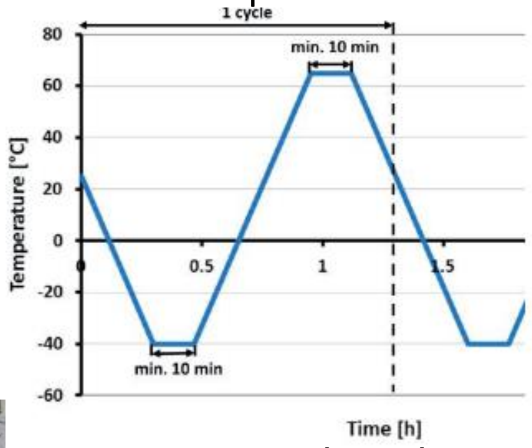
INDOOR aging facilities : THERMAL CYCLE

According to the standard IEC 61215 Test 10.11 or IEC 62108 Test 10.6 option TCA 1 ou TCA 3

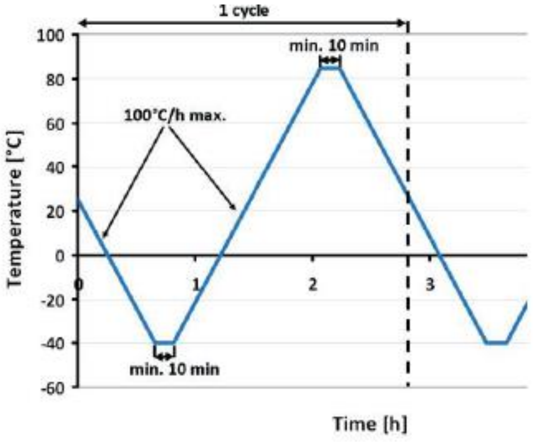
- **IEC 62108 Test 10.6 TCA 3** : **2000 cycles between – 40 °C and 65 °C**, each time with a plateau of at least 10 min within ± 3°C of the limit temperature and a number of cycles of 2000
- **IEC 62108 Test 10.6 TCA 1 :** is the same except for a maximum temperature of **85°C** and a number of cycles decreased to **1000**
- **IEC 61215 Test 10.11** is identical to the IEC 62108, 10.6 TCA 1 test reduced **to 200** instead of 1000

Mini 3 samples positioned inside the chamber :

- By the front side (glass) facing upwards
- By the back side (coating) facing upwards



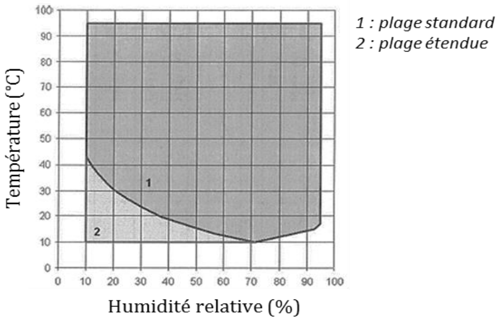
Test 10.6 (TCA 3)

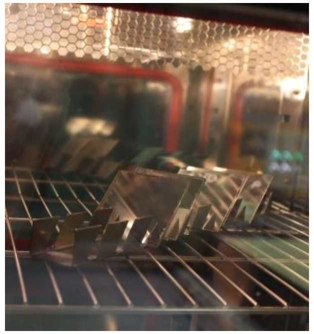


Test 10.6 (TCA 1)

Weiss WKL 100/40

T°=-40 to 95°C
RH = 10 to 95%





IEC 61215: Crystalline silicon terrestrial photovoltaic (PV) modules - Design qualification and type approval
IEC 62108: Concentrator photovoltaic (CPV) modules and assemblies - Design qualification and type approval

INDOOR aging facilities : HUMIDITY FREEZE

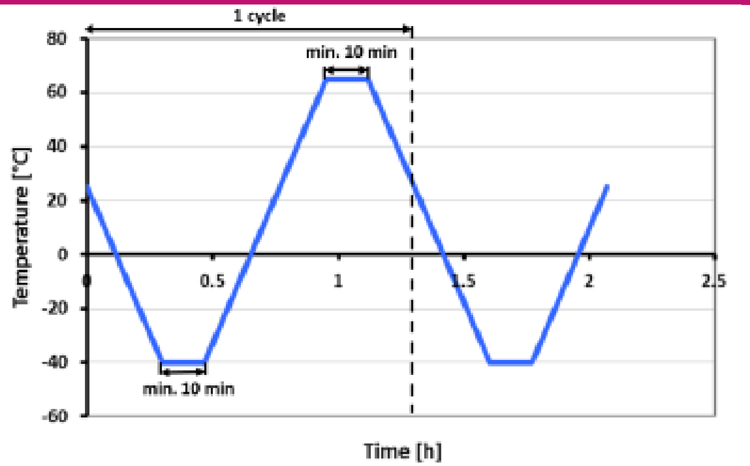
According to the standard IEC 62108 Test 10.8 **reduced at 65°C**

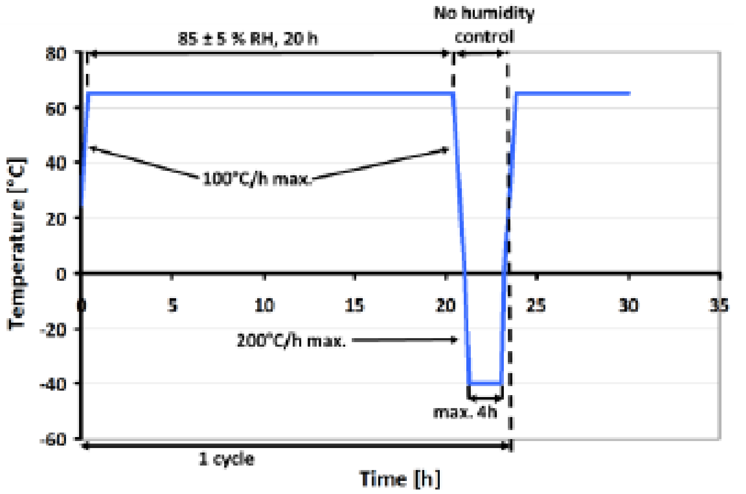
two stages:

- **400 cycles from – 40°C to 65°C**, with a plateau of at least **10 min** in an interval of ± 3°C limit temperature;
- a plateau of **20 h at 65°C and 85% RH followed by another at -40°C**, lasting less than **4 h with temperature ramps of less than 100°C/h.**
- The first stage should include **10 to 18 cycles per day, the second 40 cycles, and the whole should last about 1500 hours.**

Mini 3 samples positioned inside the chamber :

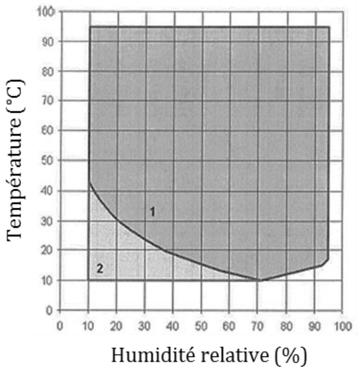
- By the front side (glass) facing upwards
- By the back side (coating) facing upwards





Weiss WKL 100/40

T°=-40 to 95°C
RH = 10 to 95%



IEC 62108: Concentrator photovoltaic (CPV) modules and assemblies - Design qualification and type approval

INDOOR aging facilities : UV Xenon radiation + Temperature

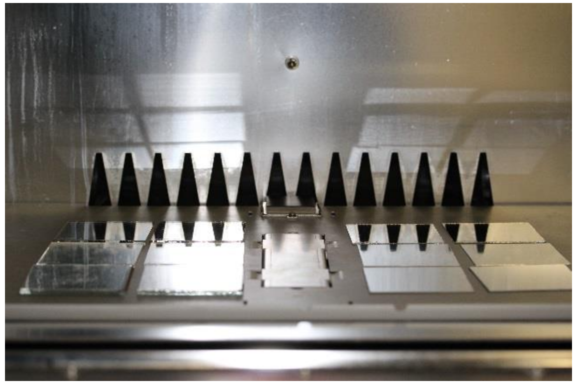
According to no standard

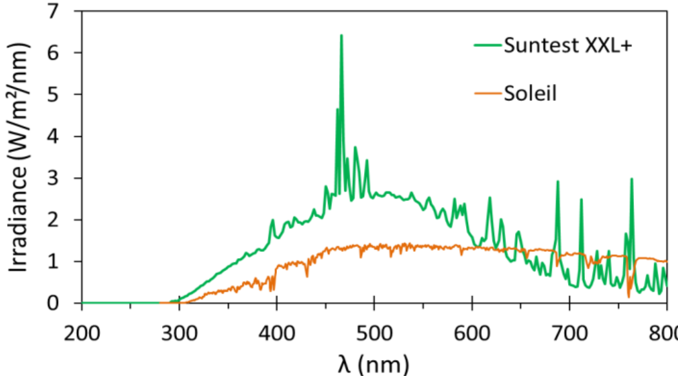
- Air temperature : 70°C
- Sample temperature : 85°C
- Irradiation level : 65 W/m² (300-400 nm)
- Testing time : 1000 hours each side (total: 2000 hours)

3 samples positioned inside the chamber :

- By the front side (glass) facing upwards x 3
- By the back side (coating) facing upwards x 3

ATLAS SUNTEST XXL





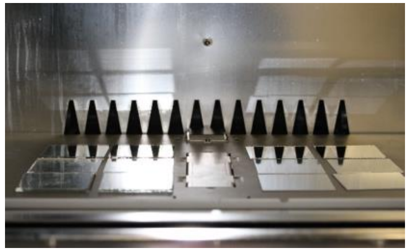
Emission spectrum of lamps (xenon NXE 1700) and the sun (reference Air Mass 1.5, ASTM G173-03)

INDOOR aging facilities : UV Xenon radiation + Temperature + water spray

According to the standard ISO 16474-2: Methods of exposure to laboratory light sources — Part 2: Xenon-arc lamps

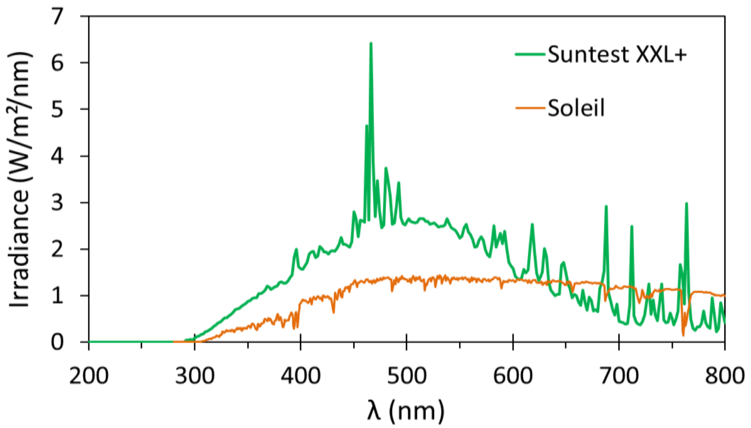
- Air temperature :70°C
- Sample temperature : 85°C
- Irradiation level : 65 W/m² (300-400 nm) : 27 min, water aspersion : 3 min, cycle duration: 30 min
- Testing time : 1000 hours each side (total: 2000 hours = 4000 cycles of 30 min)

ATLAS SUNTEST XXL



3 samples positioned inside the chamber :

- By the front side (glass) facing upwards x 3
- By the back side (coating) facing upwards x 3



Emission spectrum of lamps (xenon NXE 1700) and the sun (reference Air Mass 1.5, ASTM G173-03)

ISO 16474-2: Paints and varnishes – Methods of exposure to laboratory light sources - Part 2: Xenon-arc lamps.

INDOOR aging facilities : UV + Saline mist NSS

According to no standard

- Irradiation test xenon lamp with filtre (65 W/m² between 300-400 nm), t=200h, air T=70°C
- NSS (T=(35±2)ºC; 100% RH; [NaCl]=(50±5) g/l; pH=6.5-7.2), t=200h
- Cleaning of the sample with deionized water after NSS phase
- Testing time : 1 cycle : 400 hours➔ 10 cycles

SUNTEST XXL

+ Weiss SC450

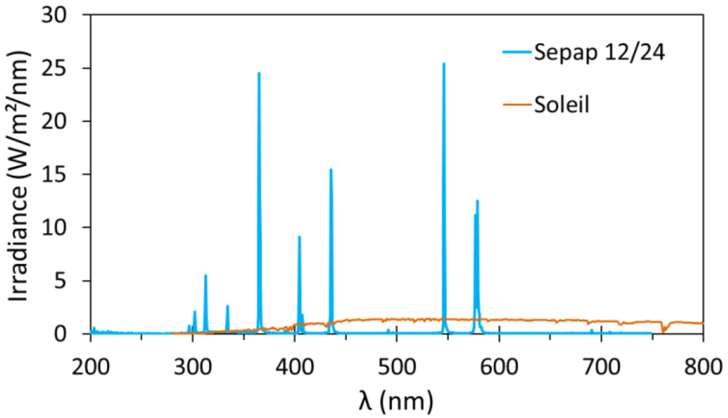
INDOOR aging facilities : UV Mercury radiation + Temperature

According to no standard

- Air temperature: 70°C, sample temperature ~ 85°C
- Irradiation level: 90 W/m² (300-400 nm), RH no control
- Testing time : 1000 hours each side (total: 2000 hours)

3 samples positioned inside the chamber :

- By the front side (glass) facing upwards x 3
- By the back side (coating) facing upwards and glass is protected with a special tape



Emission spectrum of lamps (Novalamp RVC 4000W) and the sun (reference Air Mass 1.5, ASTM G173-03)

ATLAS SEPAP 12/24

INDOOR aging facilities : UV-5X Metal halide radiation + Temperature + Humidity

According to no standard

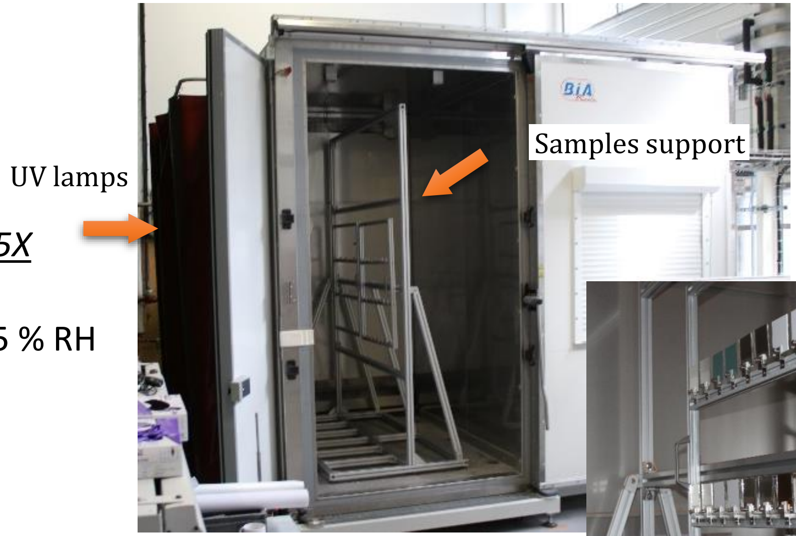
- 4 hours at 60°C to UV-radiation (300-800 nm), relative humidity controlled
- 4 hours at 50°C to condensation without irradiation, 95% relative humidity
- Testing time : 1000 hours each side (total: 2000 hours)

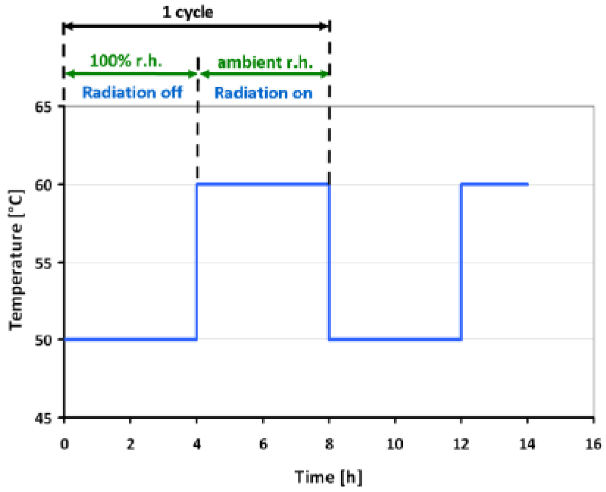
3 samples positioned inside the chamber :

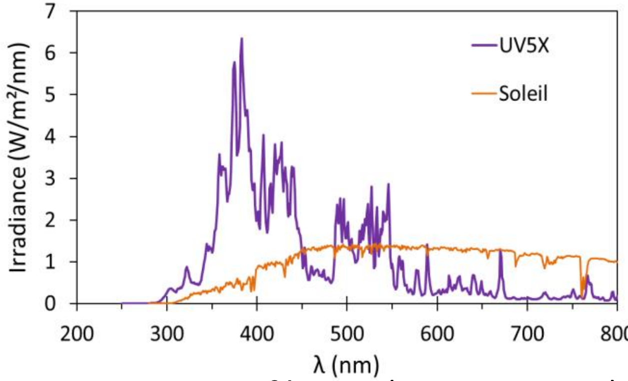
- By the front side (glass) facing upwards x 3
- By the back side (coating) facing upwards and glass is protected with a special tape

AMTC UV-5X

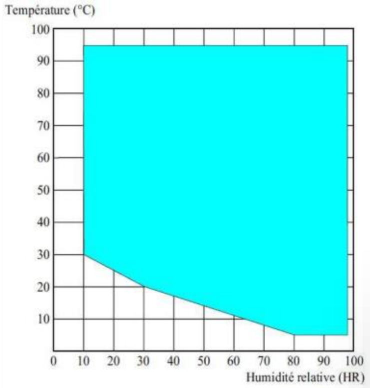
Size : 220 x 150 x 284 cm
T°= -40°C to 100°C and 5-95 % RH







Emission spectrum of lamps (HTC 2000-349) and the sun (reference Air Mass 1.5, ASTM G173-03)



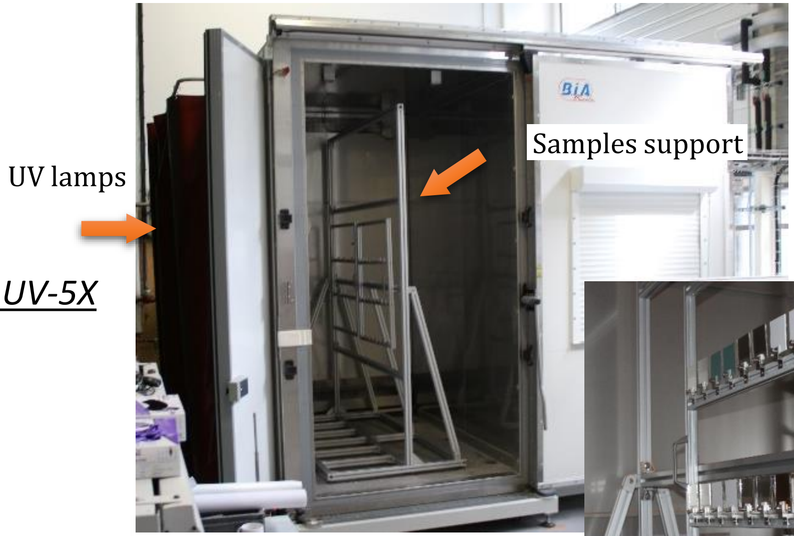
INDOOR aging facilities : UV-5X Metal- halide radiation + Temperature + Humidity

According to no standard

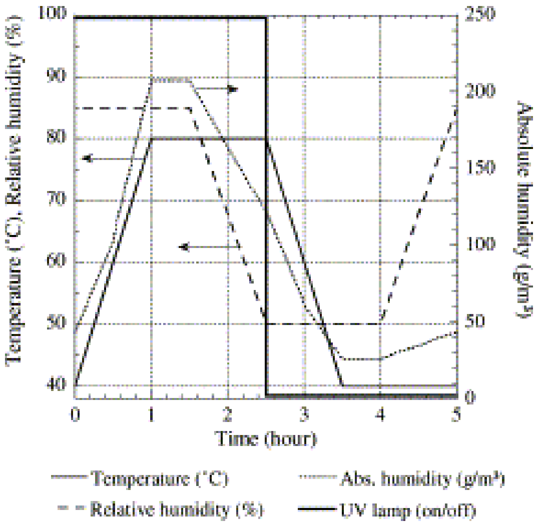
- 2,5 hours at 80°C to condensation without irradiation, 85% relative humidity +UV
- 2,5 hours at 40°C to UV-radiation (300-800 nm), 50% relative humidity
- Testing time : 1000 hours each side (total: 2000 hours)

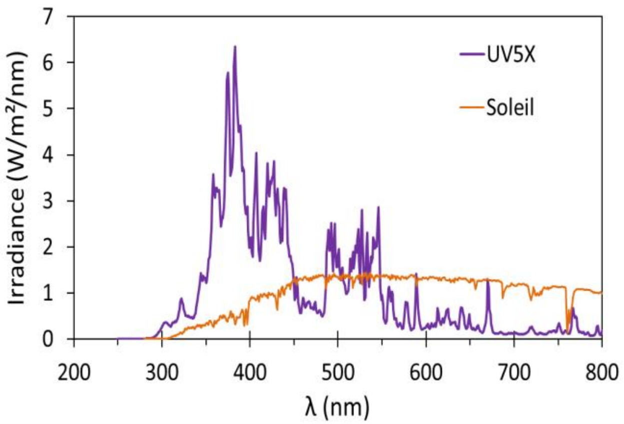
3 samples positioned inside the chamber :

- By the front side (glass) facing upwards x 3
- By the back side (coating) facing upwards and glass is protected with a special tape



AMTC UV-5X





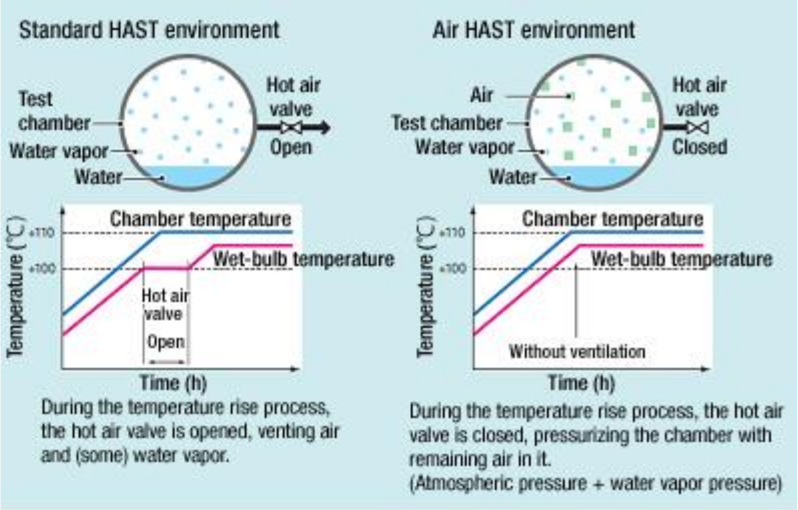
Emission spectrum of lamps (HTC 2000-349) and the sun (reference Air Mass 1.5, ASTM G173-03)

INDOOR aging facilities : HAST test Humidity and pressure for mirrors

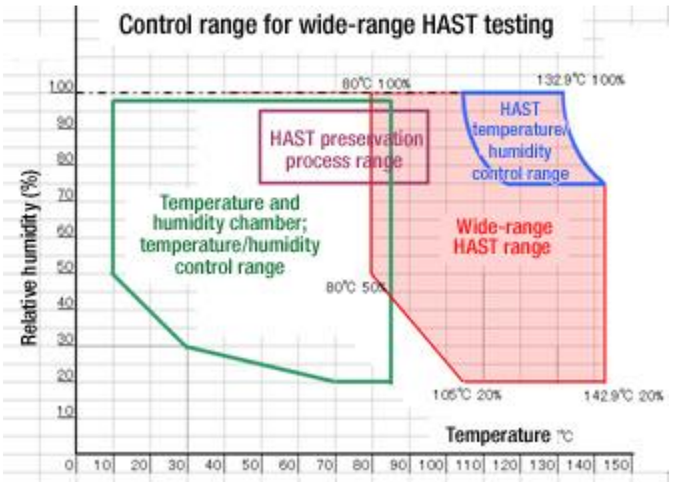
According to standard IEC 68-2-66

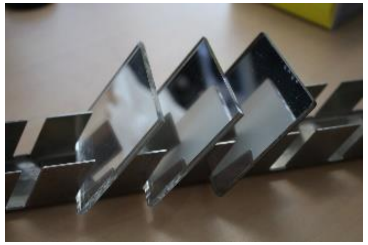
- ➢ Constant conditions until P : 2 bars
- ➢ T: 121°C
- ➢ RH: 100%
- ➢ Testing time : 240 hours

3 samples positioned inside the chamber



HAST environment





IEC 60068-2-66: Compact electrical and electronic components

INDOOR aging facilities : Solar Simulator 1 SUN radiation

Technical specifications of lamp field

Technical specification	Details
Effective degrees of freedom of lamp rig and lamps	3 linear, 1 rotational (0° to 90°), actuators electrically controlled, height and inclination sensors
Lamp type	ATLAS MTT “Solar Constant 4000”
Spectral Quality	according to EN12975: 2006 and ISO 9806-1:1994
Life expectancy of lamps	1000 hours
Max. Intensity on test area without artificial sky	1200 W/m² (280-3000 nm)
Max. Intensity on test area with artificial sky	1100 W/m² (280-3000 nm)
Size of test area with 1200 W/m² (without artificial sky), ± 10% homogeneity	2.0 m x 2.4 m
Temporal stability of light intensity	± 1%
Collimation	approx. 90% of the emitted radiation lies in the range in which the IAM of a regular flat plate collector varies by no more than 2%
Intensity Control	75 - 100%

Technical specifications of the collector test platform

Technical specification	Details
Test surface	net: 2.4 m x 3.2 m, gross: approx. 2.5 m x 3.3 m
Max. load	approx. 400 kg laminar
Range of incline	0° to 90°
Precision	± 1°

Ventilation Unit

Technical specification	Details
Number of cross-flow fans	2
Max. air flow speed	4 m/s
Electrical power	approx. 1000 W each
Electrical connection	230 V/50 Hz

Technical specifications of the thermostat

Technical specification	Details
Temperature range	10° C - 110° C
Temperature control	±0.1° C
Heating power / Cooling power	6 kW / 4 kW
Max. pump pressure	4 bar
Max. pump flow	600 kg/h
Volume flow range (min. / max.)	approx. 70 to 420 l/h
Max. deviation	±1%

E. Le Baron CEA

INDOOR aging facilities : Constant Temperature

According to no standard

- Constant conditions of 70 ± 2°C or 85°C or 100°C
- Testing time : 2000 hours

3 samples positioned inside the chamber :

CTS Venticell

T° < 250°C

INDOOR aging facilities : Constant Temperature for absorbers

According to standard ISO 22975-3:2014

- Constant conditions until 850°C
- Testing time : 10 000 hours

3 samples positioned inside the chamber :

Nabertherm N30/85HA < 850°C

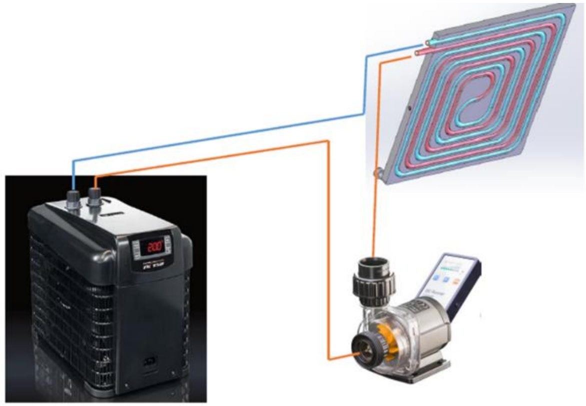
ISO 22975-3: Solar energy - Collector components and materials - Part 3: Absorber surface durability

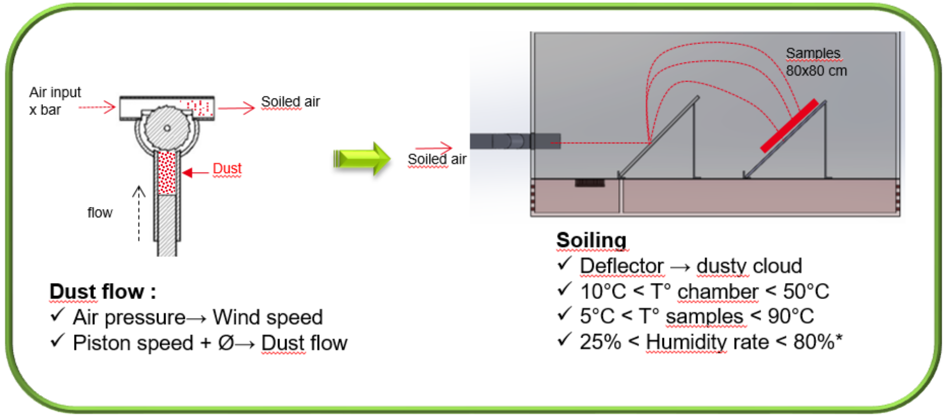
INDOOR facilities : artificial soiling for mirrors

According to no standard

- « Standard test dust »: SAE J 726, MIL 810, GARNET 120 or local one
- T of the chamber : between 10 and 50°C as throughout the day or night
- T of the sample : between 5 and 90°C
- RH of the chamber : between 25 and 80%
- The sand is sprayed constantly inside the enclosure with a speed of 350 to 550 mm/h. The projected sand rebounds on the deflector positioned in the foreground, creating a cloud of dust which will settle slowly (approximately 1 hour) on the sample

4 samples positioned inside the chamber





Standardized INDOOR aging tests :

Test	Testing conditions	Proposed duration	Chamber	Standard
NSS	T=(35±2)ºC; RH=100%; [NaCl]=(50±5) g/l; pH=6.5-7.2	480 h	Weiss SC450	ISO 9227
Condensation	T=(40±3)ºC; RH=100%	480 h	Vötsch VC0018	ISO 6270-2 (CH) and UNE 206016
Cyclical temperature and humidity	4 hours at T=85ºC; 4 hours at T=-40ºC; 16 hours at T=40ºC and RH=97 ± 3 %	10 cycles	Weiss WKL 100/40	UNE 206016
Humidity Freeze	From T= (-40±2)ºC to T= (65±2)ºC. Minimum dwell time 10 minutes (around 1.85 h per cycle)	40 cycles	Weiss WKL 100/40	IEC 62108 (10.8)
Damp Heat	T=(65±2)ºC; RH=(85±5)%	2000 h	Weiss WKL 100/40	IEC 62108 (10.7b)

Current standard for reflectors in IEC TC 117 :

Standard	Title	Status
IEC 62862-3-5	Part 3-5 : Laboratory reflectance measurement of concentrating solar thermal reflectors (Ciemat)	New in 2021
IEC 62862-3-6	Part 3-6 : Accelerated aging tests of silvered-glass reflectors for concentrating solar technologies (DLR)	New in 2021

CEA OUTDOOR aging facilities

OUTDOOR aging facilities :

Choice of sites:

- Easily accessible (regular measurements)
- Different climates

Exposure sites :

- ☆ INES
- ☆ CEA Cadarache
- ☆ Université de Corse Pasquale Paoli
- ☆ PIMENT

France

Ile de Corse

Ile de la Réunion

CEA OUTDOOR aging facilities at cea INES and CADARACHE :

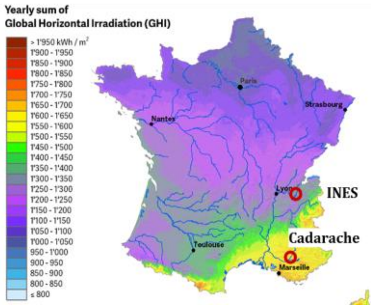
Trackers

> 10 m², >175°C (water), 2 axis (accuracy 0.05°)
2 coolers


Solar Thermal Plants


Solar Thermal Energy

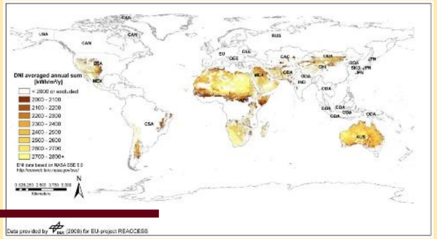

1 MW Solar Thermal Energy



Outdoor environmental monitoring



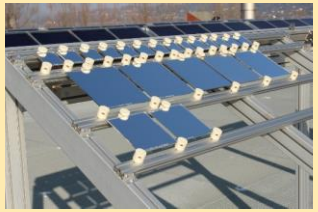




F. Trieb, C. Schillings, M. O'Sullivan, T. Pregger and C. Hoyer-Klick,
"Global Potential of Concentrating Solar Power",
SolarPACES Conference, 2009.

Racks, concentrators paraboles

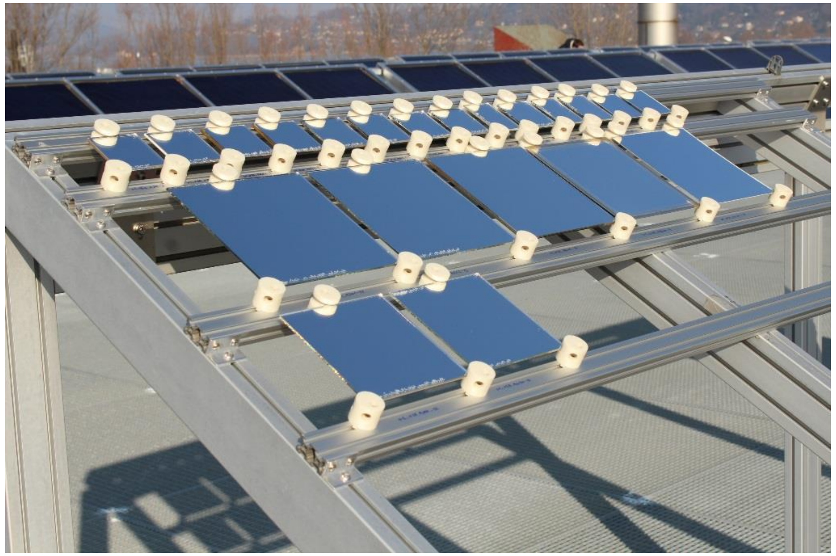
Natural aging /accelerated + coupling


Natural rack exposure


Fresnel Lens
< 500 °C


Solar concentrator with tracking system < 900°C

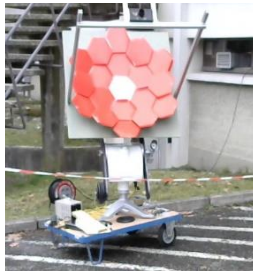
OUTDOOR aging facilities : Natural outdoor exposure at CEA INES and CADARACHE :



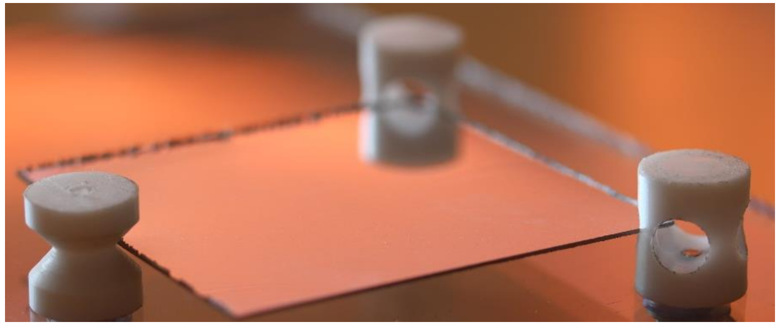
INES

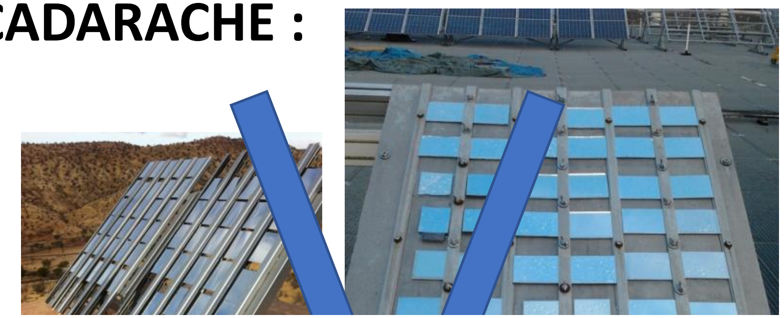
Cadarache

Fresnel Lens
< 500 °C

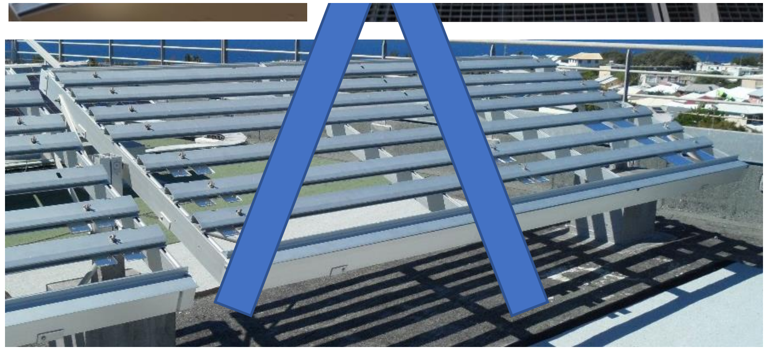


Solar concentrator with
tracking system < 900°C

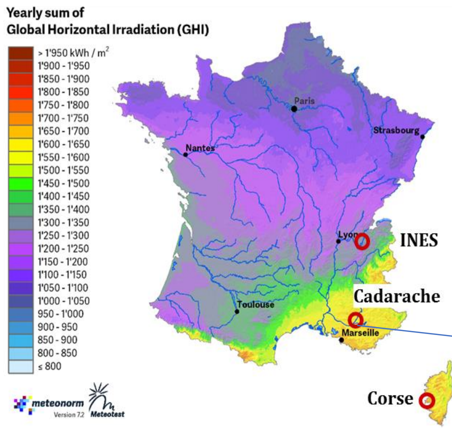


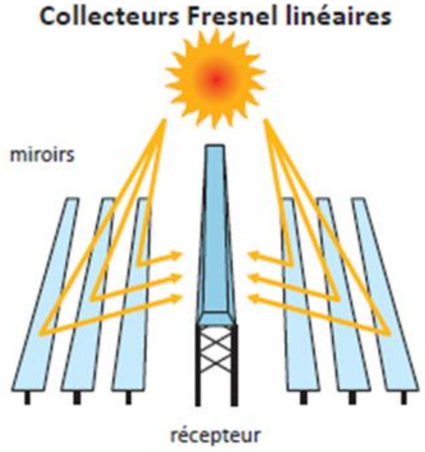


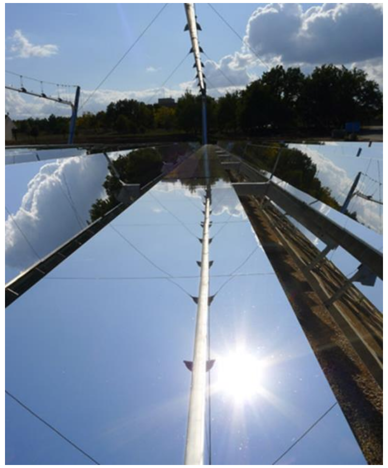
High mechanical stress (different thickness, Masked rear face, Water and dirt retention areas, corrosion with steel material of the rack



OUTDOOR aging facilities : 2 LFR solar demonstrators at CEA CADARACHE







- 1000 m^2 of mirrors
- concentration factor 50
- 20 linear reflectors of 50m
- Two receiver lines 50*0.2m
- Heat transfer fluid: Therminol oil
- Operating temperature 300°C
- Prototype capacity 400 kWth
- Electricity production: 50 kWel
- Storage capacity 1500 kWh~ 4h for night/cloud operation

- 1600 m^2 of mirrors
- concentration factor 50
- 100 ml multi-tubes cavity receiver
- Direct Steam Generator
- Steam production temperature at 450°C and a pressure of 100 bar
- Prototype capacity 780 kWth
- Storage capacity 1600 kWh innovative three-stages Thermal Energy Storage

OUTDOOR aging facilities : Natural outdoor exposure on others sites

force inépuisable de développement

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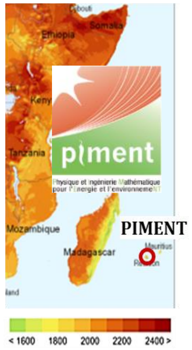
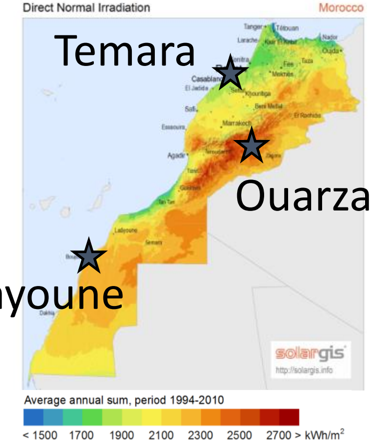
Durasol
ANR



Wet wick on Reunion Island
ISO 9225 :2002

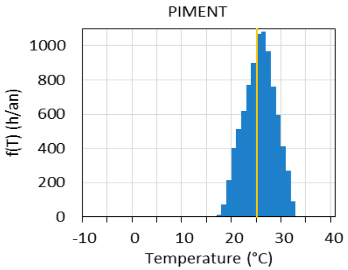
Reflector exposure

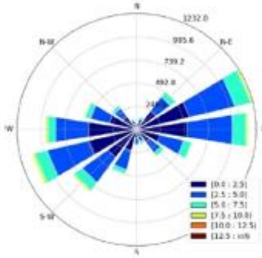
ISO 9225:2012 Corrosion of metals and alloys -- Corrosivity of atmospheres -- Measurement of environmental parameters affecting corrosivity of atmospheres

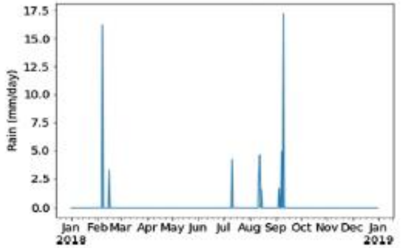


Sites with different climates / environmental stresses

Meteonorm® and meteorological station







CEA Optical Laboratory

E. Le Baron CEA

Optical Characterizations of reflectors and glass :

<u>Perkin Elmer Lambda 950 Spectrophotometer</u>

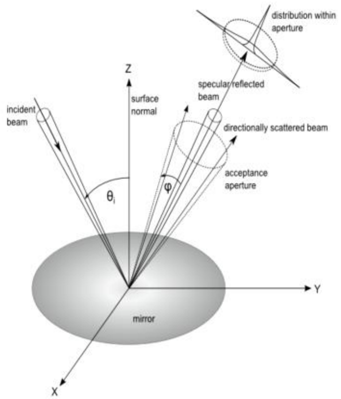
- Spectral hemispherical reflectance/transmittance : $\rho_\lambda(\lambda,\theta_i,h)$ & $\tau_\lambda(\lambda,\theta_i,h)$
- Integrating sphere of 150 mm diameter
- λ = [280,2500] nm / 5 nm intervals / θ_i = 8°
- 3 measurements on each sample (0°/90°/180°)
- max Size : 10 x 10 cm²

Spectralon®

Small Spot Kit

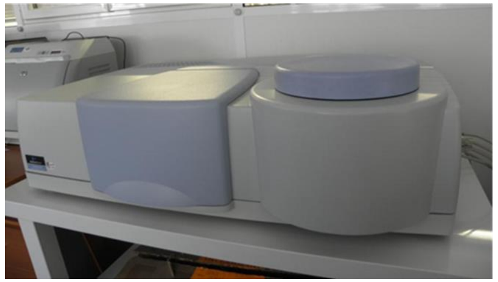
<u>D&S 15R-USB portable specular reflectance</u>

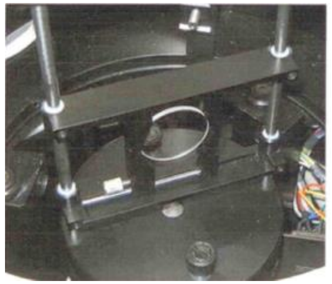
- Monochromatic specular reflectance -> $\rho_\lambda(\lambda,\theta_i,\phi)$
- θ_i = 15° / ϕ = 12,5 mrad / λ = 660 nm
- 3 or 5 different positions on each sample



Instrument	Manufacturer	Model	Accessory	Reflectance
Spectrophotometer	Perkin Elmer	Lambda 950	IS (Ø 15 cm)	$\rho_{s,h}([280,2500],8°,h)$
Reflectometer	Devices and Services	15R-USB	-	$\rho_{\lambda,\phi}(660nm,15°, 12.5\ mrad)$

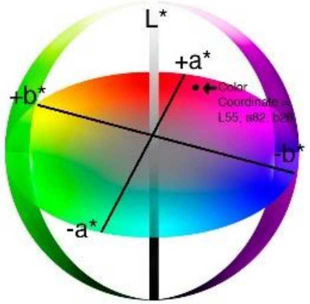
Optical Characterizations of reflectors and glass :





Perkin Elmer Lambda 950 Spectrophotometer

- Spectral specular reflectance/transmittance : $\rho_\lambda(\lambda,\theta_i,\varphi)$ & $\tau_\lambda(\lambda,\theta_i,\varphi)$
- Various incident and reflectance angles 8 to 85°
- λ = [280,2500] nm / 5 nm intervals
- 3 measurements on each sample (0°/90°/180°)
- max Size : 10 x 10 cm²



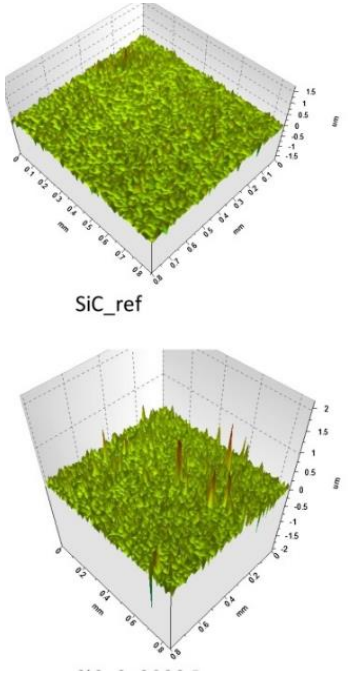
BYK Colorimeter Spectro-Guide Sphere Gloss

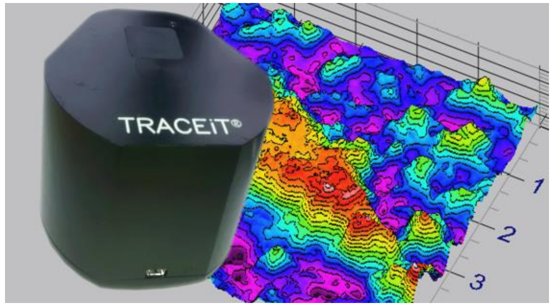
- Monochromatic specular reflectance > $\rho_\lambda(\lambda,\theta_i,\phi)$
- L, a, b , ΔE, Δ G
- photodegradation or gloss of the paint
- 3 measurements on each sample

Optical Characterizations of reflectors and glass :

Krüss Mobile Surface Analyzer® (MSA) contact angle

- Young-Dupré method thanks to the software
- two drops are deposited on the glass surface to see the homogeneity of the coating EasyDrop
- 20 measurements on each sample

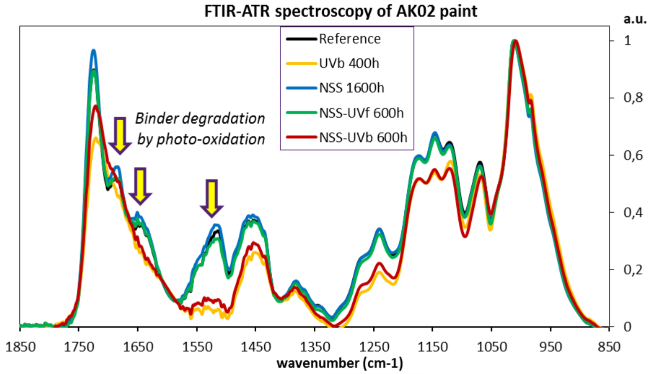




Innowep Traceit® Rugosimeter

- Surface roughness
- Rugosimetry images (5 × 5 mm) of the surface
- surface roughness, porosity
- 3 measurements on each sample

Optical Characterizations of reflectors :

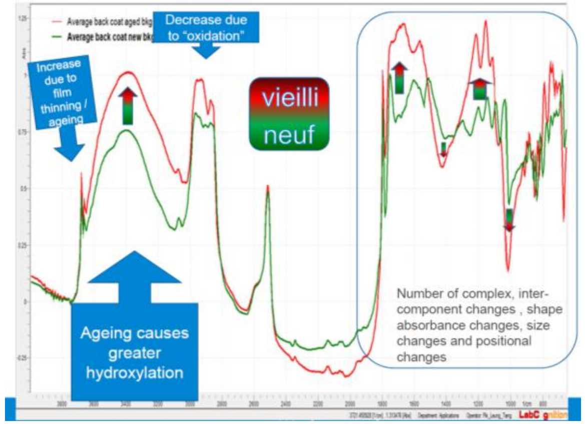


FTIR ATR Spectrophotometer

- characterization of paints by Fourier Transform Infrared Spectroscopy (FTIR) between 500 and 4000 cm^{-1} with a spectrometer equipped with an Attenuated Total Reflectance (ATR) instrument
- 3 measurements on each sample

FTIR portable Top Scan 4300 from Agilent Technologies

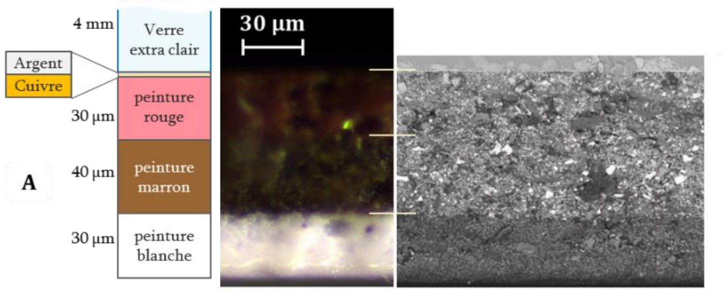
- characterization of paints by Fourier Transform Infrared Spectroscopy (FTIR) Diffuse and specular reflectance between 650 and 5000 cm^{-1}
- 3 measurements on each sample



Optical Characterizations of reflectors :

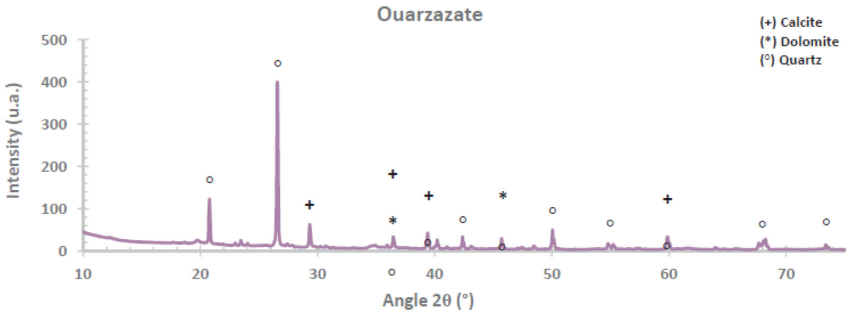
Nova Nanosem 630 scanning electron microscopy (SEM) with Energy Dispersive Spectroscopy (EDS) and X-ray diffraction (XRD)

- Surface morphology
- element analysis and atomic composition



Structure of a mirror : diagram, image under light microscope and SEM

charges \ paint	white	brown	red
$CaCO_3$	no	yes	yes
K_2CO_3	no	no	no
$BaSO_4$	yes	yes	no
$PbSO_4$	no	yes	no
$Mg_3 Si_4 O_{10} (OH)_2$	yes	yes	yes
TiO_2	yes	No	no
ZnO	no	no	yes

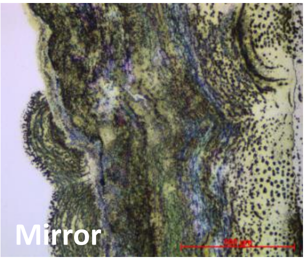


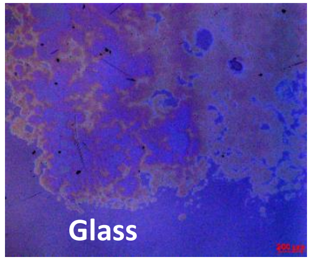
Mineralogical composition of the Moroccan sands obtained by XRD

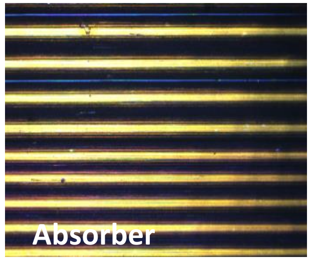
Optical Characterizations of reflectors :

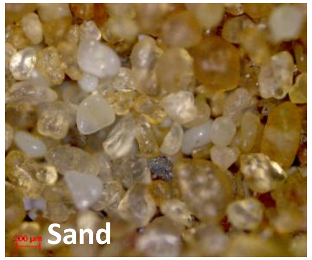
Microscope Zeiss Axio

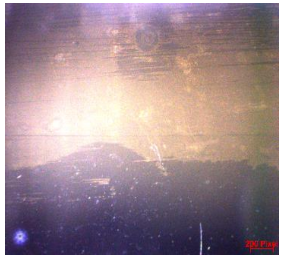
- ➢ Corrosion, corrosion on the edges, degradation of the coating, oxydation, scratches…

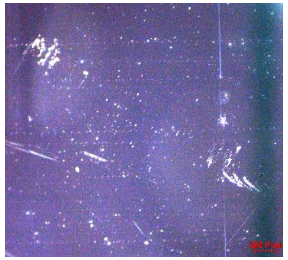












Macroscopic photography

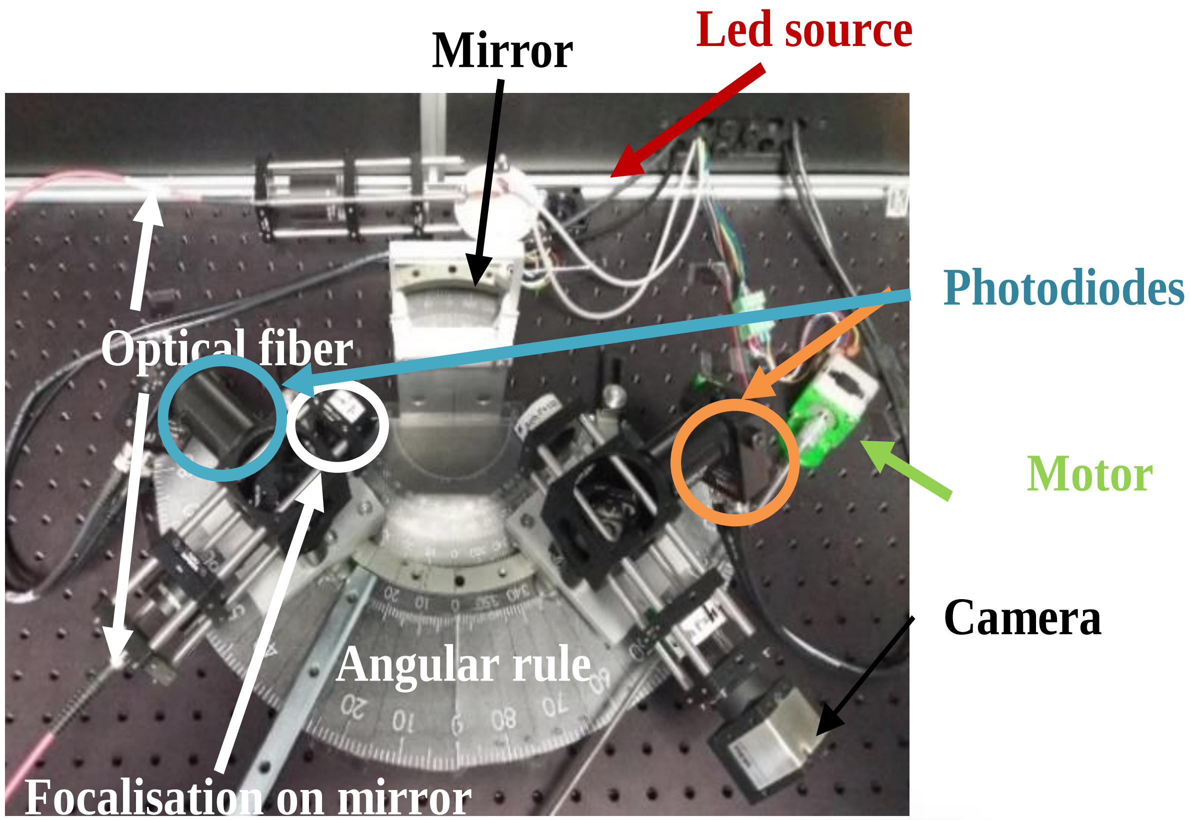
- ➢ Canon EOS 1200D camera with a conventional lens (EFS 18-55 mm)
- ➢ Corrosion spots, corrosion on the edges, scratches…
- ➢ Front side and back side of each sample

Optical Characterizations of reflectors :

New Equipment for Measurement of Soiling and Specular Reflectance and particles counting on Solar Mirrors :

<u>Soiling sensor prototype</u>

- 10 leds = λ =365 - 850 nm
- Automatic range of incidence / reflectance angles =15° - 65°
- Reflectance measuring a window of 3mm diameter
- Acceptance angle for reflectance measurement of 2φ = 40 mrad



Optical Characterizations of absorbers :

<u>Perkin Elmer Lambda 950 IS + Bruker IR Vertex 70 IS Spectrophotometer</u>

- Spectral hemispherical reflectance : $\rho_\lambda(\lambda,\theta_i,h)$
- Integrating spheres of 150 mm diameter for Perkin Elmer Lambda 950 and a PIKE 76.2 mm diameter for Bruker IR VERTEX 70
- λ = [280,2500] nm / 5 nm intervals / θ_i = 8°
- λ = [1800,16000] nm / 40 nm intervals / θ_i = 12°

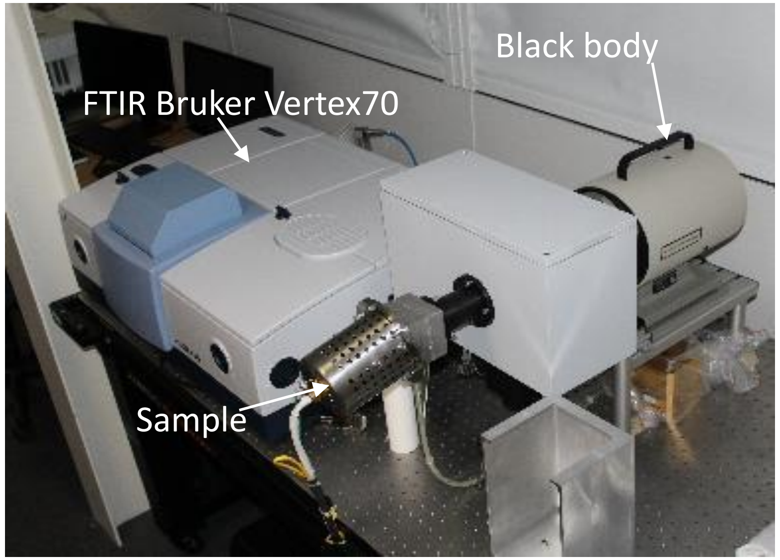
Tubular samples spectro UV/VIS (left) and IR (right)

- 3 or 4 measurements on each sample
- max Size : 10 x 10 cm²
- Flat or tubular samples ϕ 30-70 mm diameter

Etalon Infragold®

Instrument	Manufacturer	Model	Accessory	Reflectance
Spectrophotometer	Perkin Elmer	Lambda 950	IS (Ø 15 cm)	$\rho_{s,h}$([280,2500],8°,h)
Spectrophotometer	Bruker	Vertex 70/PIKE	IS (Ø 7.62 cm)	$\rho_{s,h}$([1800,16000],12°,h)

Optical Characterizations of absorbers :



Bruker IR VERTEX 70 Spectrophotometer+ high temperature test bench

- Spectral directional luminance
- λ = [1280,28500] nm / θ_i = 12°
- 1 measurement on each sample
- Flat samples size min/max : ϕ 25-70 mm diameter –thickness < 3 mm
- T = 100°C-1000°C

Portable Emissometer D&S AE1-RD1

- Total hemispherical emissivity measurement
- Flate samples size min/max : ϕ 50-120 mm

D&S AE1-RD1

Solar Facilities for the European Research Area

Programme funded by the
EUROPEAN UNION

SFERA III: On site Training for Indusry

Le Bourget-du-Lac, June, 8th – 10th 2022

Standardized tests for reflectors

Florian Wiesinger, DLR

Deutsches Zentrum
DLR für Luft- und Raumfahrt e.V.
in der Helmholtz-Gemeinschaft

www.dlr.de/enerMENA

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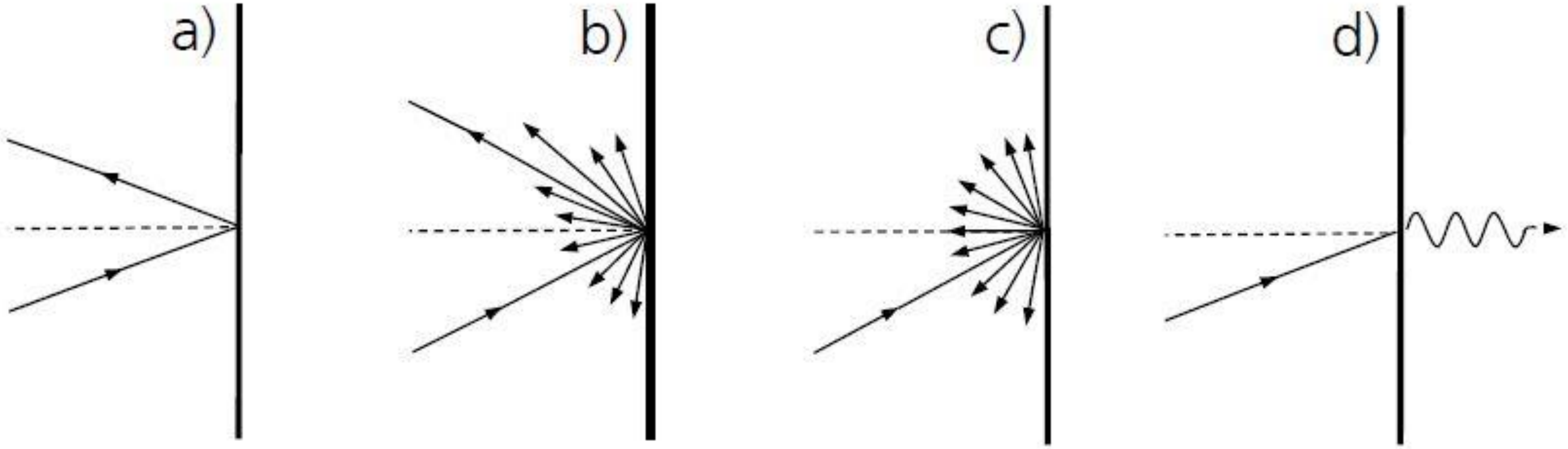
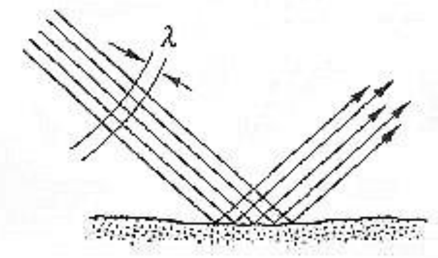


pure specular

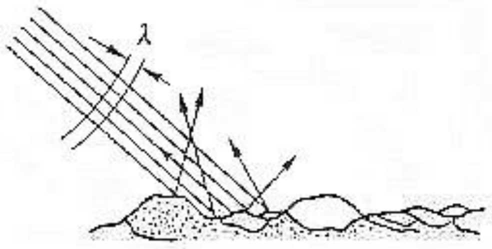
general reflectance, mixture from a) and c)

pure diffuse

absorptance/ transmittance



highly specular surface



diffuse surface

NB:
ρ = reflectance
τ = transmittance
α = absorptance

Reflectance – Crucial Parameter for CSP - Introduction

Examples for **diffuse** reflecting surfaces (room temperature)

<u>High ρ [%]:</u>

- Titaniumdioxid 99
- Magnesiumoxid 96 (vapor deposited)
- Gypsum 80
- White Paper 70

<u>Low ρ [%]:</u>

- Black platinum 0.1
- Carbon black 0.8
- Black varnish 1-1.5
- Black paper 5

Examples for **specular** reflecting surfaces

<u>High ρ [%]:</u>

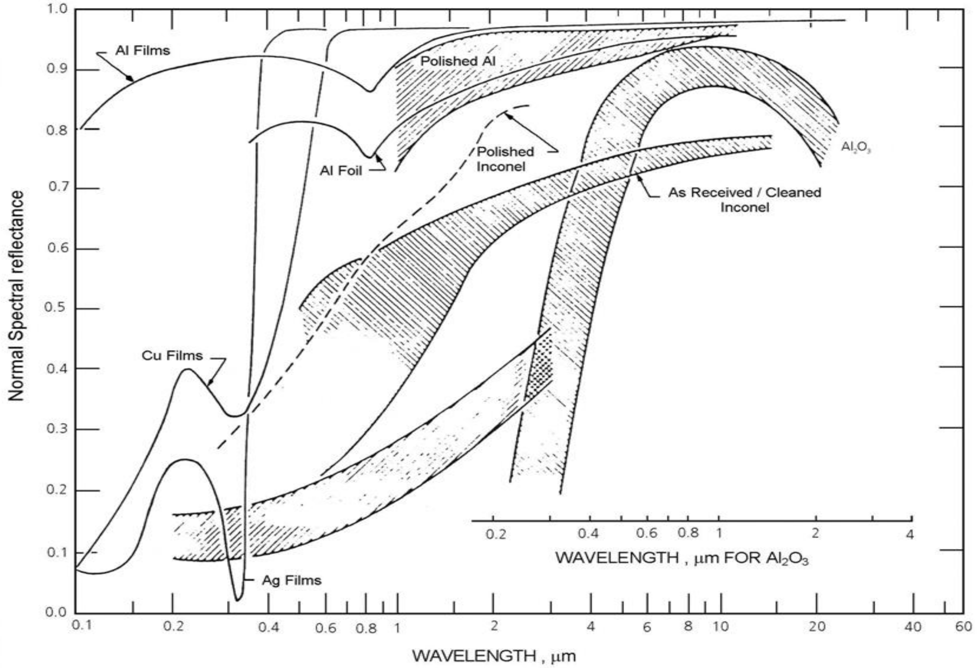
- Aluminum (polished) 87-92
- Silver (polished) 98-80 *(λ-range 0.37-1µm)*

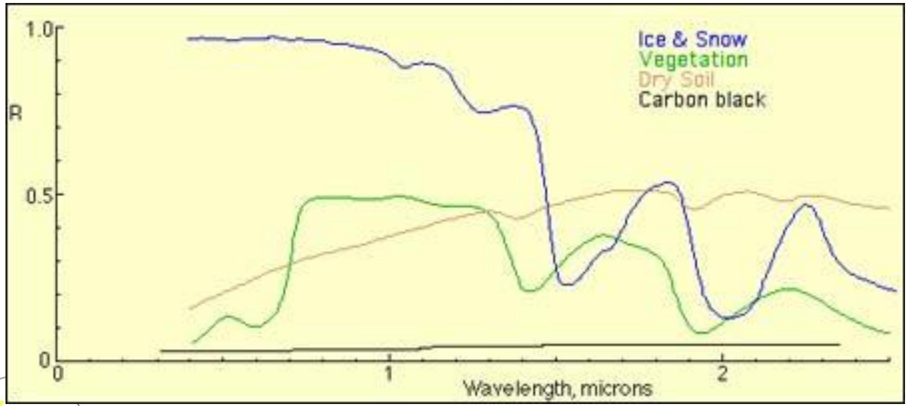
- Steel(polished) 93
- Stainless Steel 89

→ ρ is highly depending on λ

Handbook of Chemistry and Physics, 75th Edition
Manufacturer datasheet: Electro Optical Industries Inc.

Reflectance – Crucial Parameter for CSP - Introduction





Characteristics for metals:

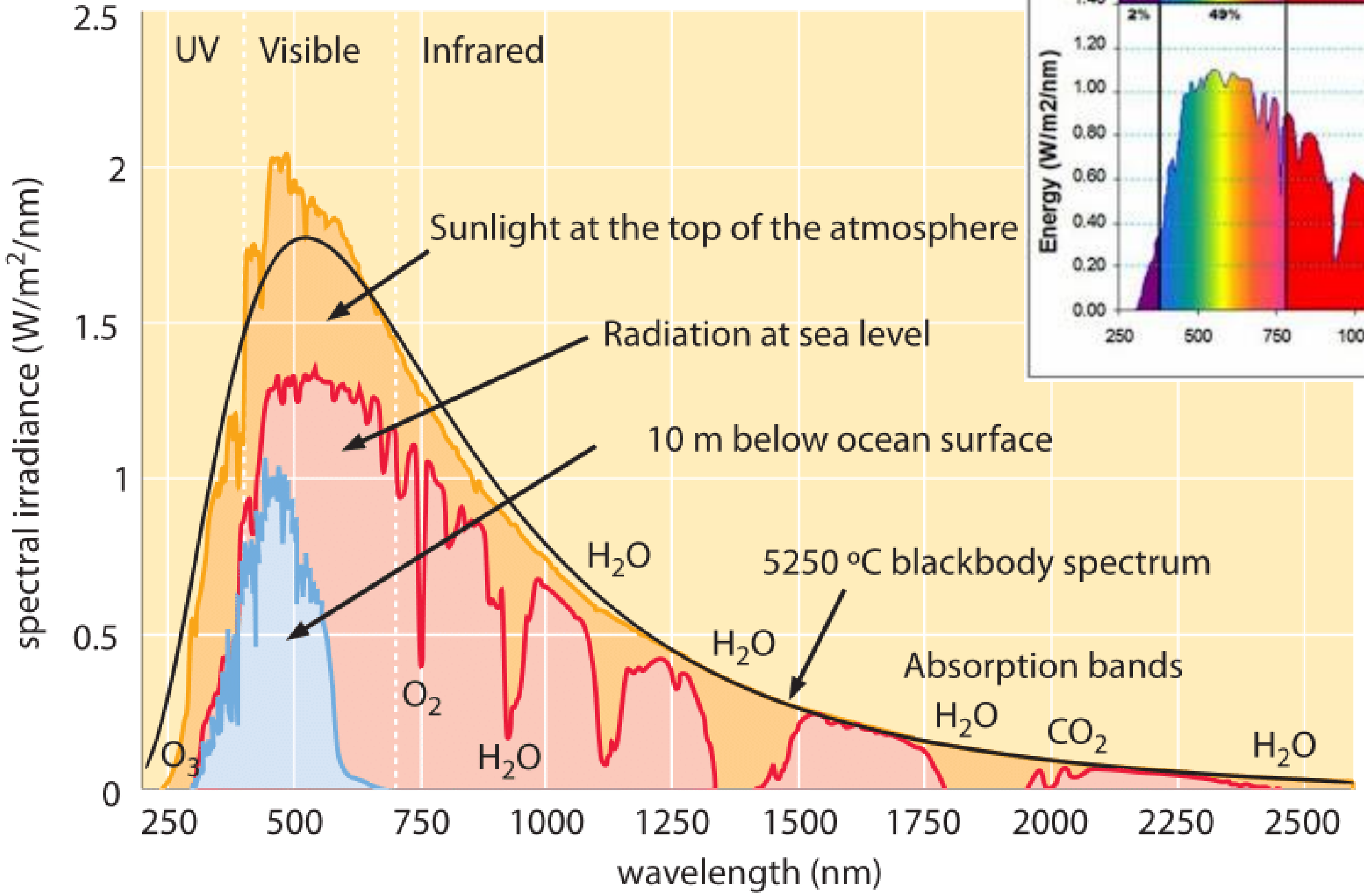
- High ρ in IR, drop at visible and UV
- Position of the edge depending on surface state and temperature.

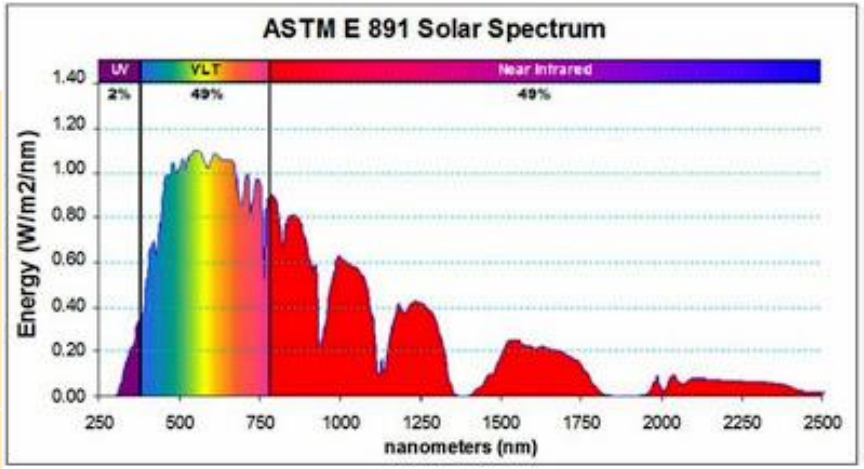
Characteristics for non-metals:

- Two absorption-edges, one in the visible and one in the IR, in between high ρ

→ How should ρ(λ) be modeled?

Reflectance – Crucial Parameter for CSP - Introduction





Reflectance – Laboratory Measurements - Overview

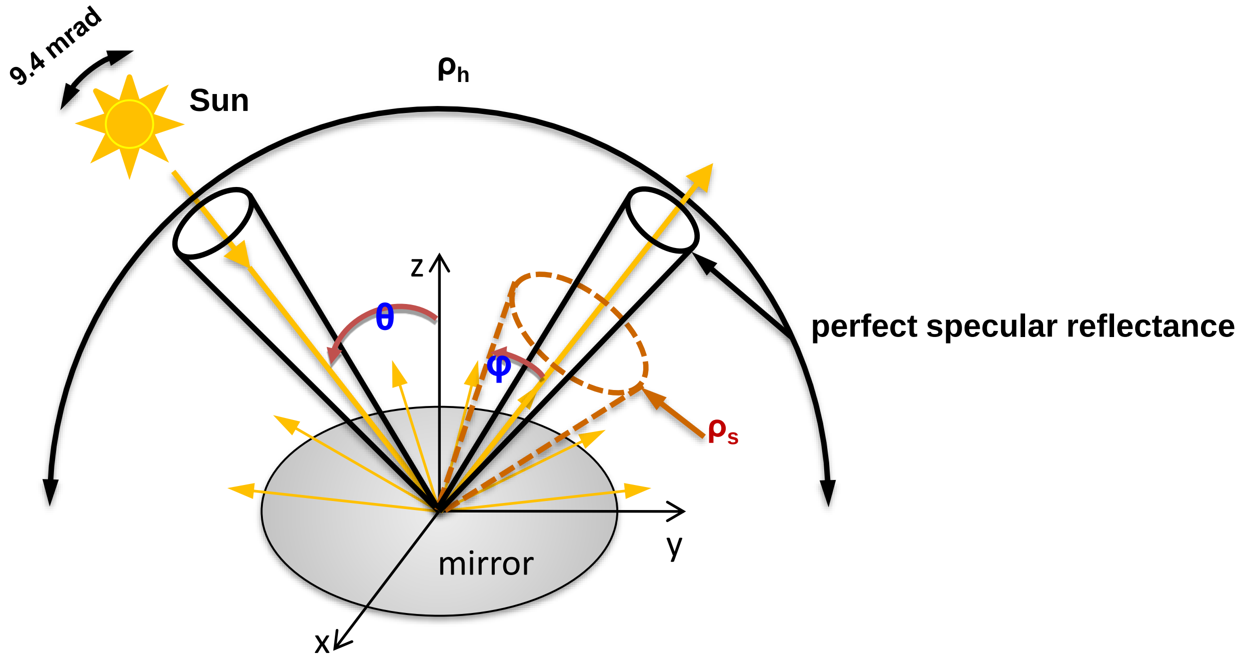
Perkin Elmer Lambda 1050 spectrophotometer

Measures hemispherical reflectance, transmittance & absorptance

Multiple Wavelength Portable Specular Reflectometer, Model 15R-RGB

Measures specular reflectance

Reflectance – Fundamental Definitions

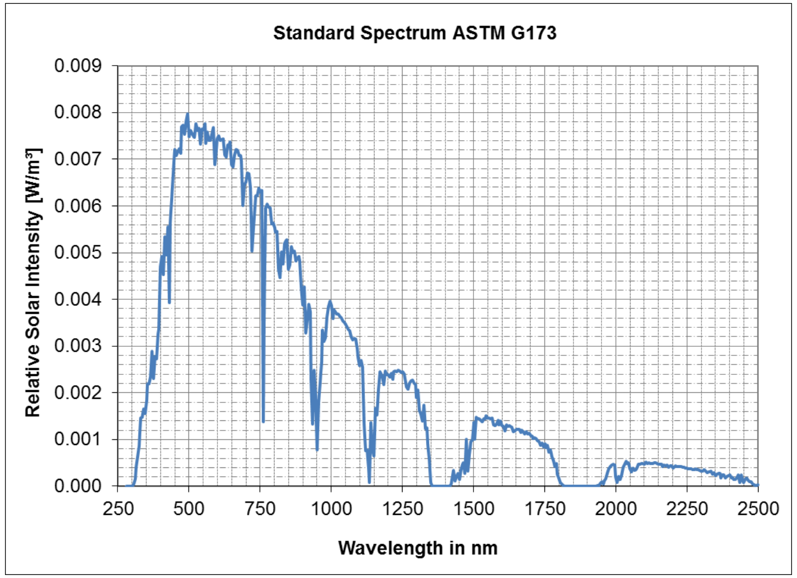


specular reflectance within acceptance angle φ

hemispherical reflectance (acceptance angle is complete hemisphere “φ=h”)

Reflectance – Fundamental Definitions

- Reflectance is wavelength dependent
- A suitable “mean value” of all relevant solar wavelengths is the solar weighted reflectance



$$\rho_{s,\varphi}([\lambda_a,\lambda_b],\theta_i,\varphi,T_s)$$

$$\rho_{s,\varphi}([\lambda_a,\lambda_b],\theta_i,\varphi,T_s)=\frac{\sum_{i=0}^{i_{\max}}\rho_{s,\varphi}(\lambda_i,\theta_i,\varphi,T_s)\cdot G_b(\lambda_i)}{\sum_{i=0}^{i_{\max}}G_b(\lambda_i)}$$

The spectral solar irradiance $G_b(\lambda_i)$ can be obtained in 5 nm steps from a reference spectrum, e.g. ASTM G173 with air mass 1.5 and 1000 W/m²

Reflectance – Fundamental Definitions

Every measured reflectance value needs to be declared in the format:

$$\boxed{\rho_{\lambda,\varphi}(\lambda, \theta_i, \varphi, T_s)}$$

λ	wavelength	[nm]
θ_i	incidence angle	[º]
ϕ	acceptance angle	[mrad]
T_s	surface temperature of the mirror [ºC]	

To indicate solar weighted values use “s“ as index and indicate the wavelength range of the weighting instead of λ

To indicate hemispherical reflectance use “h” instead of ϕ

Examples: $\rho_{\lambda,\varphi}(660\ nm, 15º, 12.5\ mrad, 25ºC) = 95.3\%$

$\rho_{s,h}([280{,}2500nm], 8º, h, 25ºC) = 94.1\%$

Optical components of CSP

Mirror types – silvered-glass mirrors

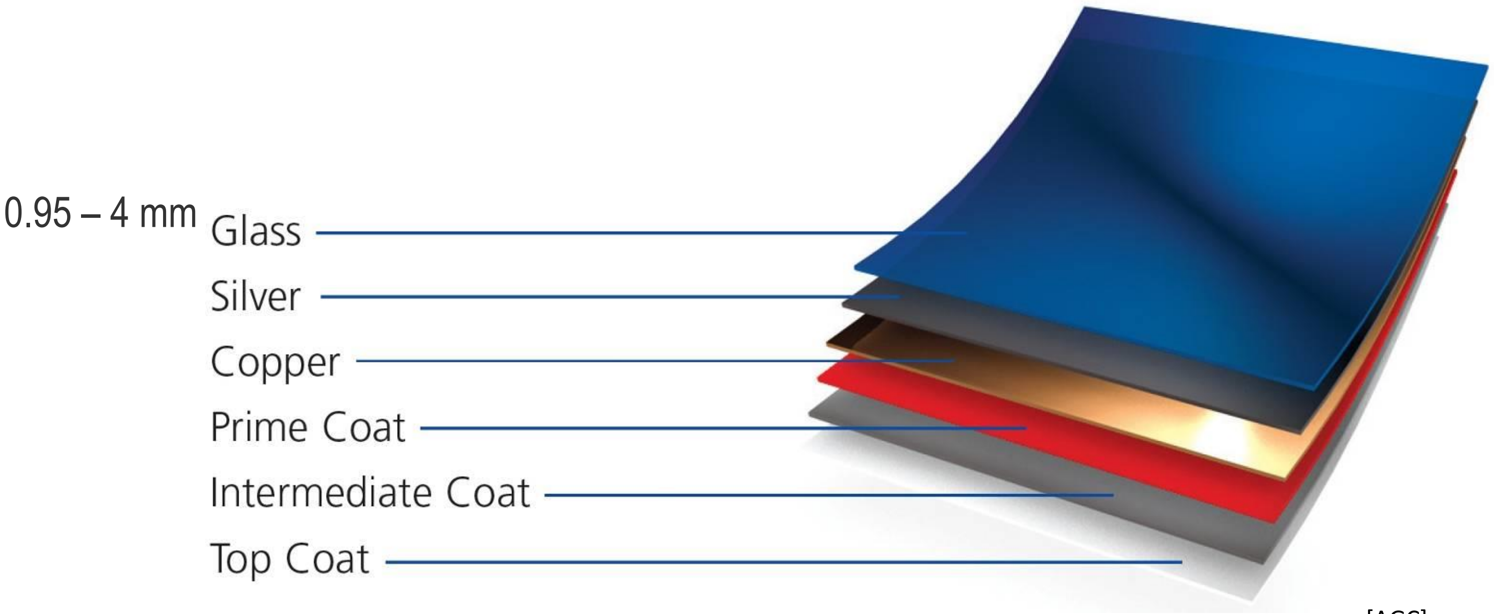
Typical reflectance values:

$\rho_{s,h}([280,2500nm], 8º, h, 25ºC) = 93.0 - 95.0\%$

$\rho_{\lambda,\varphi}(660\ nm, 15º, 12.5\ mrad, 25ºC) = 95.0 - 96.0\%$

+ cost ~15€/m²
+ good durability: Pb containing paints proofed durability >30 years

Pb free paints need to proof durability still



[AGC]

Optical components of CSP

Mirror types – laminated glass mirrors

Typical reflectance values:

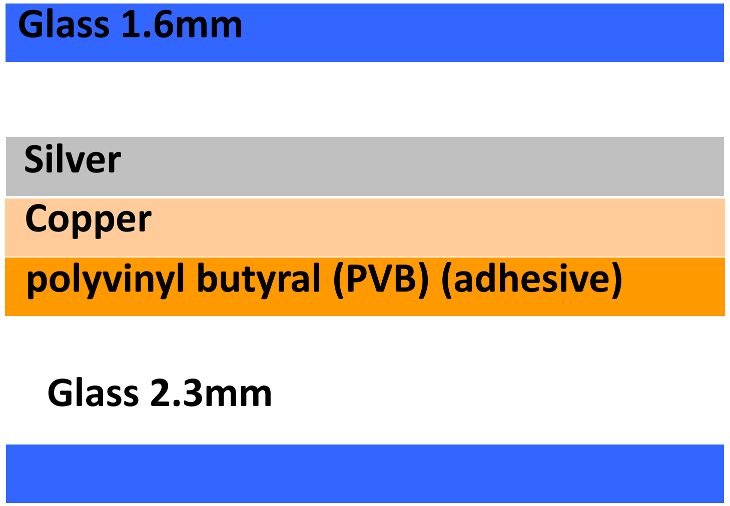
$\rho_{s,h}([280,2500nm], 8º, h, 25ºC) = 94.5\%$

$\rho_{\lambda,\varphi}(660\ nm, 15º, 12.5\ mrad, 25ºC) = 95.5\%$

+ Thin front glass increases reflectance

+ Excellent durability

- Cost



[Guardian]

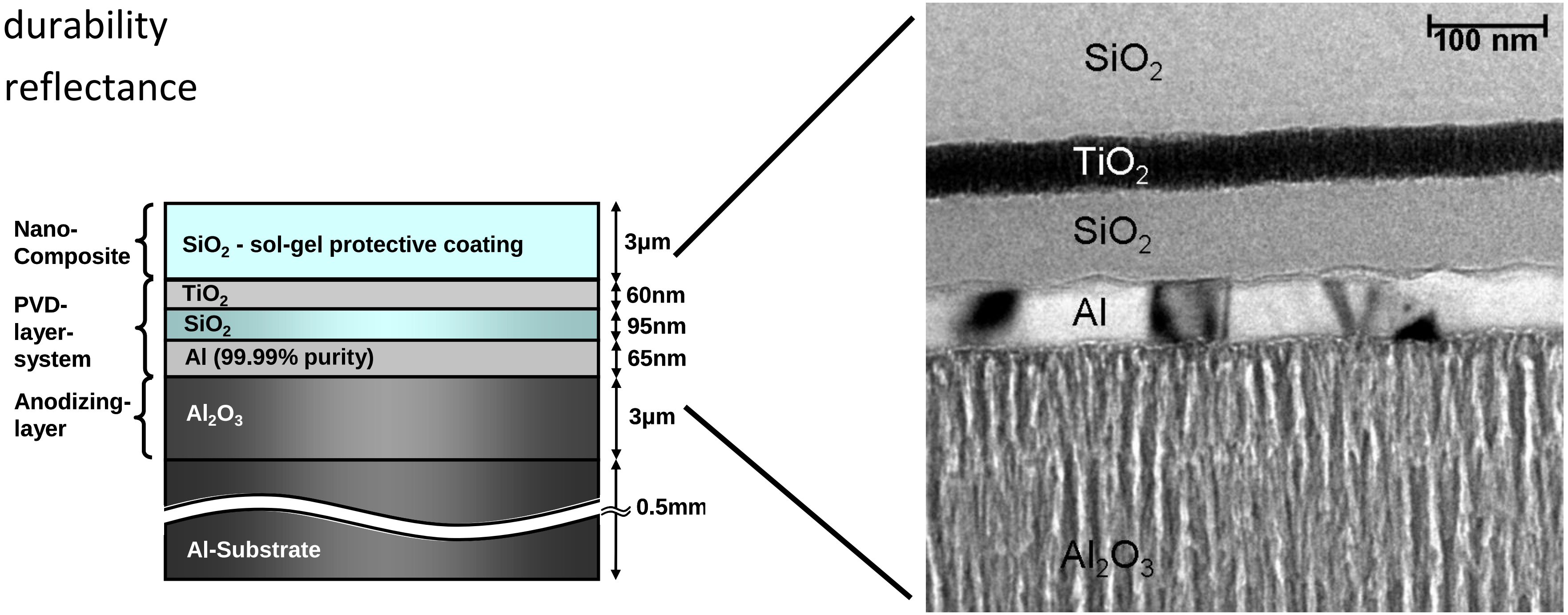
Optical components of CSP

Mirror types – PVD coated aluminum reflectors

Typical reflectance values:

$\rho_{s,h}$([280,2500nm], 8º, h, 25ºC) = 90.0%
$\rho_{\lambda,\varphi}$(660 nm, 15º, 12.5 mrad, 25ºC) = 85.5%

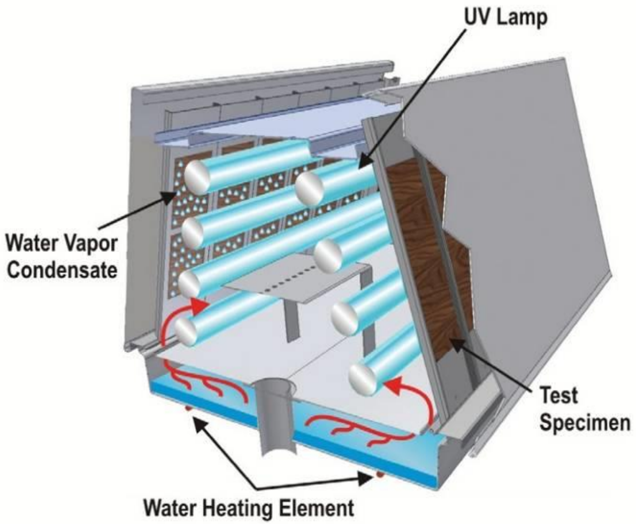
+ cost
+ flexible
- durability
- reflectance

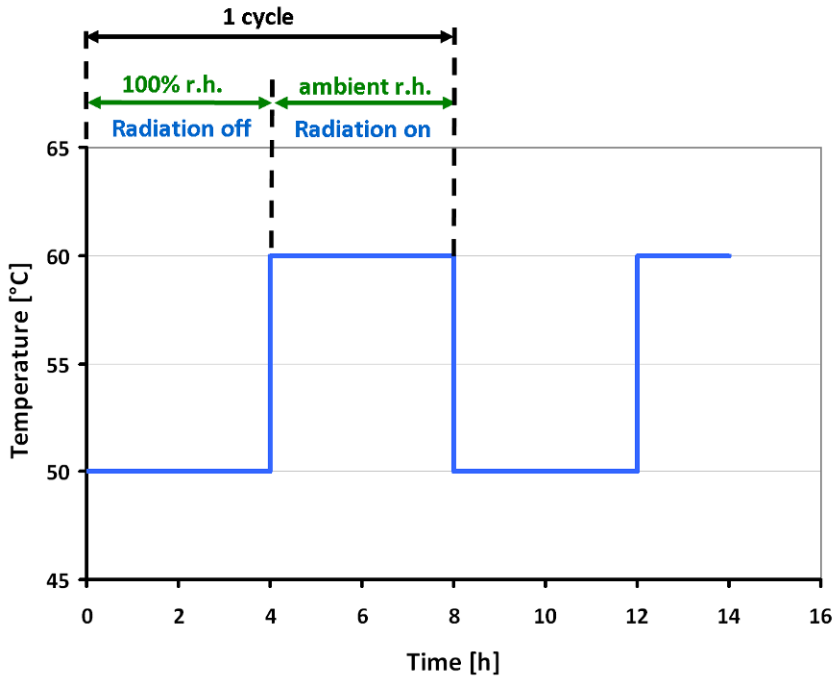


Accelerated aging tests

ISO 16474-3 (replaces ISO 11507): UV+humidity Test

Chamber temperature: 50 to 60°C
Humidity: ambient to 100% relative humidity
Radiation: lamp type II, UVA-340; 290-400 nm; peak emission at 340nm; lamp power matches 1 sun
Cycle time: 8 hours
Testing time: >1000 hours





Accelerated aging tests

IEC 62108 10.7a: Damp heat test 85/85

Chamber temperature: 85 ± 2°C
Humidity: 85 ± 5 % relative humidity
Testing time: 1000 hours

IEC 62108 10.7b: Damp heat test 65/85

Chamber temperature: 65 ± 2°C
Humidity: 85 ± 5 % relative humidity
Testing time: 2000 hours

Accelerated aging tests

ISO 9227: Neutral salt spray test (NSS)

Chamber temperature:	35 ± 2 °C
Humidity:	constant 100% relative humidity
Sprayed solution:	demineralized water + 50 g/l NaCl (pH 6.5 – 7.2)
Condensation rate:	1.5 ± 0.5 ml/h on a surface of 80 cm²
Sample position:	20 ± 5° respect to vertical
Testing time:	480 – 3500 hours

Accelerated aging tests

ISO 9227: Copper accelerated salt spray test (CASS)

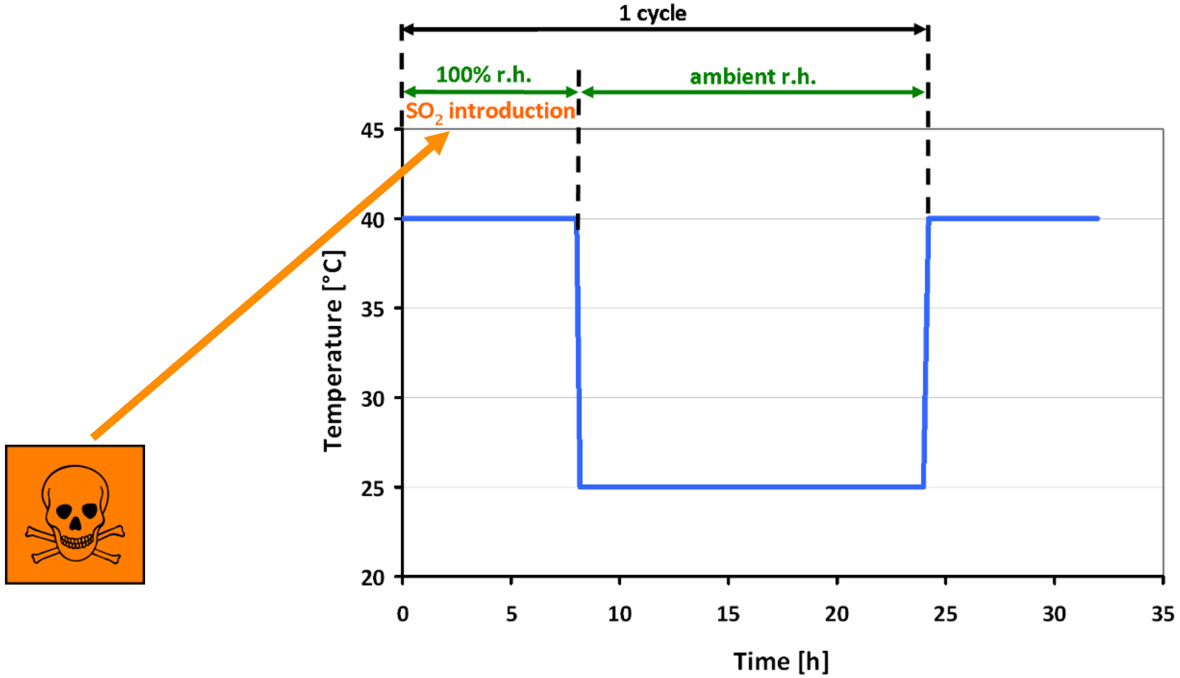
Chamber temperature: 50 ± 2 °C
Humidity: constant 100% relative humidity
Sprayed solution: demineralized water + 50 g/l NaCl + 0.26 g/l $CuCl_2$ (pH 3.1 – 3.3)
Condensation rate: 1.5 ± 0.5 ml/h on a surface of 80 cm²
Sample position: 20 ± 5° respect to vertical
Testing time: 120 – 480 hours

$CuCl_2$

Accelerated aging tests

DIN 50018 / ISO 6988: Kesternich Test

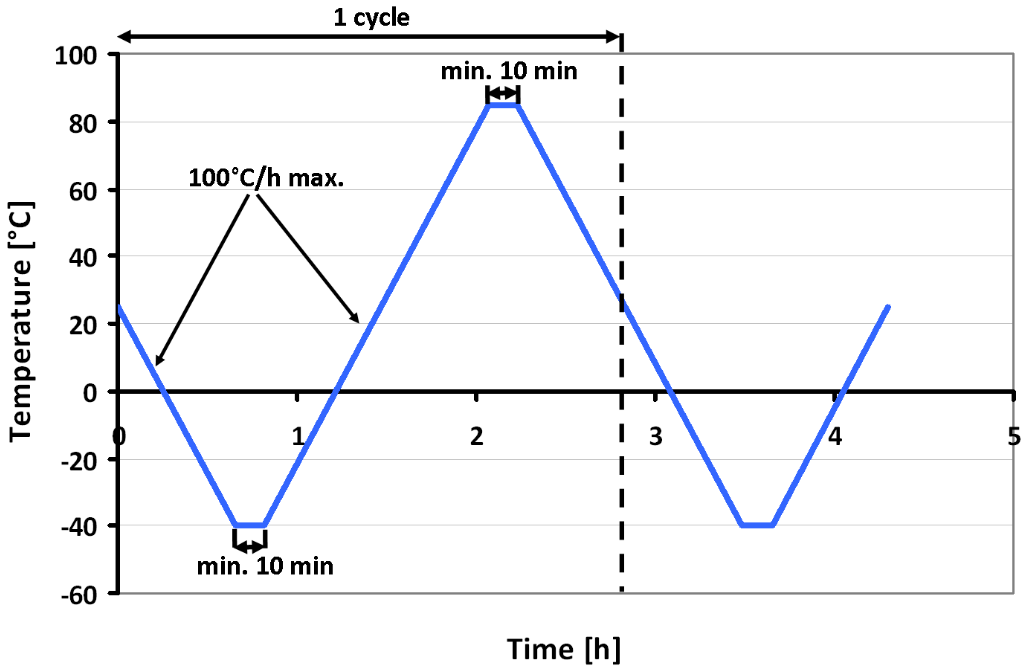
Chamber temperature:	ambient / 40 ± 3°C
Humidity:	ambient / 100% relative humidity
Initial SO_2 concentration:	0.33 or 0.67% of volume of testing chamber
Cycle time:	24 hours
Testing time:	>20 cycles



Accelerated aging tests

ISO 61215: Thermal Cycling

Chamber temperature:	-40°C to +85°C
Humidity:	dry
Cycle duration:	min. 2h 50min, max. 6h
Recommended cycle number:	>100



Accelerated aging tests

Thermal Cycling with humidity based on ISO 6270-2CH

Chamber temperature:	-40°C to +85°C
Humidity:	ambient to 100% relative humidity
Cycle duration:	24 h
Recommended cycle number:	>20

Method A

Step	Duration (h)	Temperature (ºC)	Relative Humidity (%)
1	4	85	Not controlled
2	4	-40	Not controlled
3	16	40	97±3

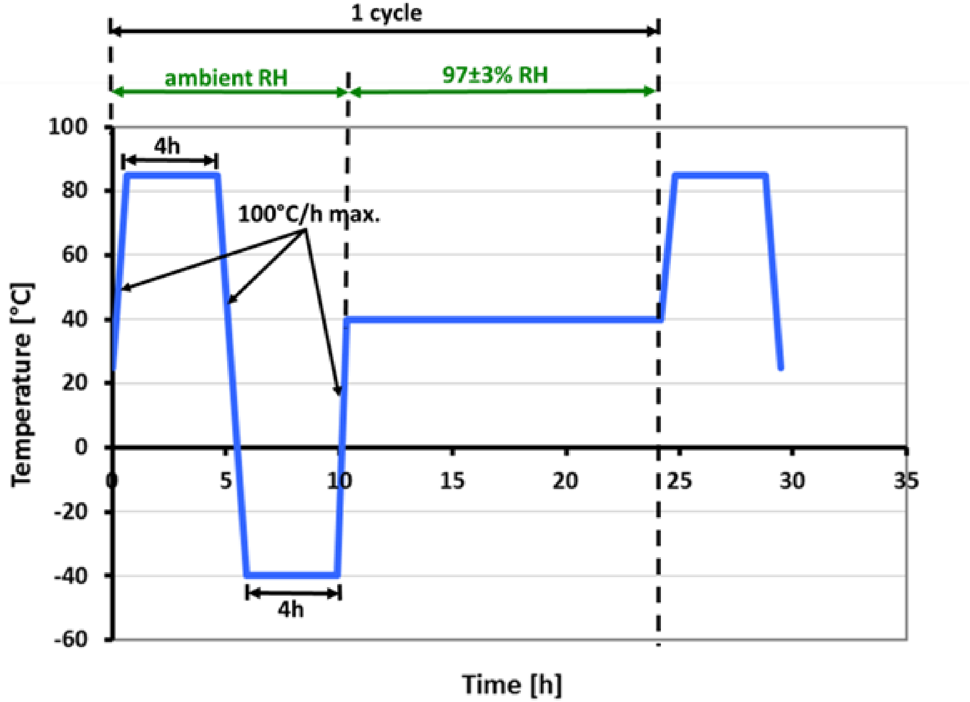
Method B1

Step	Duration (h)	Temperature (ºC)	Relative Humidity (%)
1	4	85	Not controlled
2	4	-40	Not controlled
3	16	85	85±3

Method B2

Step	Duration (h)	Temperature (ºC)	Relative Humidity (%)
1	4	85	Not controlled
2	4	-40	Not controlled
3	40	65	85±3

Method A

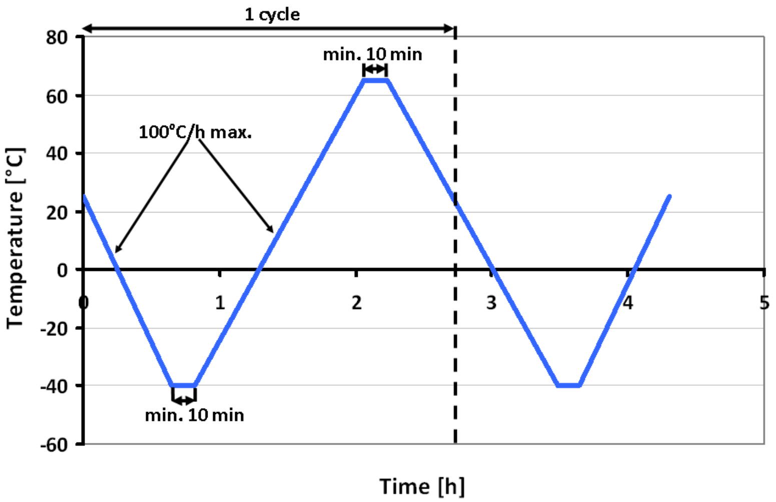


Accelerated aging tests

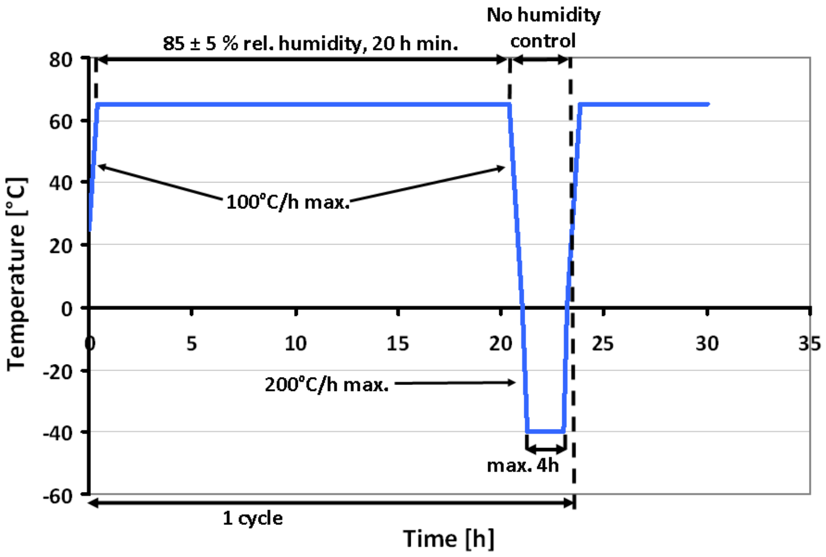
Humidity Freeze Test IEC 62108

Chamber temperature:	-40°C to +65°C
Humidity:	ambient to 85% relative humidity
Precycling:	400 cycles
Cycle duration:	24 h
Freeze cycle number:	40
Total testing time:	~2000h

400 precycles -40 to 65°C, dry



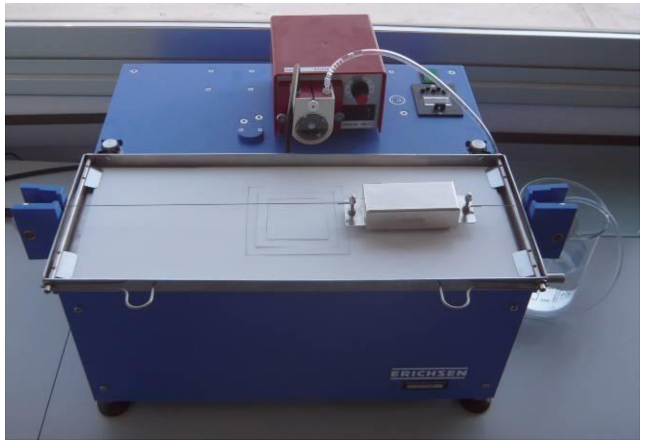
40 humidity-freeze cycles



Accelerated aging tests

Abrasion testing

Available standards: ISO 11998, DIN ISO 9211-4



Simulation of cleaning cycles

Scratching of coatings with controlled normal force

Accelerated erosion testing

Sand trickling test DIN 52348

sand container

meshes

rotating sample under impact angle α

Closed loop sand storm chamber (based on MIL-STD 810G)

Testing programs

Basic program

Test	Standard	Testing conditions	Duration
Neutral Salt Spray (NSS)	ISO 9227	T: 35ºC pH: 6.5 to 7.2 at 25ºC	480 h
Copper-accelerated acetic acid salt spray (CASS)	ISO 9227	T: 50° C pH: 3.1 to 3.3 at 25° C	120 h
Condensation	ISO 6270-2	T: 40° C RH: 100%	480 h
UV and humidity test	ISO 16474-3	4h UV exposure at 60° C; 4h 100% RH at 50° C	1000h on both sides
Combined thermal cycling and condensation test	AENOR draft Method A	4 h 85° C, 4 h -40° C, Method A: 16 h T° : 40° C and 97±3% RH	10 cycles (240 hours)

Advanced program

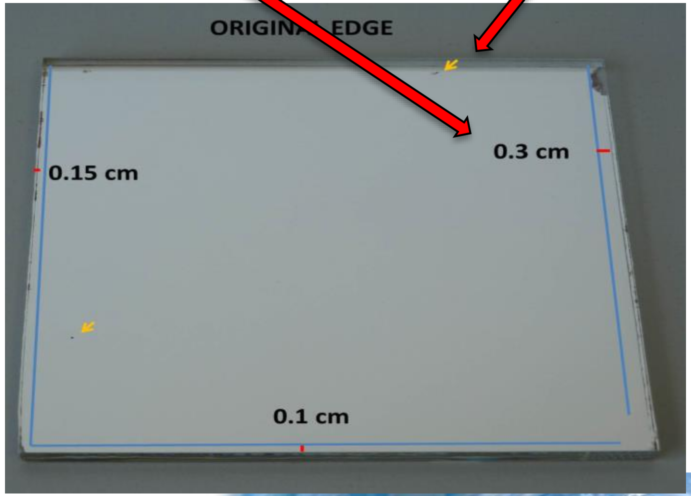
Test	Standard	Testing conditions	Duration
Neutral Salt Spray (NSS)	ISO 9227	T: 35ºC pH: 6.5 to 7.2 at 25ºC	3000 h
Copper-accelerated acetic acid salt spray (CASS)	ISO 9227	T: 50° C pH: 3.1 to 3.3 at 25° C	480 h
Condensation	ISO 6270-2	T: 40° C RH: 100%	1000 h
UV and humidity test	ISO 16474-3	4h UV exposure at 60° C; 4h 100% RH at 50° C	1000h on both sides
Combined thermal cycling and condensation test	AENOR draft	4 h 85° C, 4 h -40° C, Method A: 16 h T: 40° C and 97±3% RH	20 cycles (480 hours)
Thermal cycling	IEC 62108 (Test 10.6 TCA3)	T: 65ºC - -40ºC	150 cycles (~280 h)
Damp Heat	IEC 62108 (Test 10.7b)	T: 65ºC; RH=85%	2000 h
Combined thermal cycling and Damp Heat	IEC 62108 (Test 10.6 TCA3 + Test 10.7b)	1st step: thermal cycling as above, 2nd step: Damp Heat test	150 cycles + 2000 h
Combined thermal cycling and NSS	IEC 62108 (Test 10.6 TCA3) + ISO 9227	1st step: thermal cycling as above, 2nd step: NSS	150 cycles + 3000 h
Sand erosion test	Test dust ISO 12103-1 A4 coarse	v = 12.5 m/s, c = 100 mg/m³	10, 20, 40 and 60 min

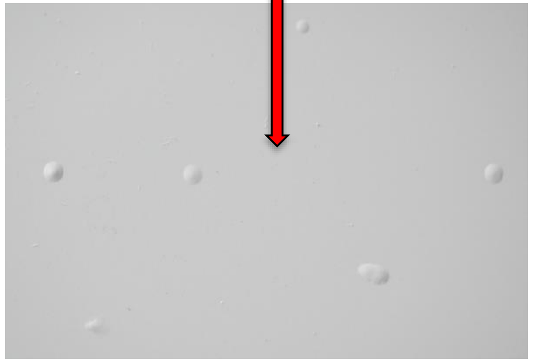
Accelerated aging testing

Analyzed parameters

Reflectance losses **$\Delta\rho_s$([280,2500],8°,h)** **$\Delta\rho_\lambda$(660nm,8°,h)** **$\Delta\rho_\lambda$(660nm,15°,12.5mrad)**

Degradation results		
Maximum edge corrosion penetration (cm)	Number of corrosion spots >200µm per 300 cm² in the silver layer	Number of bubbles **per 300 cm²** in the paint layer
0.3	4	56





CEA Advanced tests for reflectors

E. Le Baron CEA

Technologies of reflectors :

Monolithic glass mirrors

Low iron glass	1-4 mm
Silver	150 nm
Copper	150 nm
Prime coat	30 µm
Intermediate coat	30 µm
Top coat	30 µm

$95{,}5 < \rho_s < 96{,}5$ %

Laminated glass mirror

Low iron glass	1 mm
Silver	150 nm
Copper	70 nm
Polyvinyl Butyral (PVB)	< 1 mm
Glass substrate	1,5 mm

$\rho_s = 96{,}0$ %

Glass mirror on a composite polymer

Low iron glass	1 mm
Silver	150 nm
Prime coat	30 µm
Composite polymer substrate	3 mm

$\rho_s = 93{,}5$ %

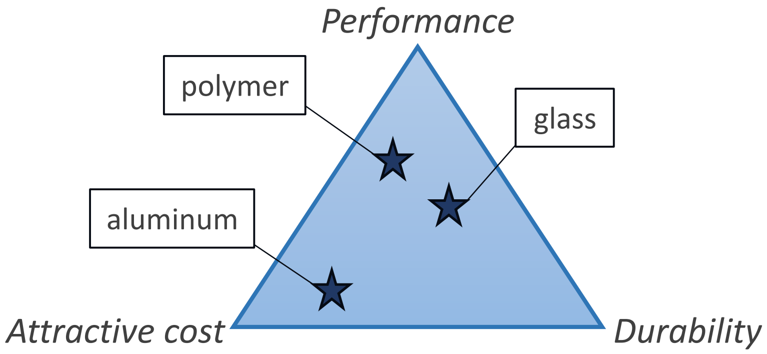
Aluminum mirrors

Sol-gel protective coating SiO_2	3 µm
TiO_2	60 nm
SiO_2	95 nm
Al (99,9% purity)	65 µm
Al_2O_3	3 µm
Al substrate	500 µm

$78 < \rho_s < 85$ %

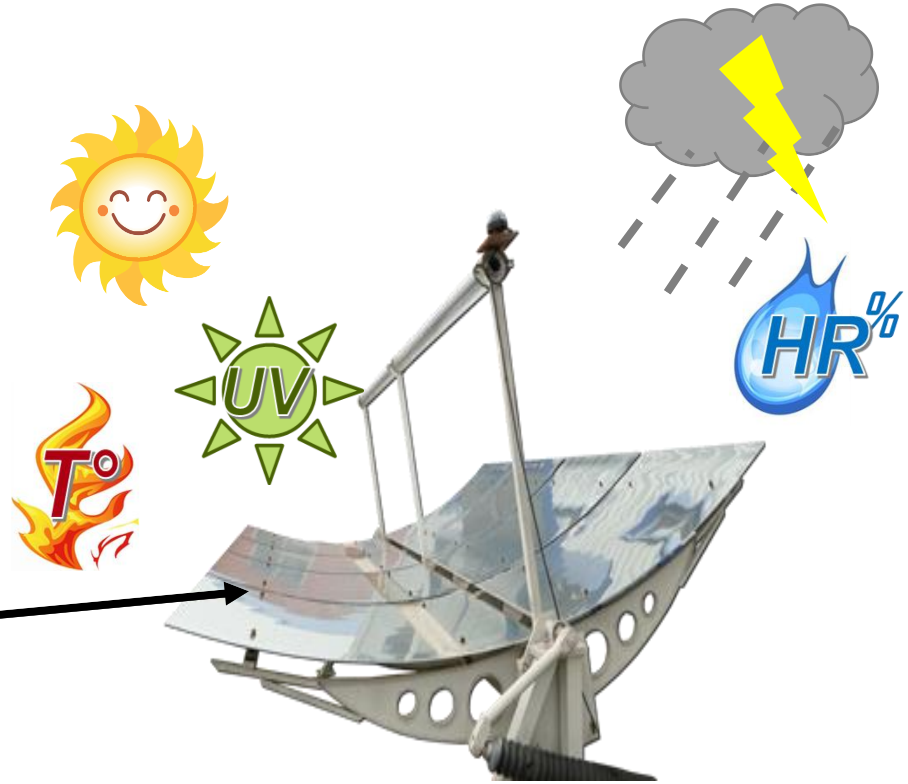
Technologies of reflectors :

Mirror	Silvered glass	Aluminum	Polymer
Specular Reflectance	93 – 95 %	86 – 91 %	96 %
Weaknesses	shocks	abrasion, cleaning	abrasion, cleaning, corrosion by edges
Weight	heavy (10 kg/m²)	light (3 kg/m²)	light
Implementation	difficult	Simple	average
mirror cost	low	low	High
reflector cost	High	low	low
Maturity	mature for a long time	mature	in development



What are the main stress factors ?

Example of solar plant



1. Temperature
2. Irradiation, UV
3. Relative Humidity

All of these stresses are applied at the same time

Example of Indoor accelerated tests of reflectors :

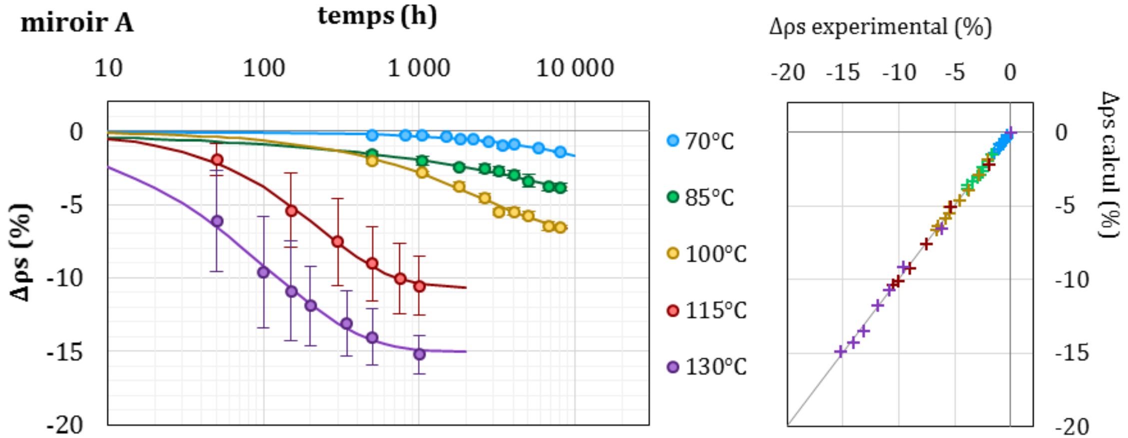
Thermal aging tests ➔ 5 conditions: 70°C, 85°C, 100°C, 115°C and 130°C

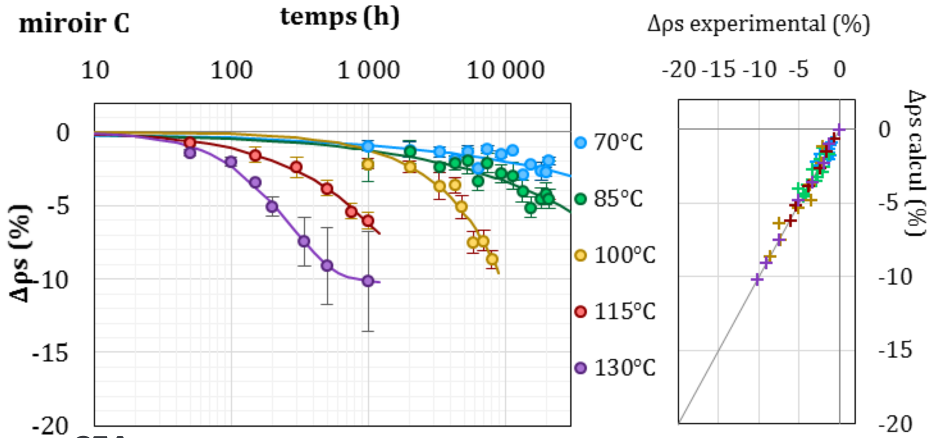
- Evolution of specular reflectance ρs over time t punctual measurements
- Equation ➔ extrapolate the loss at any time

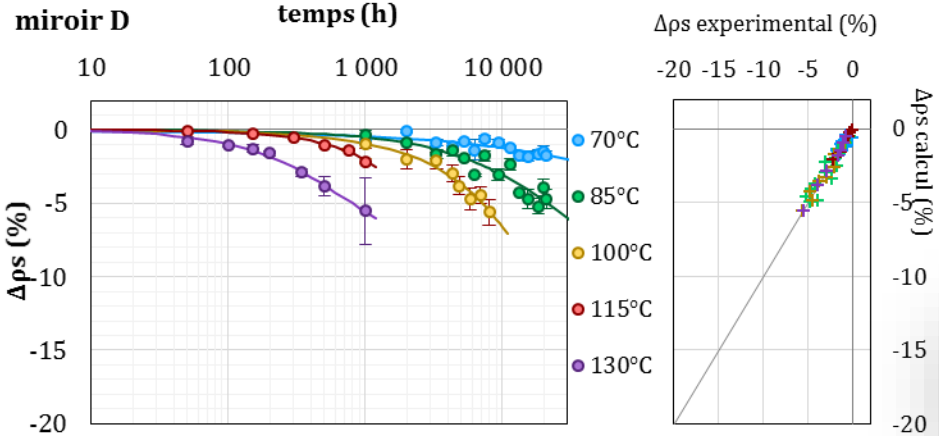
Weibull equation :

$$\Delta\rho_s = K\left(1 - exp\left(-\frac{(t.10^{-3})^a}{b}\right)\right)$$

Regression on the experimental points thanks to the parameters (a, b, K)



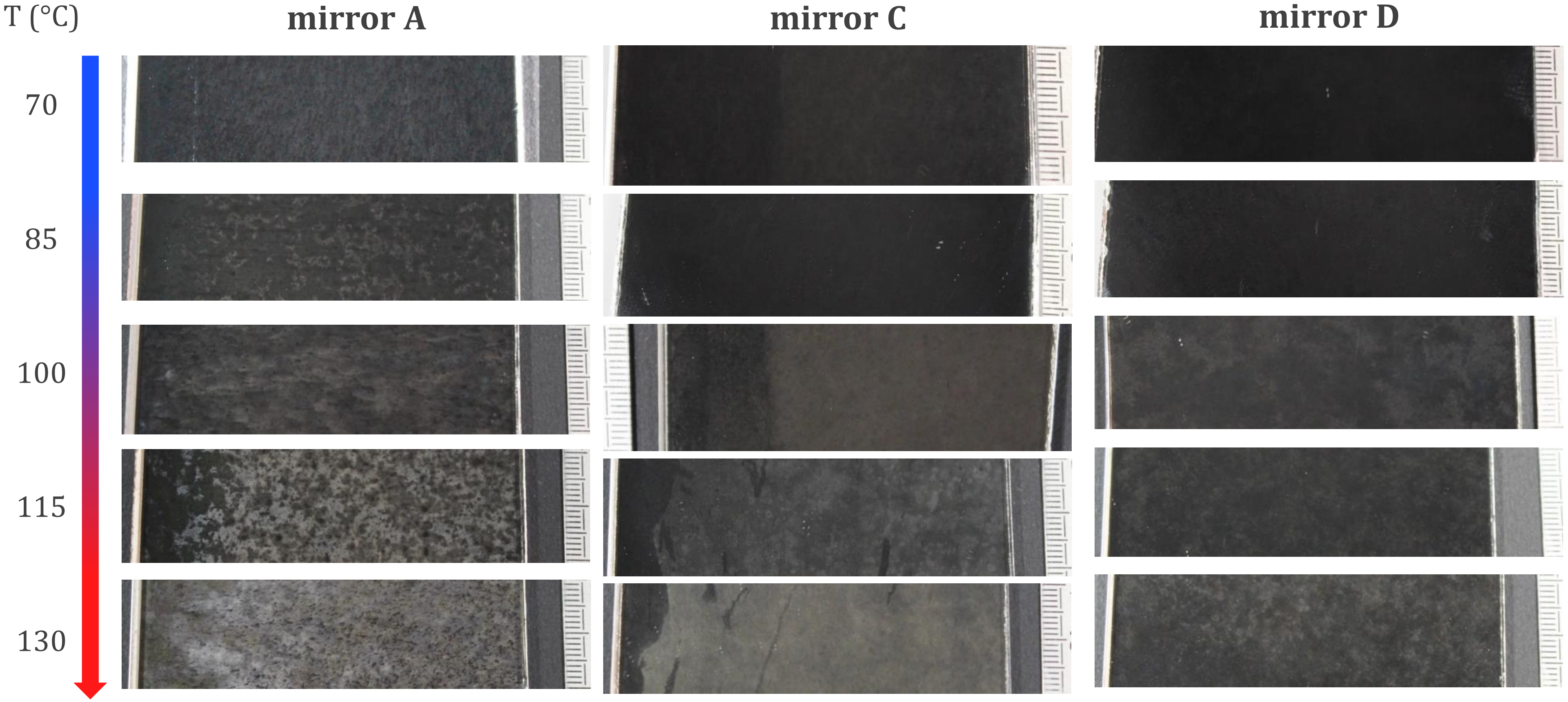




Example of Indoor accelerated tests of reflectors :

Thermal aging tests Macroscopic observation at the final exposure times :

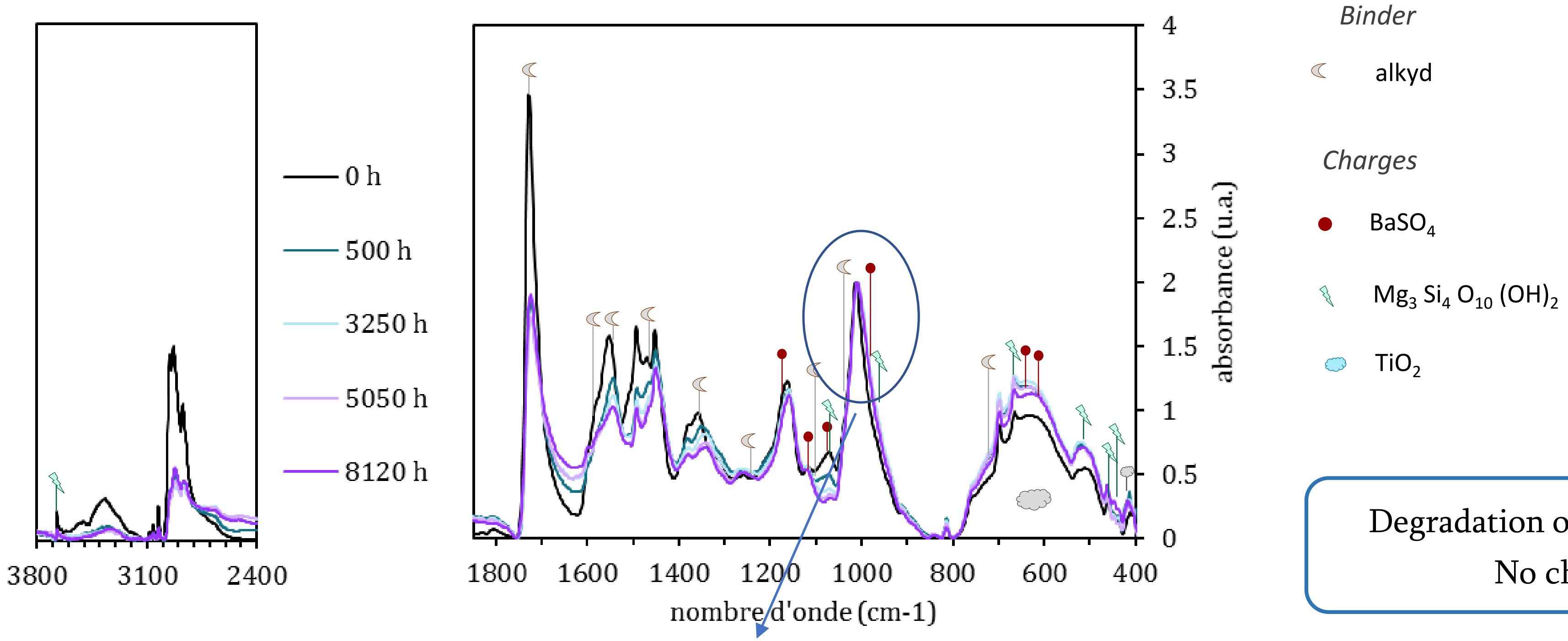
- Formation of a homogenous veil on the silver
- Intensity ↗ with T



E. Le Baron CEA

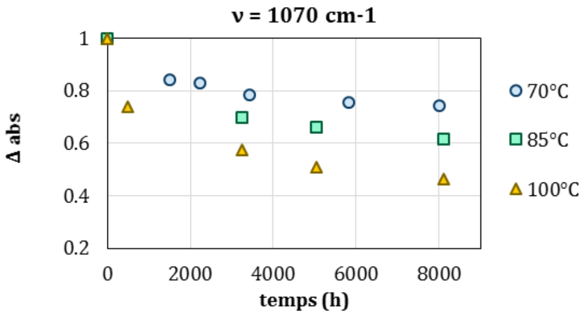
Example of Indoor accelerated tests of reflectors :

Thermal aging tests FTIR-ATR spectrum of **mirror A** surface paint at **100°C** :



Degradation of the alkyd binder
No charge loss

kinetics relative to the band
ν =1070 cm-1



↗ T → acceleration of the same aging mecanism

Example of Indoor accelerated tests of reflectors :

Damp Heat aging tests ➔ 5 conditions: 70°C/85%HR, 85°C/75%HR, 85°C/85%HR, 85°C/95%HR and 95°C/85%HR

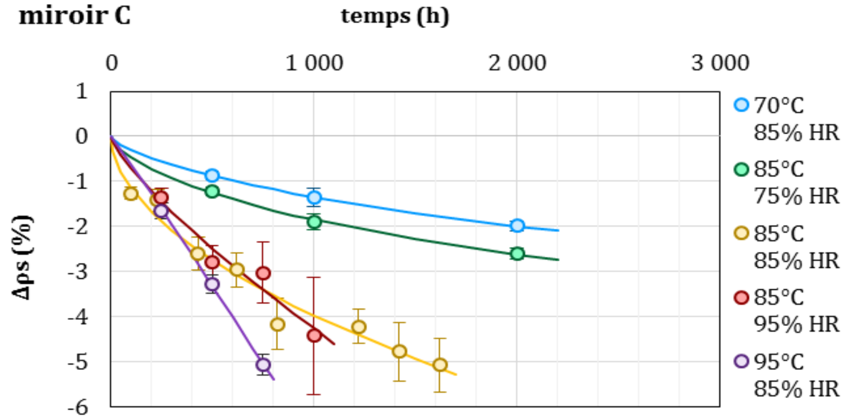
Evolution of specular reflectance ρs over time t

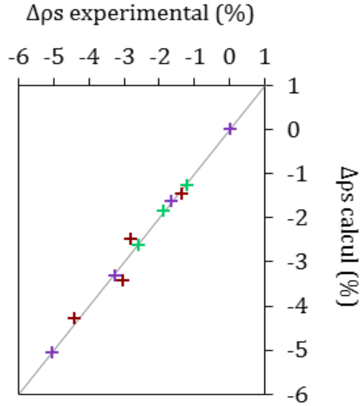
Equation ➔ extrapolate the loss at any time

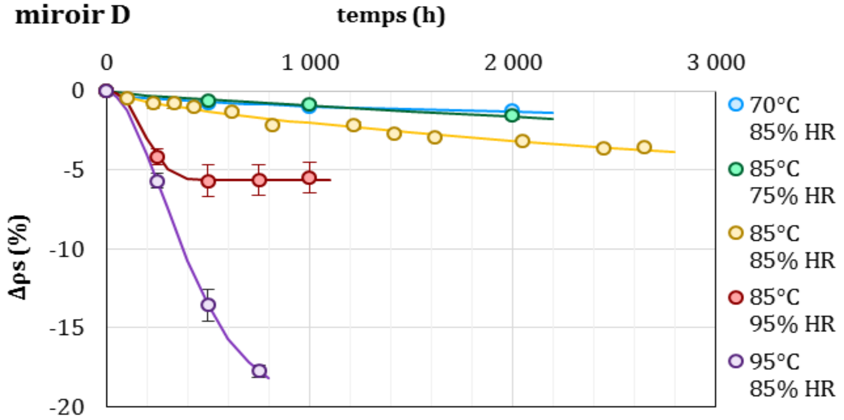
Weibull equation(classic form for aging studies)

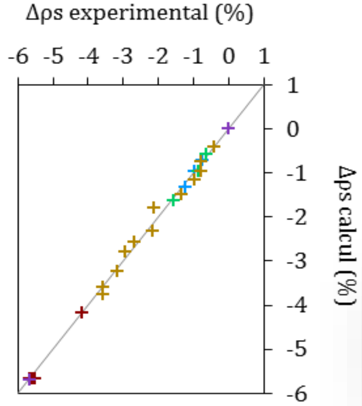
$$\Delta\rho_s = K\left(1 - exp\left(-\frac{(t.10^{-3})^a}{b}\right)\right)$$

Regression on the experimental points thanks to the parameters (a, b, K)









Example of Indoor accelerated tests of reflectors :

Damp Heat aging tests ➔ 5 conditions: 70°C/85%RH, 85°C/75%RH, 85°C/85%RH, 85°C/95%RH and 95°C/85%RH

Macroscopic observation at the final exposure time (2000 h) :

- Corrosion by pitting and by the edges with ↗ RH %
- Formation of a homogenous veil on the silver with ↗ T

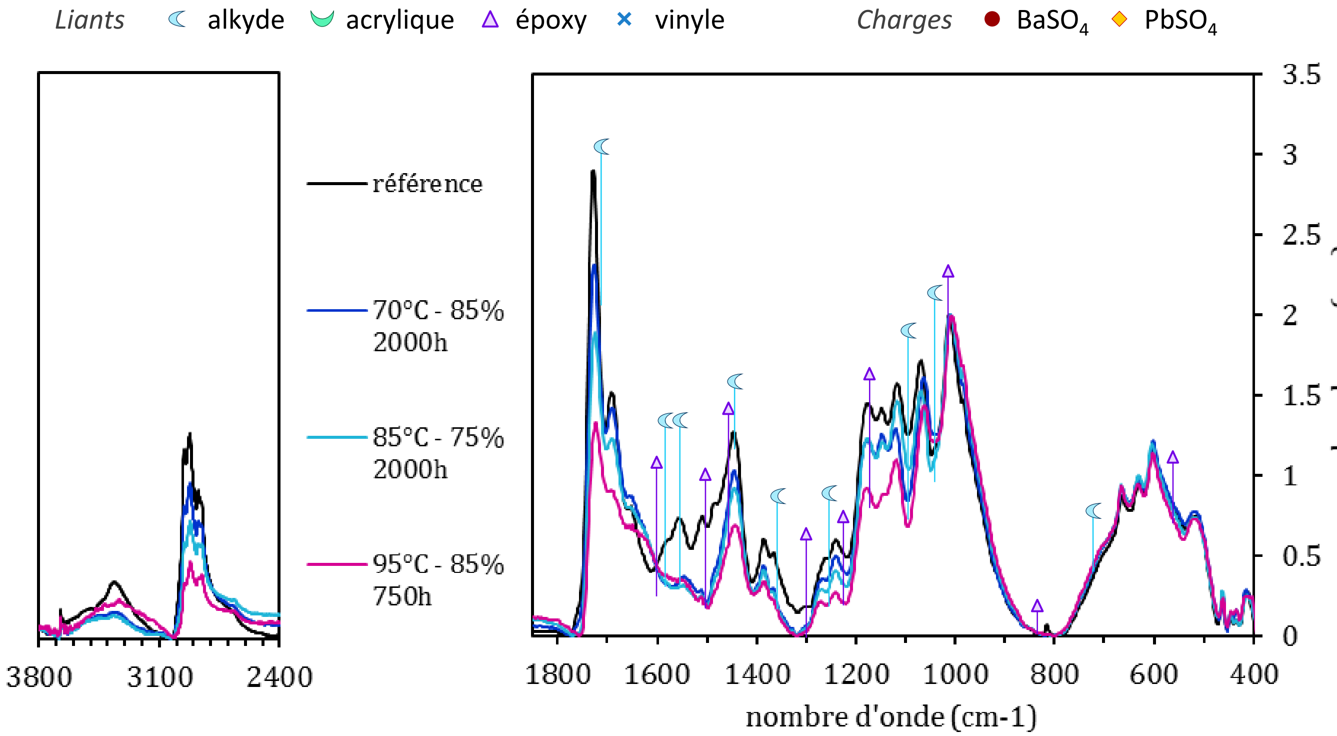
mirror C

70°C 85% HR | *85°C 75% HR* | *85°C 85% HR* | *85°C 95% HR* | *95°C 85% HR*

mirror D

Example of Indoor accelerated tests of reflectors :

Damp Heat aging tests ➔ FTIR-ATR of surface painting of **mirror C** : 70°C/85%HR, 85°C/75%HR, 95°C/85%HR



70°C 85% ;
85°C 75% ;
95°C 85%

Degradation of binders alkyd, epoxy

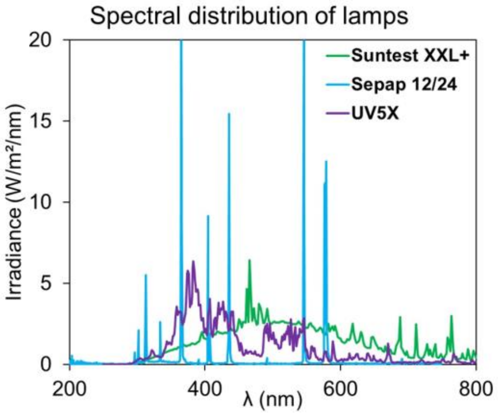
No charge loss

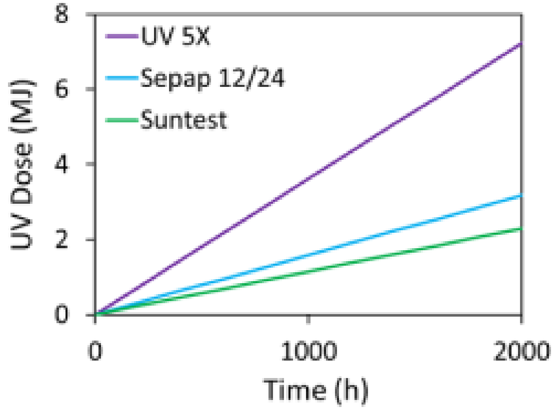
Example of Indoor accelerated tests of reflectors :

UV tests comparison ➔ Evolution of specular reflectance ρs over time t

Ageing chambers characteristics			
Name	Suntest XXL+	Sepap 12/24	UV5X
Company	ATLAS MTS	ATLAS MTS	AMC/AMTC *from CEA specifications*
Lamps	**Xenon**	**Mercury**	**Xenon**
Irradiance (300 - 400 nm)	**65 W/m²**	**90 W/m²**	**205 W/m²**
Temperature of order	70 °C	70 °C	70 °C
Samples placement	put on the fix bottom plate	rotation on a carrousel	fix support
Samples number (7x7 cm²)	12	6	≈ 100
Acceleration Ratio relative to Suntest XXL+ acceleration	**1**	**1.4**	**3.2**

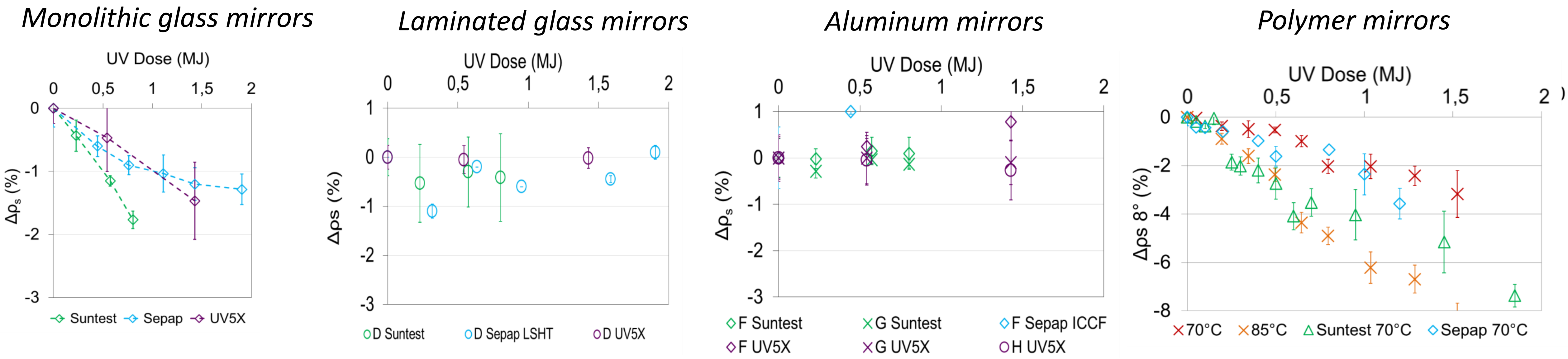






Example of Indoor accelerated tests of reflectors :

UV tests comparison ➔ Evolution of specular reflectance ρs over time t on 4 types of mirrors



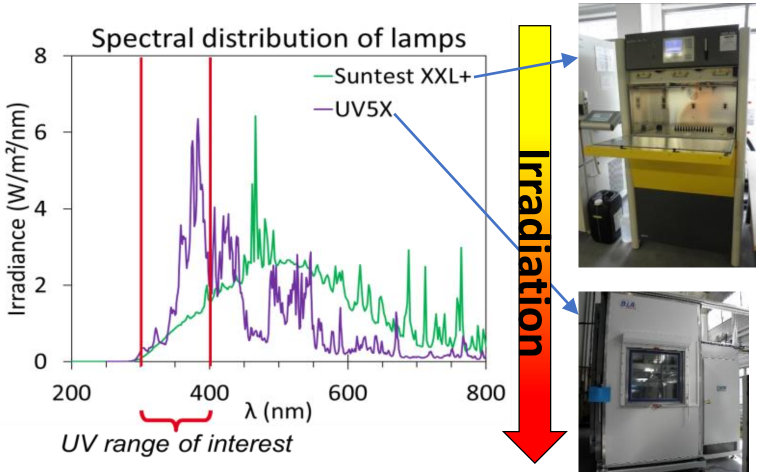
- Aluminum mirrors = resistant to UV irradiation ≠ Polymer mirrors
- Expected: Suntest < Sepap < UV5X — Experimental: Sepap ≤ UV5X < Suntest

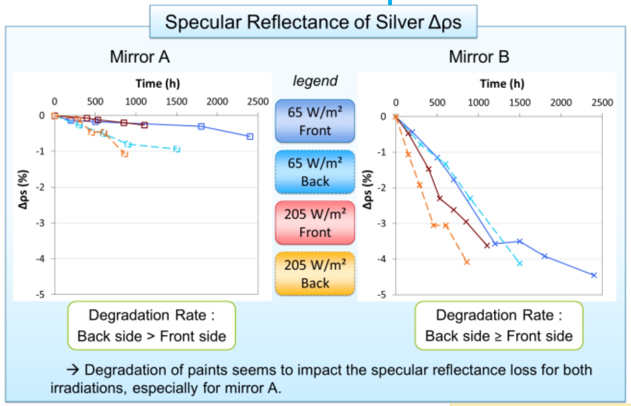
70 °C, 82 °C, 88 °C

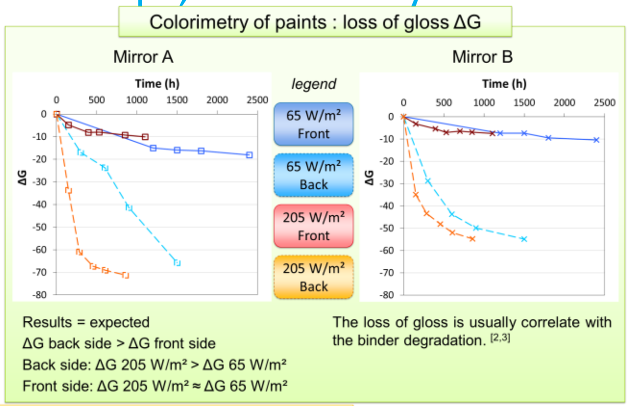
"Accelerated aging test of solar mirrors: Comparison of different UV chambers", Avenel, C.; Gardette, J.-L.; Therias, S.; Disdier, A. & Raccurt, O. (**2017**), AIP Conference Proceedings 1850(1), 130001.

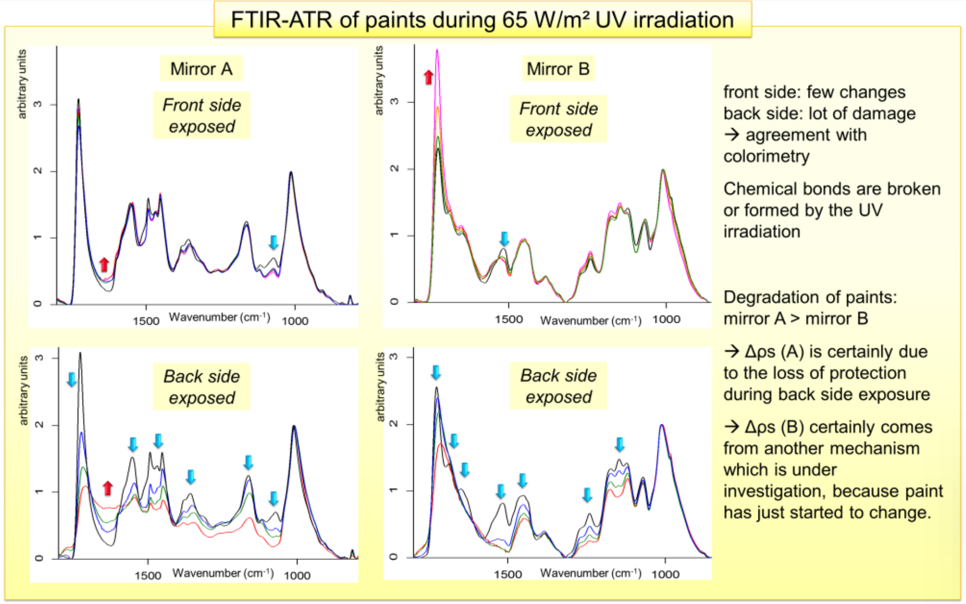
Example of Indoor accelerated tests of reflectors :

UV tests comparison back side/front side ➔ Evolution of specular reflectance ρs, colorimetry and FTIR-ATR over time t on 2 types of monolithic glass mirrors









Conclusion :

- Back side paint exposure is more sensible to the photodegradation for the 2 mirrors (reflectance + colorimetry + FTIR-ATR)
- Mirror A paint is more sensible to the photodegradation (colorimetry + FTIR-ATR)

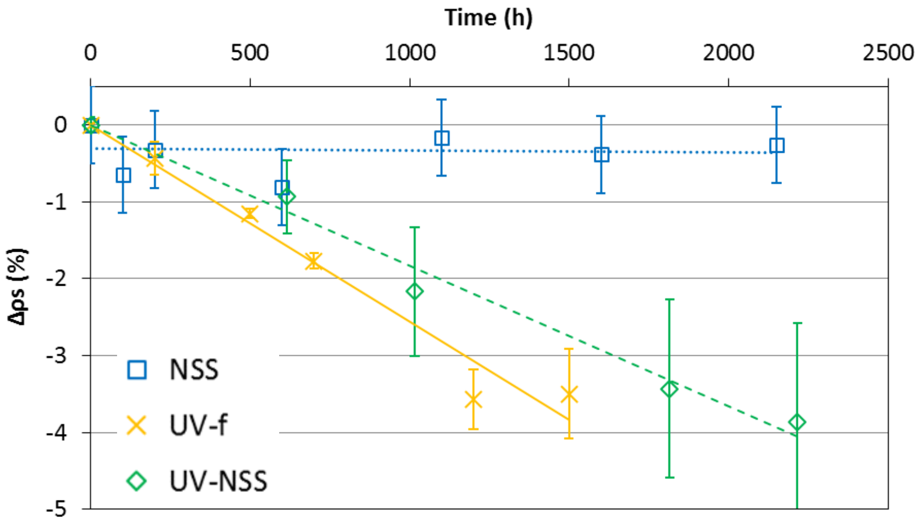
E. Le Baron CEA

Example of Indoor combination of accelerated tests of reflectors :

3 successive conditions:

1. NSS : Neutral Salt Spray (NSS) ISO 9227 alone = 1600 h
2. UV-f : UV radiation alone in Suntest XXL+ 85 °C and 65 W/m² (300 - 400 nm) front side = 400 h
3. UV-NSS : alternation of cycles 300 h of UV radiation + 300 h of saline mist

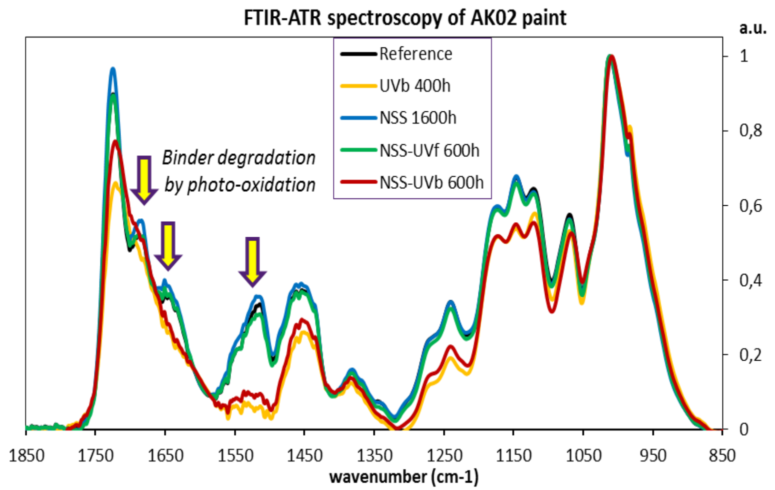
Evolution of specular reflectance ρs over time t



$\Delta\rho_s$ (NSS) < $\Delta\rho_s$ (UV-NSS) < $\Delta\rho_s$ (UV) :

- Degradation by UV is predominant during alternation
- Different degradation in NSS / UV-NSS / UV (binder photo-oxidation)

FTIR-ATR of surface painting of mirror over time t



Example of Outdoor tests of reflectors :

Macroscopic observation at the final exposure times ➔ Corrosion by pitting and by the edges

		A	C	F
Time (days)	INES	587		
	PIMENT			

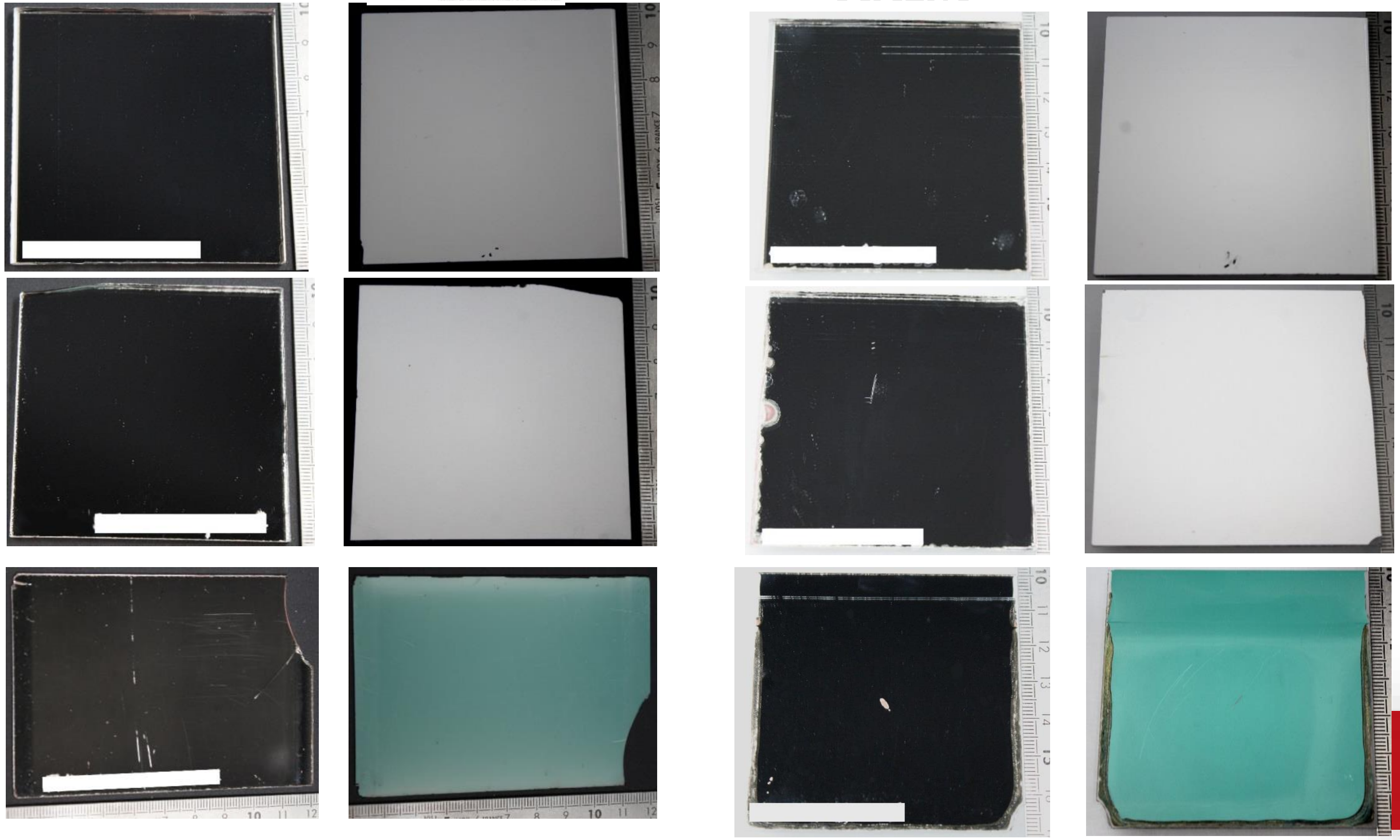
INES

PIMENT

mirror A

mirror C

mirror F



edge corrosion : mirror F> mirror C > mirror A

Example of Outdoor tests of reflectors :

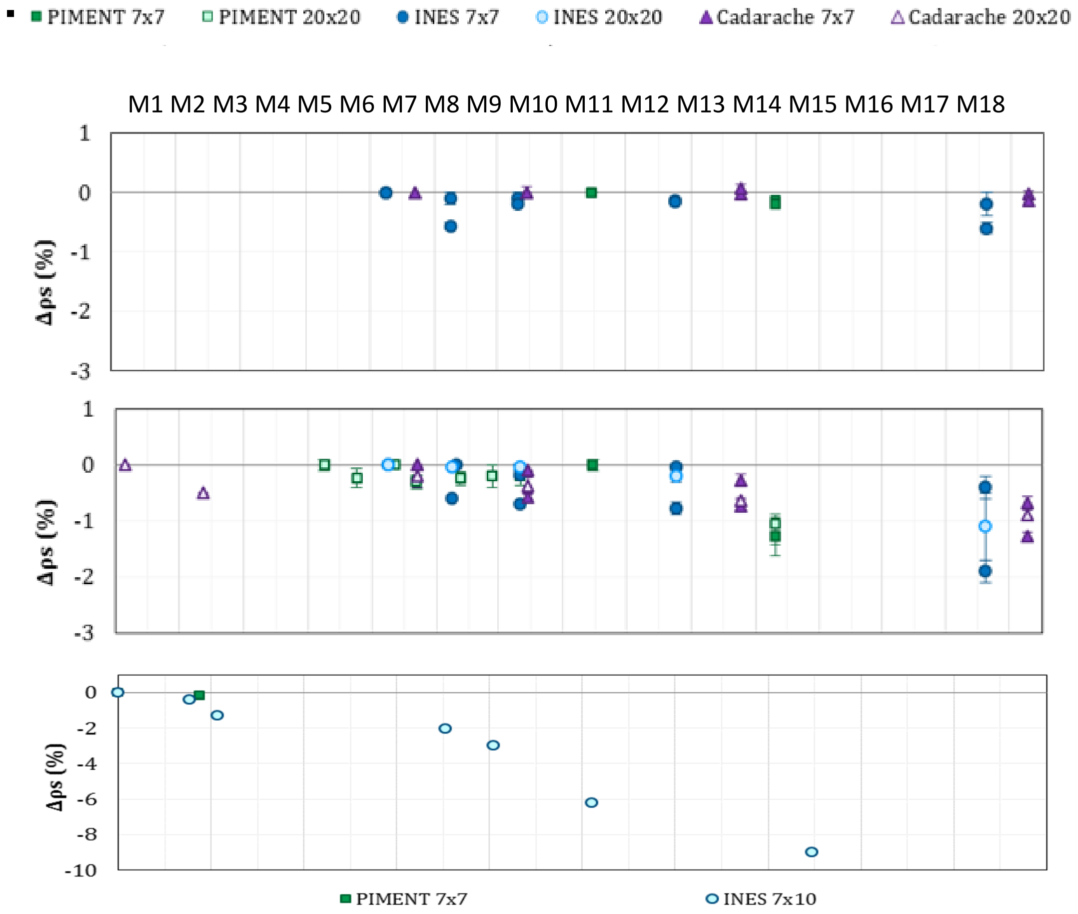
Evolution of specular reflectance ρs over time t

		A	C	D
Time (days)	INES	587		
	PIMENT			

mirror A

mirror C

mirror F



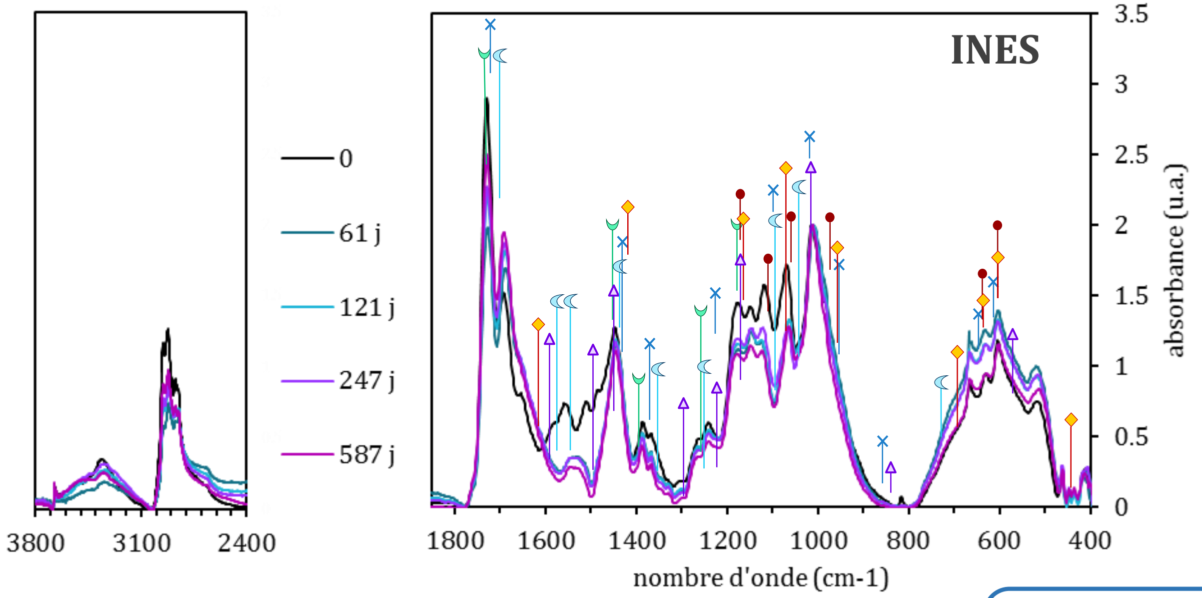
specular reflectance loss :
mirror F> mirror C > mirror A

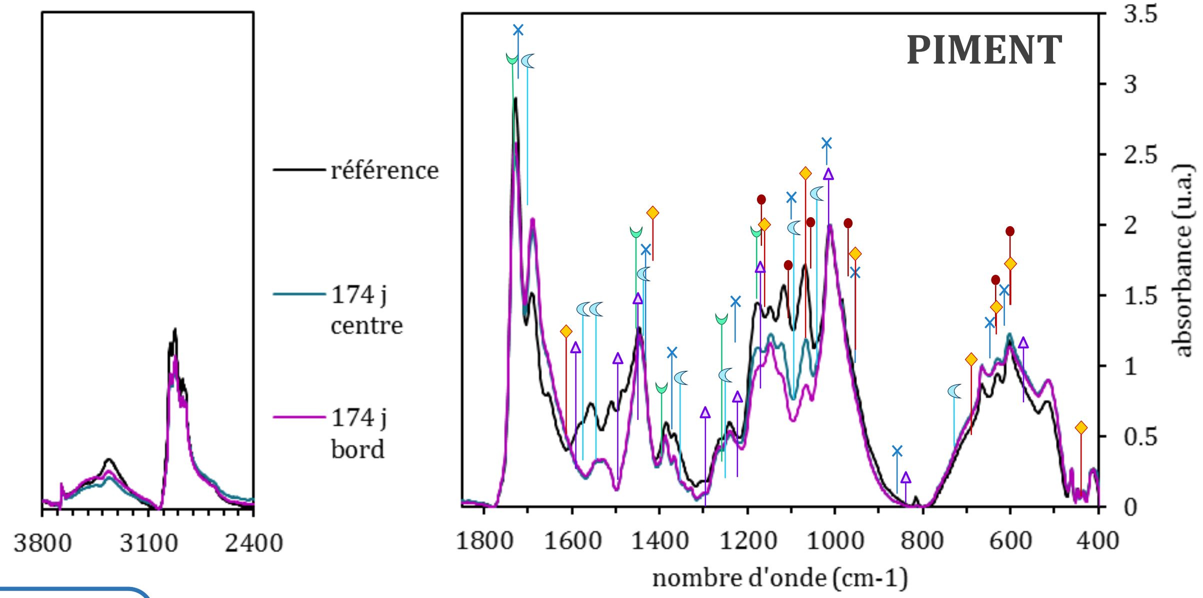
Example of Outdoor tests of reflectors :

FTIR-ATR of surface painting of **mirror C** at initial and final exposure times

		A	C	D
Time (days)	INES	587		
	PIMENT			

Liants ☾ alkyde ◡ acrylique △ époxy × vinyle *Charges* ● $BaSO_4$ ◆ $PbSO_4$





Degradation of binders
alkyd ☾, epoxy △

No charge loss

Solar Facilities for the European Research Area

Programme funded by the EUROPEAN UNION

SFERA III: On site Training for Indusry

Le Bourget-du-Lac, June, 8th – 10th 2022

Erosion of Reflectors and Sandstorm Simulation

Florian Wiesinger, DLR

www.dlr.de/enerMENA

Deutsches Zentrum für Luft- und Raumfahrt e.V.
in der Helmholtz-Gemeinschaft

Contents

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Outdoor campaign

Laboratory Test Setups

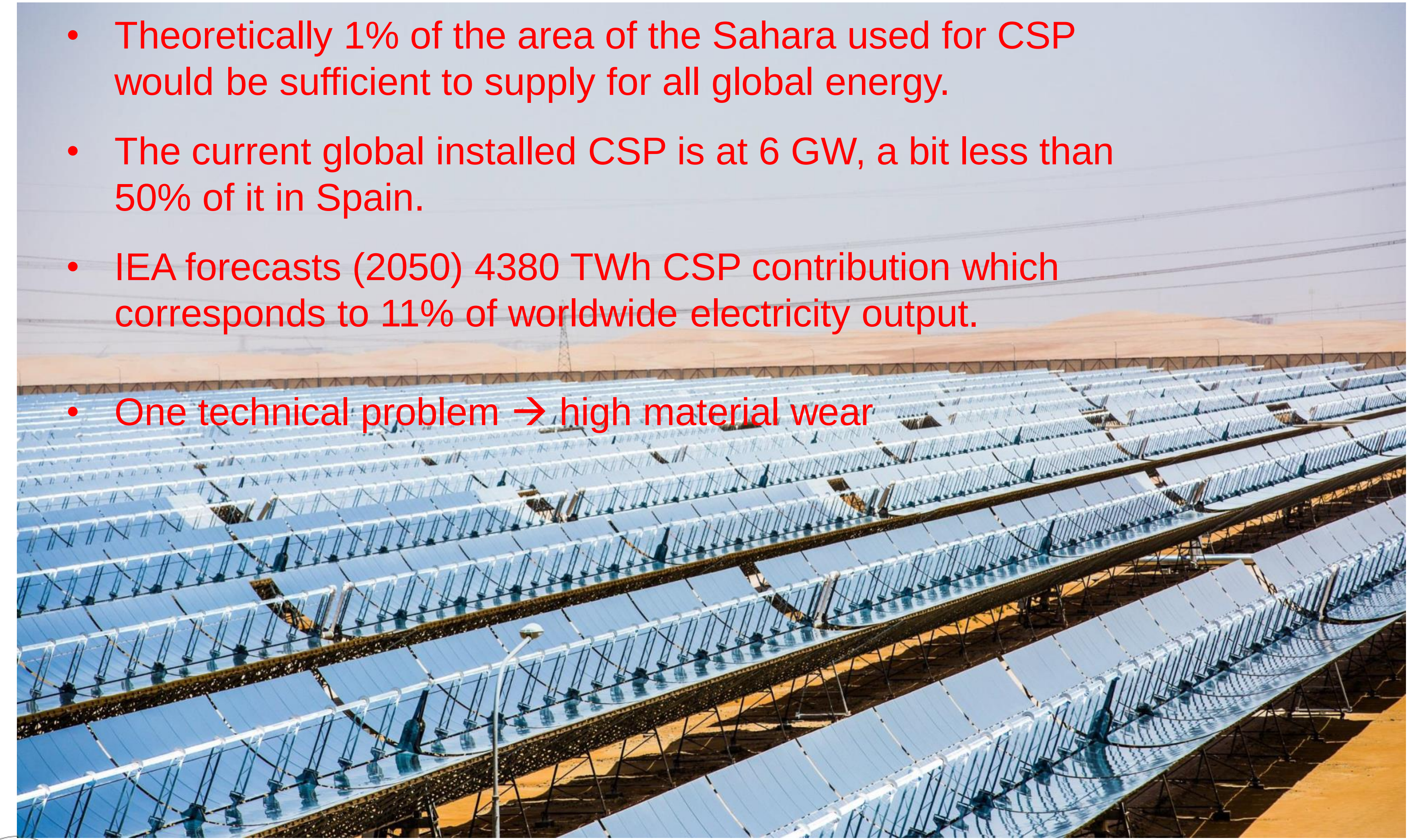
Results of parameter studies

Summary

Motivation – Oil Consumption

100 million barrels of oil every day

Motivation – Solar Power Potential



- Theoretically 1% of the area of the Sahara used for CSP would be sufficient to supply for all global energy.
- The current global installed CSP is at 6 GW, a bit less than 50% of it in Spain.
- IEA forecasts (2050) 4380 TWh CSP contribution which corresponds to 11% of worldwide electricity output.
- One technical problem → high material wear

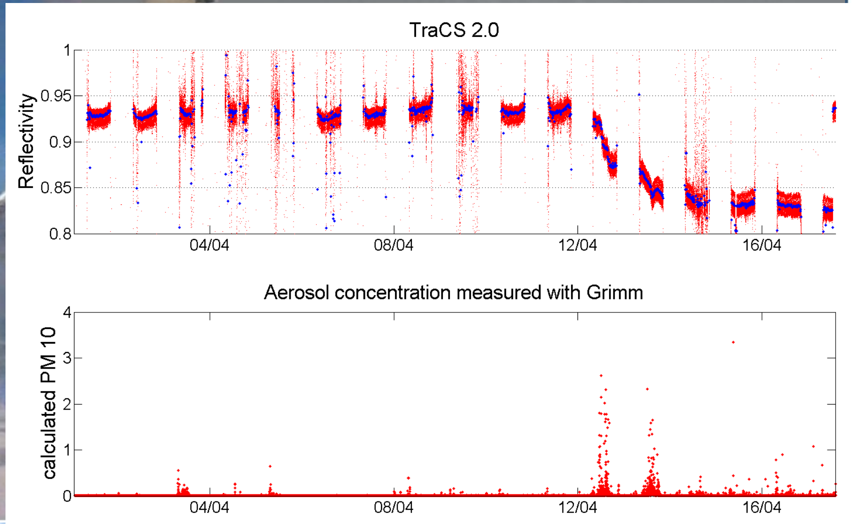
Motivation – Issues implementing CSP in desert environments

Deposited particles:

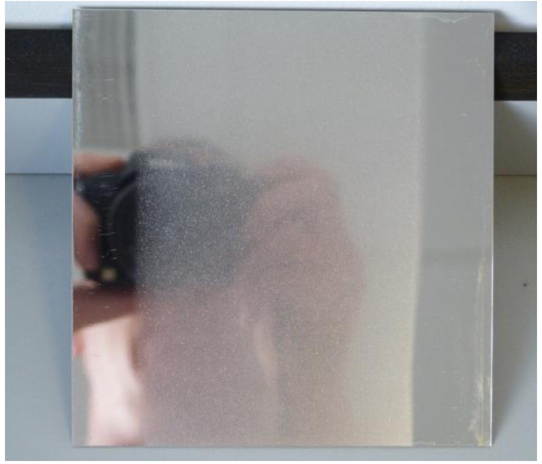
- Soiling of mirrors leads to loss of optical plant efficiency

Suspended particles:

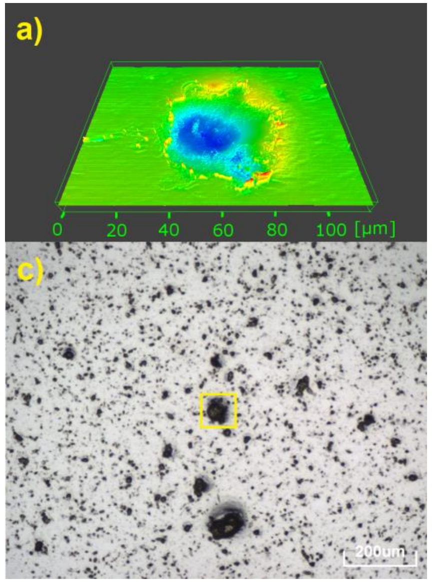
- Atmospheric dust load causes extinction of radiation in tower plants
- Permanent damage on mirrors and materials

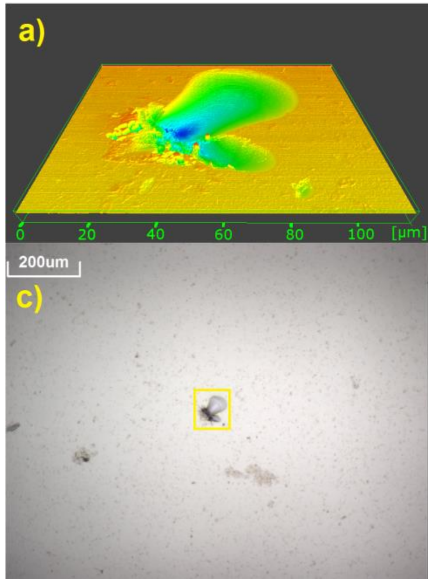


Motivation – Issues implementing CSP in desert environments



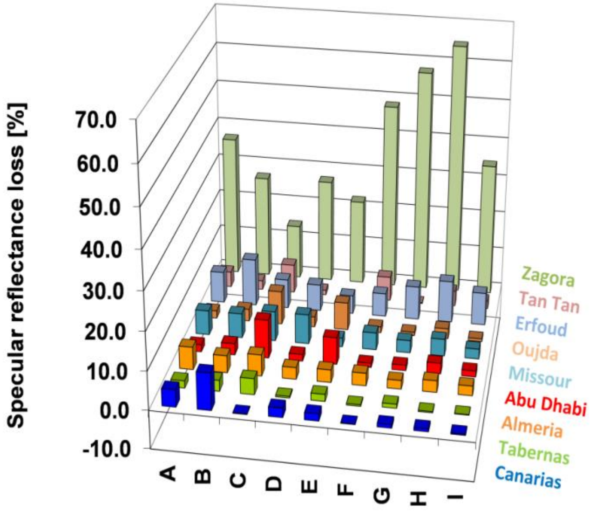
aluminum mirror





Zagora for 20 month

glass mirror



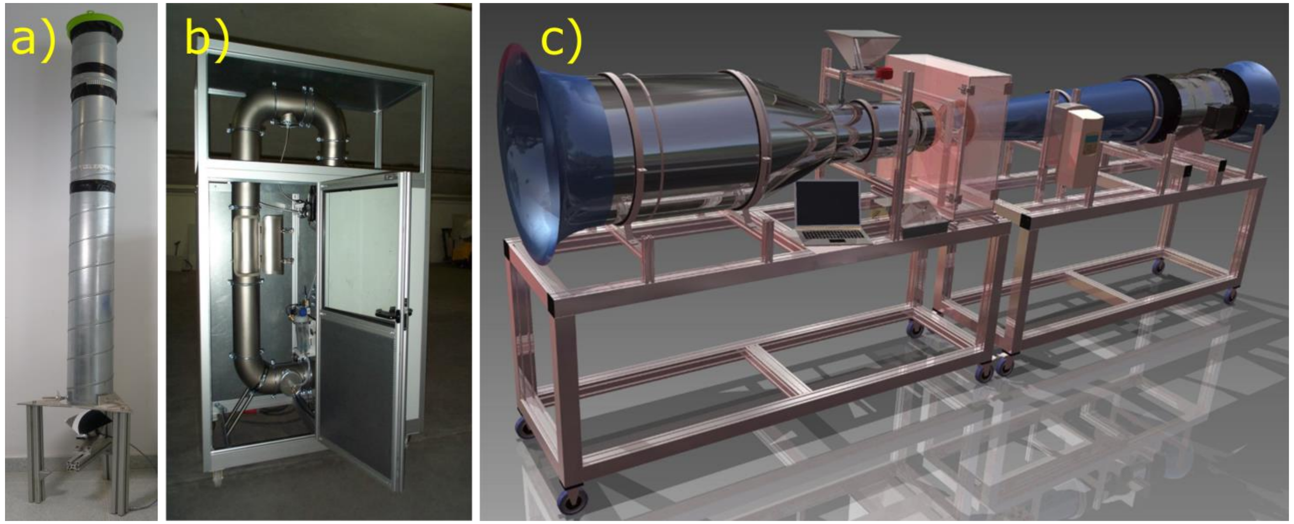
specular reflectance drop after 20 month in Zagora:

aluminum	glass
32.9%	5.2%

annual economical loss of average 50MW plant due to 1% reflectance drop = 600 000$

Motivation - Objective

Three different erosion simulation setups: a) soil pipe, b) closed loop wind tunnel and c) open loop wind tunnel.

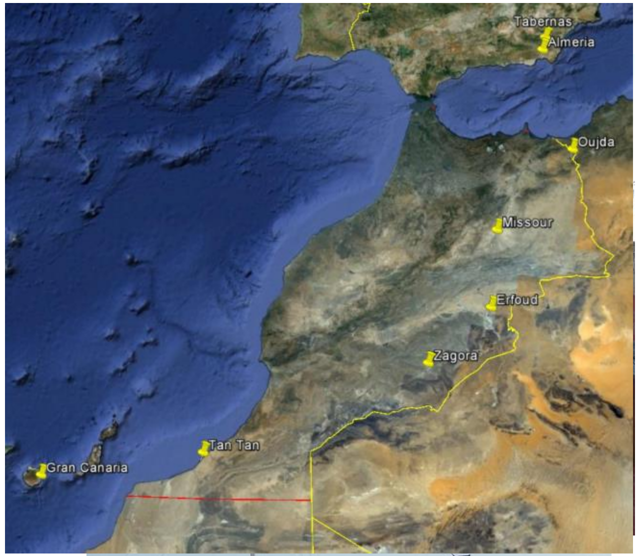


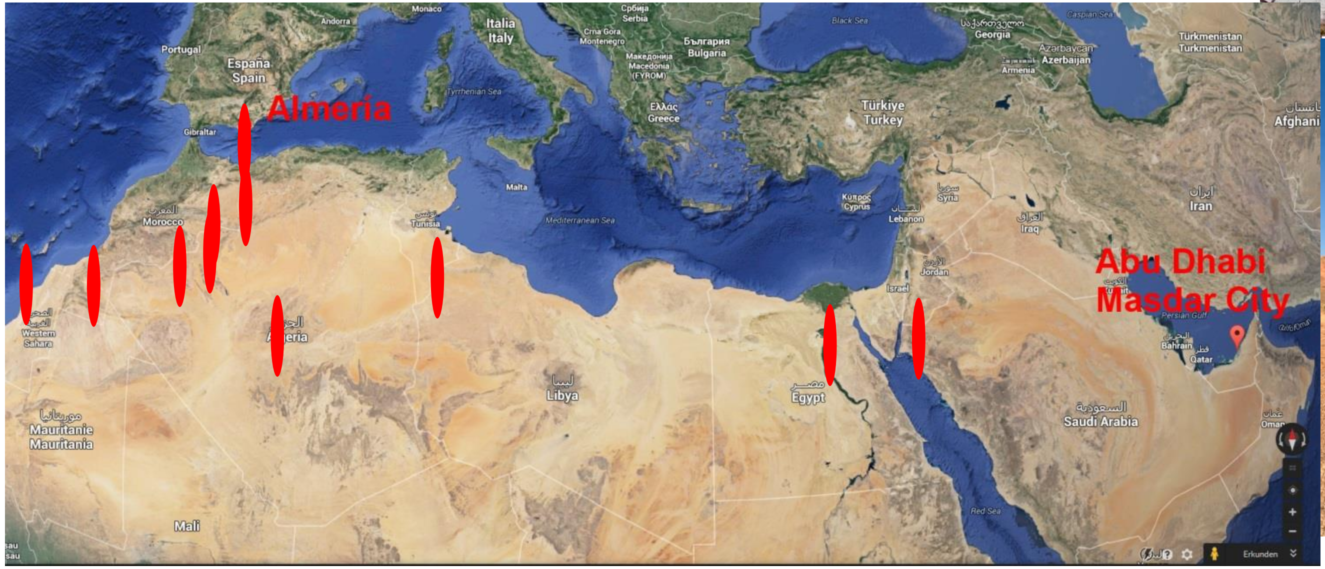
Outdoor Campaign

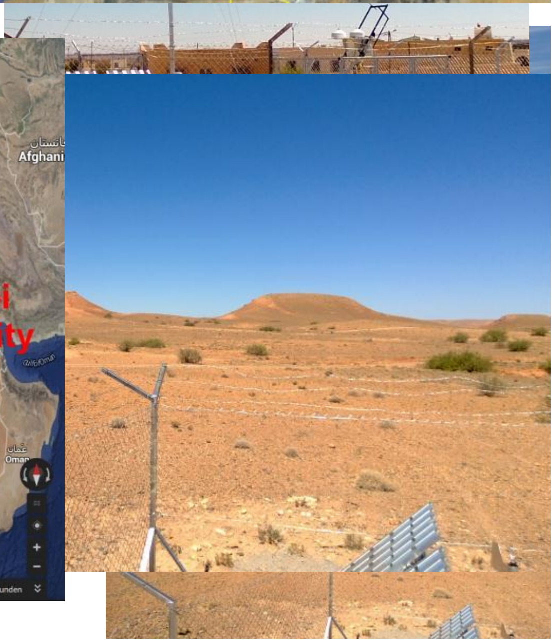
- Extensive outdoor exposure campaign on 13 sites: Almeria, Tabernas, Gran Canaria, Abu Dhabi, Oujda, Missour, Erfoud, Zagora, Tan Tan, Maan, Tatauine, Adrar, Cairo

- Variety of site conditions, from urban over coastal to desert

- On-site measurements of parameters (temperature, wind, irradiation, humidity, particles, etc.)







Motivation - Dust Measurements

Operation of severall passive sampling devices.

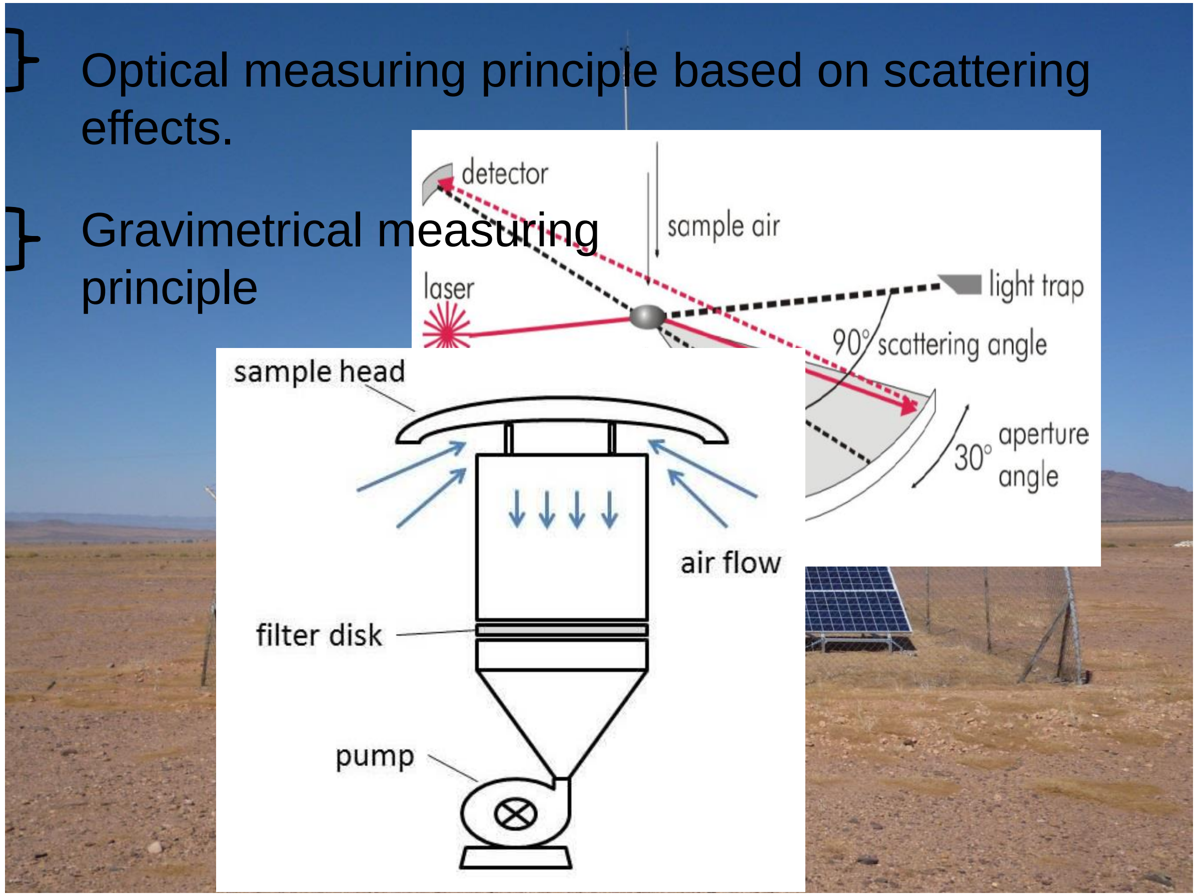
Motivation - Dust Measurements

Three different active dust measurements samplers:

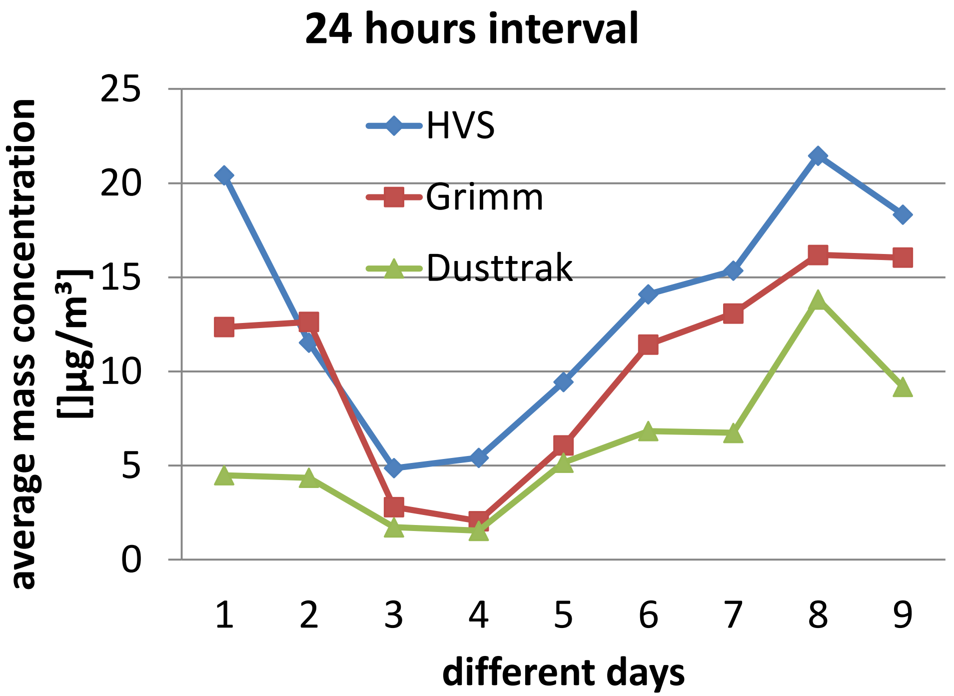
- Dusttrak 8533 from TSI
- EDM164 from Grimm
- HVS-TSP16 from MCZ

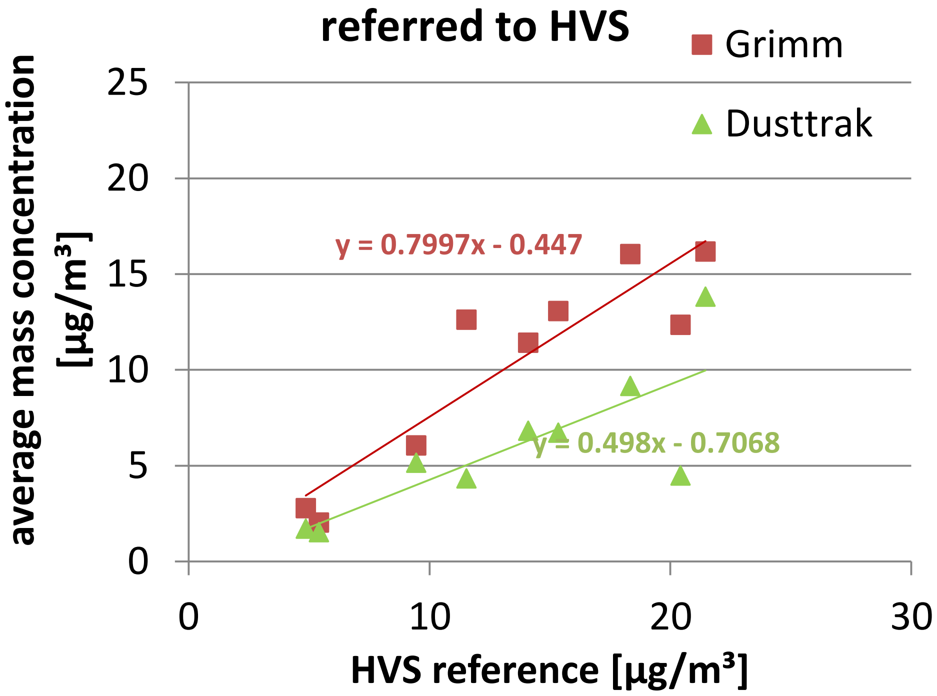
Optical measuring principle based on scattering effects.

Gravimetrical measuring principle

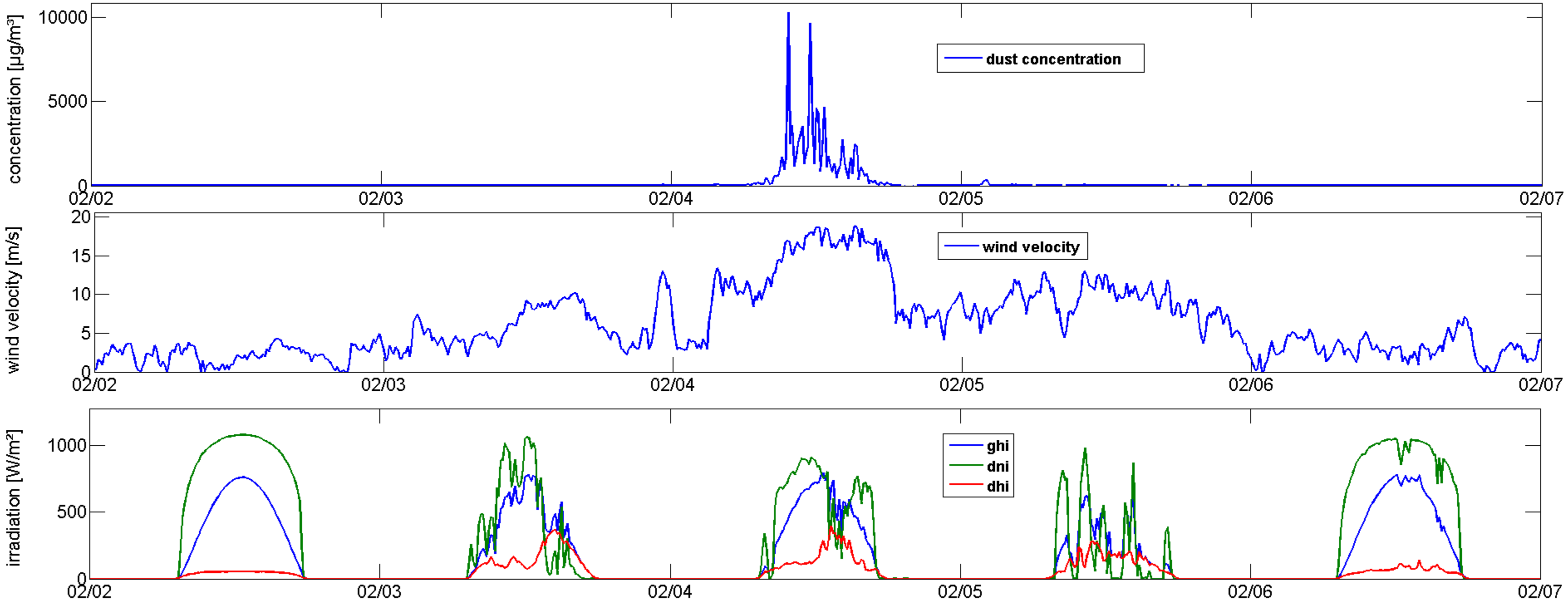


Outdoor Campaign - TSP Dust Concentration @ PSA

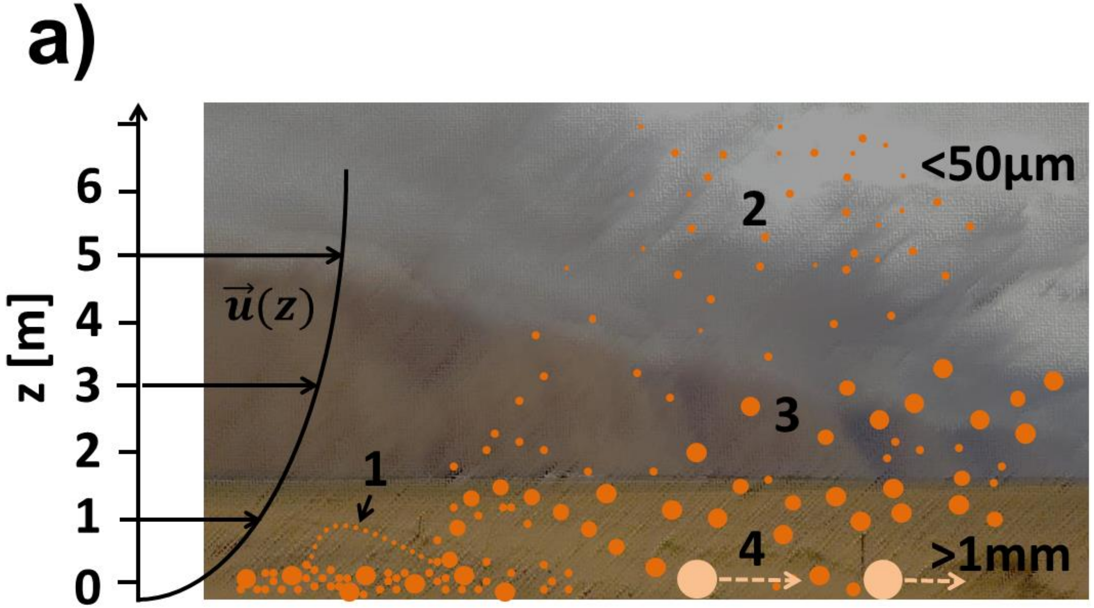




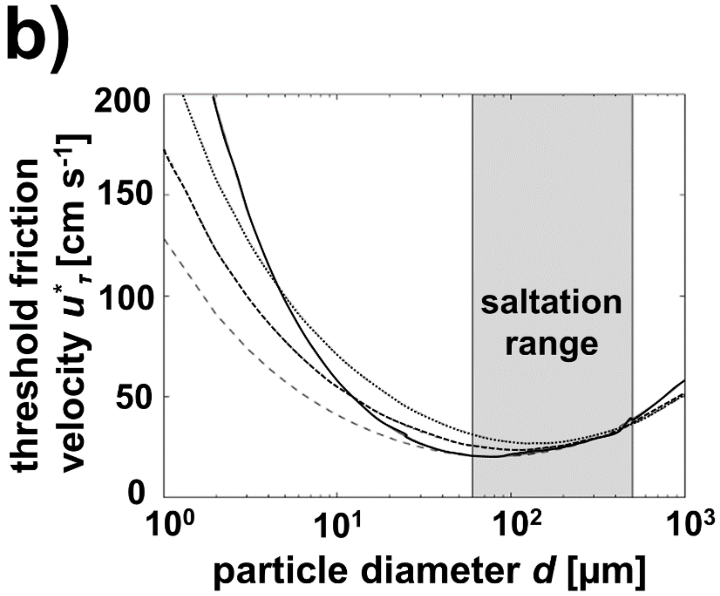
Outdoor Campaign - Dust Concentration @ Missour



Outdoor Campaign - Dust Movement



1) first particle dislodgement from the ground which later impacts the ground, releasing a new particle wave; 2) small particles in suspension mode; 3) the saltation cloud; 4) surface creep

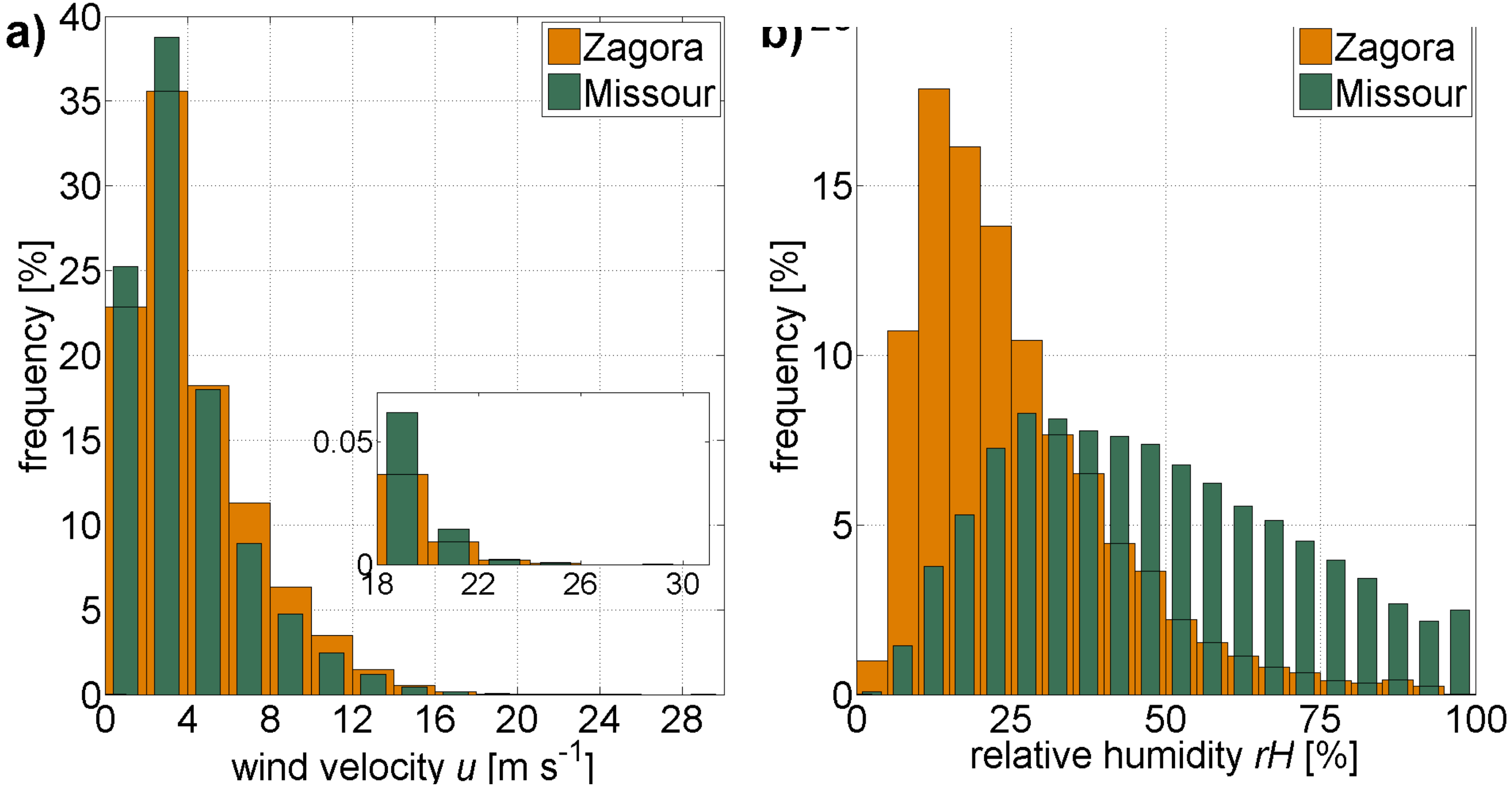


Darmenova et al. 2009

Outdoor Campaign - Dust Movement

Zagora high erosion, Missour low erosion

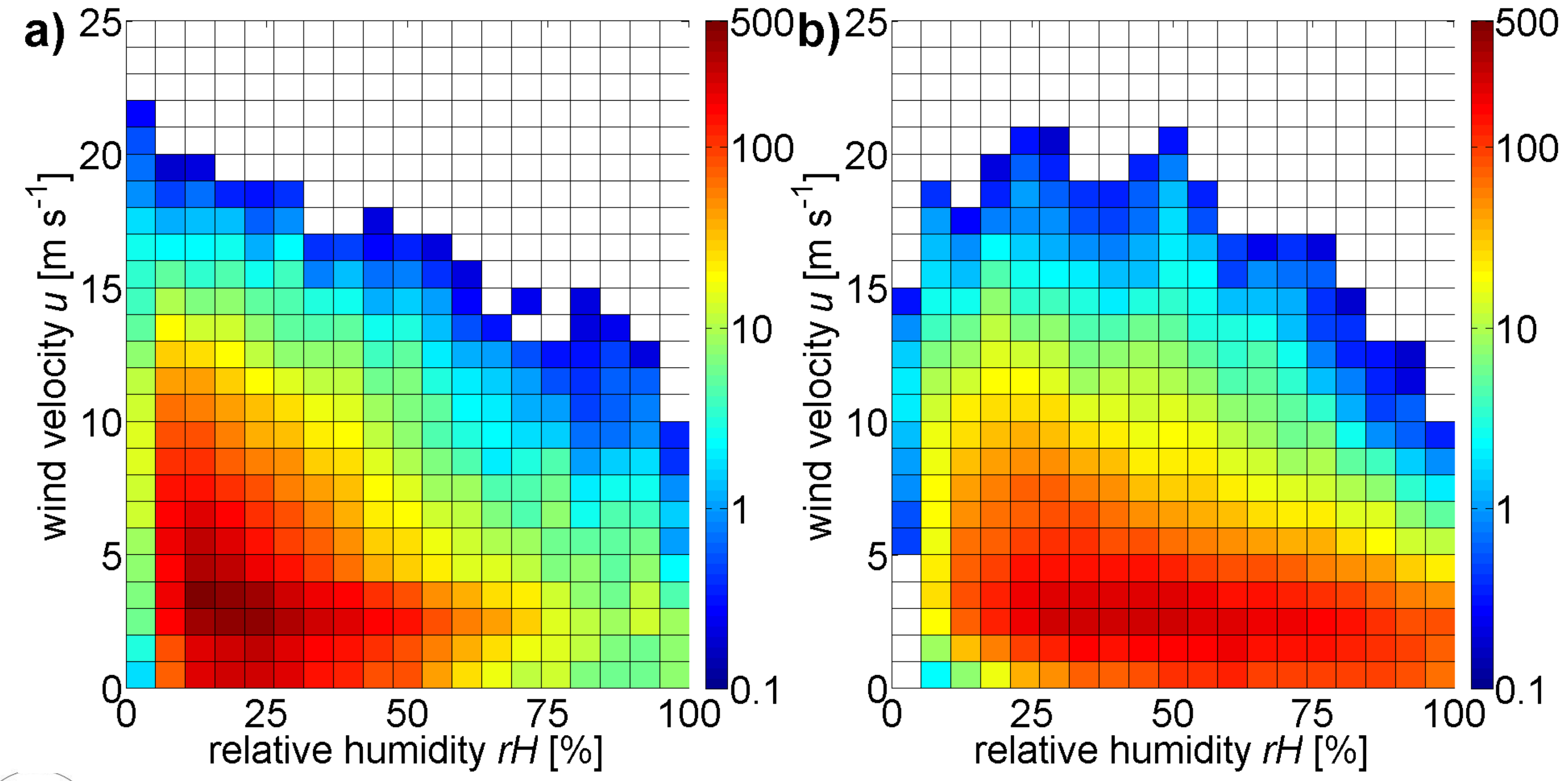
Strong wind ≠ Strong dust movement/erosion



Outdoor Campaign - Dust Movement

Zagora (a) high erosion, Missour (b) low erosion

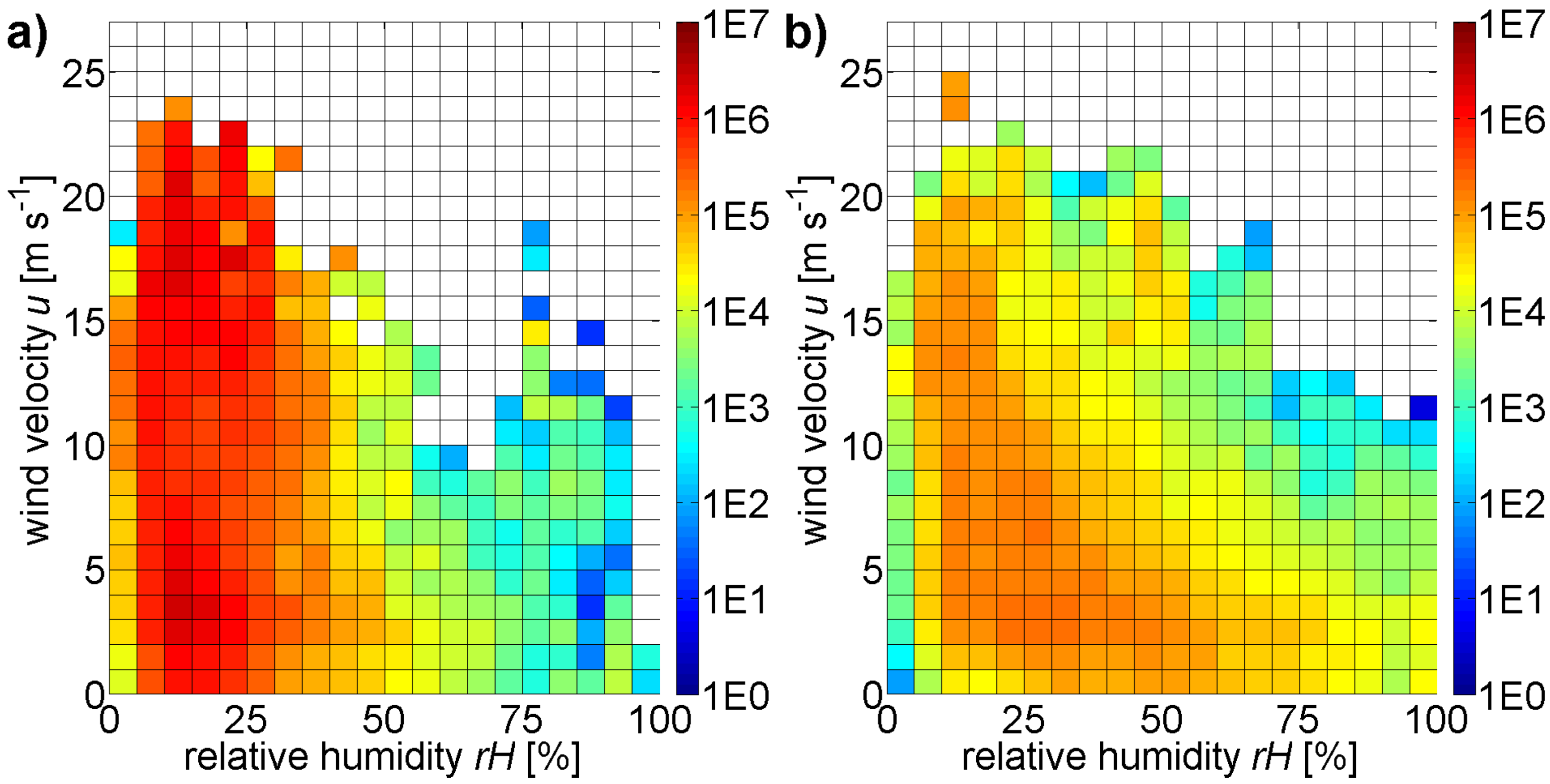
Absolute hours of u/rh couples



Outdoor Campaign - Dust Movement

Zagora (a) high erosion, Missour (b) low erosion

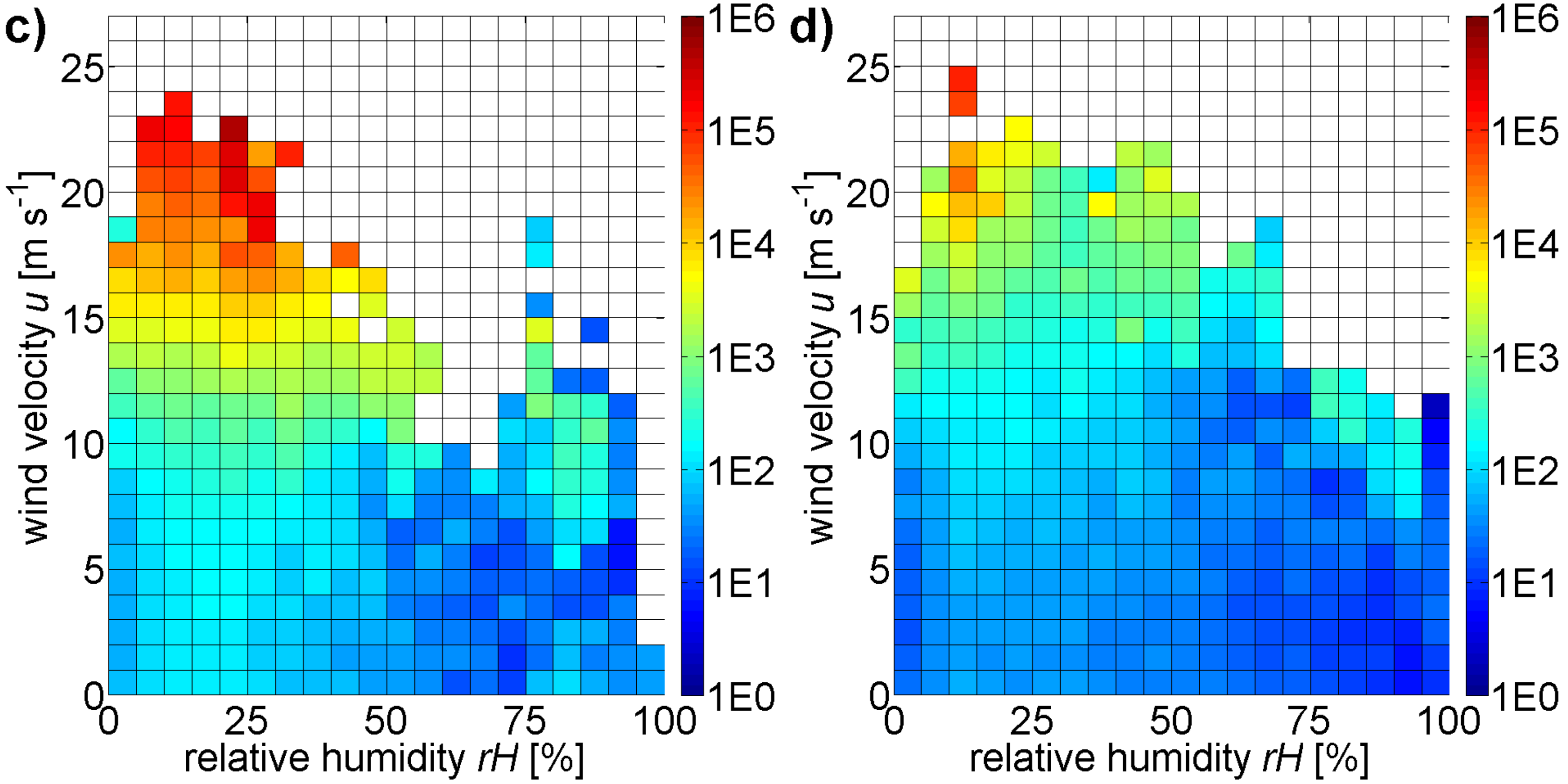
Cumulated dust concentration [µg/m³]



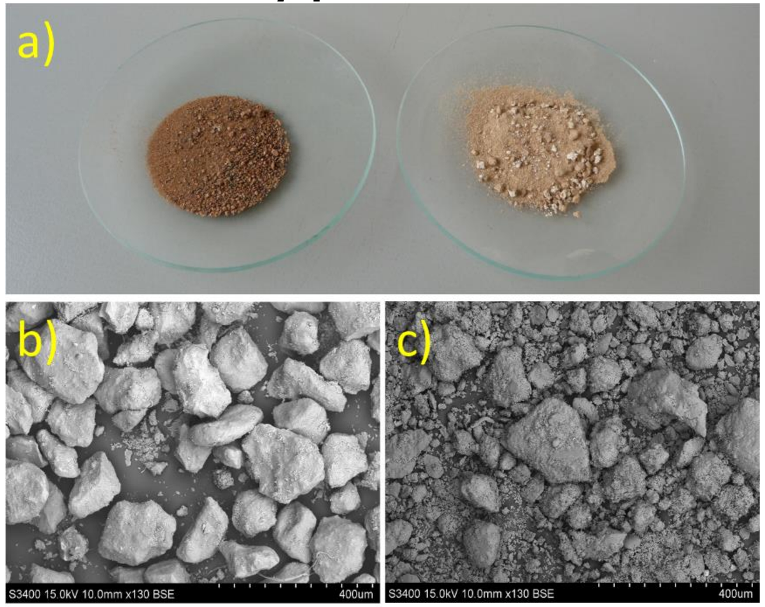
Outdoor Campaign - Dust Movement

Zagora (c) high erosion, Missour (d) low erosion

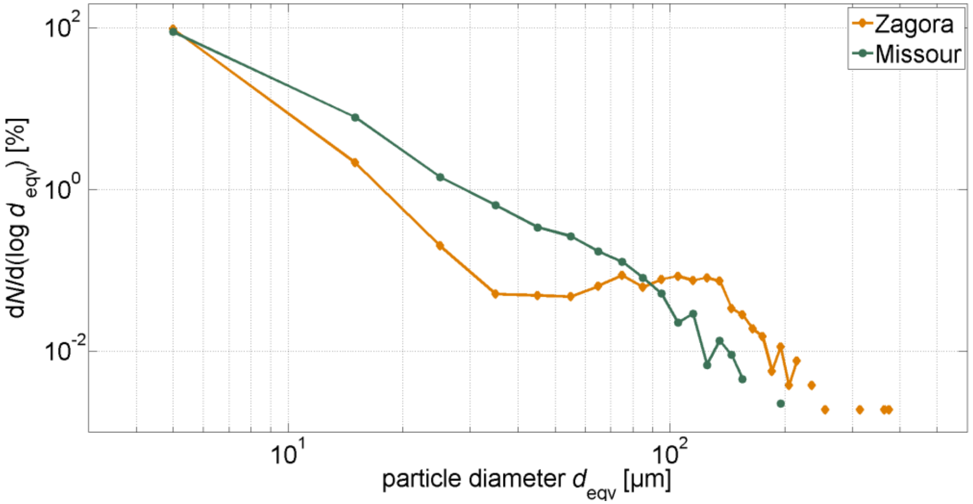
Cumulated dust concentration divided by frequency of u-rh couple = Dust activity



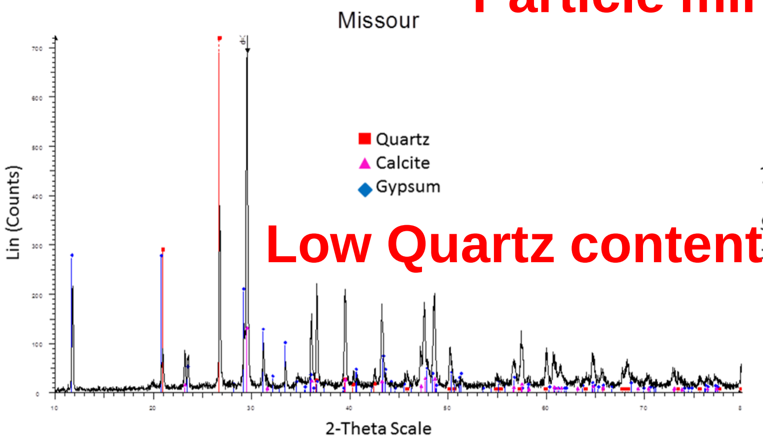
Outdoor Campaign - Dust Damage Potential

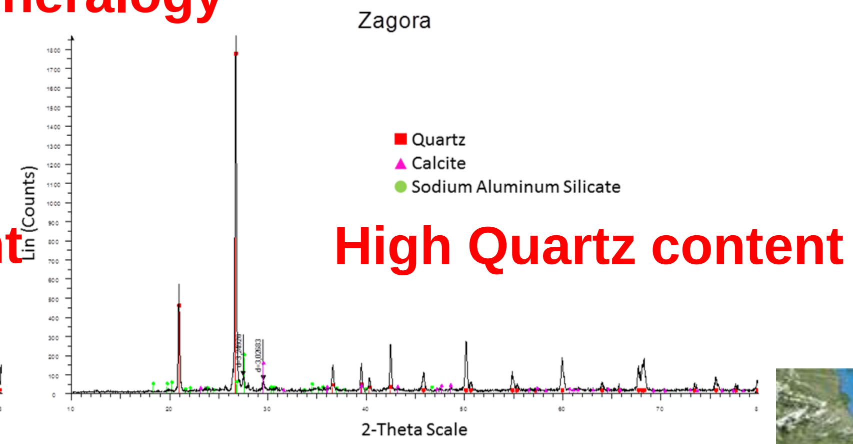


Particle size distribution



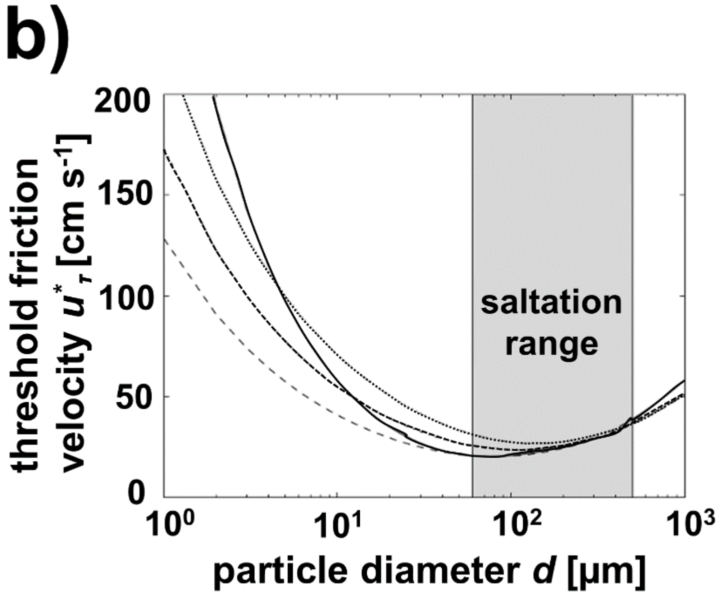
Particle mineralogy





Outdoor Campaign - Dust movement identified risks

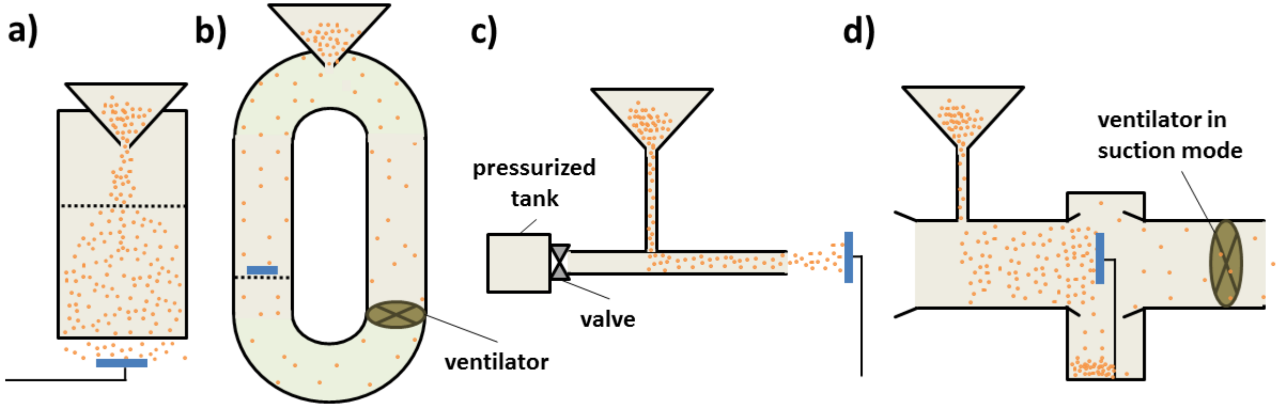
- PSD maximum at 65-200µm
- PSD bimodal
- Open terrain with winds larger than 10m/s
- Low relative humidity and high wind present at the same time
- Low clay content
- High Quartz content



Darmenova 2009
Wiesinger 2020

Sand impact theory & Testloop design

particle	diameter	d	[m]	10^{-6}-10^{-3}
	sand mass	γ	[g cm^{-2}]	0.05-30
	density	ϱ	[kg m^{-3}]	2320-2650
	velocity	v	[m s^{-1}]	0-30
	Moh's hardness	H_p	[GPa]	0.61-12.11
	fracture toughness	K_p	[MPa m$^{0.5}$]	-
	circularity	ci	-	0-1
target	Young's modulus	E_t	[GPa]	soda-lime glass: 70
	Moh's hardness	H_t	[GPa]	soda-lime glass: 5.5
	fracture toughness	K_t	[MPa m$^{0.5}$]	soda-lime glass: 0.75
environment	temperature	T	°C	room temperature
	impact angle	β	°	0-90

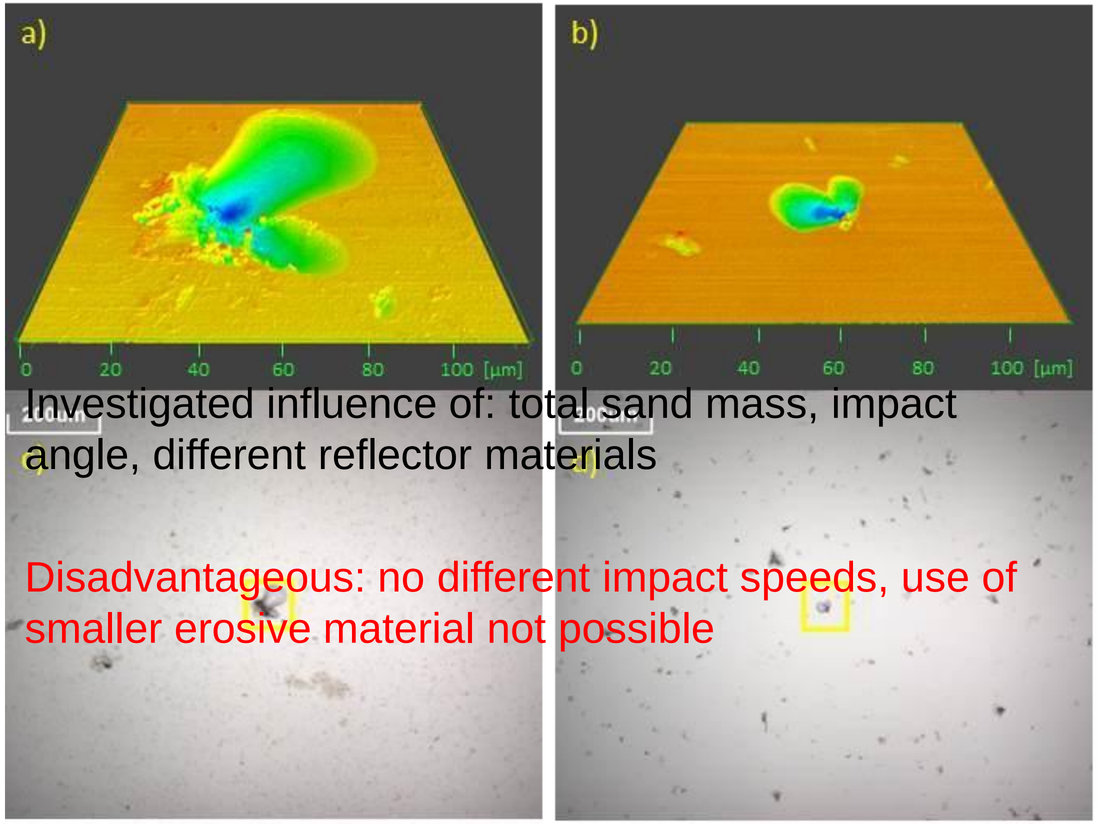


Erosion Testing- Testloop A

Used erosive material: Silica particles (diameter between 300-625 µm).

Outdoor - Zagora

Laboratory – soil pipe

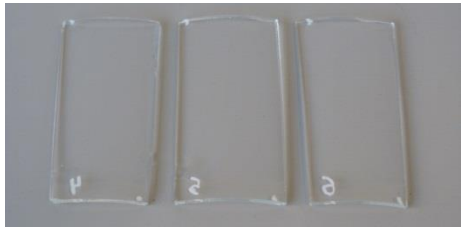


Investigated influence of: total sand mass, impact angle, different reflector materials

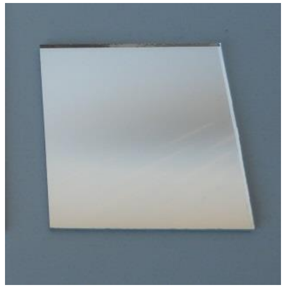
Disadvantageous: no different impact speeds, use of smaller erosive material not possible

Wiesinger et al. 2016

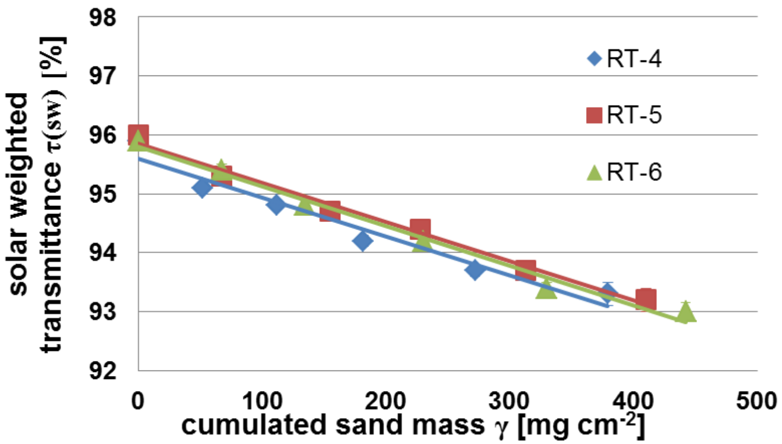
Erosion Testing- Testloop B

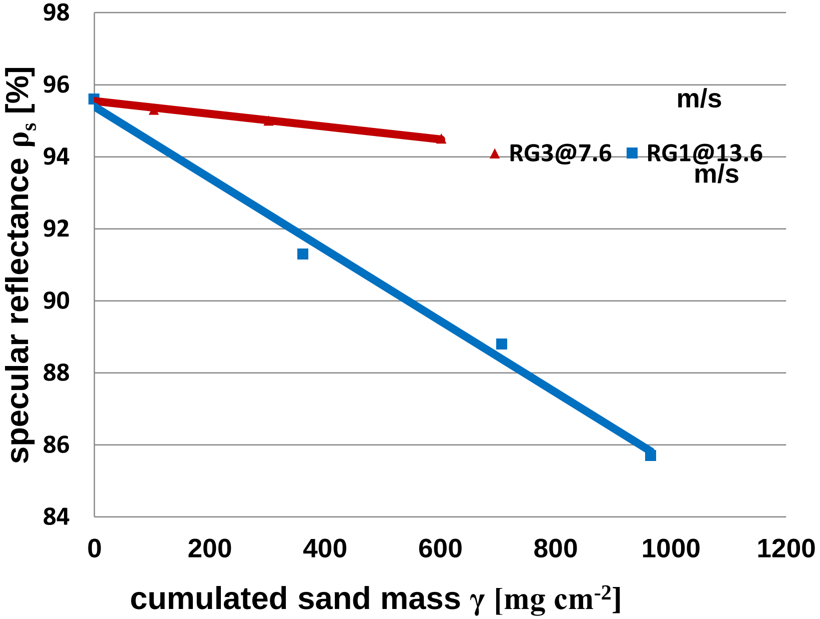


Glass envelope tubes - reproducibility



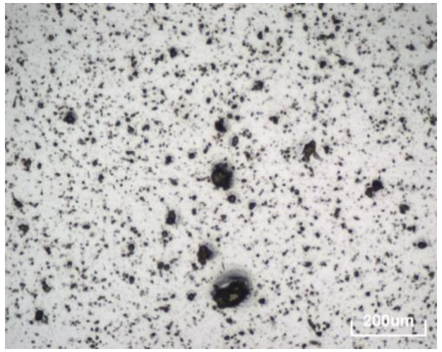
Glass reflectors – velocity influence



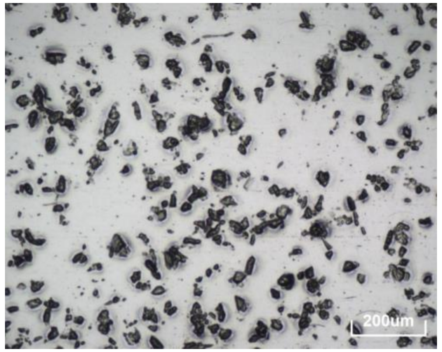


Erosion Testing- Testloop B

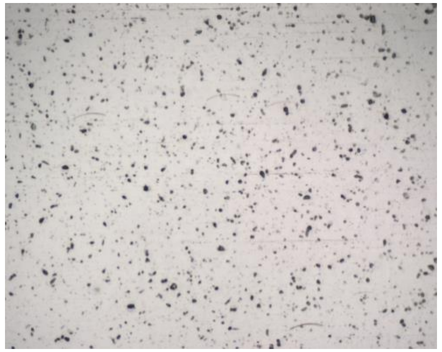
Zagora 20 month



Soil Pipe



SSC



Investigated influence of impact speed, smaller erosive material.

Disadvantages: no satisfying dust concentration control, no easy change of dust type, deterioration of test dust.

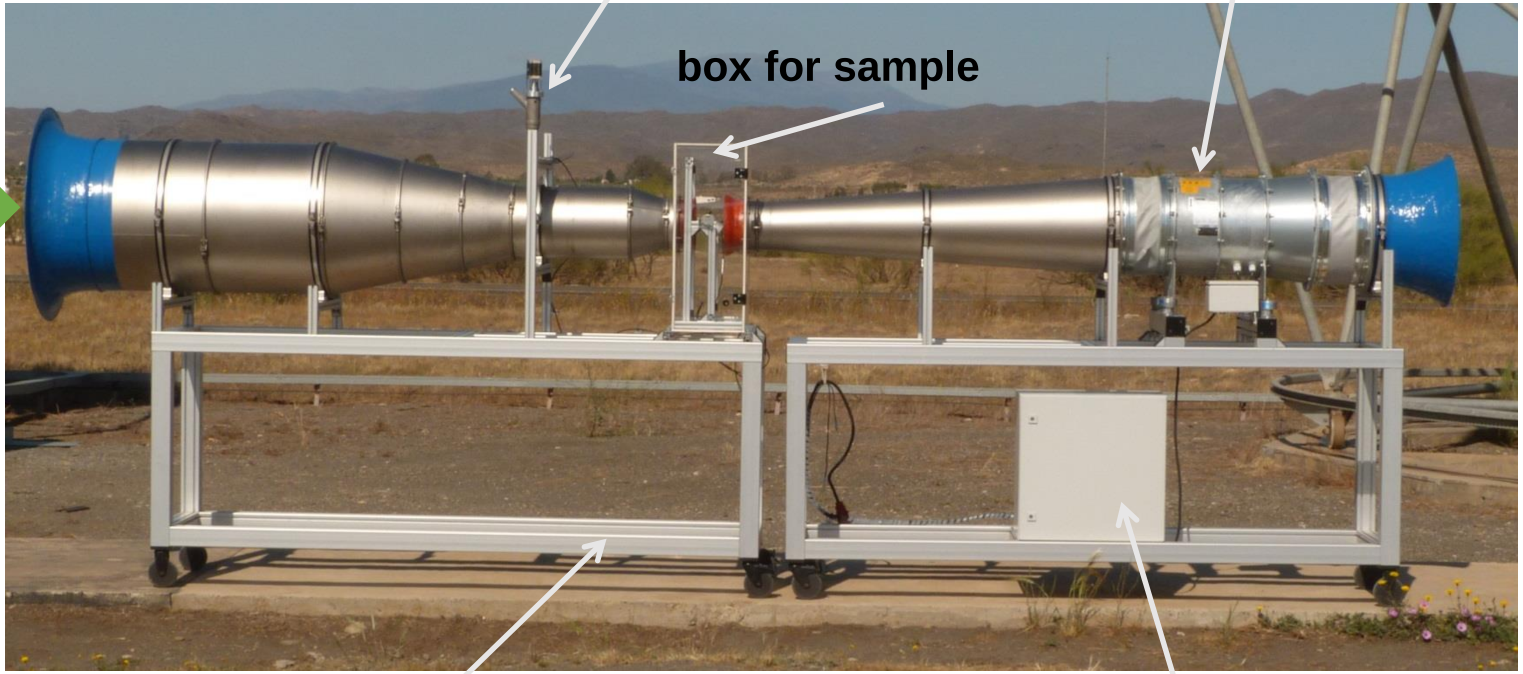
Accelerated aging tests

Sand erosion test to simulate sand storms

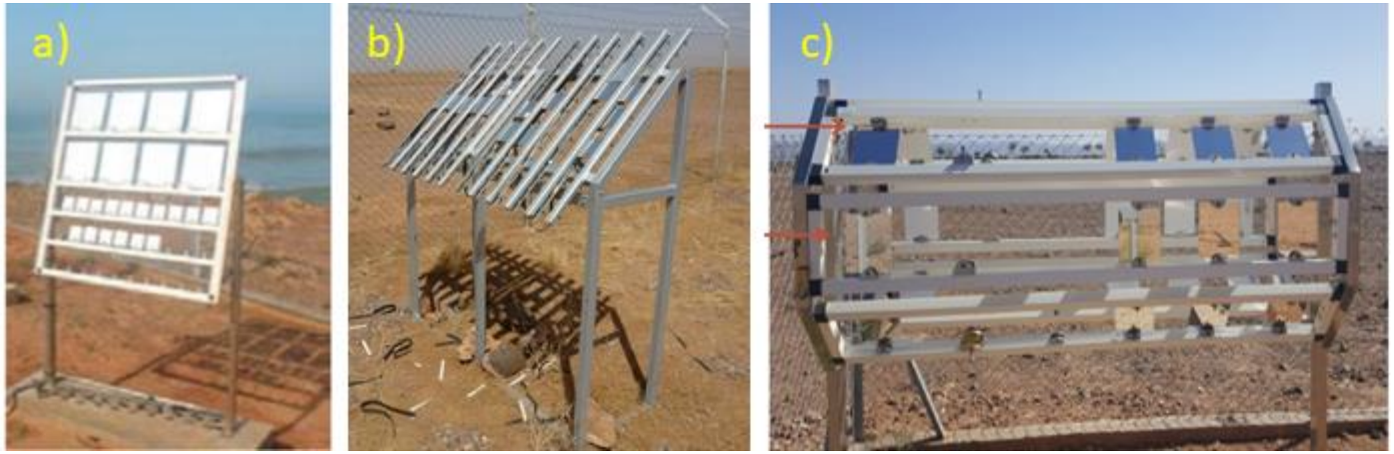
- Wind velocity up to 45 m/s.
- Highly homogeneous flow.
- All different types of test dusts applicable and easy to be changed.
- Screw-conveyer dust injection facilitates concentration control.
- No test dust degradation.

Accelerated aging tests

Sand erosion test to simulate sand storms



Outdoor Erosion – field study on height and orientation



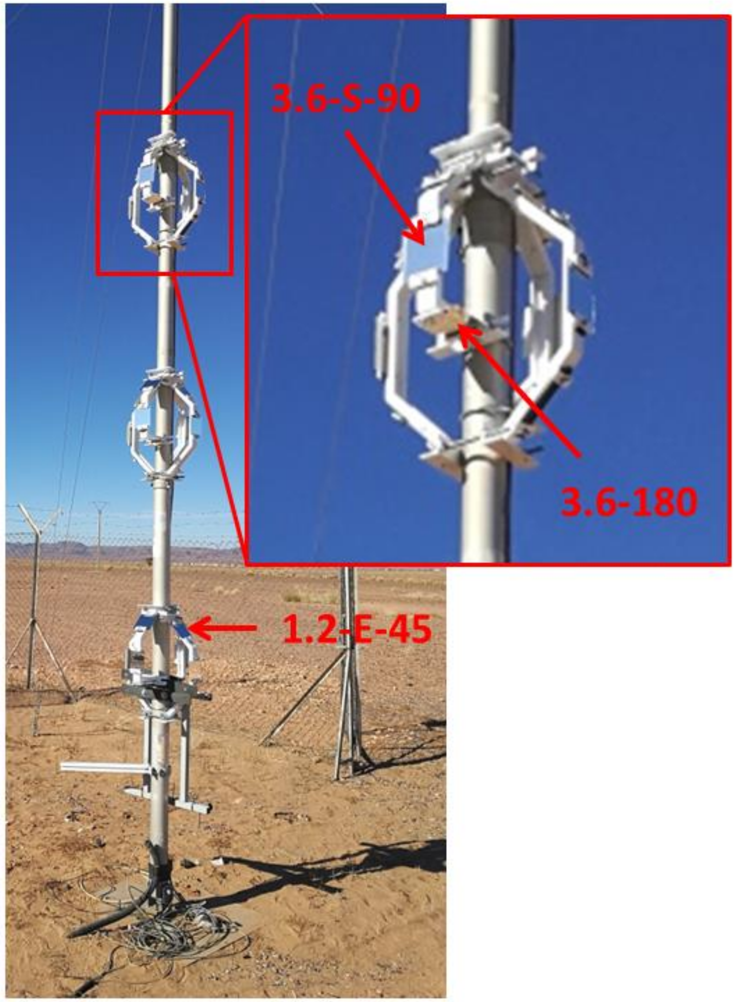
Rack structure for the exposure of reflector samples from different groups

- State of the art sample exposure is usually conducted in racks.
- For some aspects not 100% reproducing real plant conditions.
- Shielding, orientation, height, SPP operational positioning.
- Many simulations but lacking field data.

Karim et al. 2015
Matal et al. 2020

DLR
OPAC
Ciemat

Outdoor Erosion – field study on height and orientation

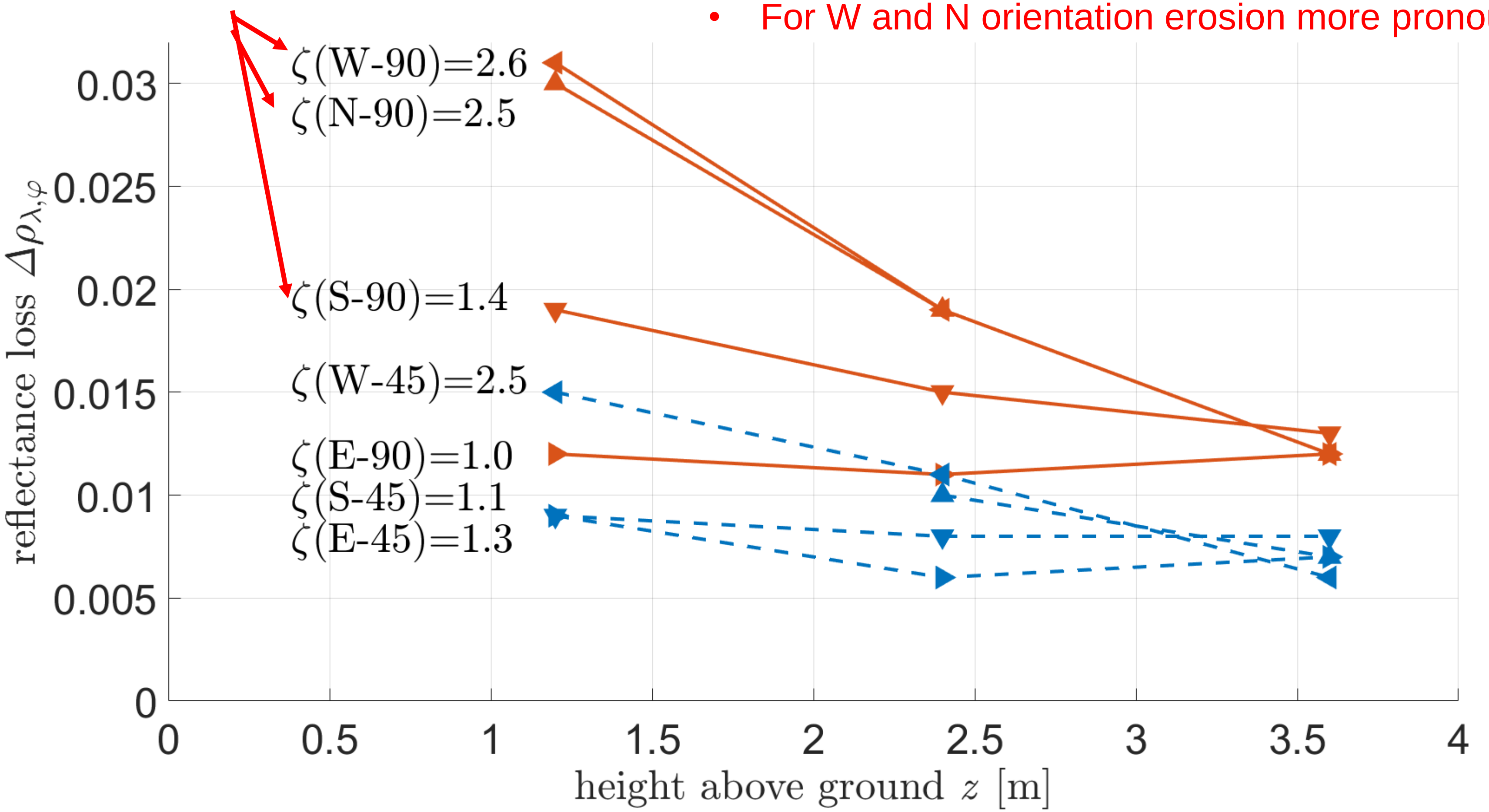


Erosion tree in Zagora equipped with 27 reflectors.

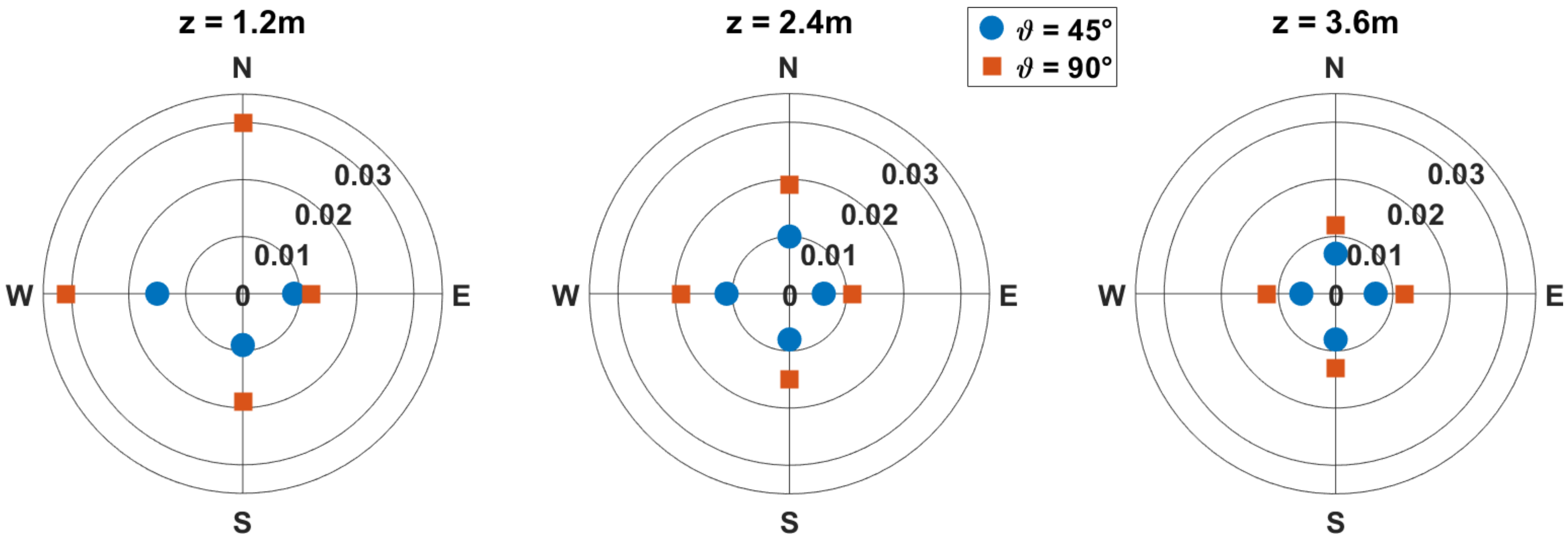
- Exposure on three different heights ***z*** above ground (**1.2**, **2.4** and **3.6**m).
- For every ***z***, four principal orientations (North, East, South and West).
- For every orientation, two elevation angles ϑ (45° and 90°). In addition one elevation at 180° per ***z.***
- In addition wind measurement
- Reflector characterization after 1 year.

Outdoor Erosion – field study on height and orientation

- Erosion damage decreases with increasing height z.
- For W and N orientation erosion more pronounced.

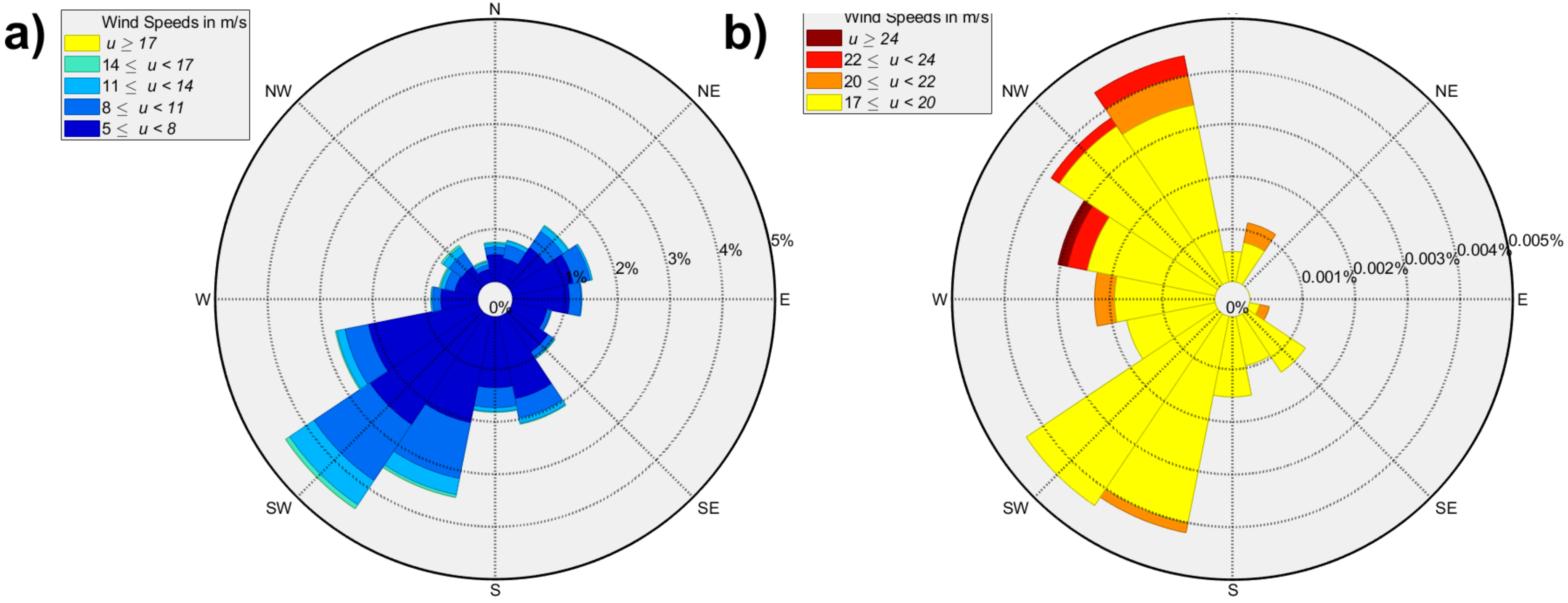


Outdoor Erosion – field study on height and orientation



Open question: where does this anisotropic erosion effect com from?

Outdoor Erosion – field study on height and orientation



- Wind velocities greater than 5m/s are present over 25% of the time.
- Most prominent direction is SW ca. 10%.

MISLEADING

- Only winds stronger than 17m/s.
- Strong winds (>22m/s) exclusively from NW.

HIGH VELOCITIES MORE IMPORTANT THAN DURATION

SFERA III – On-site training for industries – Characterization and accelerated aging of parabolic trough receiver materials

Florian Wiesinger,

Johannes Pernpeintner

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Outline

- Introduction to parabolic trough receivers
- Qualification methods
  - Measurement of receivers
    - Optical efficiency
    - Heat loss
    - Accelerated aging
  - Measurement of small samples

Introduction to Parabolic Trough Receivers

Demand for independent measurement

The receiver is …

- produced by specialized companies, not the EPC
- not easy to do right
- a core component of a parabolic trough power plant
- part of the efficiency chain and directly impacts the overall efficiency of the plant
- ~10% of capital investment of power plant

Introduction to Parabolic Trough Receivers

Environment during operation

- Irradiated by ~ 80 suns
- Heat transfer fluid VP-1: 250…400 °C
- Heat transfer fluid silicon oil: up to 450 °C
- Heat transfer fluid solar salt: up to 550 °C

Introduction to Parabolic Trough Receivers

Core technologies

- Selective absorber coating
- Glass-to-metal seal
- Anti-reflective coating on glass

Durability topics

- ~25 years, ~10,000 day/night-cycles
- Absorber coating aging
- AR-coating aging (cleaning, sand storms, UV, aerosols, salt, acid rain, etc.)
- Vacuum quality
    - Glas-to-metal seal and bellow tightness
    - H2 diffusion
    - Corrosion

Introduction to Parabolic Trough Receivers

Performance parameters

- Optical efficiency $\eta_{opt,rec}(T)$
- Thermal loss power $P_{th,loss}(T)$

$$\boxed{Q_{coll} = \eta_{opt,rec}\, Q_{in} - Q_{th,loss}}$$

$\eta_{opt,rec} = \tau\ \alpha\ \psi_{net}$

Typical numbers

transmittance τ ~ 0.96

absoprtance α ~ 0.96

net area factor ψ_{net} ~ 0.96

$\psi_{net} = l_{aperture}/l_{rec}$

emittance ε ~ 0.07…0.11

opt. efficiency $\eta_{opt,rec}$ ~ 0.89

heat loss $Q_{th,loss}$ ~ 200…1500 W (@250° C…400° C)

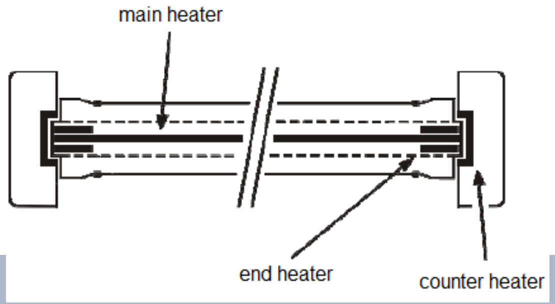
Lab testing of parabolic trough receivers

Labs: CENER, DLR, CIEMAT, ENEA, IEECAS, NREL

Receivers

Non-Destructive Performance Tests

Heat loss $Q_{th,loss}$

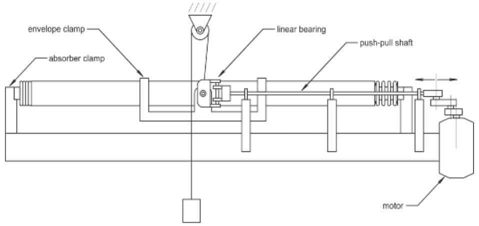


Optical efficiency $\eta_{opt,rec}$

Accelerated Ageing

Overheating

Bellow Fatigue



Small glass/absorber samples

Performance Tests

Spectrophotometer τ α ε

Accelerated Ageing

- Salt spray
- UV
- Sandstrom chamber
- Vacuum furnace (Overheating + Arrhenius)

Heat Loss Measurement

Principle

- Electrical cartridge heater assembly in absorber tube
- At steady state:

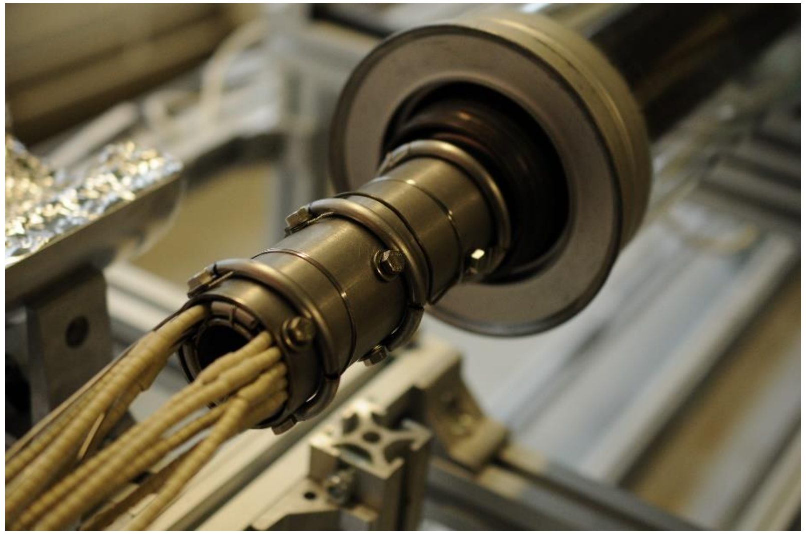
  Electrical heating power = heat loss power

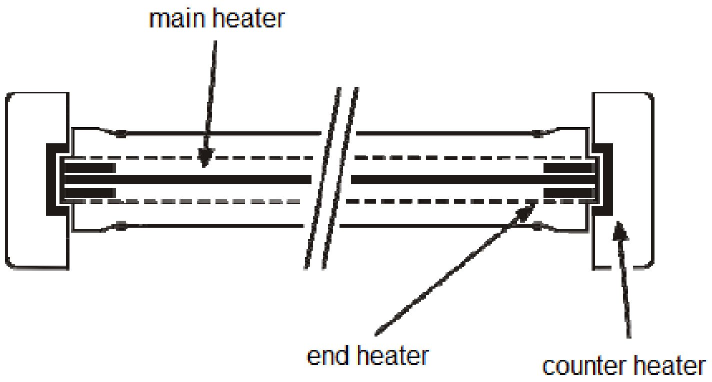
Features

- End heaters for homogeneous longitudinal temperature profile
- Counter heaters for adiabatic conditions at ends
- Temperature measurement at inner side of absorber

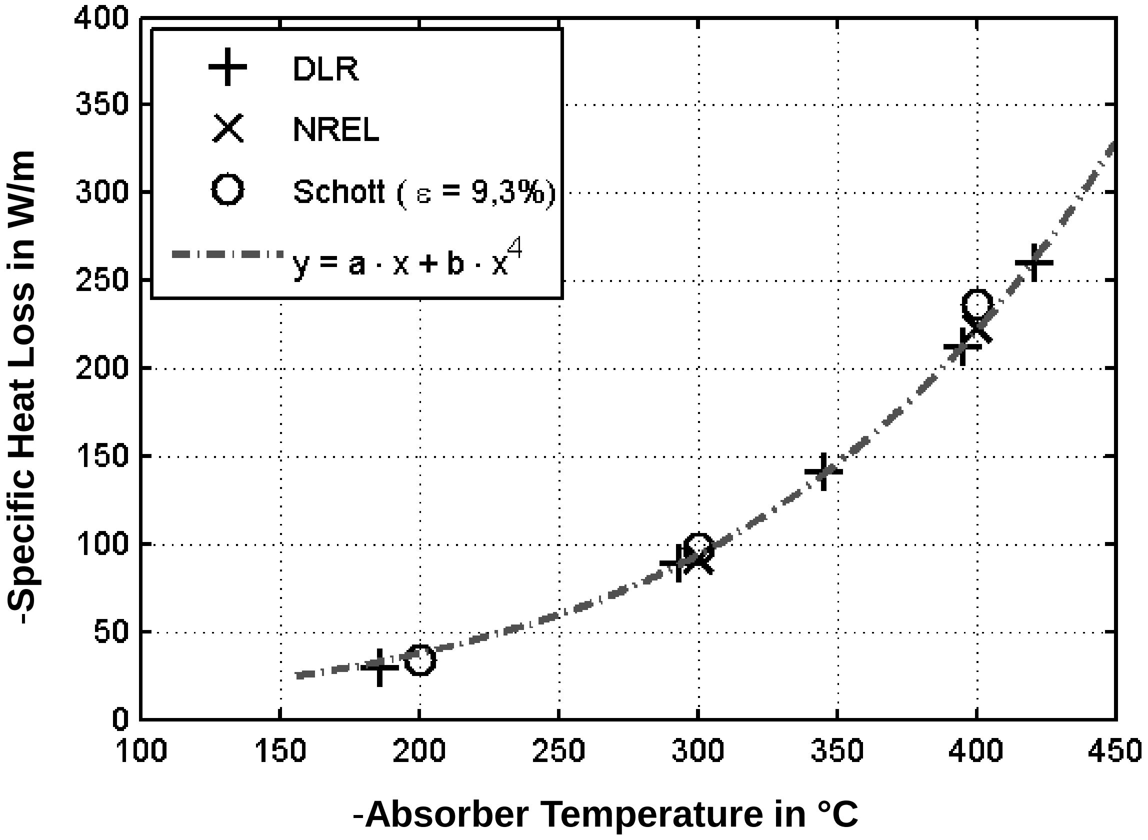
Difficulties

- Temperature measurement of absorber
- Standardization not yet good enough for sufficient reproducibility between labs





Heat Loss Measurement - Typical Result

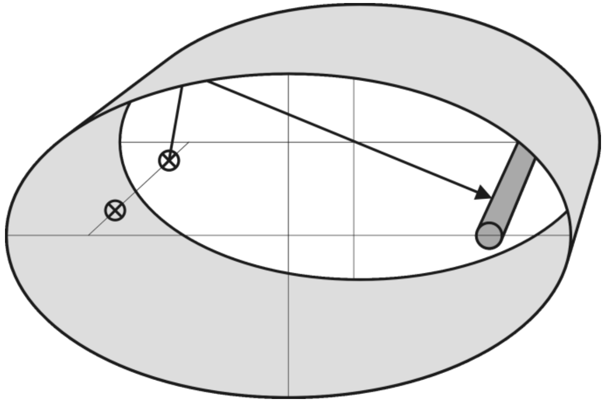


-Eichel et al.: Heat Loss Measurements on Parabolic Trough Receivers, 2010, Proceedings of SolarPACES Conference, France, Perpignan

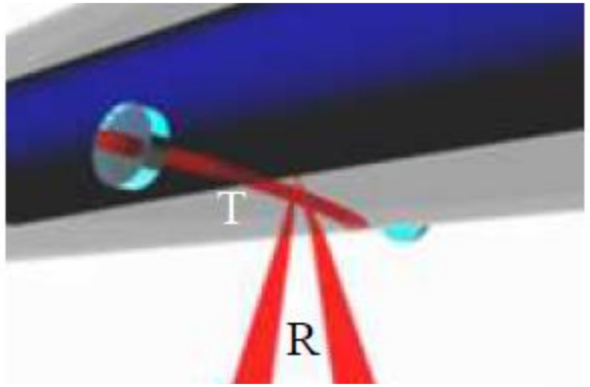
Non-Destructive Optical Efficiency Measurement

Various setups in use

Linear focus solar simulator, IEECAS, DLR



Spectroscopy through glass, CENER [1]



Non-concentrating outddoor test bench, NREL/ CIEMAT-PSA

Concentrating outdoor test bench, DLR/CIEMAT-PSA

Optical Efficiency Measurement

Measurement Principle

- Heating by Metal-Halide Lamps and Elliptical Concentrator
- No Thermal Losses, as Ambient Temperature
- Measuring Flow Rate of Water
- Measuring Temperature Increase (ΔT ~ 4…7 K)
  → Absorbed Power
- Exact Lamp Power unknown, but constant

→ *Comparative Measurements* to one Virtual 70-mm Master Receiver

Overheating test bench

- Goal: Simulate ageing of absorber coating due to high temperature (e.g. 400 °C for 25 years)

- Method: Heating of receivers with heating cartridge (similar to heat loss testing) to significantly above operating temperature

- Model: Arrhenius equation

- Necessary for Arrheinus:
  - activation energy E_n
  - validity

$$a_n = \exp\left[\frac{E_n}{R}\left(\frac{1}{T_{ref}} - \frac{1}{T_n}\right)\right]$$

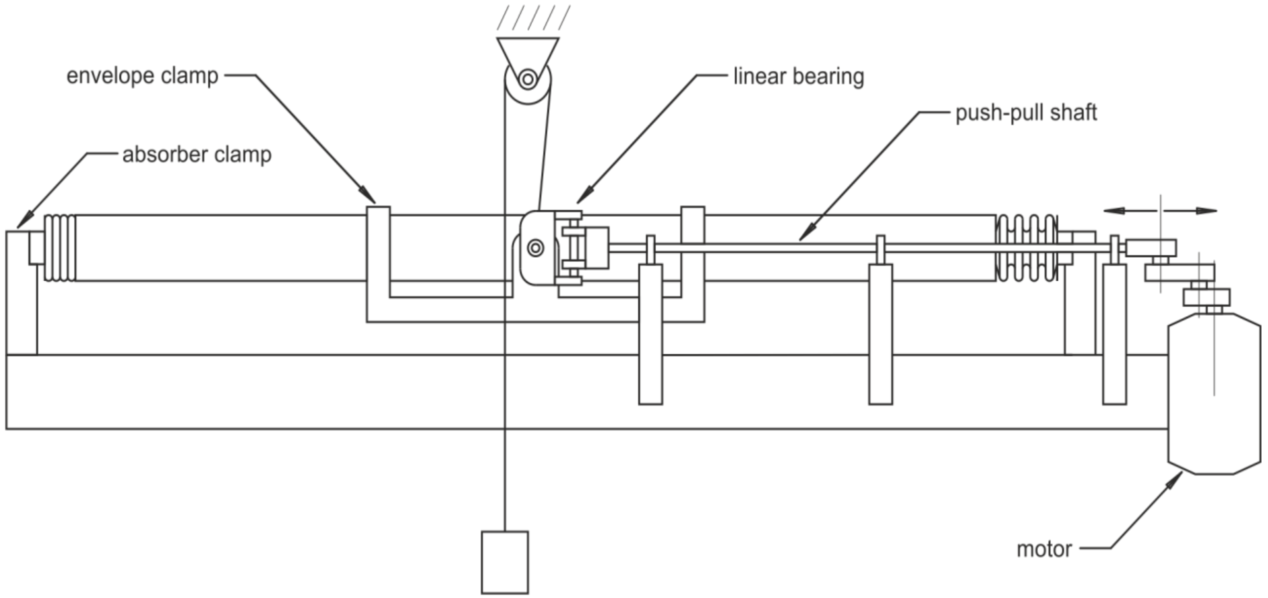
Acceleration according to Arrhenius equation

Overheating Parameters

- Overheating
  - 478 °C
  - 1000 h

- Thermal cycling
  - between 200°C and 478°C
  - 100 cycles

Bellow Fatigue Test

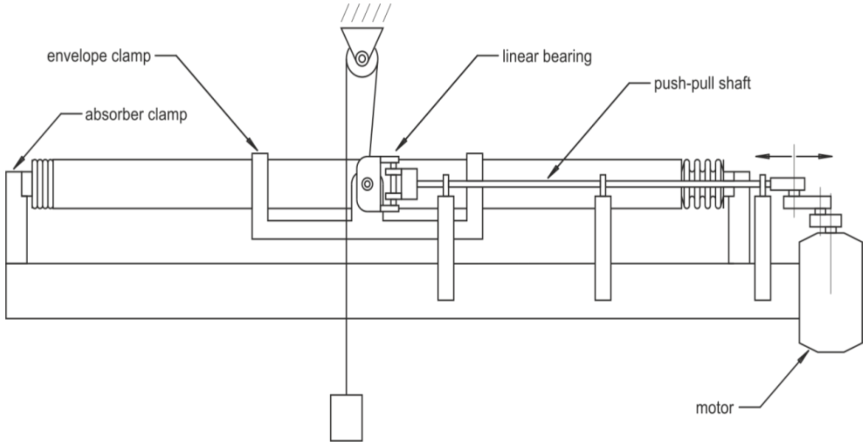


Bellow fatiuge test bench

- Goal: Check bellow and glass-to-metal seal tightness after multiple compression/ expansion cycles
- Receiver heated to 200 °C

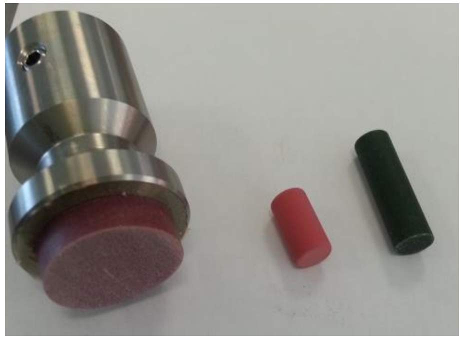
  → expansion half of maximum
- Absorber ends heated to 400 °C

  → maximum temperature
- Fix glass envelope
- Move absorber (0.3…1 Hz)
- Monitor heating power for detection of leakage
- Test: 20 000 cycles and wait 24 h
- Pass, if increase in HL < 30%

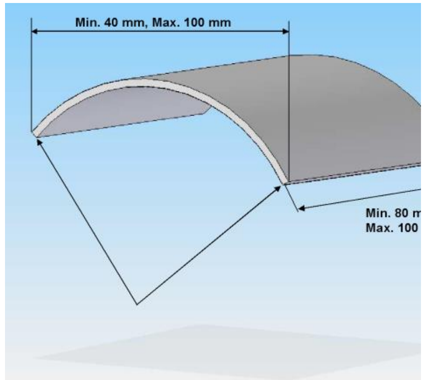


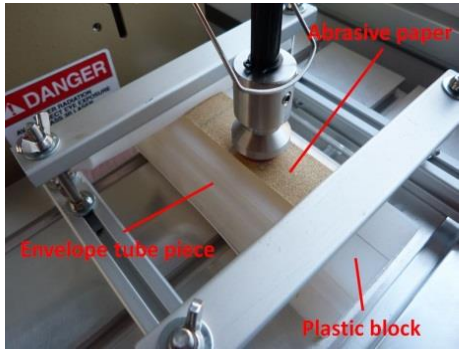
Testing anti-reflective coating abrasion with the Taber Linear Abrasor

- Goal: Test AR-coating for abrasion stress
- Machine: Taber Linear Abrasor
- Transmittance measurement with spectrophotometer (Lambda 950/1050)
- Rubber preparation with abrasive paper
- Parameters
    - rubber type
    - rubber diameter
    - cycle number
    - weight

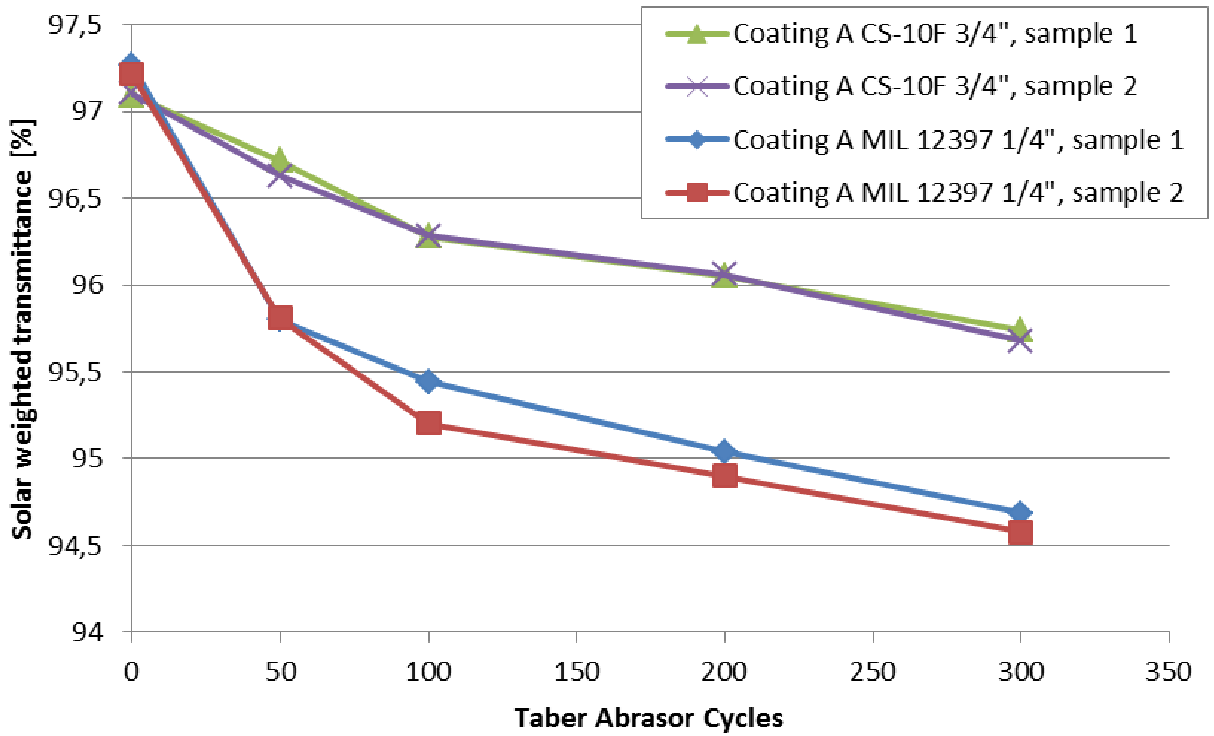


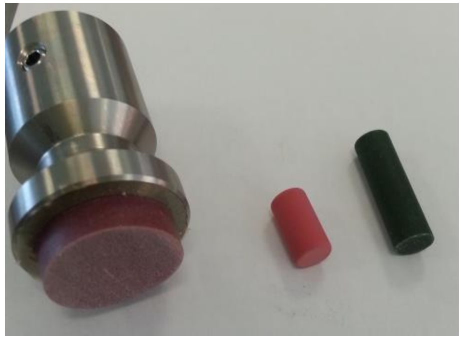
¾'' ¼''



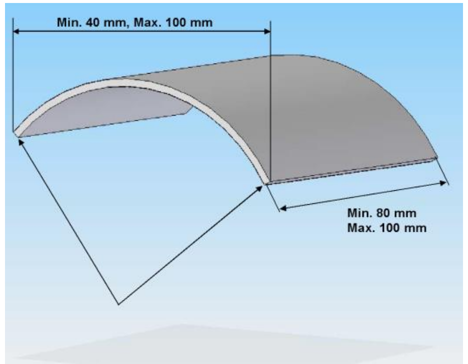


Examplary results

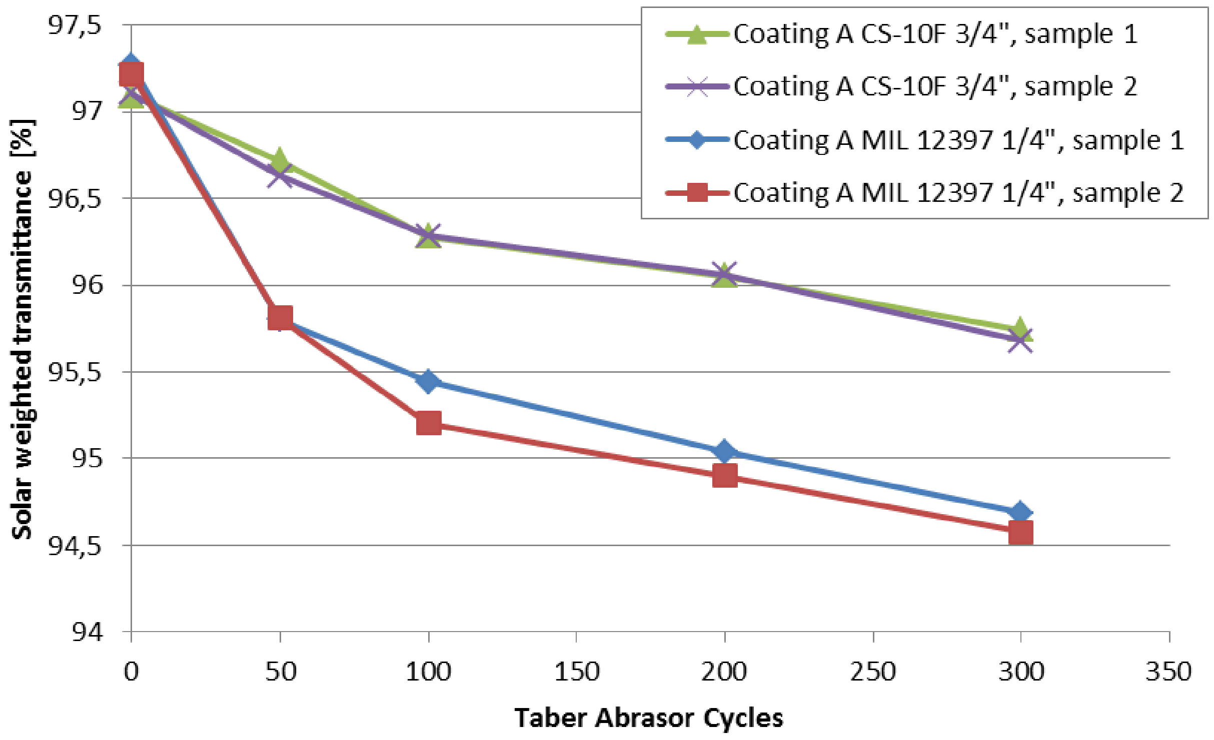




¾“ ¼“

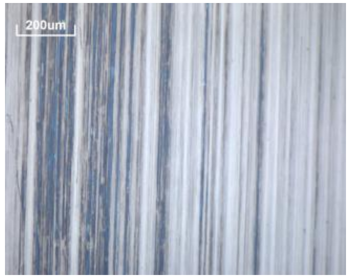


Examplary results

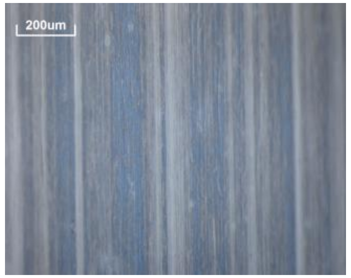


initial

100



300



Conclusion - Typical Testing Scope

Receivers

1. Sight check
2. Performance Tests
   - Heat Loss
   - Optical Efficiency
3. Overheating Test
4. Thermal Cycling Test
5. Performance Tests
   - Heat Loss
   - Optical Efficiency
6. Bellow Fatigue

Small glass envelope samples

1. Performance Test
   - Transmittance
2. Taber Abraser Test
3. Performance Test
   - Transmittance

Solar Facilities for the European Research Area

Training for Industries “Optimization of CST plant output by optical and thermal characterization and target-oriented O&M”
08 – 10 June 2022, Bouget-du-Lac, France

Components aging: Receiver coatings

Florian Wiesinger (DLR), Simon Caron (DLR)

NETWORKING

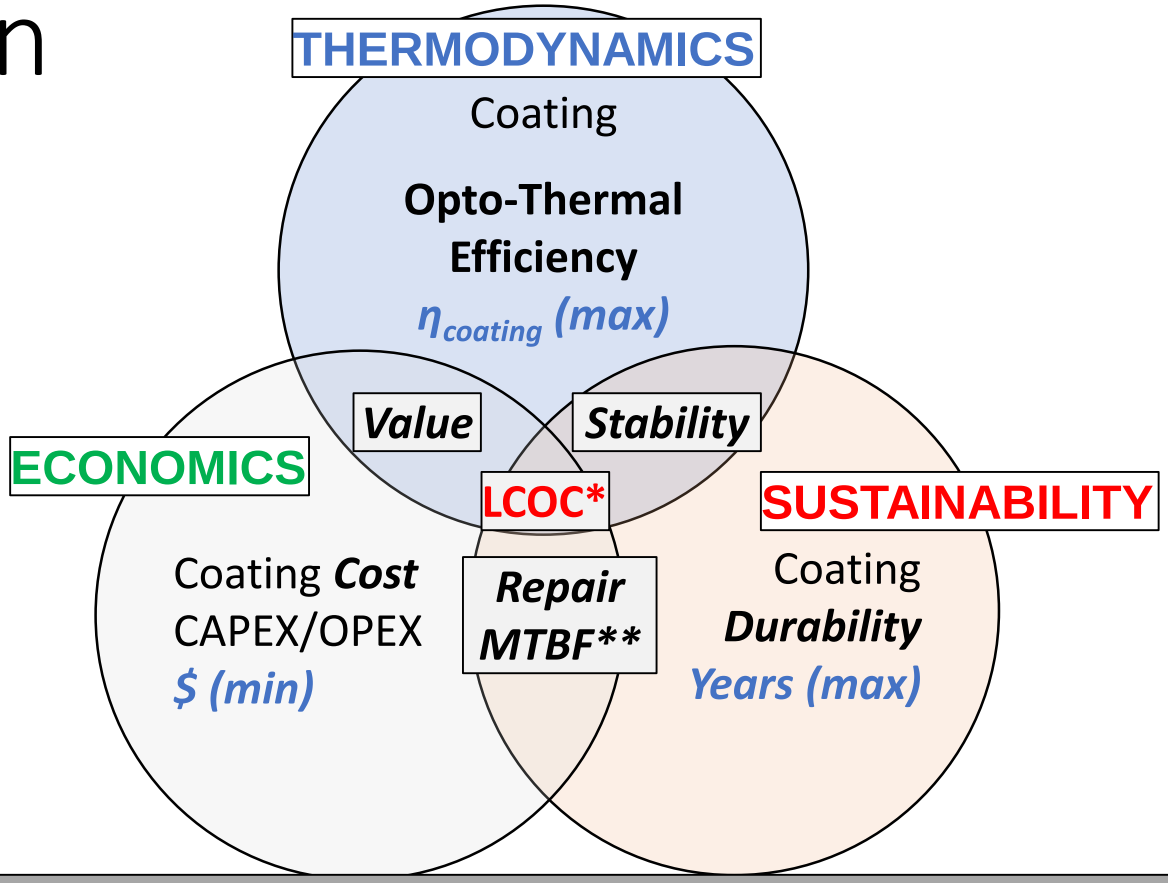
THIS PROJECT HAS RECEIVED FUNDING FROM THE EUROPEAN UNION’S HORIZON 2020 RESEARCH AND INNOVATION PROGRAMME UNDER GRANT AGREEMENT NO **823802**

Outline

- **Introduction**
- **Materials and Methods**
    - Substrates and Coatings
    - Optical Characterization
    - Durability Test Program
- **Results and Discussion**
    - Solar Cycling Tests
    - Climate Chamber Tests
    - Summary for Gen 2 Coatings
- **Conclusion & Outlook**

https://torresolenergy.com/gemasolar/

Introduction



Metrological inspection system
(Solar absorptance, thermal emittance, Skin temperature)

*LCOC**: Levelized Cost of Coating
(Ho et al., Sol. Energy 108 (2014) 315-321)

*MTBF***: Mean Time Between Failure
(Optimization of Recoating interval)

Materials and Methods
Substrates

- SRSG* (Water/steam)
  - Ferritic-martensitic alloys
  - Manufactured by Vallourec
  - Standard Boiler technology
  - Max. Temp. 600 – 650 °C
  - Cheap alloys, require coatings

T91/P91 (X10CrMoVNb9-1)

VM12-SHC

*SRSG**: **Steam** Receiver Super Generator

- MSR** (Molten Salt)
  - Nickel-Chromium superalloys
  - Inconel 617 (**Inc617**); Haynes 230 (**H230**)
    Aerospace Industry, Gas Turbines
  - High Temp. (1000 – 1150 °C)
  - [...]lloys, but less corrosion

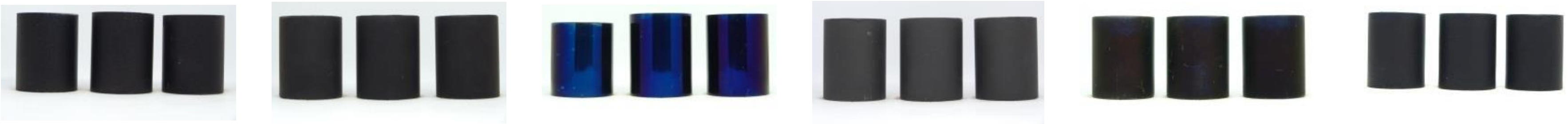
*MSR***: **Molten Salt** Receiver

http://www.vallourec.com/fossilpower/EN/Products/Pages/tp91.aspx
http://www.vallourec.com/fossilpower/EN/Products/Pages/vm12-shc.aspx

Materials and Methods
Coatings

- A ceramic spray consisting of a primer coating and a high solar absorptance (HSA) top coating (Coating A)
- A slurry aluminide primer coating protecting the steel substrate from hot oxidation, in combination with the above ceramic HSA top coating (Coating B)
- A magnetron-sputtered multi-layered thin film cermet solar selective coating (SSC) applied on a polished substrate (Coating C)
- A multi-metallic Cr-Mn diffusion coating applied with the pack cementation process (Coating D)
- A combination of the above slurry aluminide primer *(b)* with a thin film cermet SSC on top (Coating E)
- A combination of the multi-metallic diffusion coating *(d)* as a primer coating combined with the ceramic HSA top coating *(a)* (Coating F)

Coating/Substrate	T91	VM12	Inc617	H230
Coating A	Yes	Yes	Yes	Yes
Coating B	Yes	Yes	No	No
Coating C	Yes	No	Yes	No
Coating D	Yes	Yes	Yes	No
Coating E	Yes	No	Yes	No
Coating F	No	Yes	No	No



Coating A **Coating B** **Coating C** **Coating D** **Coating E** **Coating F**

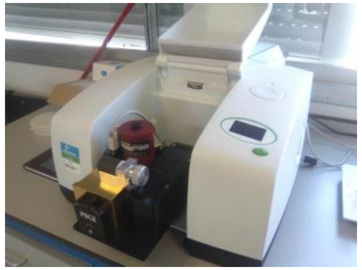
Coating	Substrate	Thickness (DFT, µm)	Selective ?	Surface preparation	Coating application	Thermal treatment
A	T91 | VM12 Inc617 | H230	55 (Primer) 35	No	Grit blasting	Spraying	Curing
B	T91 | VM12	85 | 55	No	Grit blasting	Spraying	Curing (x2)
C	T91 | Inc617	0.6	Yes	Polishing, mirror finish	Sputtering	-
D	T91 | VM12 | Inc617	35	No	Glass bead blasting	Cementation	Pre-oxidation
E	T91 | Inc617	~ 65	No	Polishing of primer coating (B)	Spraying + Sputtering	-
F	VM12	~ 70	Yes	Glass bead blasting	Cementation + Spraying	Pre-oxidation + Curing

Materials and Methods
Optical characterization

Room Temperature (RT)
Discrete meas. (points)

Optical characterization (OPAC, CIEMAT-DLR)

- Spectral measurements
  - Measurement Equipment
    - Lambda1050 (0.28 – 2.5 µm)
    - Frontier FTIR (2 … 16 µm)
  - Quantitative analysis
    - α_{sol} (AM1.5, ASTM G173-03)
    - $\varepsilon_{th,calc}$ (Tmax)
- Visual surface inspection
  - mm scale (Camera)
  - µm scale (Microscope)



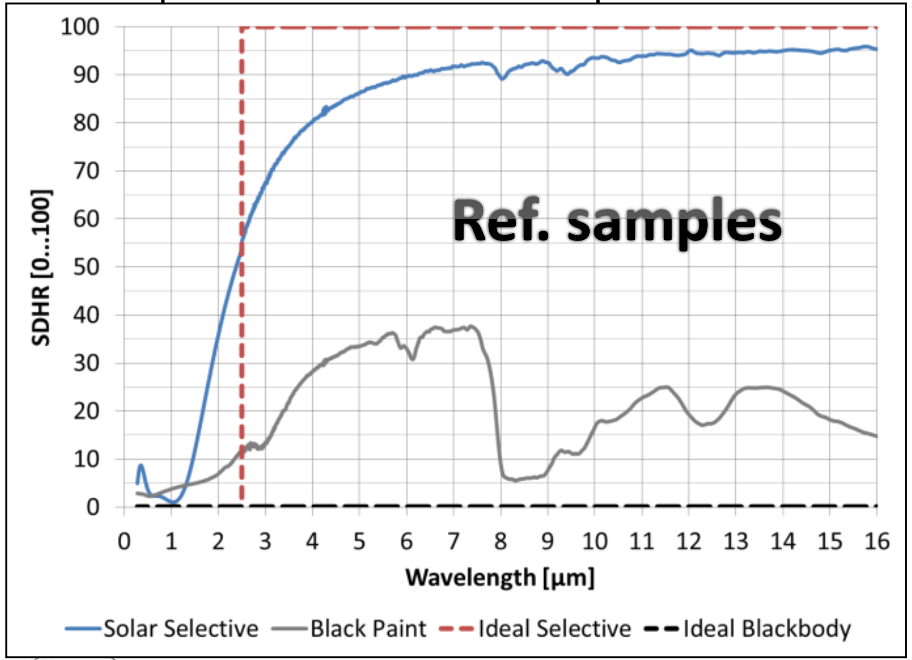
No quantitative adhesion test
No thermal conductivity data
No metallographic analysis

Materials and Methods
Spectral measurements

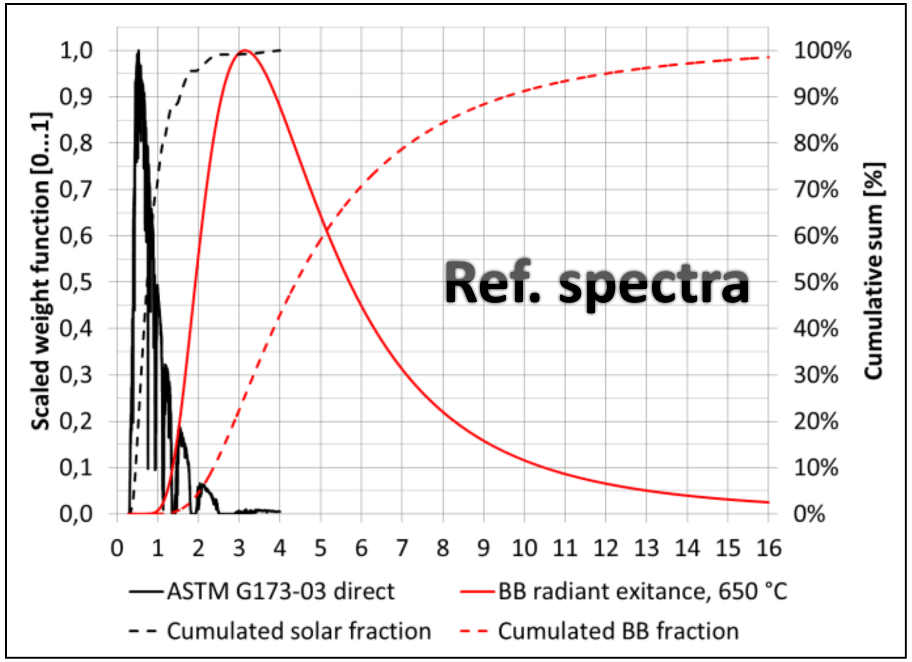
- **Baseline calibration**

$$\rho_{sample}(\lambda) = \frac{R_{sample,meas}(\lambda)}{R_{baseline,meas}(\lambda)} \cdot \rho_{baseline,ref}(\lambda)$$

SDHR: Spectral Directional –Hemispherical Reflectance

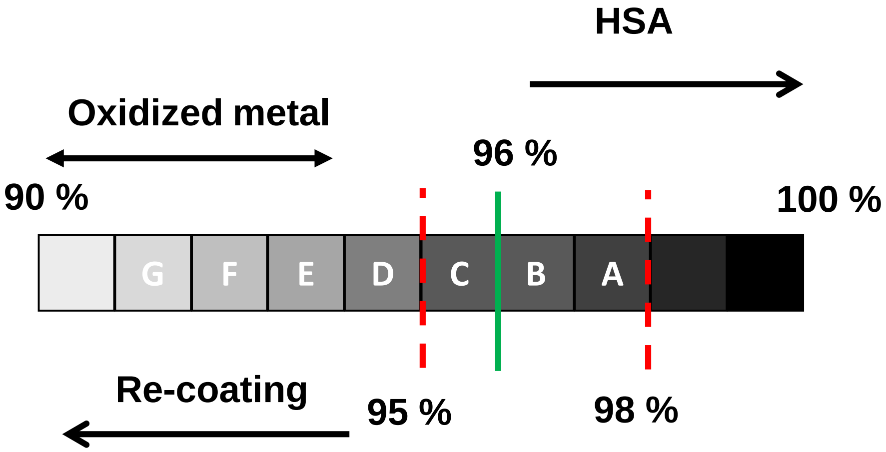


- **Weight functions**:
  - α_{sol}: ASTM G173-03 direct, AM1.5
  - ε_{th}: Blackbody spectrum (650/750 °C)
  - 8-12° incidence angle (Near normal)

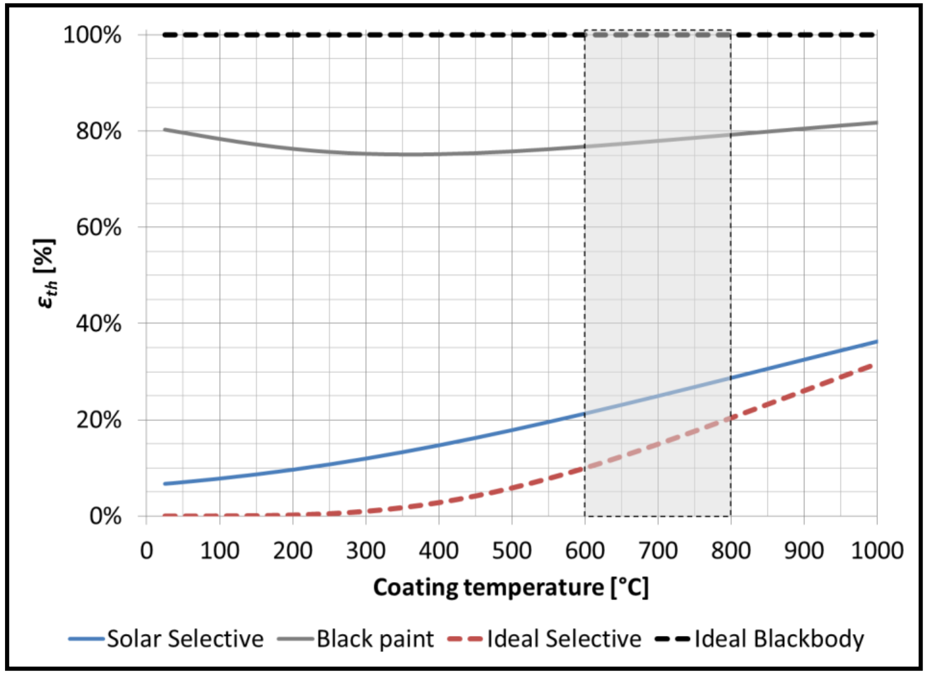


Materials and Methods
Solar absorptance and thermal emittance

- Solar absorptance α_{sol}
  - HSA: High Solar Absorptance (> 96%)



- Thermal emittance ε_{th} (T)



Materials and Methods
Opto-thermal coating efficiency

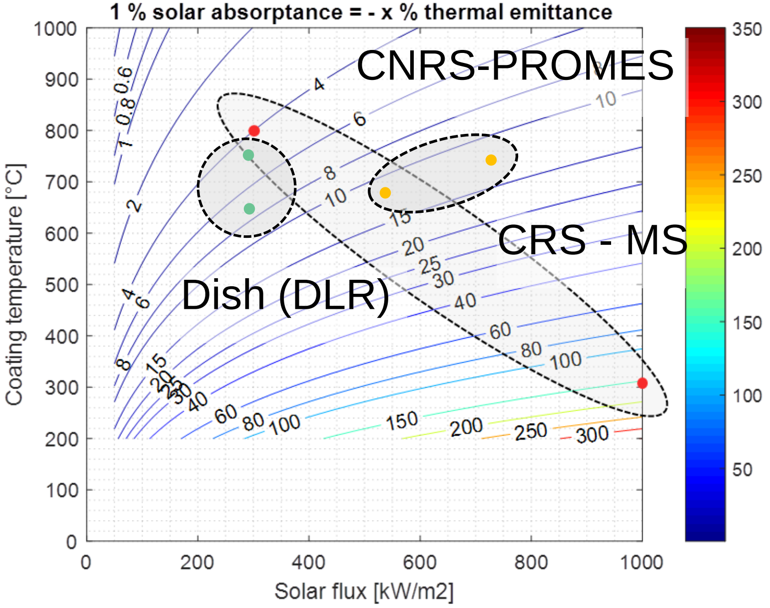
- Opto-thermal efficiency:

$$\eta_{coating} \approx \frac{\alpha_{sol} \cdot \dot{q}''_{sol} - \varepsilon_{th}(T_{abs}).\sigma.T^4_{abs}}{\dot{q}''_{sol}}$$

$$Z = \frac{\Delta\alpha_{sol}}{\Delta\varepsilon_{th}} = -\frac{\dot{q}''_{sol}}{\sigma.T^4_{abs}}$$ or Z:

- Solar absorptance predominant for Central Receiver System (CRS)

- Allowable Flux Density (AFD)
  Vant-Hull, *J. Sol. Energy Eng*. 2002, 124(2): 165-169
  - for Molten Salt HTF (Corrosion)
  - ***High Flux** & **Low** Temp*, ***Low Flux** & **High** Temp*.



Materials and Methods
Durability Test Program

<u>Solar cycling:</u>
CIEMAT-DLR
CNRS-PROMES

<u>Climate chambers (CIEMAT-DLR)</u>
- Damp Heat (DH)
- Humidity Freeze (HF)
- ***Neutral Salt Spray (NSS)***
- ***Sand Erosion (SE)***

Solar cycling
- Slow (DLR)
- Fast (CNRS)
- („ON-SUN“)

Climate chambers

(„OFF-SUN“)

Isothermal, Muffle furnace

(2000 h)

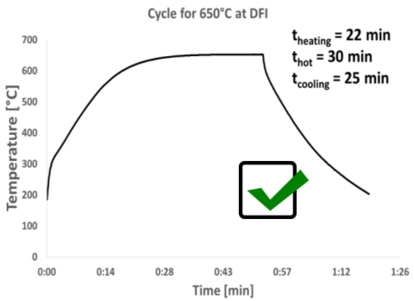
T1/T2/T3

Cyclic,

Muffle Furnace

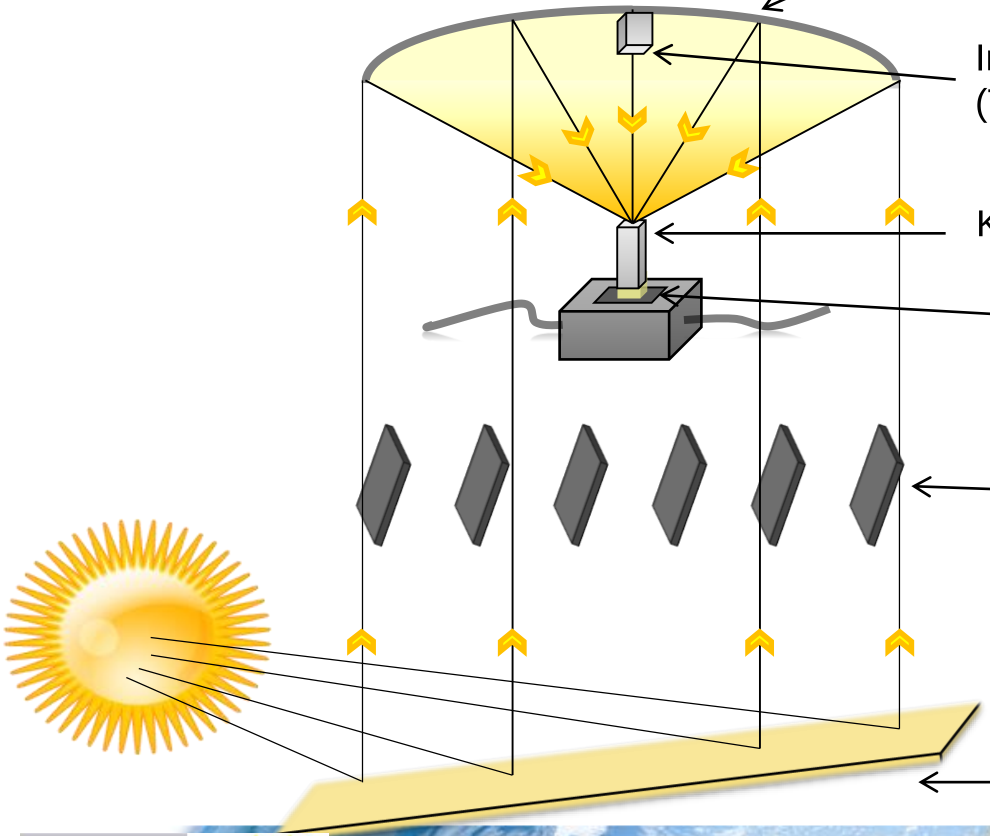
(1000 cycles)

<u>T91/VM12:</u>
600/620/650 C
<u>Inc617/H230:</u>
680 / 710 / 750 C



Materials and Methods
Solar Cycling Tests (1)

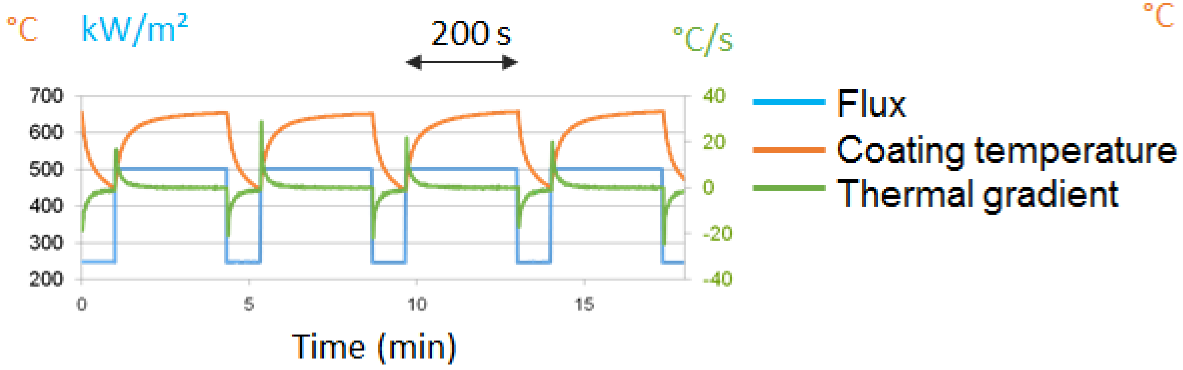
- CNRS-PROMES (Odeillo, France)
  - SAAF: Solar Accelerated Aging Facility



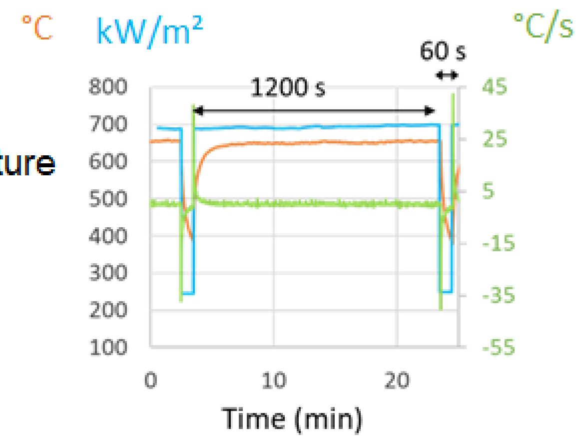
Materials and Methods
Solar Cycling Tests (2)

2 strategies

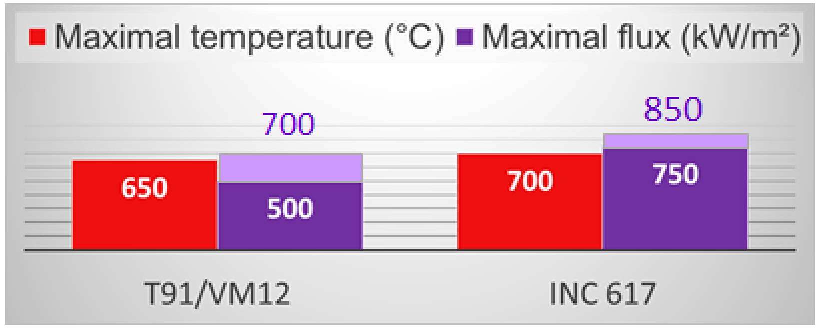
200 short cycles



40 long cycles



& nominal conditions

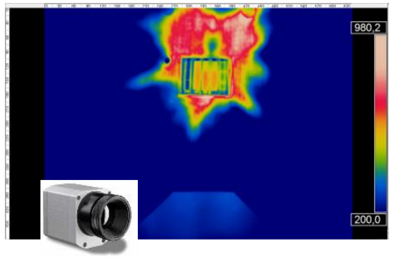


& higher flux

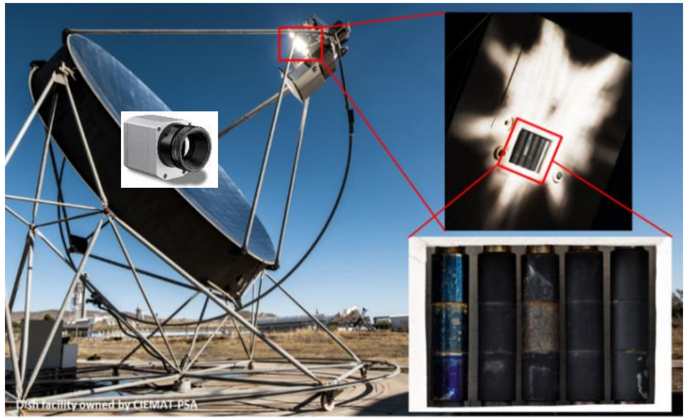
Steam receiver super generator

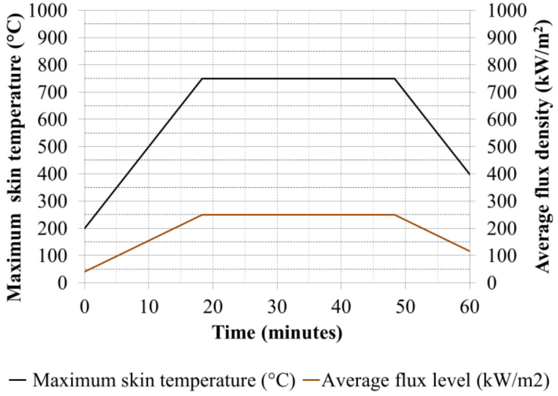
Molten salt receivers

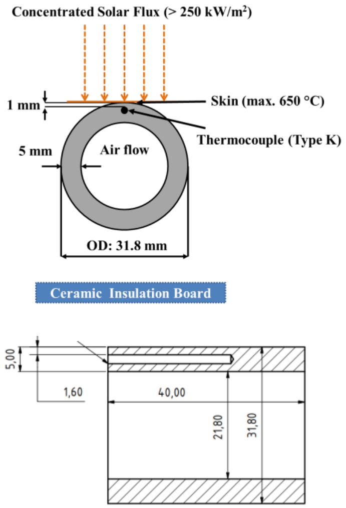
Materials and Methods
Solar Cycling Tests (3)



- **The Distal II facility is located at Plataforma Solar de Almeria, owned by the Spanish research center CIEMAT.**







Initial → **1000 h, 650/750 C, muffle furnace** → **50 dish cycles (650/750 C)** → **100 hours cond.** → **50 dish cycles (650/750 C)**

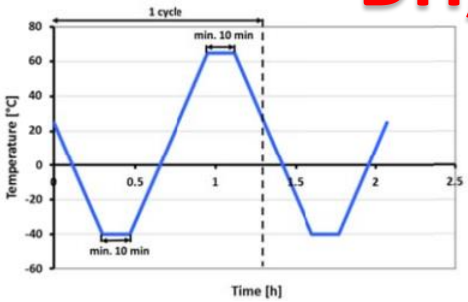
Materials and Methods
Climate Chamber Tests

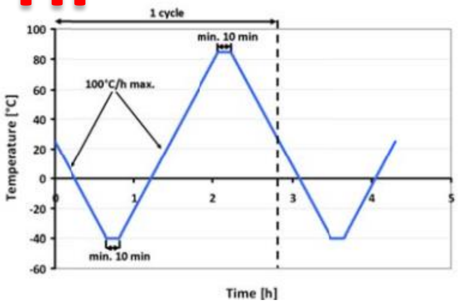
- Standard climate chamber tests performed on flat absorber samples

Test	DH	HF	NSS	SE
Standard	IEC 62108, Test 10.7b	IEC 62108, Test 10.8	ISO 92237	Based on MIL-STD 810 G
Duration	1000 hours	1500 hours	120, 480 hours	-
Parameters	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	20 m/s; 3x 70 g std blowing dust

Site characterization:
a. **Corrosivity class**
b. **Erosivity class**

DH, HF





NSS

SE

Results and discussion
Pristine State (before test)

Coating	Substrate	Thickness (DFT, µm)	Selective ?	Surface preparation	Coating application	Thermal treatment
A	T91 | VM12 Inc617 | H230	55 (Primer) 35	No	Grit blasting	Spraying	Curing
B	T91 | VM12	85 | 55	No	Grit blasting	Spraying	Curing (x2)
C	T91 | Inc617	0.6	Yes	Polishing, mirror finish	Sputtering	-
D	T91 | VM12 | Inc617	35	No	Glass bead blasting	Cementation	Pre-oxidation
E	T91 | Inc617	~ 65	No	Polishing of primer coating (B)	Spraying + Sputtering	-
F	VM12	~ 70	Yes	Glass bead blasting	Cementation + Spraying	Pre-oxidation + Curing


Coating A


Coating B


Coating C


Coating D


Coating E


Coating F

Coating\Substrate	Optical characterization Measurand	Units	T91 *Tmax = 650 °C*	VM12 *Tmax = 650 °C*	Inc617 *Tmax = 750 °C*	H230 *Tmax = 750 °C*
Coating A (BSII)	α_{sol} (AM1.5, direct)	[%]	96,4%	96,2%	97,2%	97,1%
	ε_{th} (Tmax)	[%]	78,4%	76,4%	89,5%	89,5%
Coating B (INTA+BSII)	α_{sol} (AM1.5, direct)	[%]	96,6%	96,2%	*N.A.*	*N.A.*
	ε_{th} (Tmax)	[%]	76,0%	77,2%	*N.A.*	*N.A.*
Coating C (Fraunhofer)	α_{sol} (AM1.5, direct)	[%]	94,9%	*N.A.*	94,7%	*N.A.*
	ε_{th} (Tmax)	[%]	26,8%	*N.A.*	30,6%	*N.A.*
Coating D (Dechema)	α_{sol} (AM1.5, direct)	[%]	94,6%	94,7%	95,3%	*N.A.*
	ε_{th} (Tmax)	[%]	85,9%	84,8%	87,3%	*N.A.*
Coating E (INTA+Fraunhofer)	α_{sol} (AM1.5, direct)	[%]	96,2%	*N.A.*	95,7%	*N.A.*
	ε_{th} (Tmax)	[%]	41,6%	*N.A.*	38,9%	*N.A.*
Coating F (Dechema+BSII)	α_{sol} (AM1.5, direct)	[%]	*N.A.*	96,8%	*N.A.*	*N.A.*
	ε_{th} (Tmax)	[%]	*N.A.*	78,9%	*N.A.*	*N.A.*

Results and discussion
Solar Cycling Tests / Inc617 & H230

Inc617 (A,C,D,E)
H230 (A)

CNRS-PROMES

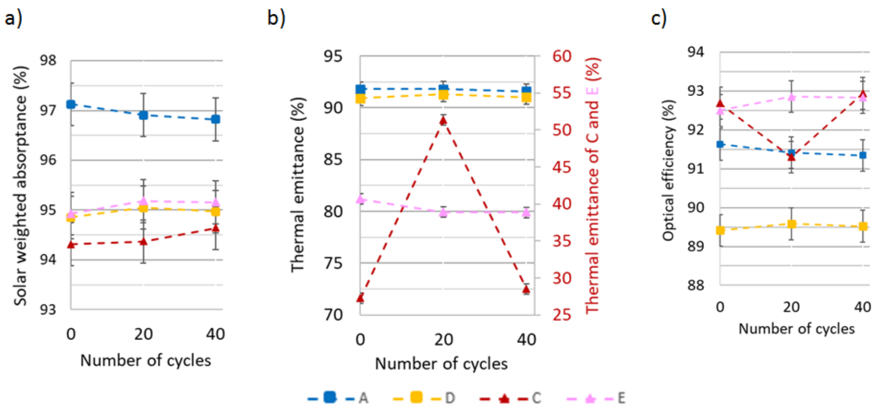
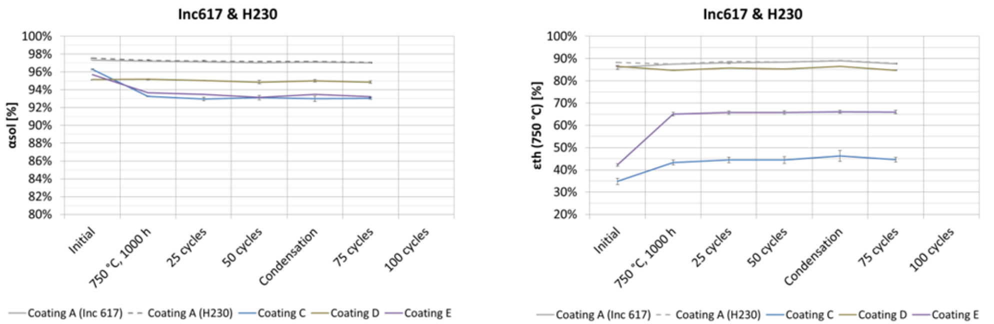


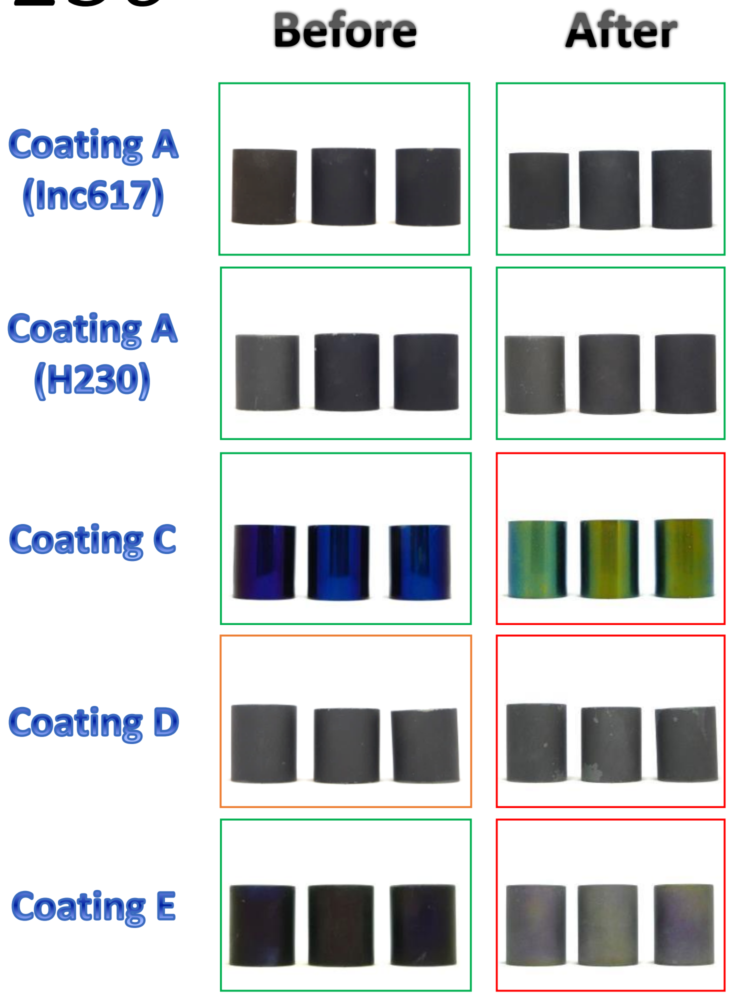
Figure 12: Optical characteristics (%) of Inconel 617 samples with 3 coatings after high flux accelerated aging tests

CIEMAT-DLR



(a) Combined testing, Inc617 and H230 substrates, α_{sol} (b) Combined testing, Inc617 and H230 substrates, ε_{th} (750°C)

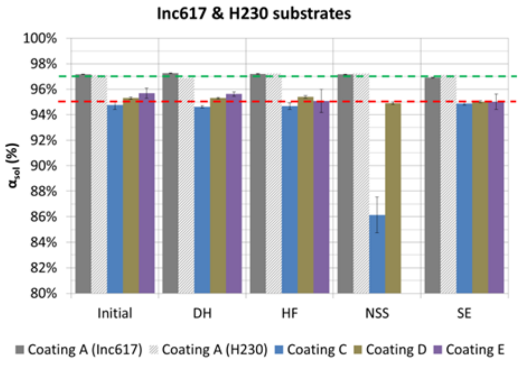
Figure 18: Optical characterization of Inc617 and H230 coated samples over the solar cycling test sequence at DLR. (a) Evolution of solar absorptance over the test sequence. (b) Evolution of thermal emittance over the test sequence.



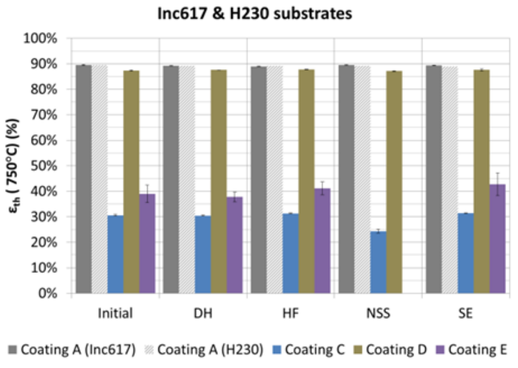
Results and discussion

Climate Chamber Tests / Inc617 & H230

Inc617 (A,C,D,E)
H230 (A)



(a) Combined testing, Inc617 and H230 substrates, α_{sol}



(b) Combined testing, Inc617 and H230 substrates, ε_{th} (750°C)

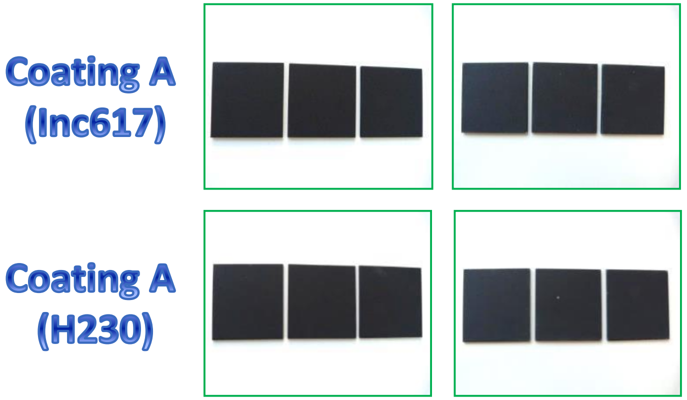
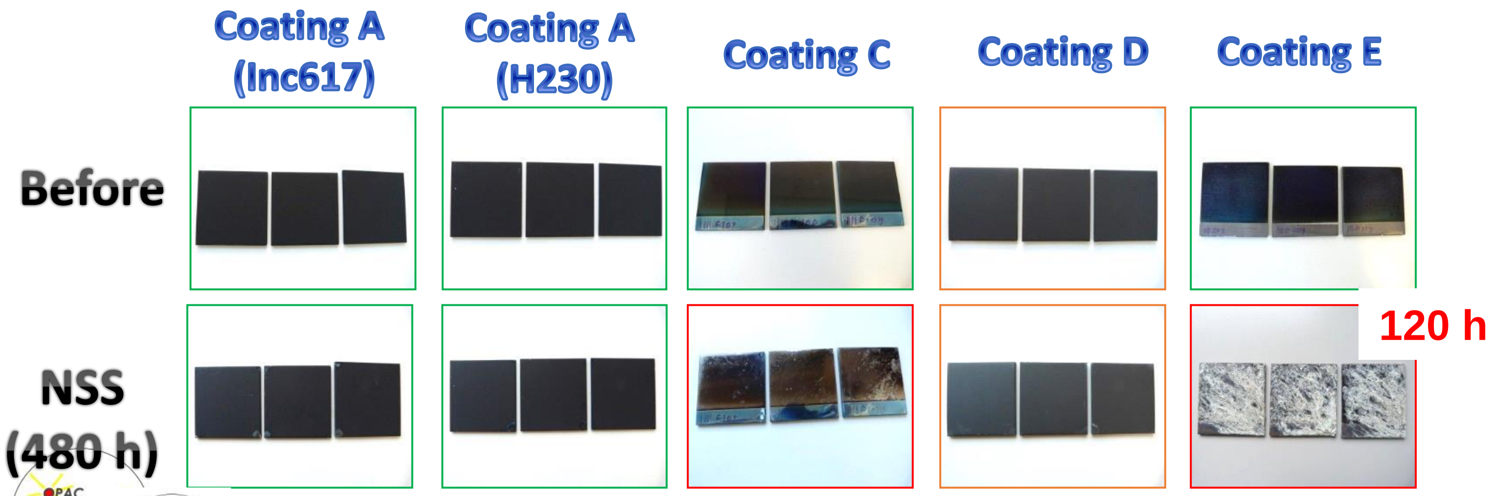


Figure 29: Optical characterization of Inc617 and H230 flat coated samples before and after climate chamber tests. (a) Evolution of solar absorptance over the test sequence. (b) Evolution of thermal emittance over the test sequence.



Results and discussion
Summary for Gen2 Coatings (1)

- Inc617 / H230

Variation in solar absorptance $\Delta\alpha_{sol}$			Initial value	Solar cycling		Isothermal, 2000 hours			500 cycles	Climate chambers			
Generation	Substrate	Coating	α_{sol}	SC-DLR	SC-CNRS	T1	T2	T3	Cyclic	DH	HF	NSS	SE
Gen 2	Inc617	A (BSII, Inc617)	97,2%	-0,4%	-0,3%	-0,3%	-0,4%	-1,1%	On going	0,1%	0,0%	0,0%	-0,3%
Gen 2	H230	A (BSII, H230)	97,1%	-0,4%	On going	N.A.	N.A.	On going	On going	0,1%	0,1%	0,0%	-0,2%
Gen 2	Inc617	C (Fraunhofer)	94,7%	-4,2%	0,3%	-2,2%	-5,7%	-9,9%	On going	-0,1%	-0,1%	-8,6%	0,1%
Gen 2	Inc617	D (Dechema)	95,3%	-0,2%	0,1%	-0,1%	-0,3%	-0,9%	On going	0,0%	0,1%	-0,4%	-0,3%
Gen 2	Inc617	E (INTA+Fraunhofer)	95,7%	-2,3%	0,2%	-0,3%	-2,7%	-1,4%	On going	-0,1%	-0,6%	FAIL	-0,7%

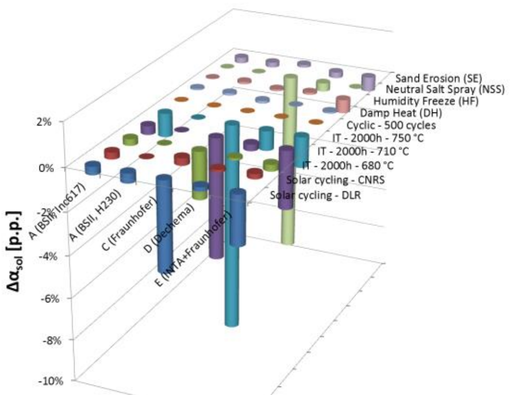
Variation in thermal emittance $\Delta\varepsilon_{th}$			Initial value	Solar cycling		Isothermal, 2000 hours			500 cycles	Climate chambers			
Generation	Substrate	Coating	ε_{th} (750 °C)	SC-DLR	SC-CNRS	T1	T2	T3	Cyclic	DH	HF	NSS	SE
Gen 2	Inc617	A (BSII, Inc617)	89,5%	1,0%	-0,2%	0%	0%	0%	N.A.	-0,3%	-0,5%	0,0%	-0,1%
Gen 2	H230	A (BSII, H230)	89,5%	0,4%	On going	N.A.	N.A.	On going	On going	-0,2%	-0,2%	-0,5%	-0,3%
Gen 2	Inc617	C (Fraunhofer)	30,6%	9,5%	1,3%	11%	10%	12%	N.A.	-0,1%	0,7%	-6,2%	0,8%
Gen 2	Inc617	D (Dechema)	87,3%	1,3%	0,1%	0%	0%	-1%	N.A.	0,3%	0,5%	-0,2%	0,3%
Gen 2	Inc617	E (INTA+Fraunhofer)	38,9%	25,7%	-1,8%	23%	22%	26%	N.A.	1,2%	2,2%	FAIL	3,8%

Ranking:

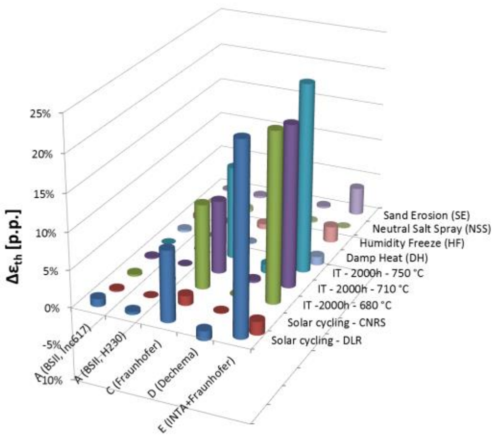
Inc617 (**A**,**C**,D,**E**)

H230 (**A**)

Inc617/Gen 2 - Solar absorptance



Inc617/Gen 2 - Thermal emittance



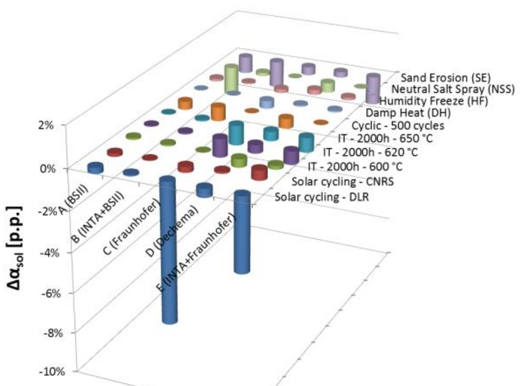
Results and discussion
Summary for Gen2 Coatings (2)

- T91

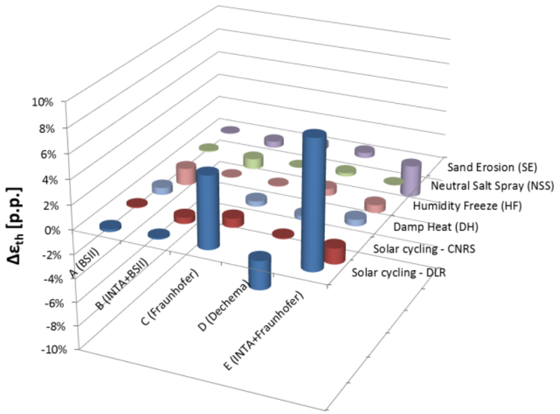
Variation in solar absorptance $\Delta\alpha_{sol}$			Initial value	Solar cycling		Isothermal, 2000 hours			500 cycles	Climate chambers			
Generation	Substrate	Coating	α_{sol}	SC-DLR	SC-CNRS	T1	T2	T3	Cyclic	DH	HF	NSS	SE
Gen 2	T91	A (BSII)	96,4%	-0,3%	-0,2%	0,1%	0,0%	0,0%	-0,4%	0,0%	-0,1%	-1,4%	-0,8%
Gen 2	T91	B (INTA+BSII)	96,6%	-0,1%	0,0%	0,1%	-0,1%	-0,1%	-0,7%	0,0%	0,1%	-0,2%	-1,3%
Gen 2	T91	C (Fraunhofer)	94,9%	-6,8%	-0,3%	0,0%	-0,9%	-1,0%	On going	-0,4%	-0,2%	FAIL	-0,4%
Gen 2	T91	D (Dechema)	94,6%	-0,4%	0,1%	-0,4%	-0,4%	-0,5%	-0,5%	0,1%	0,2%	-0,5%	-0,3%
Gen 2	T91	E (INTA+Fraunhofer)	96,2%	-3,6%	0,5%	-0,2%	-0,6%	-0,7%	On going	0,1%	0,1%	FAIL	-1,4%

Variation in thermal emittance $\Delta\varepsilon_{th}$			Initial value	Solar cycling		Isothermal, 2000 hours			500 cycles	Climate chambers			
Generation	Substrate	Coating	ε_{th} (650 °C)	SC-DLR	SC-CNRS	T1	T2	T3	Cyclic	DH	HF	NSS	SE
Gen 2	T91	A (BSII)	78,4%	-0,2%	0,1%	N.A.	N.A.	N.A.	N.A.	-0,6%	-1,4%	-0,1%	0,0%
Gen 2	T91	B (INTA+BSII)	76,0%	0,1%	-0,5%	N.A.	N.A.	N.A.	N.A.	-0,3%	0,0%	-0,9%	-0,5%
Gen 2	T91	C (Fraunhofer)	26,8%	5,8%	0,7%	N.A.	N.A.	N.A.	N.A.	0,4%	0,1%	FAIL	0,4%
Gen 2	T91	D (Dechema)	85,9%	-2,3%	-0,1%	N.A.	N.A.	N.A.	N.A.	-0,3%	0,6%	0,3%	0,4%
Gen 2	T91	E (INTA+Fraunhofer)	41,6%	11,0%	-1,3%	N.A.	N.A.	N.A.	N.A.	0,5%	-0,6%	FAIL	-2,6%

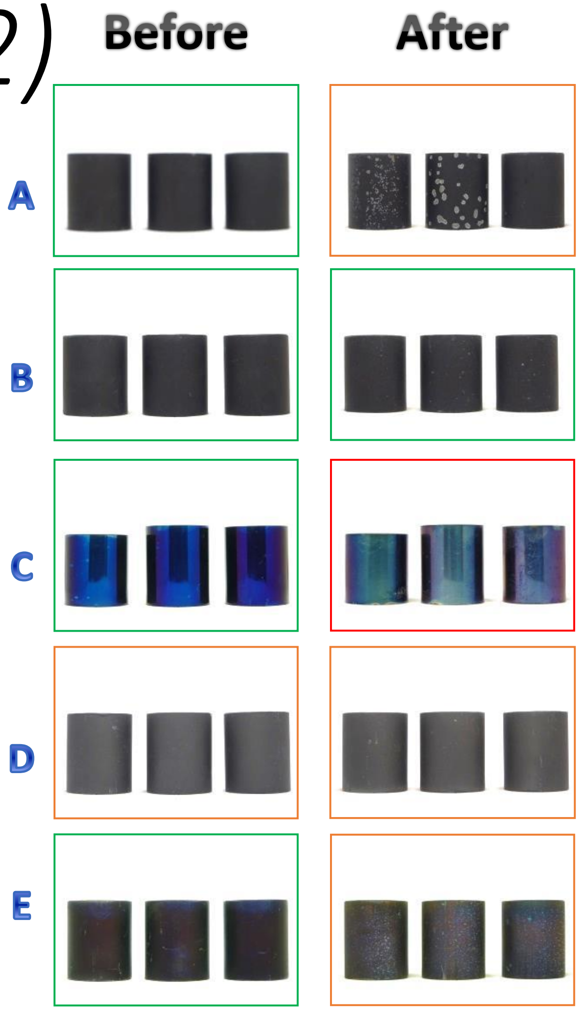
T91/Gen 2 - Solar absorptance



T91/Gen 2 - Thermal emittance



T91 (A,B,C,D,E)



Conclusion and Outlook

- <u>Conclusions:</u>

- <u>Inc617/H230</u>:
  - Best coating: Coating A
  - Brightsource (commercial): $\alpha_{sol} \geq 97$ %
- <u>T91/VM12</u>:
  - Slurry aluminide primer coating protects metal substrate better against corrosion (NSS).
  - Most durable Coating : B *(INTA+Brightsource)*
  - Best α_{sol} value: Coating F (>96.5%) *(Dechema + Brightsource)*

- Coating D stable, but lower efficiency
- Solar selective coatings C/F efficient … but not durable (isothermal, NSS)

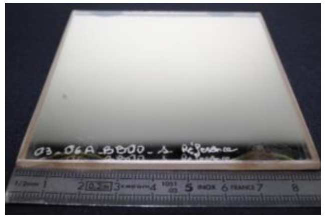
- <u>Outlook:</u>
  - **Coating A commercialized**
  - Aging models in development, Service Lifetime Prediction (SLP)
  - Estimation of LCOC (*Levelized Cost of Coating)*

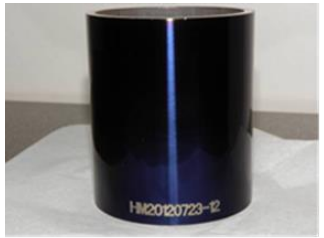
Sample and data management

Sample and data management of reflectors :

	Characterizations		
	Measurement	Equipment	Number of measurement
1 - Engraving			
2- Photography	Macroscopic Visual Inspection	Canon	Front side /back side
3- Specular Reflectance	$\rho\lambda$ (660nm,15°,12.5mrad)	15R-USB D&S	3 or 5 Front side
4- Edge corrosion	Macroscopic Visual Inspection	Canon	8 corrosion Front side /back side (edges + spots)
5-Hemispherical réflectance/transmittance/ absorptance	ρh([280,2500],8°,h) αh([280,2500],8°,h) τh([280,2500],8°,h)	Lambda 950 with IS (ϕ 150mm)	3 Front side (0°/90°/180°)
6-Colorimetry	ΔE : Color variation ΔG : Gloss variation	BYK-Garner	3 back side
7-Optical microscopy	Macroscopic Visual Inspection	Zeiss Axio Imager A.2M	Front side /back side
8- Contact angle	θ contact angle (°) surface energy (mN/m)	Mobile Surface Analyzer (MSA) KRÜSS	20 Front side

Engraving samples



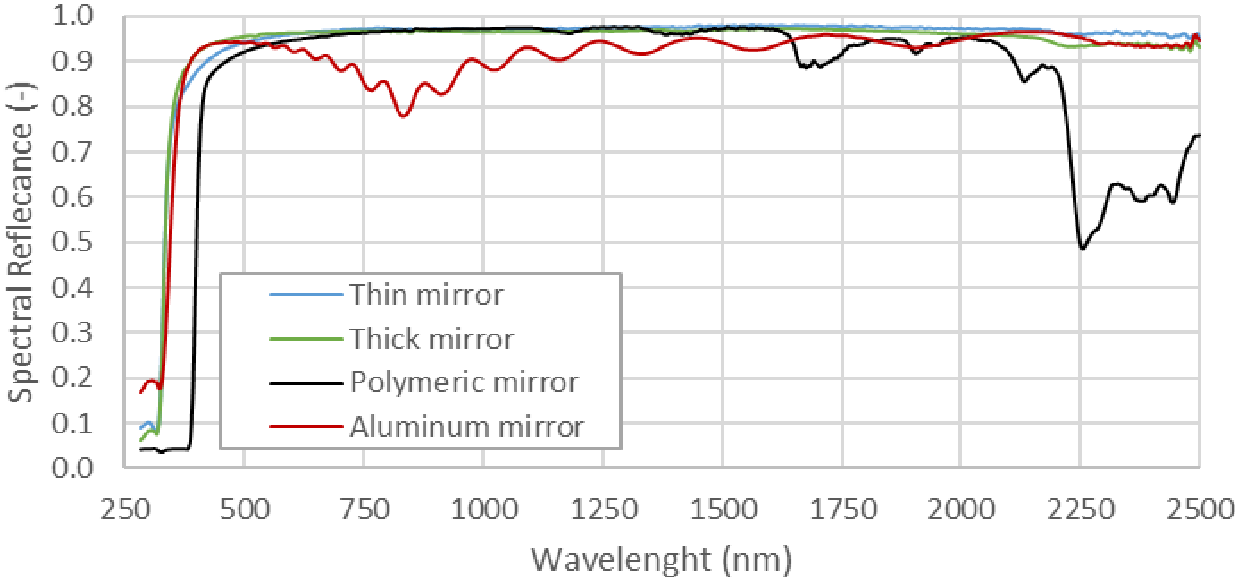


Example of spectral Optical reflectance analysis of Solar mirrors :

- Thin and thick solar silvered glass mirrors are quite similar
- Differences with the polymeric mirror, especially in the infrared
- Aluminum mirror has a particular spectral reflectance, due to thin layers

Perkin Elmer lambda 950

Spectral hemispherical reflectance, $\rho_{\lambda,h}$



Solar-weighted hemispherical reflectance, $\rho_{s,h}$

$$\rho_{s,h} = \int_{\lambda\,=\,280nm}^{2500nm} \frac{\rho_{\lambda,h}(\lambda) \times S(\lambda)}{S\,(\lambda)}\,d\lambda$$

Where:

$\rho_{\lambda,h}(\lambda)$	Hemispherical reflectance measurement
$S(\lambda)$	Solar spectra ASTM G173-03

+ specular reflectance, colorimetry, microscopic analysis and visual inspection…

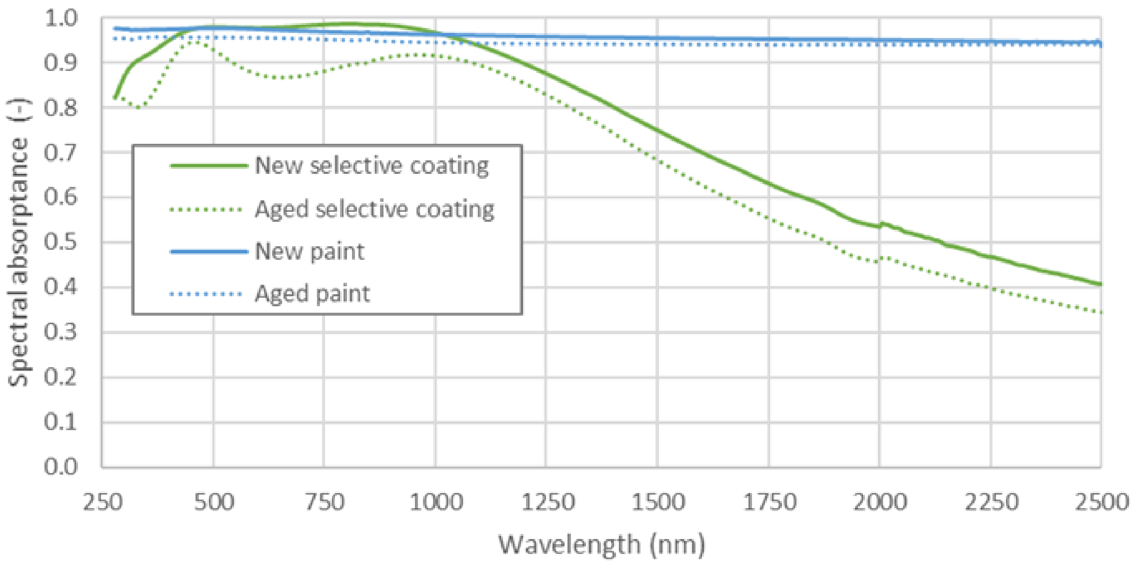
Example of spectral Optical analysis of absorbers :

- Black paint : high solar absorptance in all wavelength
- Selective coating : various spectral absorptance with differences between new and aged samples

Perkin Elmer lambda 950

Bruker IR Vertex 70

Spectral hemispherical absorptance, $\alpha_{\lambda,h}(\lambda, \theta_i, h)$



Solar-weighted hemispherical absorptance, $\alpha_{s,h}$ and thermal emittance $\varepsilon(T)$

$$\alpha_{s,h} = \int_{\lambda\,=\,280nm}^{2500nm} \frac{[1-\rho_h(\lambda)] \times S(\lambda)}{S\,(\lambda)} d\lambda \qquad \varepsilon(T) = \int_{\lambda\,=280\,nm}^{16\,000\,nm} \frac{[1-\rho_h(\lambda)] \times B_T(\lambda)}{B_T(\lambda)} d\lambda$$

Where:

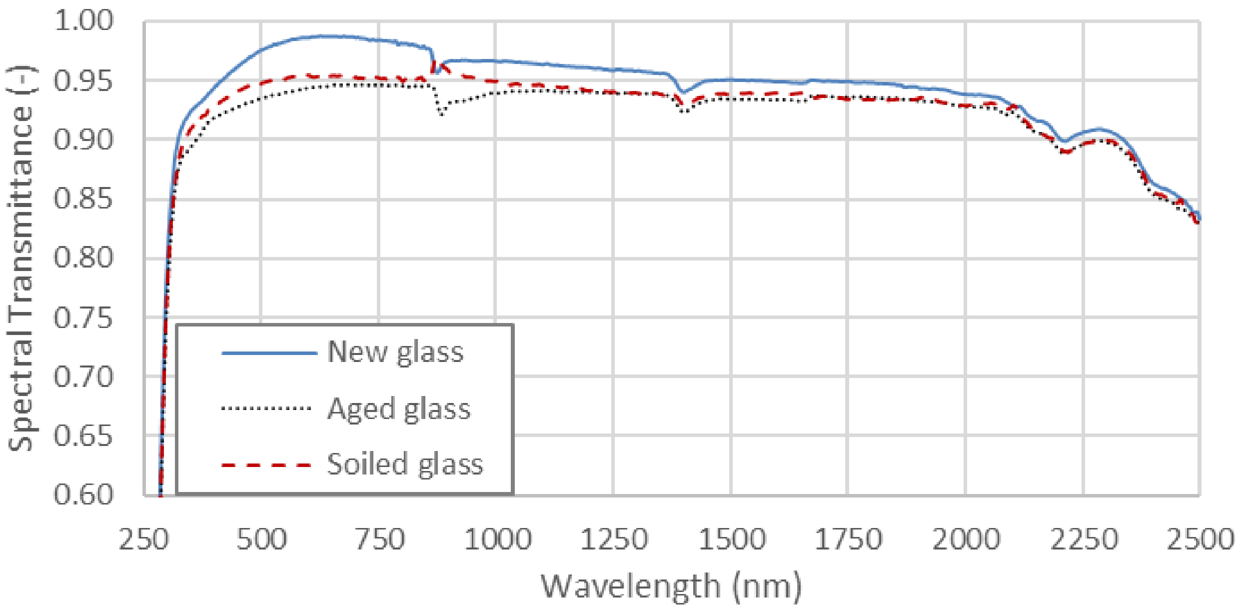
$\alpha_{s,h}$	Total solar absorbance
$\varepsilon(T)$	Total emittance at temperature T
$\rho_h(\lambda)$	Hemispherical reflectance measurement
$S(\lambda)$	Solar spectra ASTM G173-03
$B_T(\lambda)$	Black body spectra at temperature T

Example of spectral Optical transmittance analysis of Solar glass :

- All samples have very low transmittance in under 320 nm
- High spectral transmittance in 500 to 1000 nm
- Spectral differences between new, aged and soiled glasses

Perkin Elmer lambda 950

Spectral hemispherical transmittance, $\tau_{\lambda,h}$



Solar-weighted hemispherical transmittance, $\tau_{s,h}$

$$\tau_{s,h} = \int_{\lambda\,=\,280nm}^{2500nm} \frac{\tau_{\lambda,h}(\lambda) \times S(\lambda)}{S\,(\lambda)} d\lambda$$

Where:

$\tau_{\lambda,h}(\lambda)$	Hemispherical transmittance measurement
$S(\lambda)$	Solar spectra ASTM G173-03

Sample and data management : INDOOR tests


Climatic chamber


Spectrophotometer


D&S 15R-USB

Byk Spectro Guide Gloss

Camera

		SI					Rs (660nm, 15°, 12,5 mrad)								Colorimetrie									Fronts de corrosion											
Echantillon	temps (h)	SI-0°	SI-90°	SI-180°	Reflection moyenne	Δρ	1.00	2.00	3.00	4.00	5.00	Moy	Ecart type	Δρ	L	DL	a	Da	b	Db	DE	G	ΔG	Epaisseur des fronts de corrosion face avant				surface Initiale (cm²)	% Surface Restante face miroir	Epaisseur des fronts de corrosion face arrière				surface Initiale (cm²)	% Surface Restante face arrière
Tsing-1	0.00	94.13	94.15	94.17	94.15		95.70	95.60	95.60	95.60	95.60	95.62	0.04		94.35	0.00	-0.68	0.00	-0.58	0.00	0.00	48.39		0.00	0.00	0.00	0.00	25.00	100%	0.00	0.00	0.00	0.00	25.00	100%
Tsing-2	0.00	93.97	94.04	93.99	94.00		95.40	95.40	95.30	95.30	95.40	95.36	0.05		94.50	0.00	-0.67	0.00	-0.23	0.00	0.00	52.32		0.00	0.00	0.00	0.00	25.00	100%	0.00	0.00	0.00	0.00	25.00	100%
Tsing-3	0.00	93.87	93.90	93.86	93.88		95.30	95.30	95.30	95.30	95.30	95.30	0.00		94.33	0.00	-0.68	0.00	-0.57	0.00	0.00	49.18		0.00	0.00	0.00	0.00	25.00	100%	0.00	0.00	0.00	0.00	25.00	100%
Tsing-4	0.00	94.08	94.11	94.08	94.09		95.50	95.50	95.50	95.50	95.50	95.50	0.00		94.47	0.00	-0.68	0.00	-0.52	0.00	0.00	49.23		0.00	0.00	0.00	0.00	25.00	100%	0.00	0.00	0.00	0.00	25.00	100%
Tsing-5	0.00	94.07	94.08	94.08	94.07		95.40	95.60	95.60	95.60	95.60	95.56	0.09		94.35	0.00	-0.68	0.00	-0.46	0.00	0.00	49.18		0.00	0.00	0.00	0.00	25.00	100%	0.00	0.00	0.00	0.00	25.00	100%
Tsing-6	0.00	94.18	94.16	94.21	94.18		95.70	95.60	95.60	95.70	95.70	95.66	0.05		94.18	0.00	-0.67	0.00	-0.46	0.00	0.00	46.45		0.00	0.00	0.00	0.00	25.00	100%	0.00	0.00	0.00	0.00	25.00	100%
Average	0.00	**94.05**	**94.07**	**94.07**	**94.06**		**95.50**	**95.50**	**95.48**	**95.50**	**95.52**	**95.50**	**0.04**		**94.36**	**0.00**	**-0.68**	**0.00**	**-0.47**	**0.00**	**0.00**	**49.13**		**0.00**	**0.00**	**0.00**	**0.00**	**25.00**	**100%**	**0.00**	**0.00**	**0.00**	**0.00**	**25.00**	**100%**
Deviation	0.00	**0.11**	**0.10**	**0.13**	**0.11**		**0.17**	**0.13**	**0.15**	**0.17**	**0.15**	**0.14**	**0.03**		**0.11**	**0.00**	**0.00**	**0.00**	**0.13**	**0.00**	**0.00**	**1.89**		**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
Tsing-1	203.00	94.34	94.32	94.32	94.32	0.17	95.70	95.80	95.70	95.60	95.60	95.68	0.08	0.06	94.12	-0.23	-0.72	-0.04	-0.39	0.20	0.31	37.31	-11.08	0.00	0.00	0.00	0.00	25.00	100%	0.00	0.00	0.00	0.00	25.00	100%
Tsing-2	203.00	94.14	94.11	94.13	94.13	0.13	95.50	95.40	95.30	95.50	95.40	95.42	0.08	0.06	94.40	-0.09	-0.70	-0.03	-0.16	0.07	0.12	42.40	-9.92	0.00	0.00	0.00	0.00	25.00	100%	0.00	0.00	0.00	0.00	25.00	100%
Tsing-3	203.00	94.00	94.06	93.83	93.97	0.09	95.40	95.40	95.40	95.40	95.40	95.40	0.00	0.10	94.15	-0.19	-0.71	-0.03	-0.46	0.11	0.22	39.42	-9.76	0.00	0.00	0.00	0.00	25.00	100%	0.00	0.00	0.00	0.00	25.00	100%
Tsing-4	203.00	94.17	94.14	94.15	94.15	0.07	95.40	95.50	95.60	95.40	95.40	95.46	0.09	-0.04	94.30	-0.16	-0.72	-0.04	-0.37	0.15	0.22	39.96	-9.28	0.00	0.00	0.00	0.00	25.00	100%	0.00	0.00	0.00	0.00	25.00	100%
Tsing-5	203.00	94.23	94.27	94.25	94.25	0.17	95.60	95.60	95.60	95.40	95.60	95.56	0.09	0.00	94.19	-0.16	-0.70	-0.02	-0.37	0.09	0.19	39.73	-9.45	0.00	0.00	0.00	0.00	25.00	100%	0.00	0.00	0.00	0.00	25.00	100%
Tsing-6	203.00	94.31	94.36	94.34	94.34	0.15	95.40	95.40	95.70	95.60	95.60	95.54	0.13	-0.12	94.03	-0.15	-0.71	-0.04	-0.36	0.10	0.18	37.54	-8.90	0.00	0.00	0.00	0.00	25.00	100%	0.00	0.00	0.00	0.00	25.00	100%
Average	0.00	**94.20**	**94.21**	**94.17**	**94.19**	**0.13**	**95.50**	**95.52**	**95.55**	**95.48**	**95.50**	**95.51**	**0.08**	**0.01**	**94.20**	**-0.16**	**-0.71**	**-0.03**	**-0.35**	**0.12**	**0.21**	**39.39**	**-9.73**	**0.00**	**0.00**	**0.00**	**0.00**	**25.00**	**1.00**	**0.00**	**0.00**	**0.00**	**0.00**	**25.00**	**100%**
Deviation	0.00	**0.12**	**0.12**	**0.18**	**0.14**	**0.05**	**0.13**	**0.16**	**0.16**	**0.10**	**0.11**	**0.10**	**0.04**	**0.08**	**0.13**	**0.05**	**0.01**	**0.01**	**0.10**	**0.05**	**0.06**	**1.86**	**0.75**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**

Sample and data management : OUTDOOR tests

Cadarache solar field

Outdoor samples exposure

D&S 15R-USB

Byk Spectro Guide Gloss

Camera

- selection of a satisfactory outdoor site
- exposed for more than 5 years or more ➔ **Currently Aging > 7 years**

	A	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AK	AL	AM	AN	AP	AQ	AR	AS
1				Remplissage automatique					Bord protégé		Bord coupé						Pas pour miroirs aluminium ni polymère											largeur (bord 2 et 4)		
2																													Face avant	
3	Site :								Face AVANT								Face ARRIERE						Dégradation rapportée à un miroir de 1m²						2	
4	Référence / Caractéristiques	Date de retrait	Temps total d'exposition (jrs)	ρ(660nm) avant nettoyage (%)	Ecart type (%)	ρ(660nm) après nettoyage (%)	Ecart type (%)	Δρs (%)	Front de dégradation (cm)				Autres dégradations (mm²)	Surface restante (%)	ρs équivalente (%)	Perte (%)	Front de dégradation (cm)				Autres dégradations (cm²)	Surface restante (%)	front moyen (mm)	Surface restante (%)	ρs équivalente (%)	Δρs équivalente (%)	Bord protégé (en général)	1		3
5									Bord 1	Bord 2	Bord 3	Bord 4					Bord 1	Bord 2	Bord 3	Bord 4								gravure	4	
6	**01_02A_AD01-9**	29/03/17	105	87.4	0.6	94.5	0.1	0.0	0	0	0	0	0	100	94.5	0.0	0	0.1	0	0.1	0	100	0	100	94.5	0.0				
7	Longueur (cm)	18/10/17	308	86.8	0.5	94.6	0.2	0.1	0	0	0	0	0	100	94.6	0.1	0	0.1	0.1	0.1	0	100	0	100	94.6	0.1				
8	Largeur (cm)	18/07/18	581	84.7	0.8	94.6	0.1	0.1	0	0	0	0	0	100	94.6	0.1	0	0	0	0	0	100	0	100	94.6	0.1				
9	Surface (cm²)	17/09/18	642	86.6	0.7	94.6	0.1	0.1	0	0	0	0	0	100	94.6	0.1	0.1	0.1	0.1	0.05	0	99	0	100	94.6	0.1				
10	Commentaires :	07/02/19	785	92.8	0.6	94.1	0.7	-0.4	0	0	0	0	0	100	94.1	-0.4	0.1	0.3	0.1	0.1	0	99	0	100	94.1	-0.4				
11		22/07/19	950	87.8	0.3	94.1	0.1	-0.4	0	0	0	0	0	100	94.1	-0.4	0.8	1.3	0	0.6	0	96	0	100	94.1	-0.4				
12		27/11/19	1078	90.5	1.2	94.5	0.2	0.0	0	0.1	0	0	0	100	94.4	-0.1	1	1.3	0	0.9	0	95	0	100	94.5	0.0				
13																														

Example of notations of reflectors :

Overall qualitative assessment :
1 (green) = good
2 (orange) = medium
3 (red) = bad
x = not tested

Evaluating the degradation of :
1. the general appearance
2. the loss of specular reflectance
3. the colorimetric variation of the paint

Test \ mirror	A	B	C	D	E	F
Temperature	2	?	2	1	1	1
UV Irradiance front side	2	2	x	x	2	1
UV Irradiance back side	3	3	x	x	2	3
Damp Heat	x	x	3	3	2	2
Neutral Salt	2	x	2	2	2	2
Outdoor	1	2	2	2	2	3

- **Back side UV irradiance and Damp Heat tests are the most aggressive for mirrors**
- **The Damp Heat test leads to non-representative damages from outdoor**
- **The type of degradation obtained in Neutral Salt Spray & outdoor in particular at PIMENT are consistent**

Thursday, June 9, 2022

09:15 – 9:45	Overview of CEA studies on accelerated ageing and soiling of solar materials	CEA	30 min
09:45 – 10:15	Automatic corrosion detection system for solar reflectors	DLR	30 min
10:15 – 10:30	- Coffee break -		15 min
10:30 – 12:30	‘hands-on’ experience on laboratory and portable characterization tools	CEA/ DLR	120 min
12:30 – 13:30	- Lunch break -		60 min
13:30 – 14:30	Durability modeling method and Lifetime extrapolation	CEA	30 min
14:30 – 15:00	Lifetime extrapolation of reflectors (erosion and corrosion)	DLR	30 min
15:00 – 17:15	INES Visit	CEA	135 min

Overview of CEA studies on accelerated ageing and soiling of solar materials

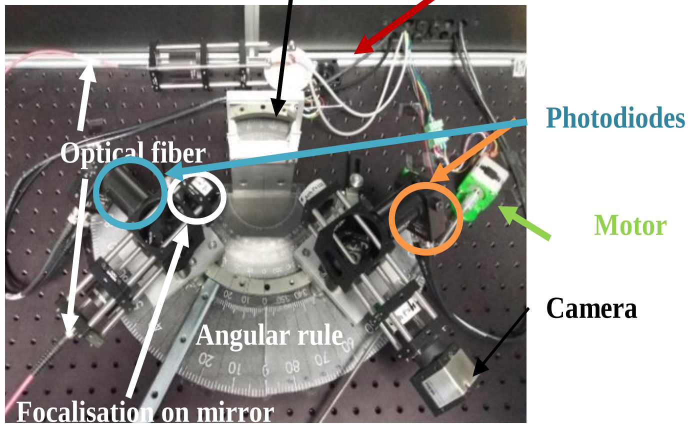
E. Le Baron CEA

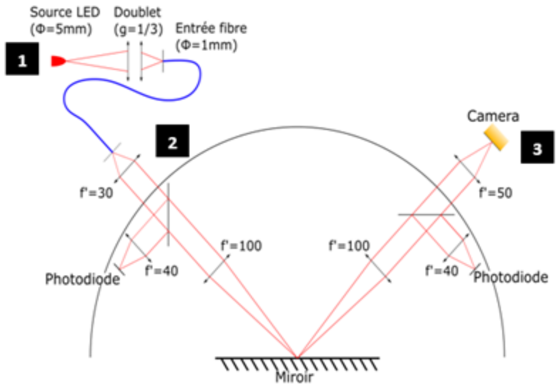
Studies on soiling of reflectors

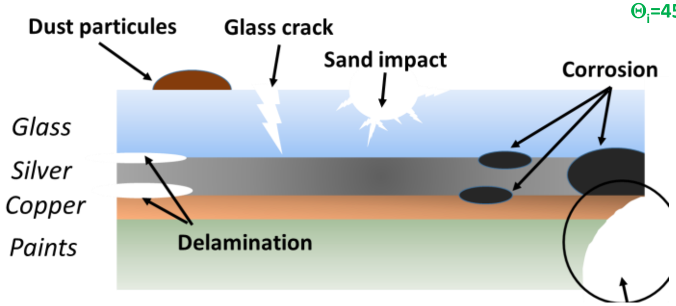
E. Le Baron CEA

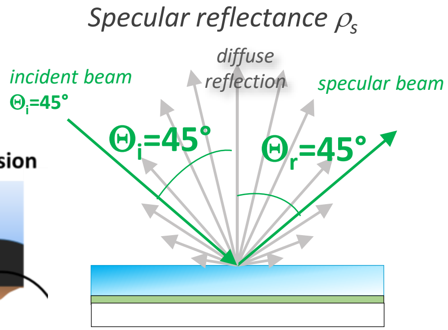
Optical Characterizations of soiling of reflectors :

Soiling sensor prototype : Specular Reflectance and particles counting on Solar Mirrors :





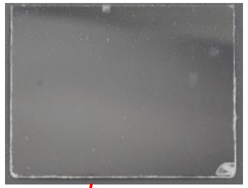
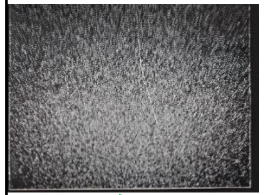




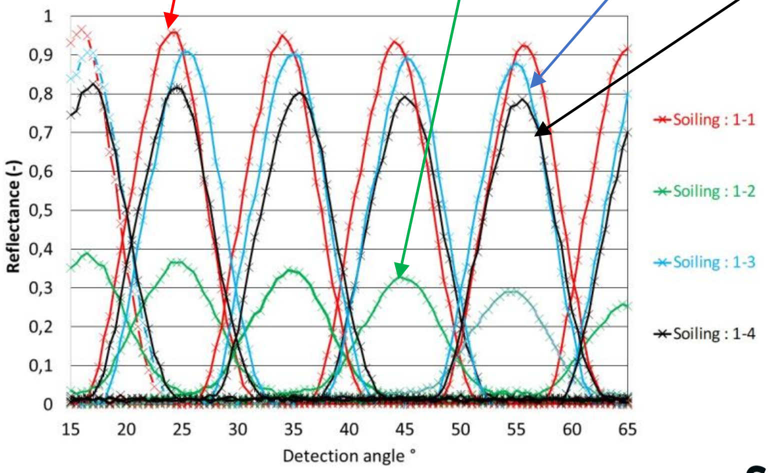
 "New Equipment for Measurement of Soiling and Specular Reflectance on Solar Mirrors", E. Le Baron, A. Grosjean, D. Bourdon, A-C. Pescheux, F. Vidal, A. Disdier, 'in Solar PACES 2017'.

Optical Characterizations of soiling of reflectors :

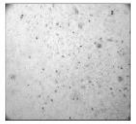
Soiling sensor prototype : Specular Reflectance and particles counting on Solar Mirrors :

	1-1 Reference	1-2 Abrasive test with sand	1-3 Natural soiled Low dust	1-4 Natural soiled high dust
Mirrors				

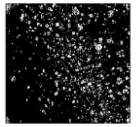
Specular reflectance ρ_s



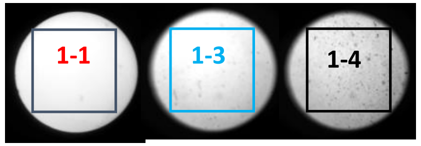
Picture of mirror

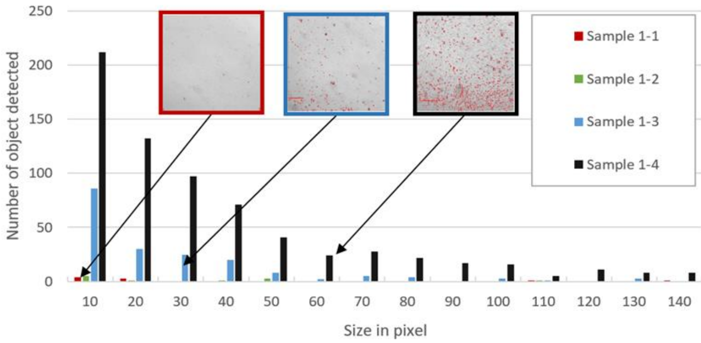


Particles



Particles counting on mirrors





Pros :

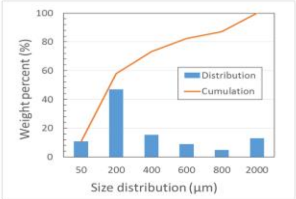
- Quickly and precisely reflectance measurement of mirrors
- Large range of incident and detection angles (15° to 65°) and wavelengths (10 leds : 365-850 nm)
- No contact between the mirror and the optical device no risk to contaminate the equipment and mirror
- Image taking : particles counting to know the level of soiling and percentage of covered area

"New Equipment for Measurement of Soiling and Specular Reflectance on Solar Mirrors", E. Le Baron, A. Grosjean, D. Bourdon, A-C. Pescheux, F. Vidal, A. Disdier, 'in Solar PACES 2017'.

Effect of sand from different Moroccan solar sites on the soiling and degradation of mirrors :

Analyses :

- Particle size distribution → Sieving method
- Particle morphology → Optical microscope
- Mineralogical composition → FTIR-ATR and XRD



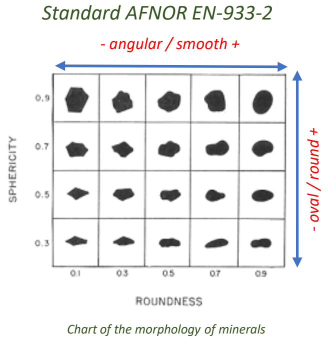
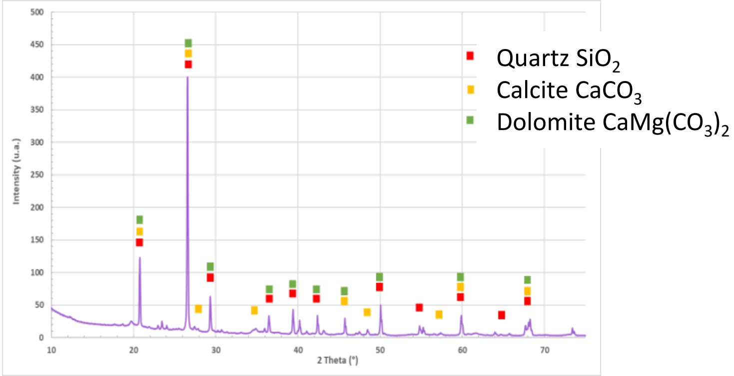
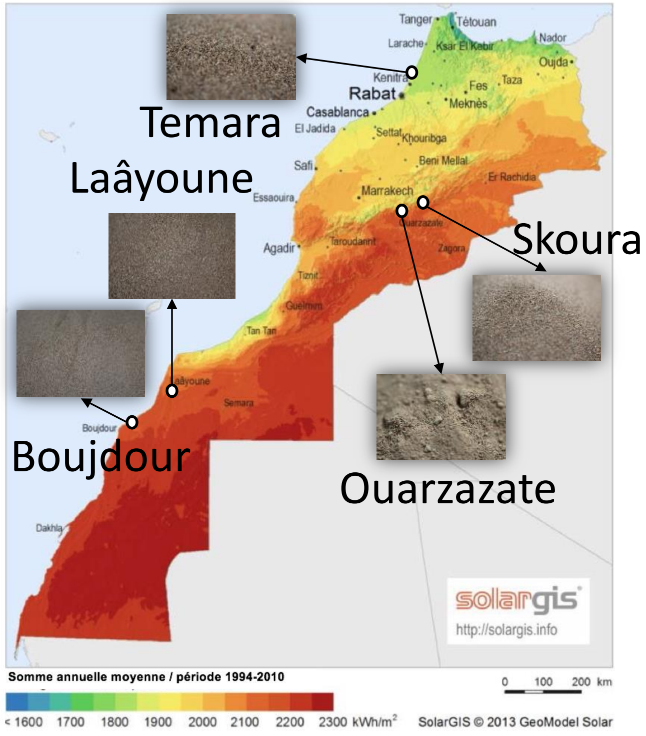


Chart of the morphology of minerals





Locations	Particle size	Morphology	Hardness
Boujdour	Fine	Smooth	~ 5
Laâyoune	Fine	Smooth	~ 5
Ouarzazate	Coarse	Smooth/sharp	~ 7
Skoura	Coarse	Smooth/sharp	~ 7
Temara	**Medium**	**Angular**	**~ 4**

Temara coastal site is a very dangerous site :

- Violent wind gusts
- Angular sand particles
- Serious risk of corrosion with a high level of saline/brine atmosphere

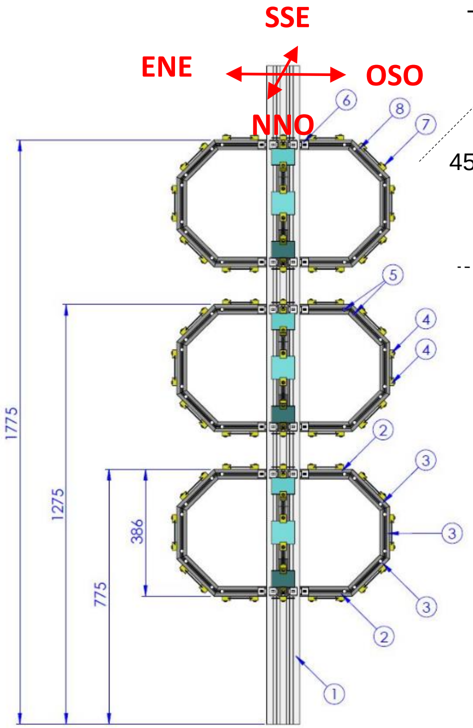
E. Le Baron CEA

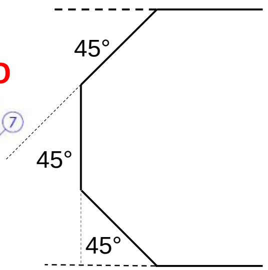
"Characterization of Different Moroccan Sands to Explain their Potential Negative Impacts on CSP Solar Mirrors", A.C Pescheux, E. Le Baron, O. Raccurt, Solar Energy, Volume 194, December 2019, Pages 959-968

Spectrophotometer

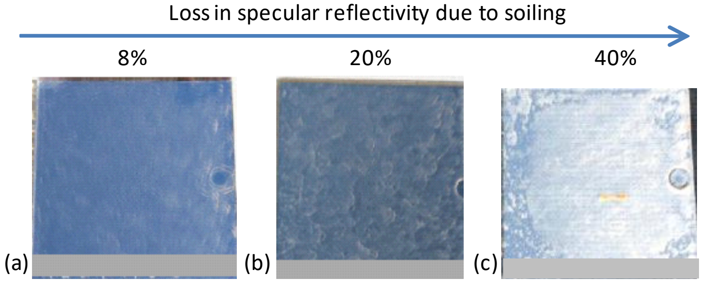
Effect of sand from different Moroccan solar sites on the soiling and degradation of mirrors

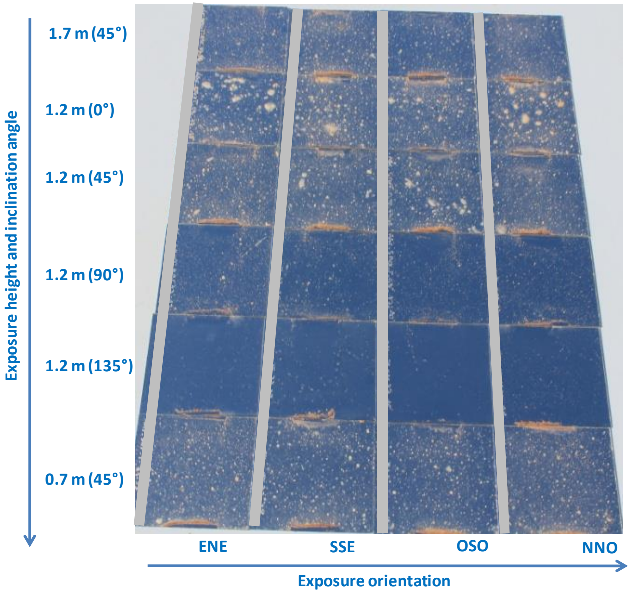
Effect of inclination angle and exposure height analyses on specular Reflectance

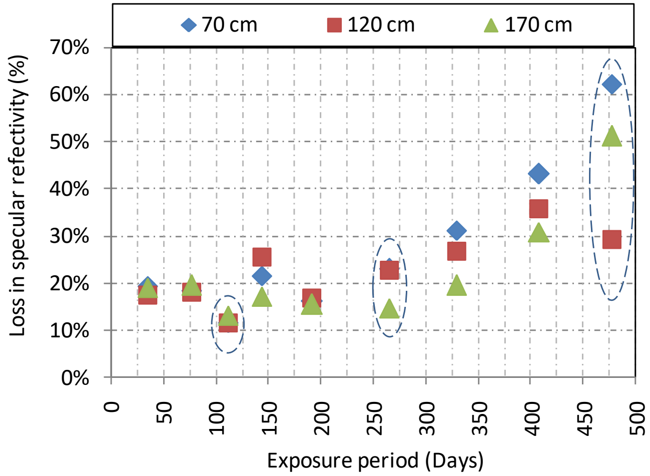




N°	Désignation	Quantité
1	A01_100x100_Pied	1
2	A02_30x30	24
3	A03_30x30	36
4	G01_Pince	120
5	T01_Coupleur	48
6	T02_Equerre	48
7	T03_Vis_M6x30	120
8	T04_Coulisseau_R8M6	120
9	T05_Vis_M8x30	48
10	T06_Coulisseau_R10M8	48







“Exposure conditions effect on soiling of solar glass mirrors”, M.Karim, C.Delord, O.Raccurt, S.Naamane, (2017), in 'Solar PACES 2017'

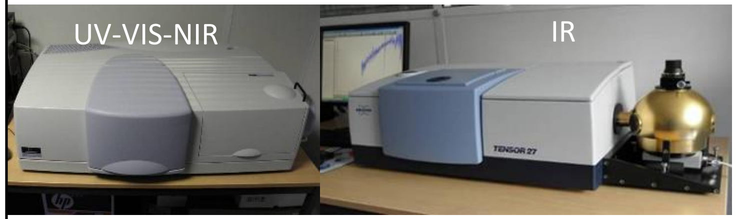
Studies on accelerated ageing of absorbers

E. Le Baron CEA

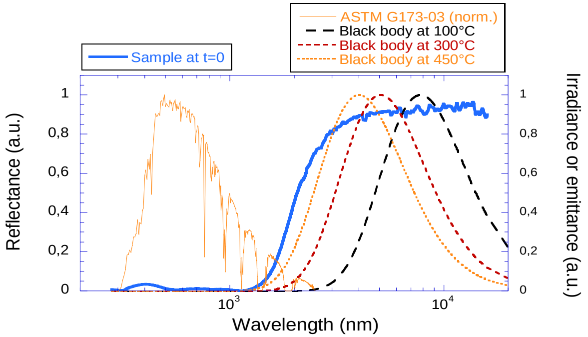
Dedicated optical bench of solar absorbers at high temperature in air

A B C

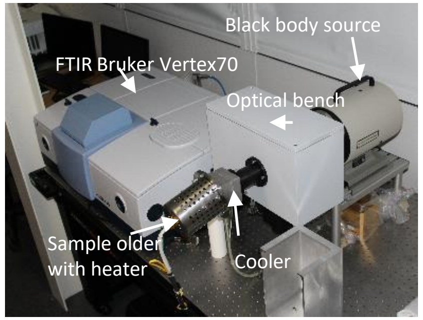
Integrating sphere



Hemispherical reflectance

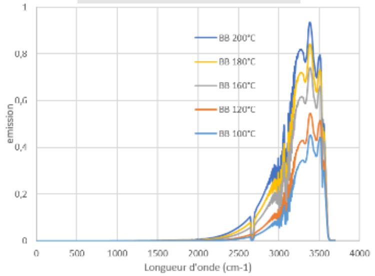


High temperature spectrale emittance optical bench

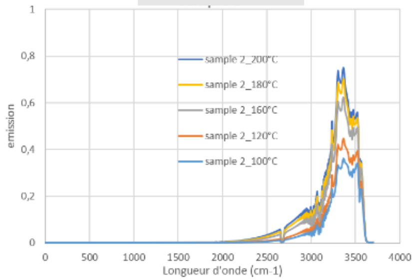


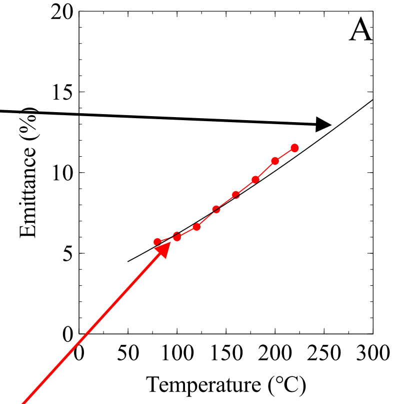
Spectral luminance

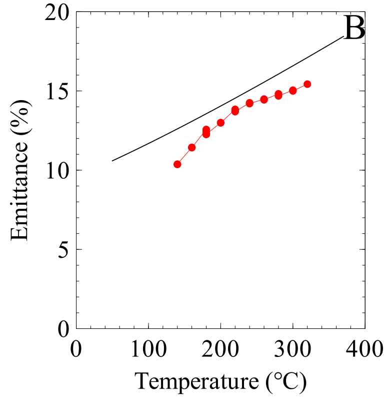
Black body

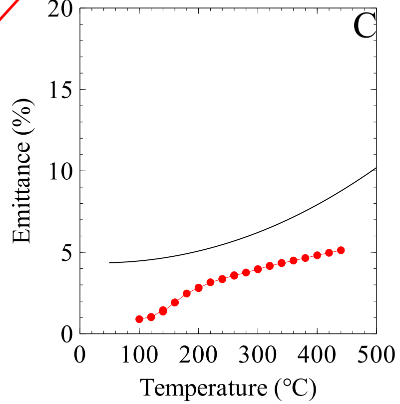


Sample









Comparison between emittance calculated from hemispherical reflectance measurement from Kirchhoff law and spectral measurement of luminescence of sample in operation temperature

E. Le Baron CEA

"Round Robin Test for the Comparison of Emittance Measurement Apparatuses", Le Baron E., Giraud P., Adier M., Raccurt O.; Barriga, J.; Echegut, P.; Meneses, D. D. S.; Capiani, C.; Sciti, D.; Soum-Glaude, A.; Escape, C.; Jerman, I.; Larsen, R.; Nørgaard, J.; Lopez, G. A.; Echaniz, T.; Tello, M. J.; Matino, F.; Maccari, A.; Mercatelli, L. & Sani, E. (2017), in 'Solar PACES 2017'. (2017), in 'Solar PACES 2017'.

Studies on accelerated ageing of glass

Spectrophotometer

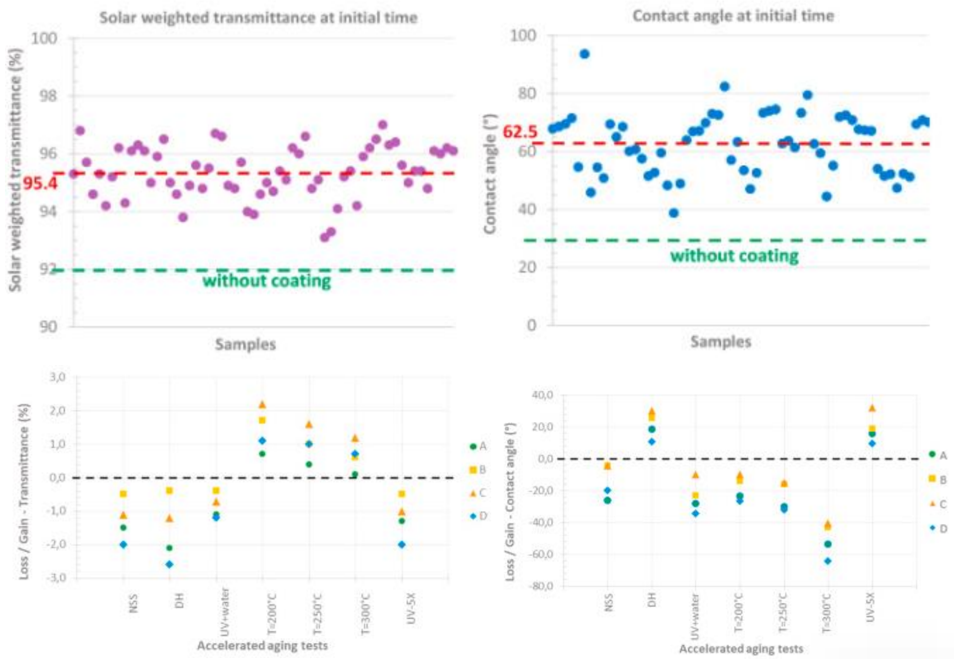
Indoor Accelerated aging of solar glass

NSS / Thermal / UV / Damp heat tests ➔ 5 conditions of tests

Durability studies of anti-soiling coatings of cylindrical-parabolic absorber glass (PTC)

- Evolution of hemispherical transmittance over time t
- Evolution of the value of the contact angle over time t

TEST	EQUIPMENT	STANDARD	TESTING TIME
NSS	Weiss SC450	ISO 9227	3000 h
Constant temperature 200 -250-300°C	Nabertherm		1500 h
UV-5X	BIA Climatic UV 5X		1600 h
Damp Heat	Climacel	IEC 62108 10.7b	2000 h
Xenon radiation with water spray	Atlas Suntest XXL+	ISO 16474-2	2000 h



Choice of the most durable coating :

- **B & C coatings are much better than the commercial coating A and the new coating B (sol-gel solution composed by SiO_2 nanoparticles)**

Accelerated aging tests and characterizations of innovated anti-soiling coatings for solar receiver glasses, A.C Pescheux, O. Raccurt, D. Bourdon, E. Le Baron, Mater. Chem. Phys. 256 (2020) 123646

Optical Characterizations of soiling of solar glass

WASCOP

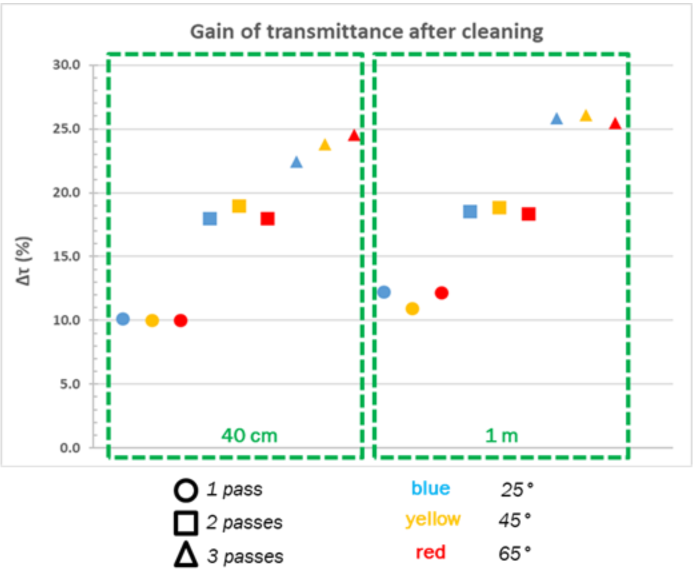
Studies of water high pressure jet cleaning of absorber glass windows:

- distances,
- Inclinations,
- number of passes
- reduction of water consumption

40 cm									1 m								
25°			45°			65°			25°			45°			65°		
1p	2p	3p	1p	2p	3p	1p	2p	3p	1p	2p	3p	1p	2p	3p	1p	2p	3p
x3	x3	x3	x3	x3	x3	x3	x3	x3	x3	x3	x3	x3	x3	x3	x3	x3	x3

Control panel :
Speed and translation

Evolution of hemispherical transmittance over time t



- **Increase in transmittance after cleaning (+25%)**
- **Slightly better results for cleaning at 1m and 45° tilt**

Solar Facilities for the European Research Area

Programme funded by the EUROPEAN UNION

SFERA III: On site Training for Indusry

Le Bourget-du-Lac, June, 8th – 10th 2022

Automatic Corrosion Detection System for Solar Reflectors

Florian Wiesinger, DLR

DLR Deutsches Zentrum für Luft- und Raumfahrt e.V. in der Helmholtz-Gemeinschaft

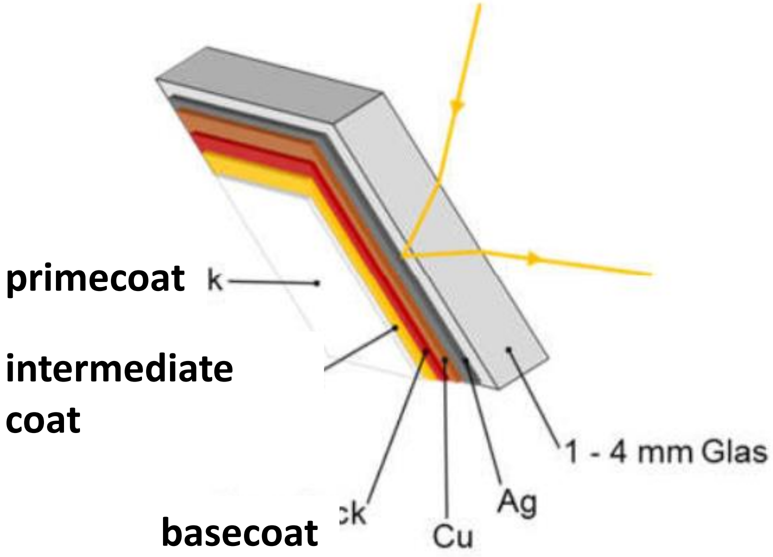
Contents

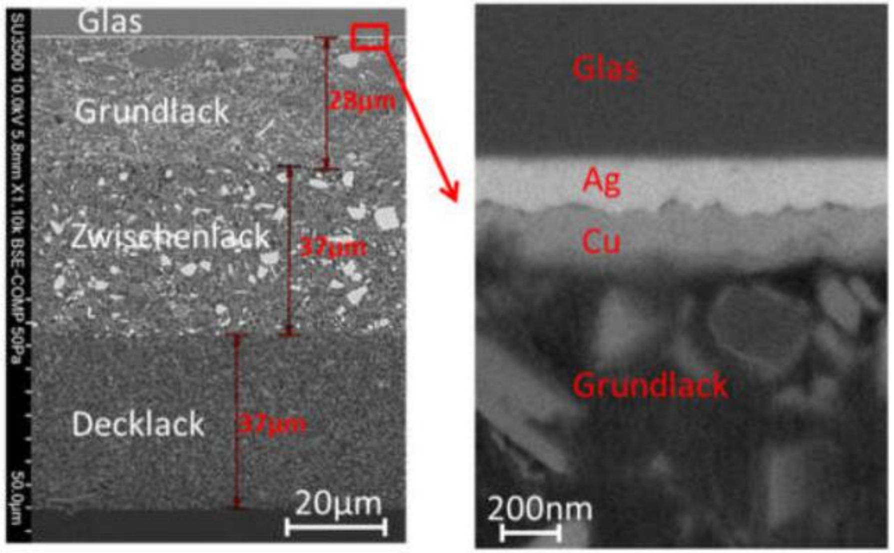
Motivation

Methodology and Setup Description

First results

Motivation – Reflector Structure

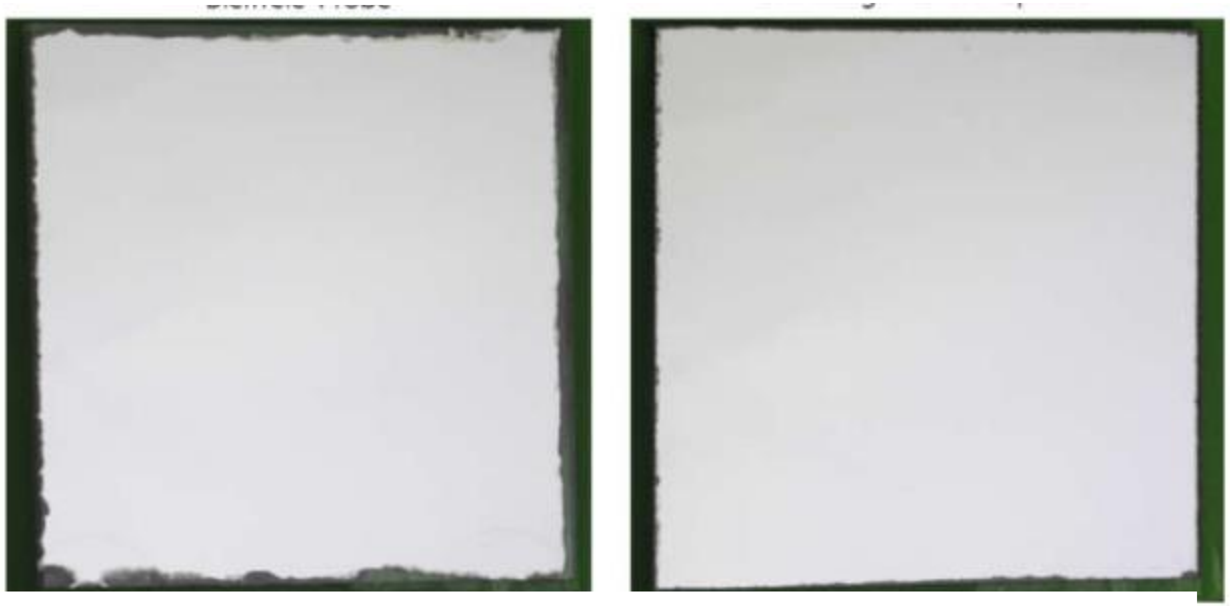




- Glas as corrosion protection
- Ag as reflecting layer and Cu as UV-protection and substrate for basecoat.
- Basecoat as humidity barrier (up to 10% Pb).
- Primecoat (TiO_2) abrasion and humidity protection

Motivation – Novel Coating Types

Non lead sample **Traditional sample containing lead**

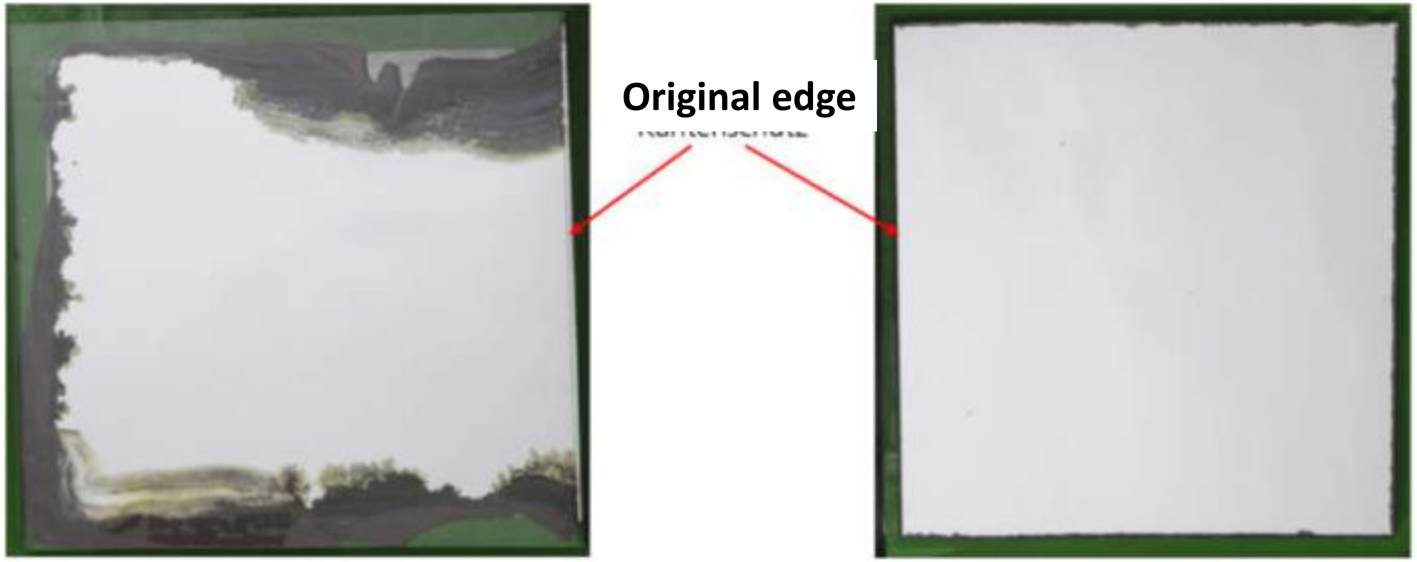


Sample after 2 years exposure in Almeria: coastal site, corrosion class C5 after ISO 9223

Higher degradtion rate for novel non-lead reflectors, especially on edges.

Motivation – Novel Coating Types

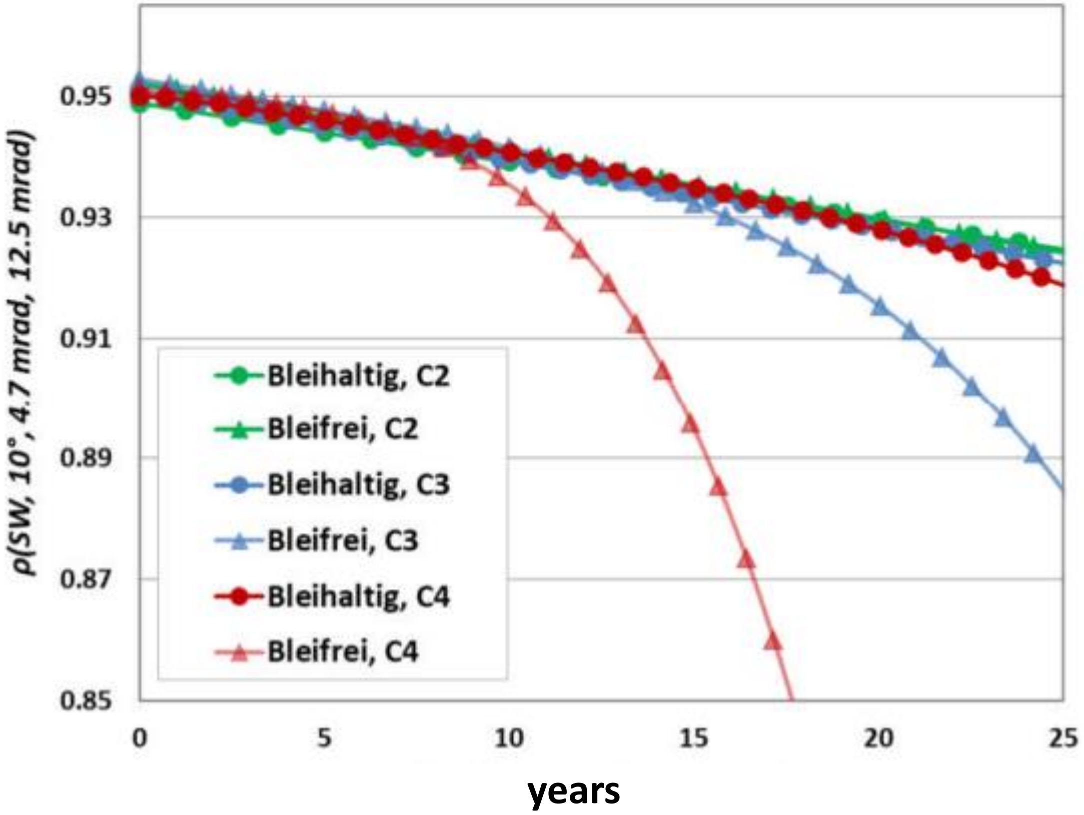
Non lead sample **Traditional sample containing lead**



Sample after 480 hours of CASS test

Higher degradtion rate for novel non-lead reflectors, especially on edges.

Motivation – High Degradation Rates



Needs:
Detect and quantify corrosion at an early stage.

Motivation – High Degradation Rates

<u>State of the art:</u>

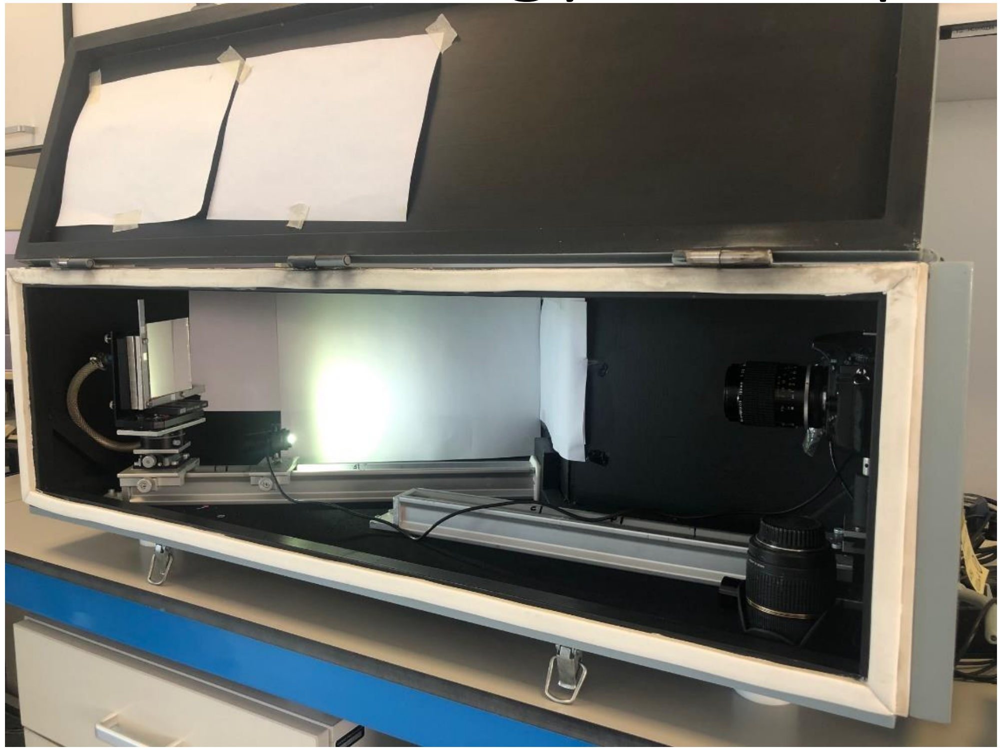
- Count corrosion spots per eye
- Mesure edge penetration with scale

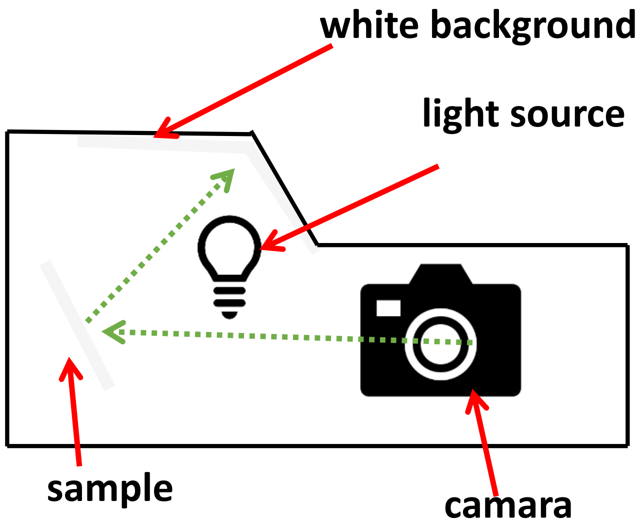
<u>Problems: Result highly depending on operator</u>

- Ilumination changes
- different sample materials
- spot / no spot
- one spot / two spots
- calculation of area imposible

→ Development of automatic image detection algorithm

Methodology - Setup



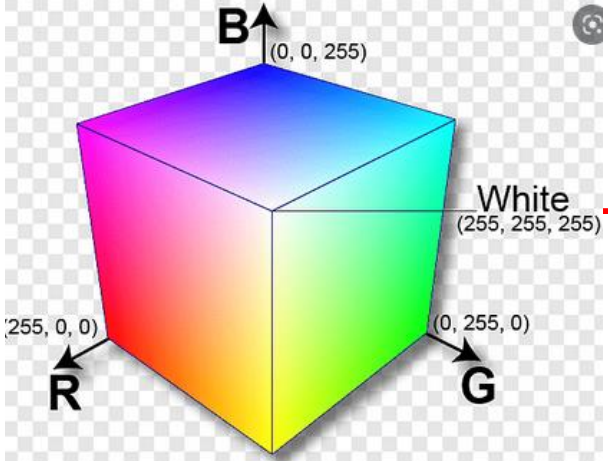


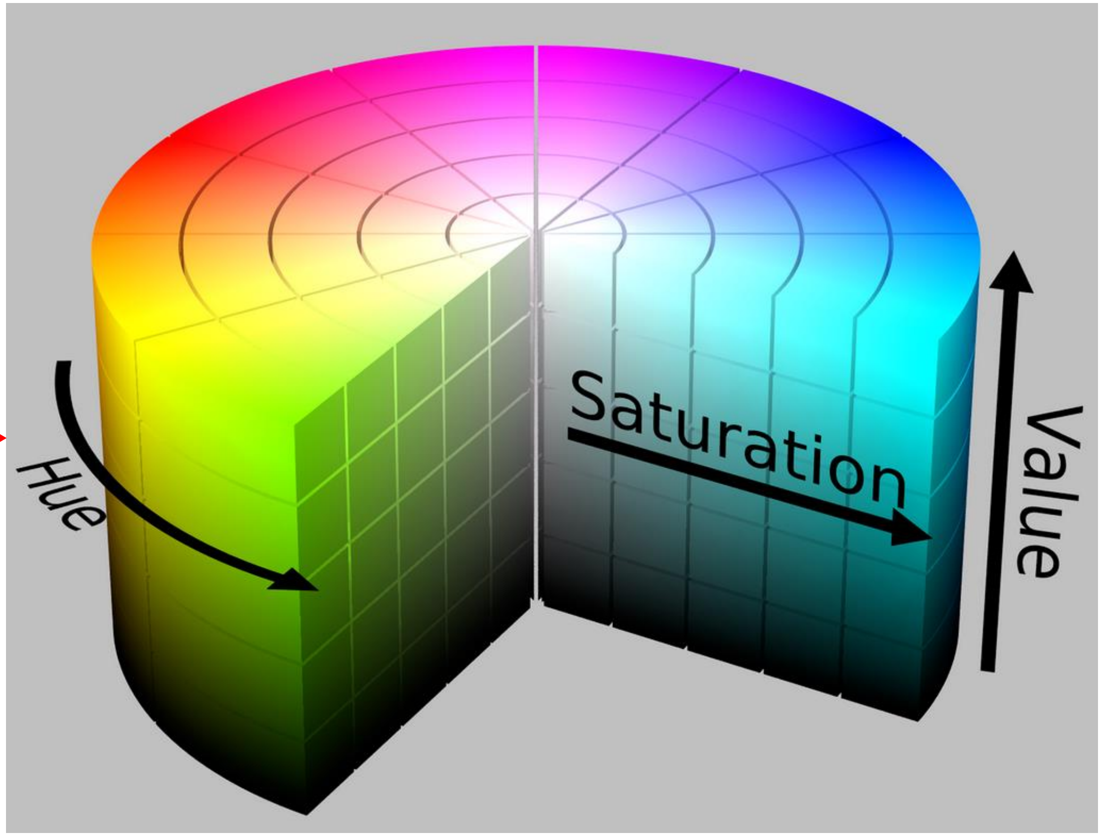
10 x 10 cm² sample results in ca. 5000 x 5000 pixel area.

→ 1 pixel = 20µm

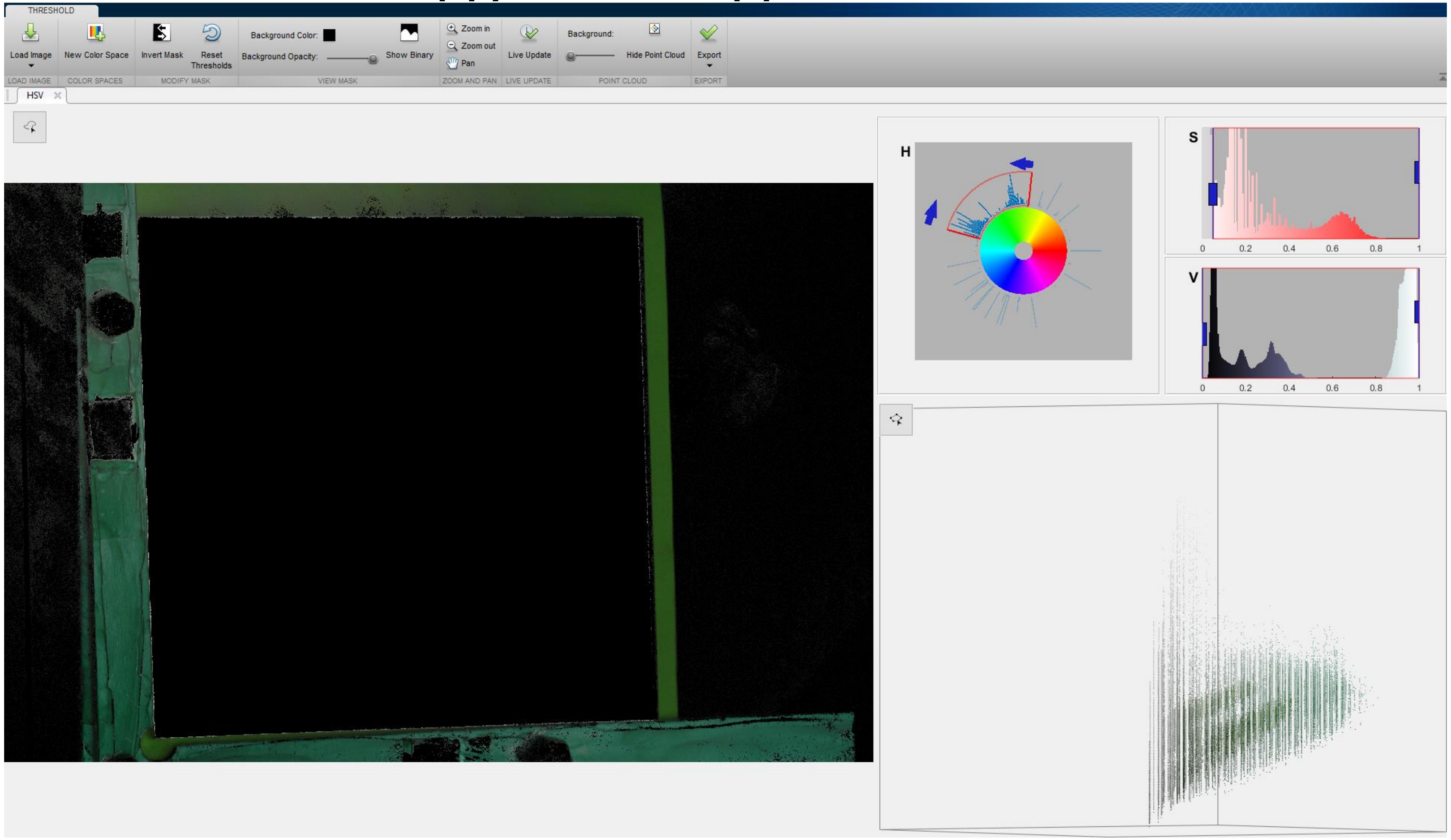
Methodology – Image Treatment

To filter out interesting area transform RGB to HSV color space

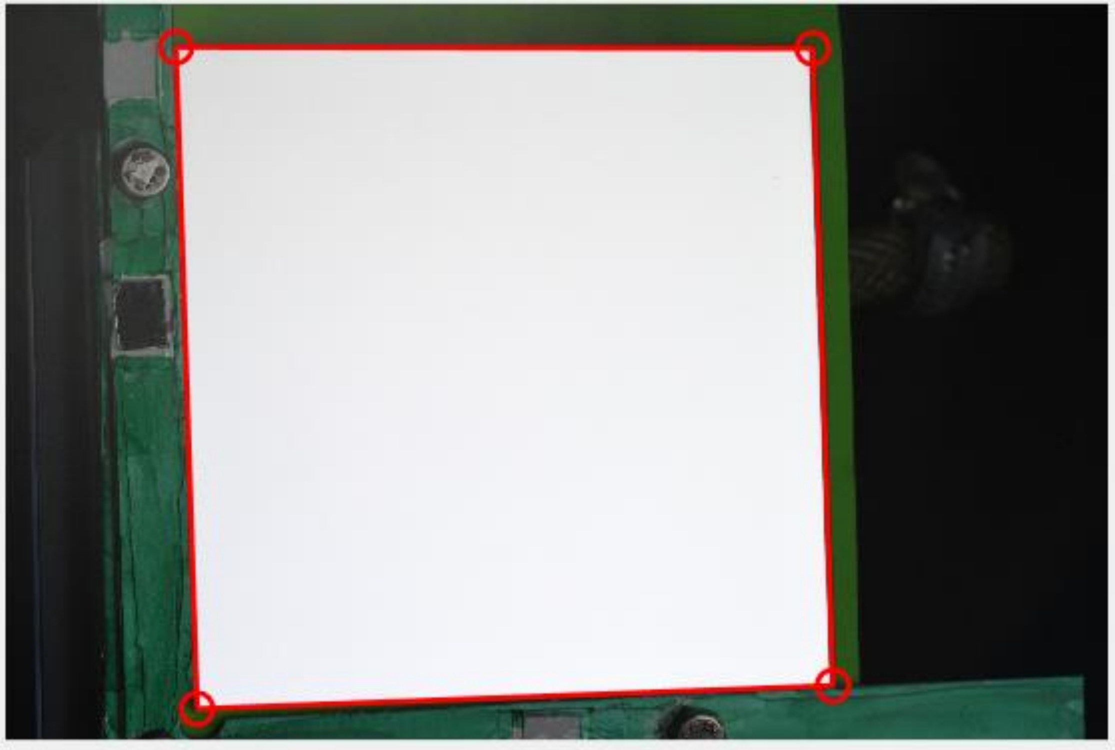




Methodology – image treatment



Methodology – image treatment

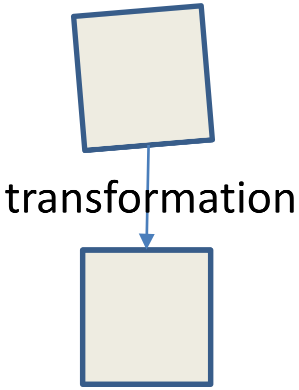


Next step is to detect the corner points of the large inner black area, assuming that it is a tetragon.

Methodology – image treatment

Transformation from tetragon to square to correct for the distortion and crop.

Aged image (AI), foto of a sample type in ist aged state.

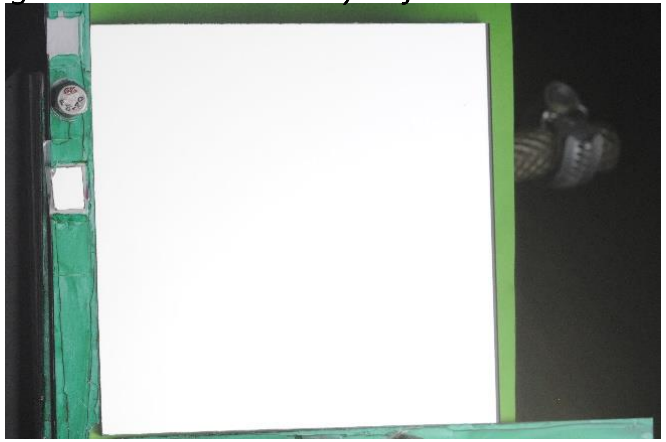


Aged image (AI) cropped and transformed

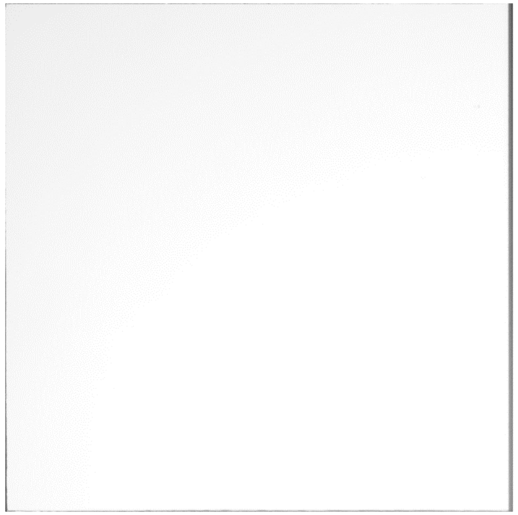
Problem: What is defect, what is shadow or coating or initial defect?

Methodology – image treatment

Reference image (RI), foto of a certain sample type in its original state without any defects or corrosion.



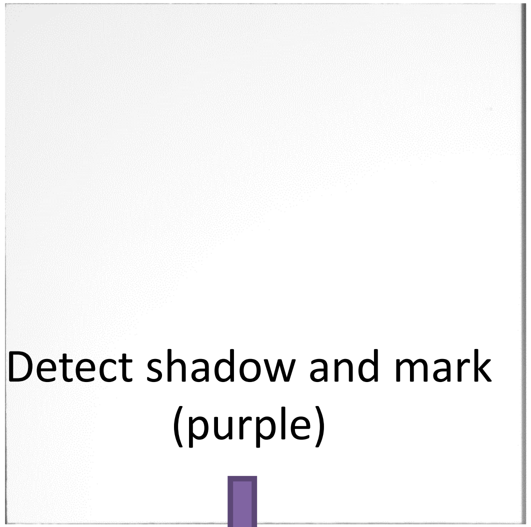
Aged image (AI), foto of a sample type in ist aged state.



Reference image (RI) cropped and transformed

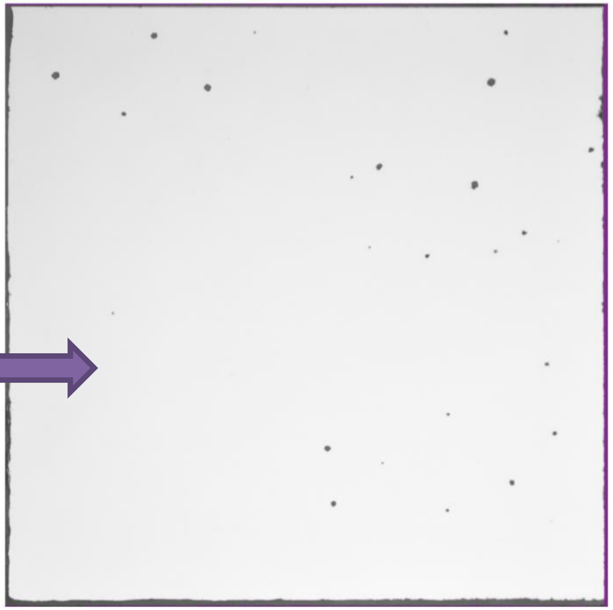
Methodology – image treatment

Aged image (A) cropped and transformed

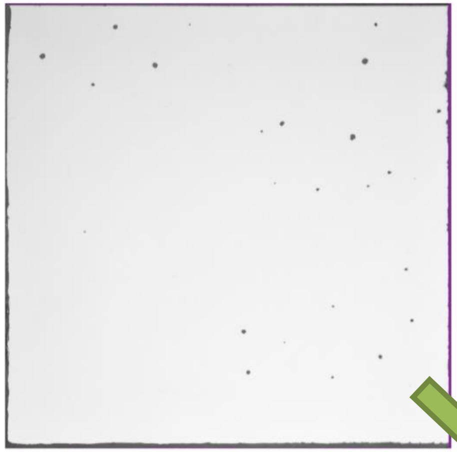


Detect shadow and mark (purple)

Burn shadow mask on aged image as well

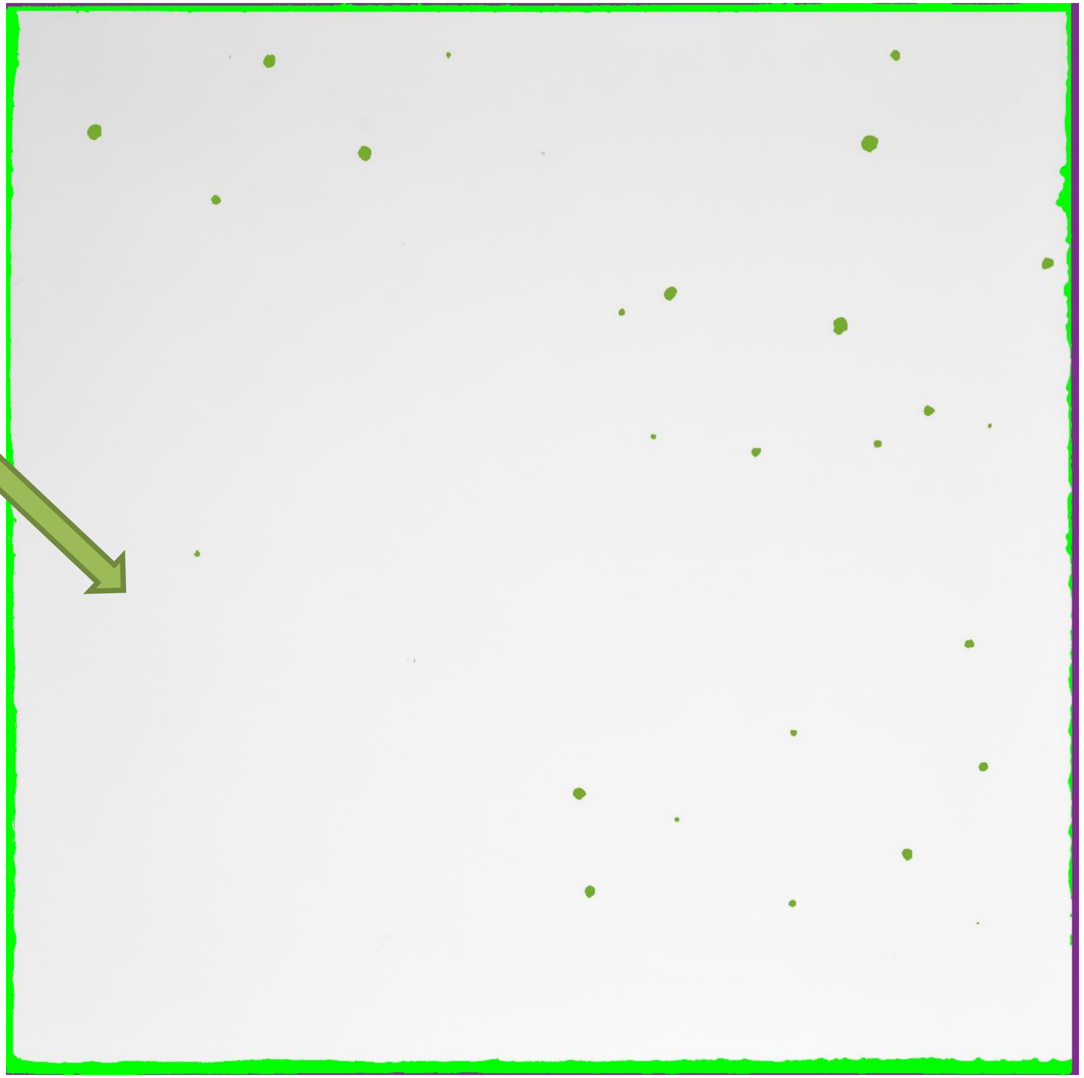


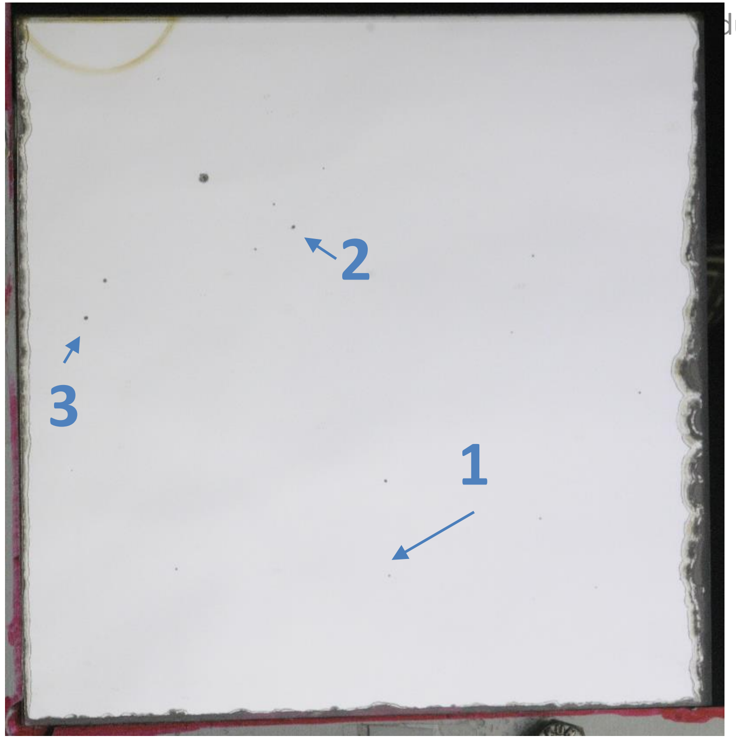
Methodology – image treatment

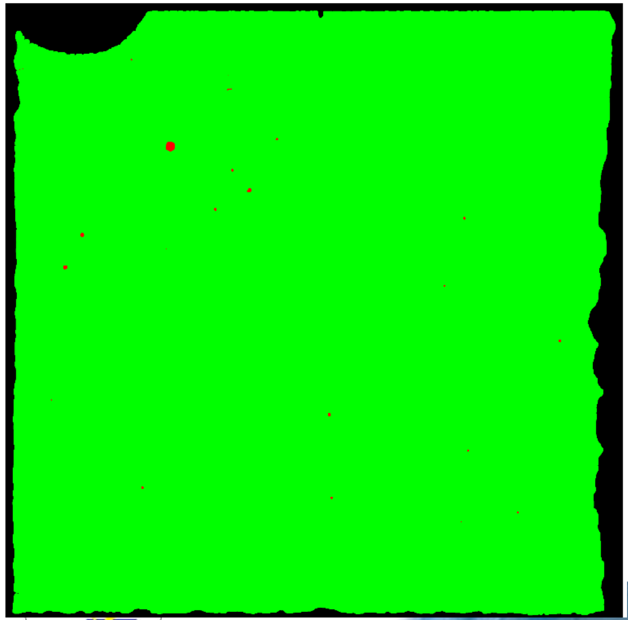


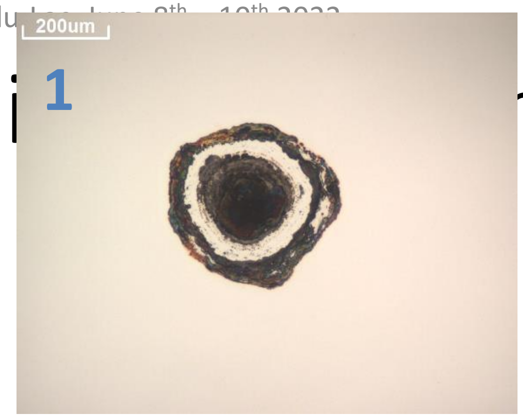
Divide Aged image (AI) by Reference Image (RI) and detect every pixel with less than certain brightness ratio of initial brightness as corrosion.

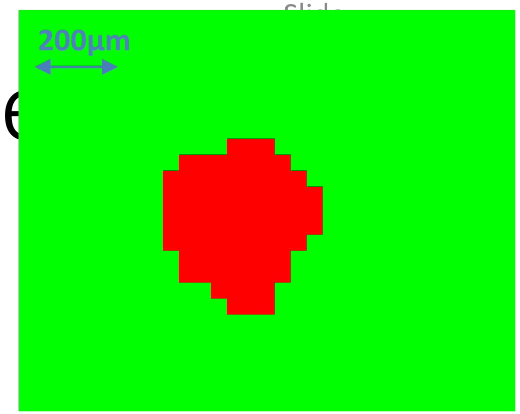
Inner corrosion (dark green) and edge corrosion (light green)

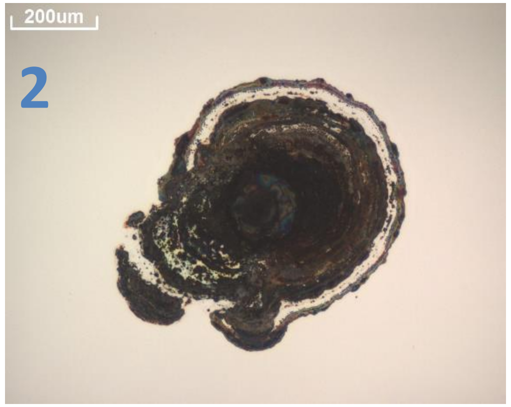


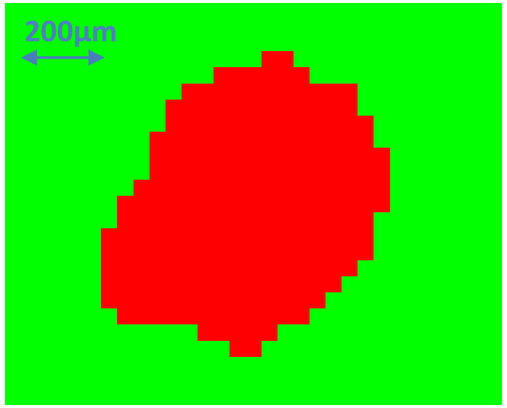

2
3
1



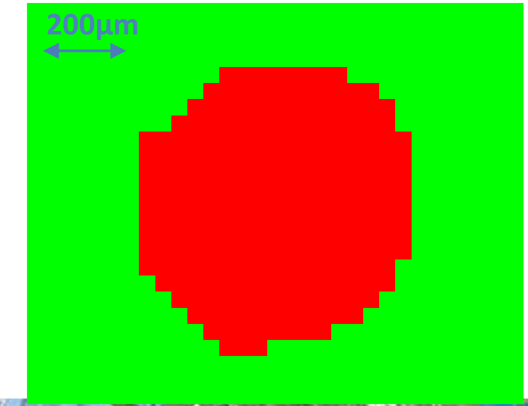

200um
1


200µm


200um
2

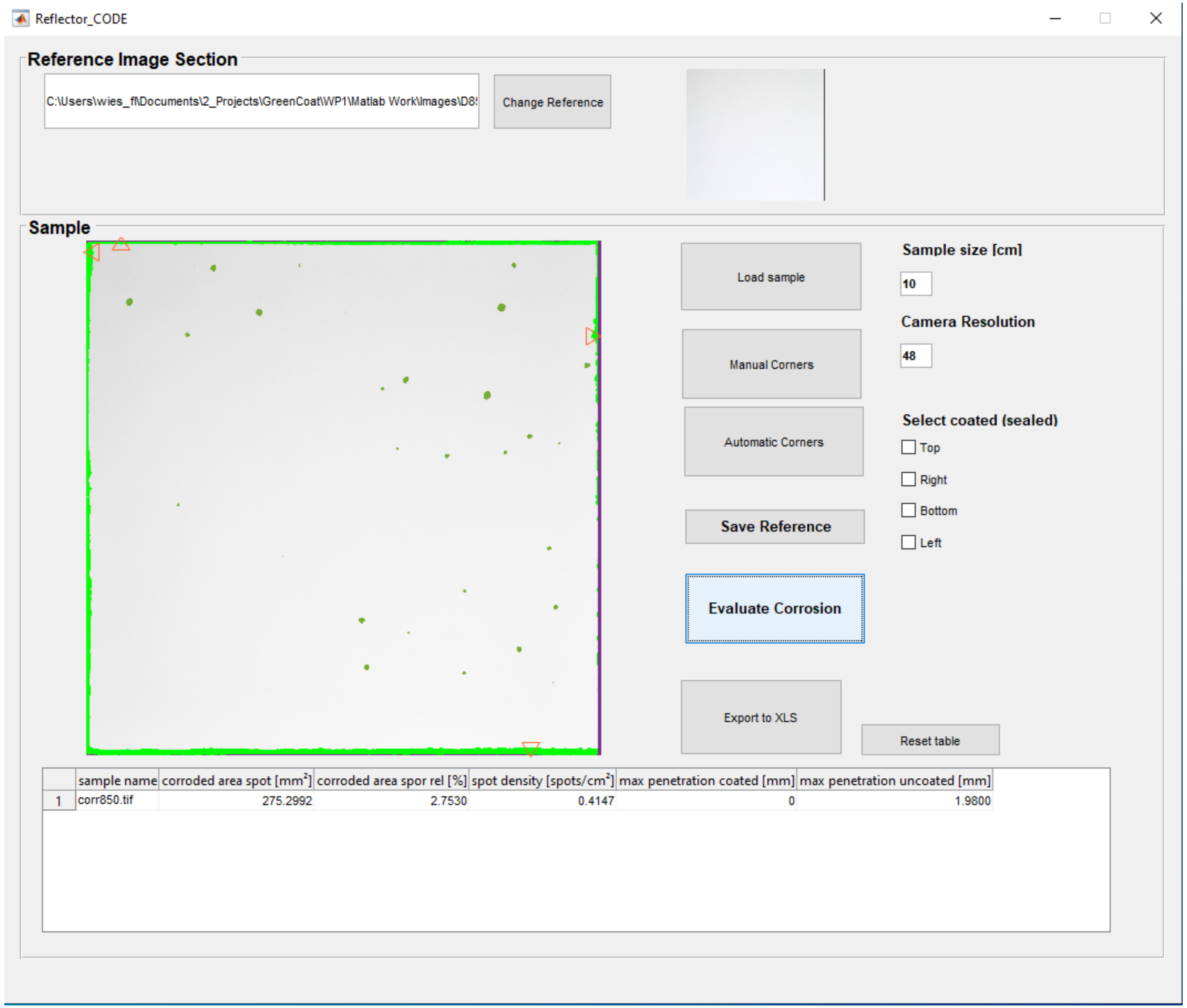

200µm


200um
3


200µm

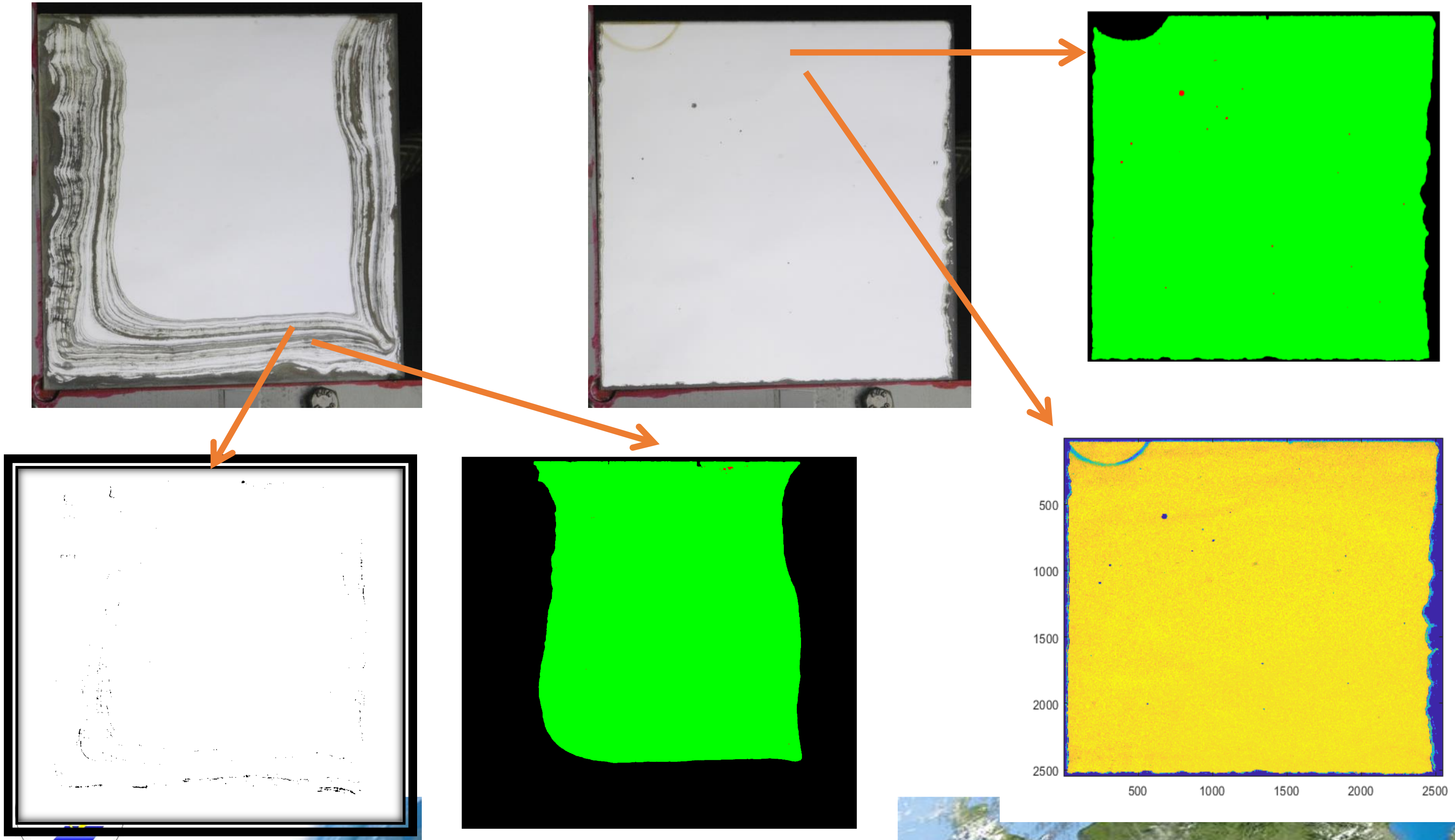
GUI:

- Simple selection of RE and corresponding AI
- Adapt basic parameters like sample size and cam res → should be automated as well.
- Selection of the coated edges.
- Marking of maximum edge penetration.
- Export important parameters in a table.

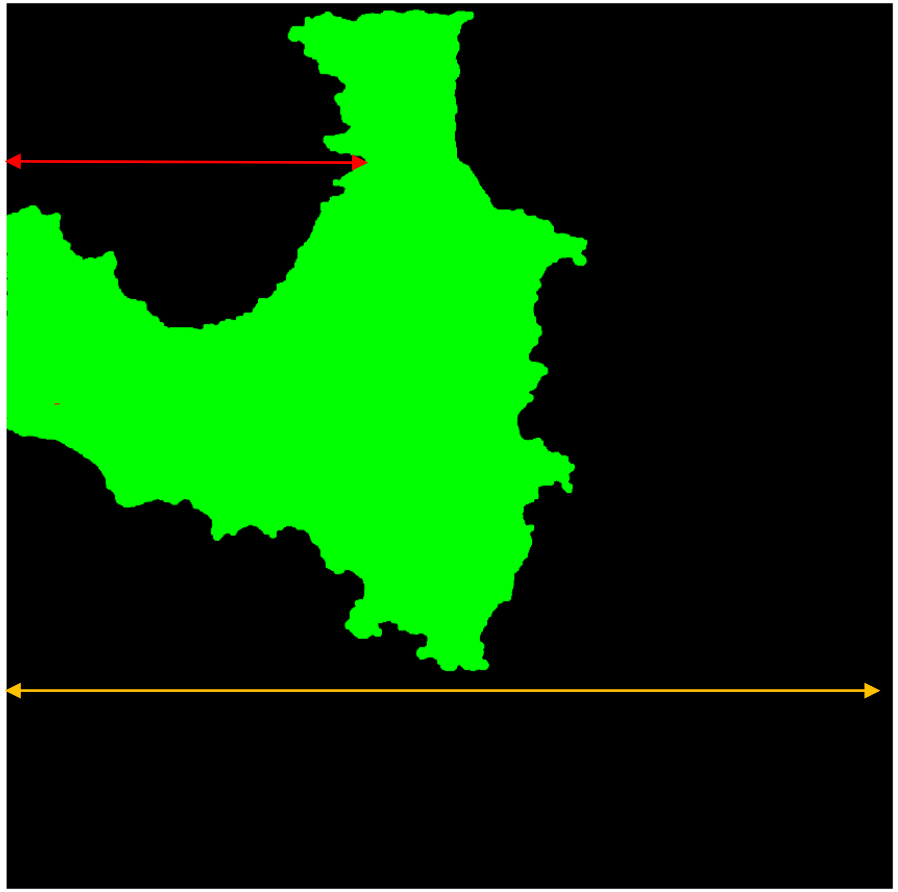


Example Pictures

4. Edge-threshold and inclusions



High Degradation Rates



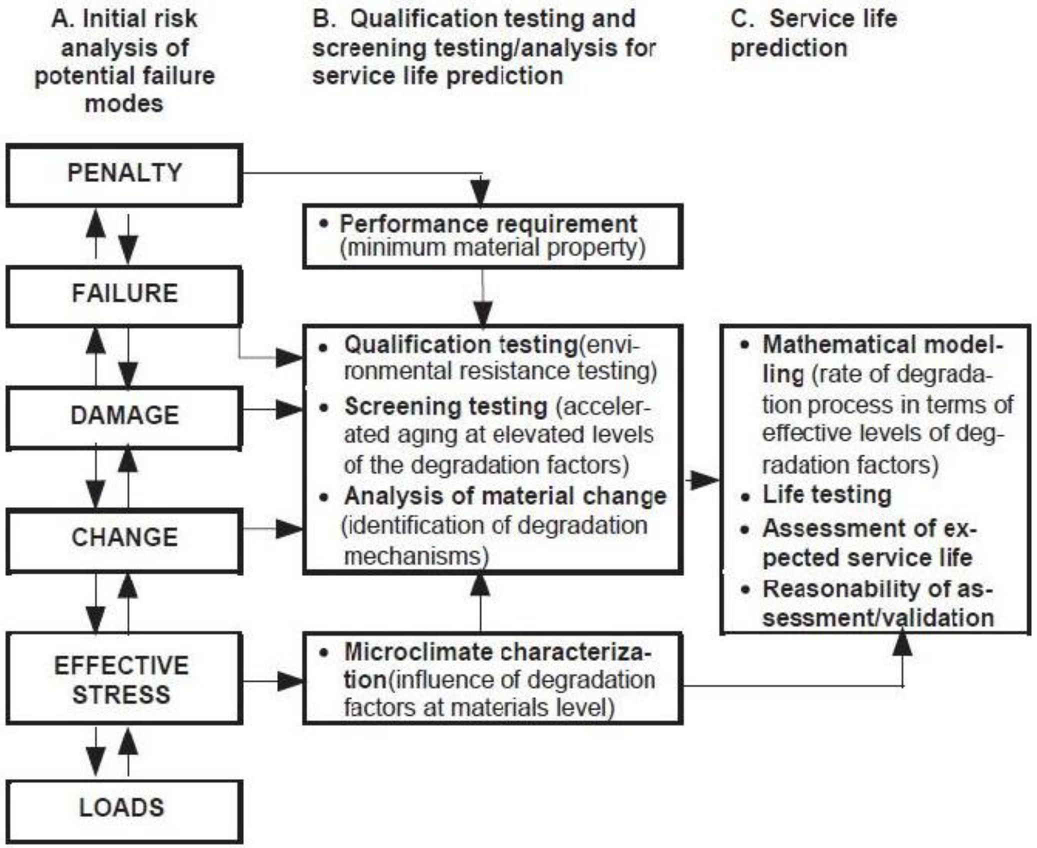
Best solution not clear so far.

Durability modeling method and lifetime extrapolation

E. Le Baron CEA

Durability modeling method and lifetime extrapolation :

IEA Task 27: predictive failure modes and effect analysis (FMEA) for service life prediction from accelerated life test results



- ***PENALTY*** is the level at which an assessment is made of the economic effects of a component failure➔ set a reliability level that must be maintained for a given number of years.
- ***FAILURE*** is the level at which performance requirements are determined. If the requirements are not fulfilled, the particular component or part of component is regarded as having failed.
- ***DAMAGE*** describes the stage of failure analysis at which various types of damage, each capable of resulting in failure, can be identified.
- ***CHANGE*** is related to the change in the material composition or structure that can give rise to the damage of the type previously identified.
- ***EFFECTIVE STRESS*** is the level at which various factors in the microclimate, capable of being significant for the durability of the component and its materials can be identified.
- ***LOADS*** is the level that describes the macro-environmental conditions (climatic, chemical, mechanical), and which is therefore a starting point for description of the microclimate or effective stress as above.

B. Carlsson, K. Moller, M. Köhl, M. Heck, S. Brunold, U. Frei, J.-C. Marechal, and G. Jorgensen, "The applicability of accelerated life testing for assessment of service life of solar thermal components," Solar Energy Materials and Solar Cells, vol. 84, no. 14, pp. 255 – 274, 2004

Durability modeling method and lifetime extrapolation :

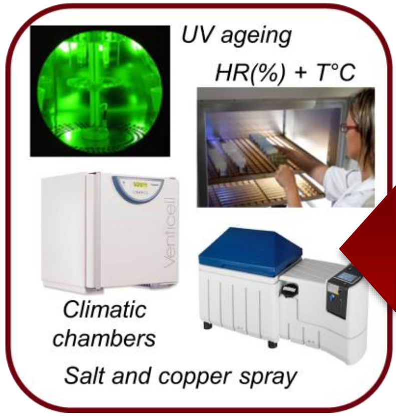
Aging laws → Lifetime extrapolation + Validate test methodologies

Kinetics Parameters

Degradation mechanisms

Accelerated tests

Artificial ageing



Characterizations

Reflectometer, Microscope, Colorimeter, FTIR-ATR…

Correlations ?

Site exposure

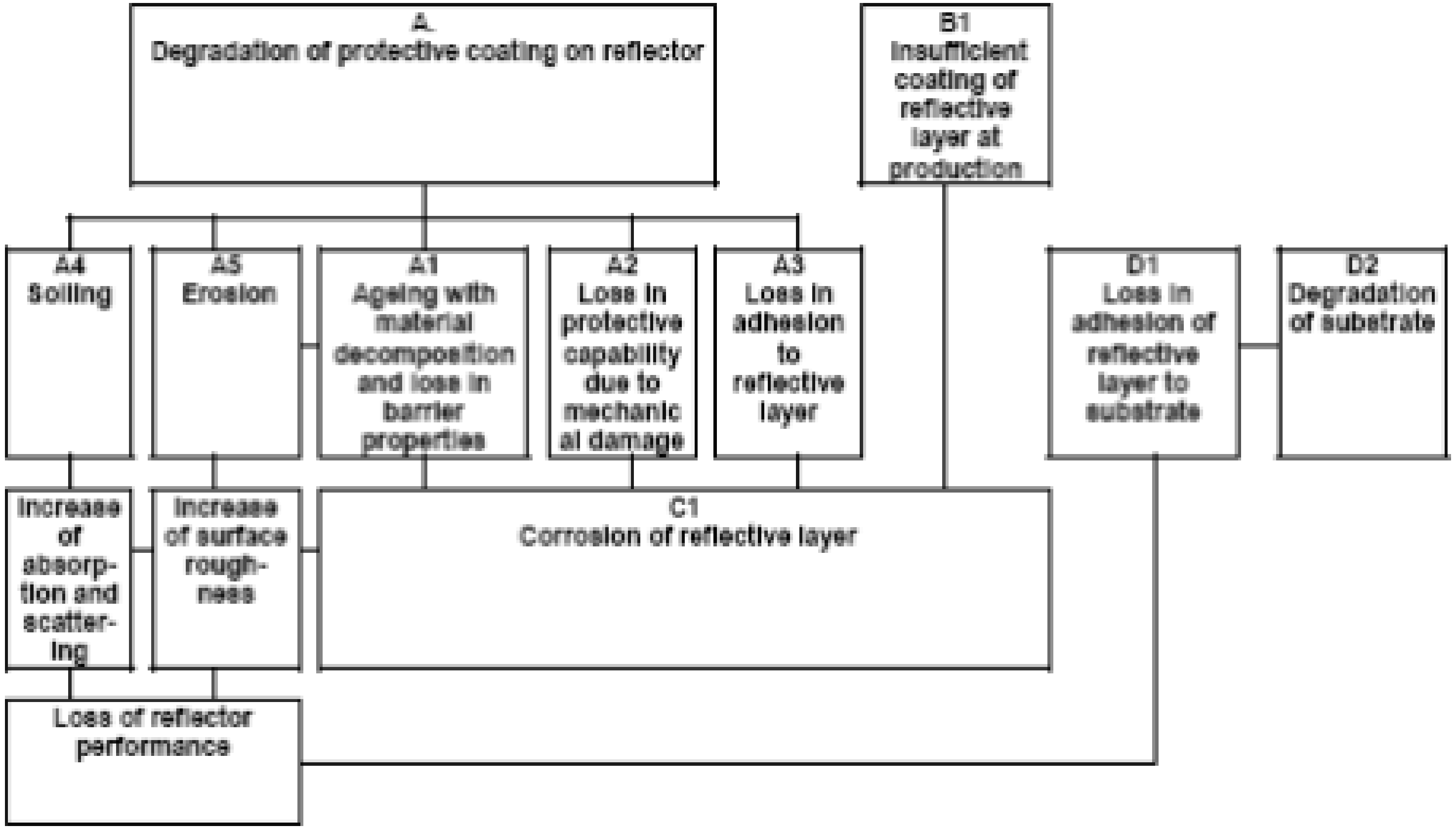
Natural ageing

Example of reflectors :

Durability modeling method and lifetime extrapolation

Durability modeling method and lifetime extrapolation :

Representation of failure modes and associated degradation mechanisms for reflectors



M. Köhl, "Performance, durability and sustainability of advanced windows and solar components for building envelopes," Final Report Task 27-B, Fraunhofer Institute for Solar Energy Systems for PTJ Jülich, 2007.

Example of solar reflectors :

Durability
= performance

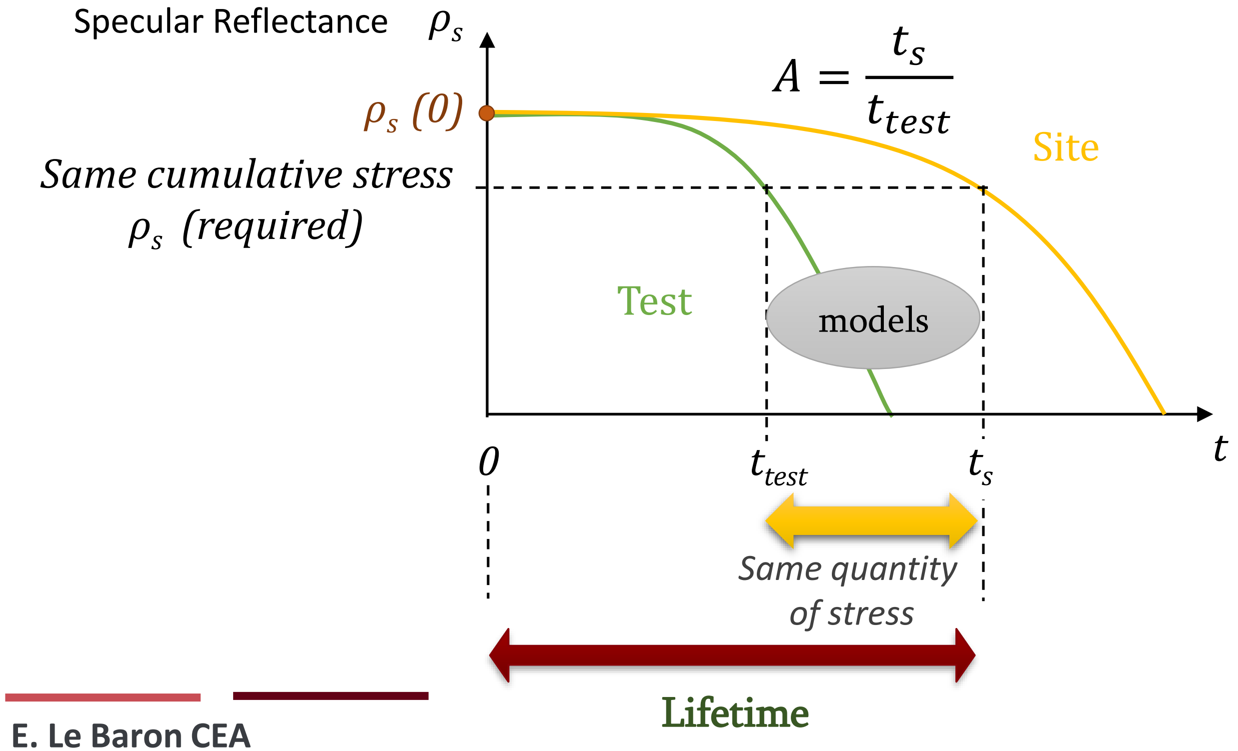
≠

aging
↘ performance

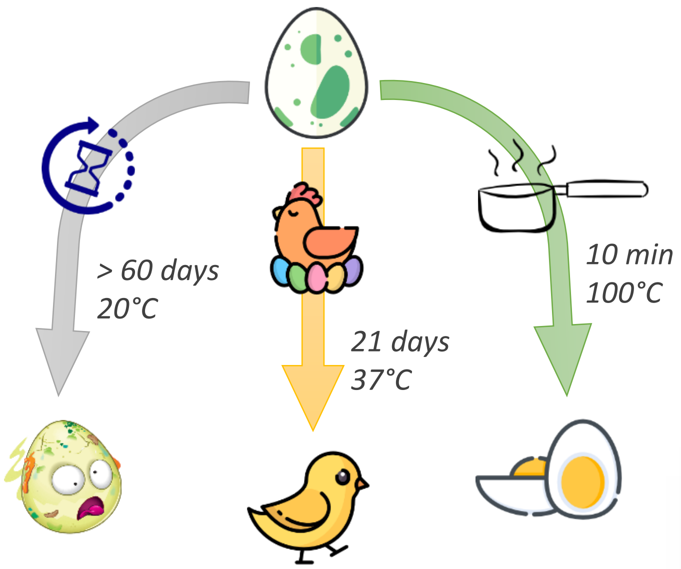
Natural site

Accelerated test

↗ level of stress ⟷ ↗ degradation rate



Representativeness of aging



Durability modeling method with one acceleration stress factor:

Acceleration stress factor : $A = \frac{t_s}{t_{test}}$? Lifetime = unknown

Temperature
Arrhenius

$$\boldsymbol{k} = \gamma . exp\left(\frac{E_a}{R.T}\right) \quad \mathrm{a_T} = \frac{\mathrm{t_s}}{\mathrm{t_{test}}} = \exp\left(\frac{-\mathrm{E_a}}{\mathrm{R}}\left(\frac{1}{\mathrm{T_t}} - \frac{1}{\mathrm{T_s}}\right)\right)$$

Humidity
Peck
Eyring

$$\boldsymbol{k} = (HR)^n . exp\left(\frac{E_a}{R.T}\right) \quad a_{RH} = \left(\frac{RH_s}{RH_t}\right)^n \cdot exp\left(\frac{E_a}{R}\left[\frac{1}{T_s} - \frac{1}{T_t}\right]\right)$$

$$\boldsymbol{k} = C. exp\left(\frac{E_a}{R.T} + \frac{\beta}{HR}\right) \quad a_{T,RH} = exp\left(\frac{E_a}{R}\left[\frac{1}{T_s} - \frac{1}{T_t}\right] + \beta\left[\frac{1}{RH_s} - \frac{1}{RH_t}\right]\right)$$

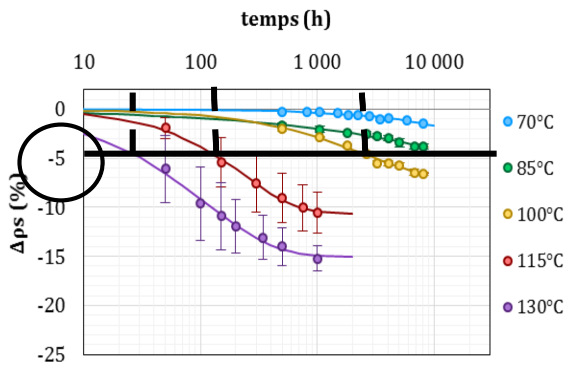
Irradiation
Reciprocity
(280-400 nm)

$$\boldsymbol{k} = \left(\frac{I_t}{I_s}\right)^p$$

a : Acceleration stress factor
t_s : time on site
t_{test}: time in test
E_a : Activation energy in $J \cdot mol^{-1}$
R : perfect gas constant in $J \cdot mol^{-1} \cdot K^{-1}$
γ : frequency factor in h^{-1}
n : Peck coefficient
HR : relative humidity
T : temperature in K
β : Eyring coefficient
p : Schwarschild's coefficient
Irr : Irradiation, in $W \cdot m^{-2}$

C. Avenel, O. Raccurt, J.-L. Gardette, and S. Therias, "Review of accelerated ageing test modelling and its application to solar mirrors," Solar Energy Materials and Solar Cells, vol. 186, pp. 29 – 41, 2018.

Durability modeling method of solar mirrors with one acceleration stress factor:



Performance criteria of mirror degradation => loss of functional property => $\Delta\rho s = -5\ \%$

One acceleration stress factor Temperature dependence :

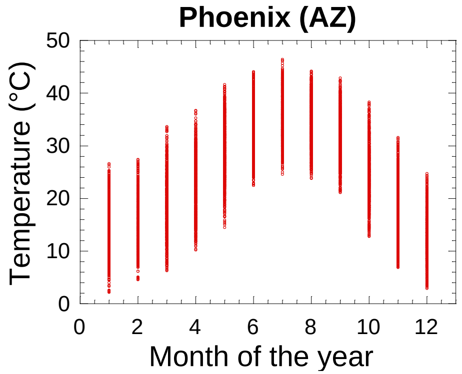
→ degradation = Arrhenius law $k = \gamma . \exp\left(\frac{-E_a}{RT}\right)$

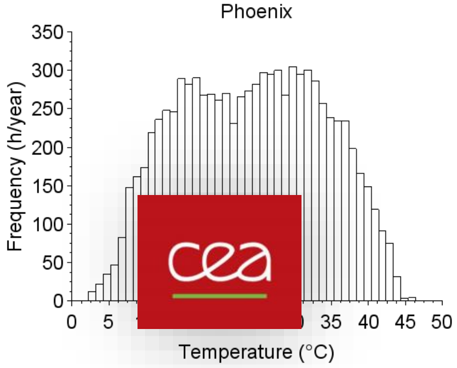
Accelerated tests at different temperatures

Acceleration factor : $$a_T = \frac{t_s}{t_t} = exp\left(\frac{-E_a}{R}\left(\frac{1}{T_t} - \frac{1}{T_s}\right)\right) \quad [1]$$

Where t_s :time of service
t_t : time of accelerated test
T_s : temperature on site
T_t : temperature of test $T_t > T_s$

T_s is not constant



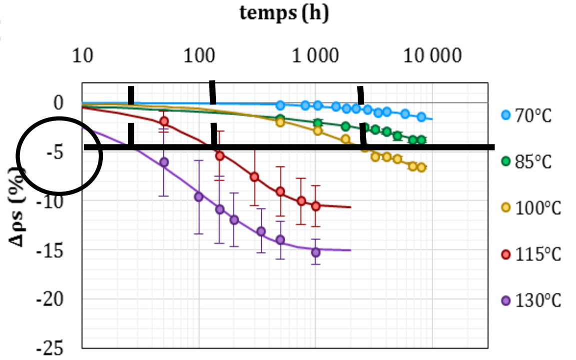


Graphical method : $$ln(t_t) = \frac{E_a}{R} \frac{1}{T_t} + ln(t_s) - \frac{E_a}{R.T_s}$$

$y = a . x + b$

[1] M. Köhl, B. Carlsson, G. Jorgensen, and A. W. Czanderna, Performance and durability assessment: Optical Materials for Solar Thermal systems. Elsevier Science, 2004

Durability modeling method of solar mirrors with a thermal acceleration stress factor:

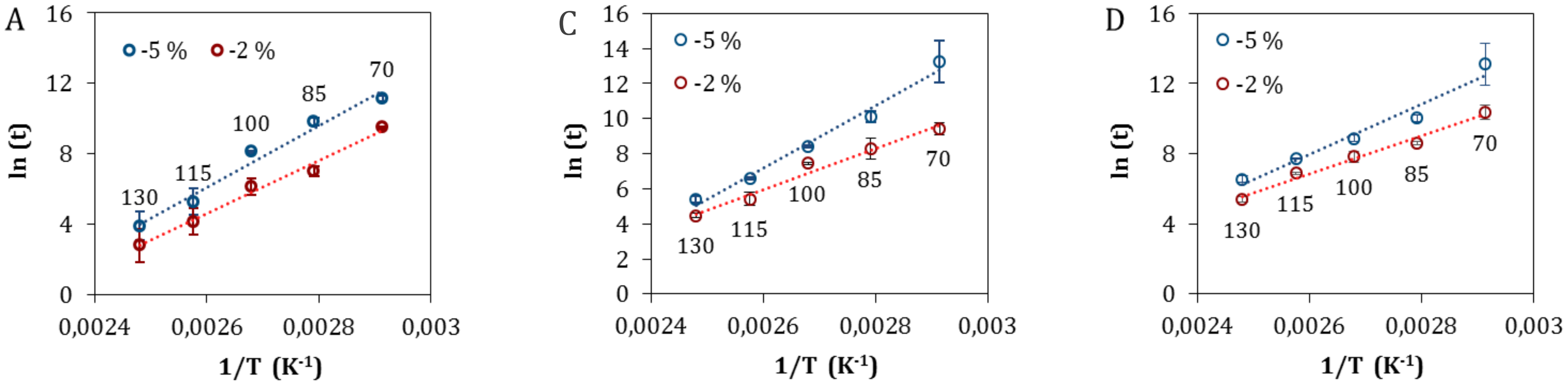


Determination of the apparent activation energy Ea for **temperature tests**

$$\ln(t_t) = \frac{E_a}{R} \cdot \frac{1}{T_t} + \ln(t_s) - \frac{E_a}{R.T_s}$$

Graphical method :

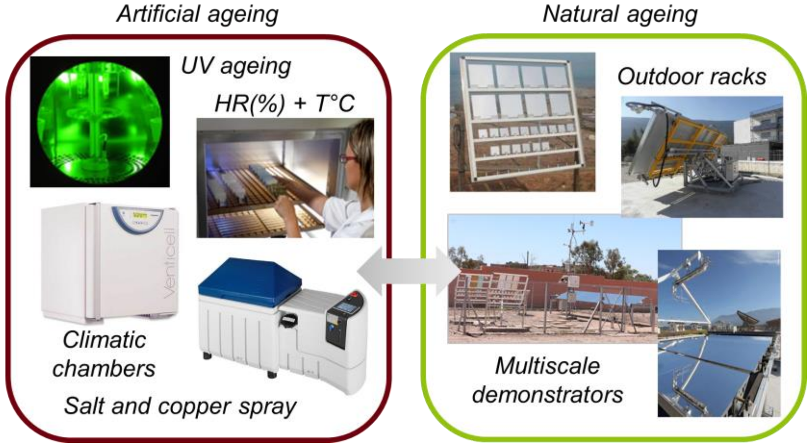
$$y = a \cdot x + b$$



mirror	Ea mean (kJ/mol)
A	136
C	133
D	94

Durability modeling method of solar mirrors with one acceleration stress factor:

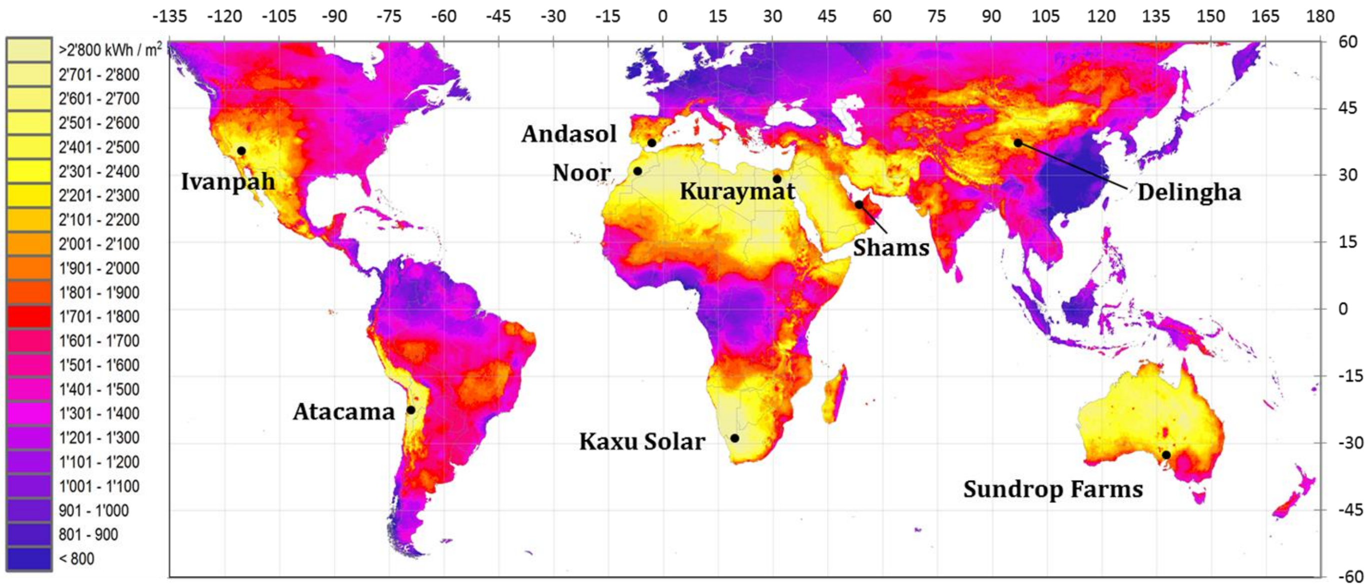
Correlation between outdoor and indoor aging thanks to multi-sites exposure on different scale and different climatic chambers



Modeling approach to take into account the variation of temperature on sites :

1. Site selection
2. Meteorological data from Meteonorm® software
3. Activation Energy calculation from accelerated tests
4. Modeling using Scilab
5. T_{eff} calculation and comparison with T_{mean}
6. Effect of taking account T_{eff} instead of T_{mean} on the Acceleration factor

Durability modeling method of solar mirrors with a thermal acceleration stress factor:

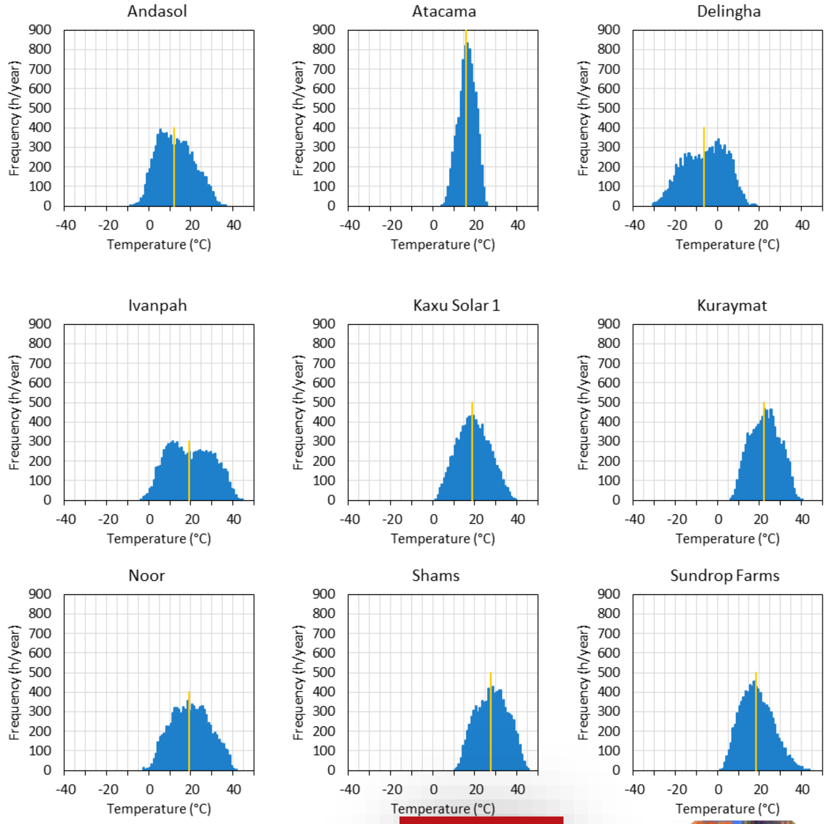


Site	T moy
Andasol	12.7
Atacama	16.3
Delingha	-5.9
Ivanpah	19.7
Kaxu Solar	19.3
Kuraymat	22.6
Noor	19.9
Shams	**28.2**
Sundrop Farms	18.7

Effective temperature [1] defined according to Arrhenius

$$T_{eff} = \frac{-E_a}{R.\ln\left[\frac{1}{t}\int_0^t \exp\left(\frac{-E_a}{R.T}\right)dt\right]}$$

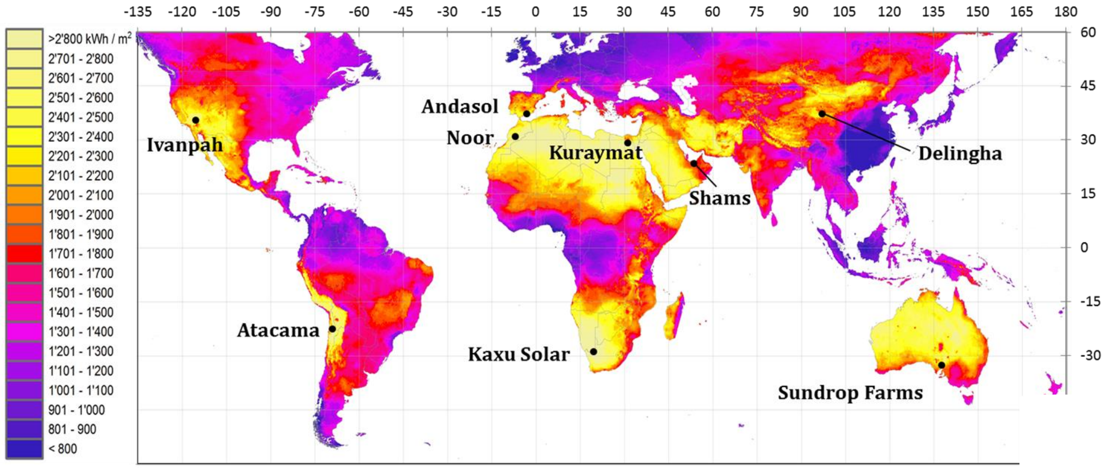
Temperatures from Meteonorm® 7



E. Le Baron CEA

[1] M. Tencer, J. S. Moss and T. Zapach. IEEE Transactions on Components and Packaging Technologies, 2004, 27, 602-607.

Durability modeling method of solar mirrors with a thermal acceleration stress factor:

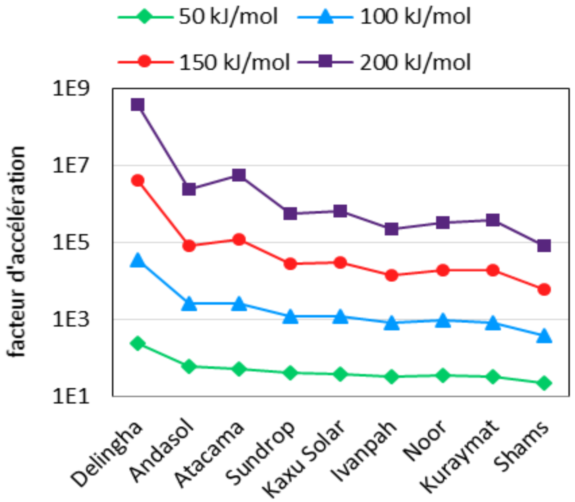


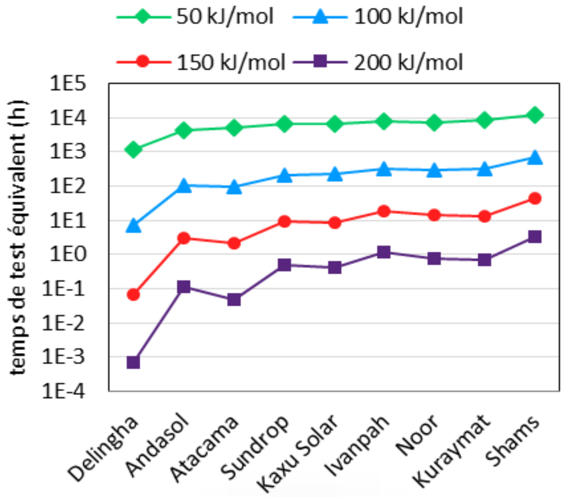
$$a_T = exp\left[\frac{-Ea}{R}.\left(\frac{1}{T_{test}} - \frac{1}{T_s}\right)\right]$$

$T_{test} = 85°C$

$t_s = 30$ years

$$t_{eq,Teff} = \frac{30\ years}{a_{Teff}}$$





Thermal effect especially for a very cold site

Durability modeling method of solar mirrors with a thermal acceleration stress factor:

Conclusion of modeling approach to take into account the variation of temperature on sites :

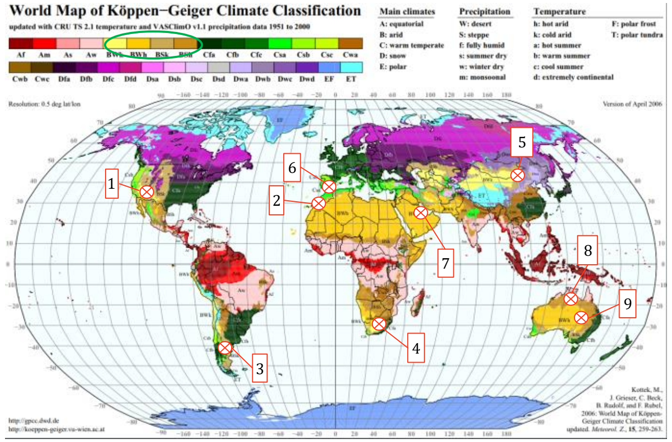
1. 9 Sites selection
2. Meteorological data from Meteonorm® software
3. Activation Energy calculation
4. Modeling Arrhenius law using Scilab
5. T_{eff} calculation and comparison with T_{mean}
6. Calculation of time of accelerated test equivalent to 30 years on site

$$T_{eff} = \frac{-E_a}{R\ln\left[\frac{1}{t}\int_0^t exp\left(\frac{-E_a}{R.T}\right)dt\right]}$$

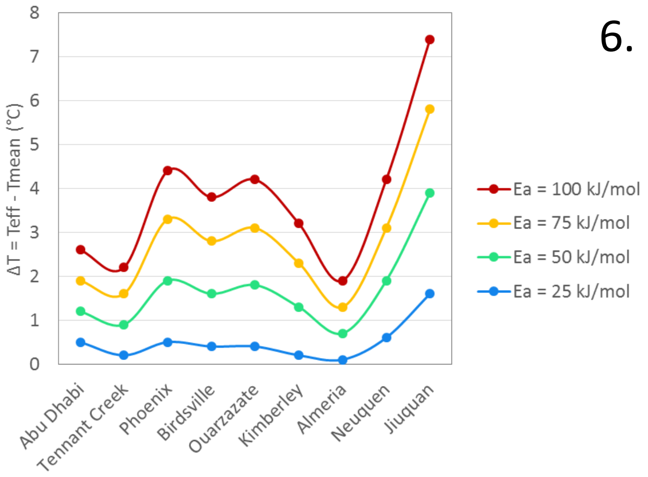
Equivalent testing time to simulate 30 years during accelerated test is :

- dependent on site temperature
- dependent on activation energy
- longer using T_{eff} than T_{mean} → importance of T_{eff} calculation

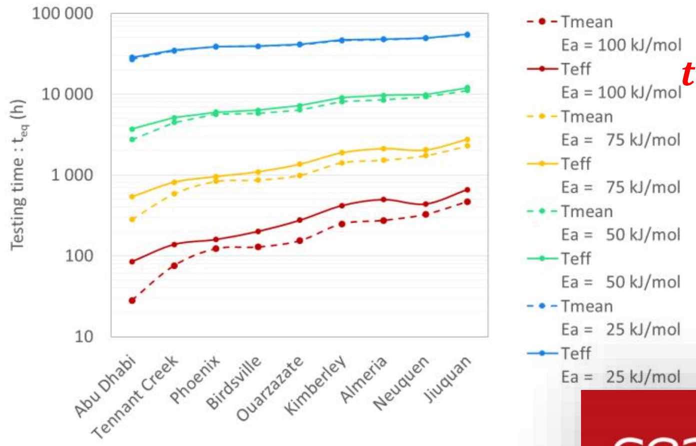
1.



5.



6.



$$t_{eq,Tmean} = \frac{30\ years}{a_{Tmean}}$$

$$t_{eq,Teff} = \frac{30\ years}{a_{Teff}}$$

$$T_t = 85\ °C$$
$$t_s = 30\ years$$

"Accelerated aging test modeling applied to solar mirrors", Avenel, C.; Raccurt, O.; Gardette, J.-L.; Therias, S'., in npj 2019'.

Durability modeling method of solar mirrors with one acceleration stress factor:

Acceleration stress factor : $A = \frac{t_s}{t_{test}}$? Lifetime = unknown

Humidity
Peck
Eyring

$$t = (HR)^{n} . exp\left(\frac{E_a}{R.T}\right) \quad a_{RH} = \left(\frac{RH_s}{RH_t}\right)^{n} \cdot exp\left(\frac{E_a}{R}\left[\frac{1}{T_s} - \frac{1}{T_t}\right]\right)$$

$$t = C. exp\left(\frac{E_a}{R.T} + \frac{\beta}{HR}\right) \quad a_{T,RH} = exp\left(\frac{E_a}{R}\left[\frac{1}{T_s} - \frac{1}{T_t}\right] + \beta\left[\frac{1}{RH_s} - \frac{1}{RH_t}\right]\right)$$

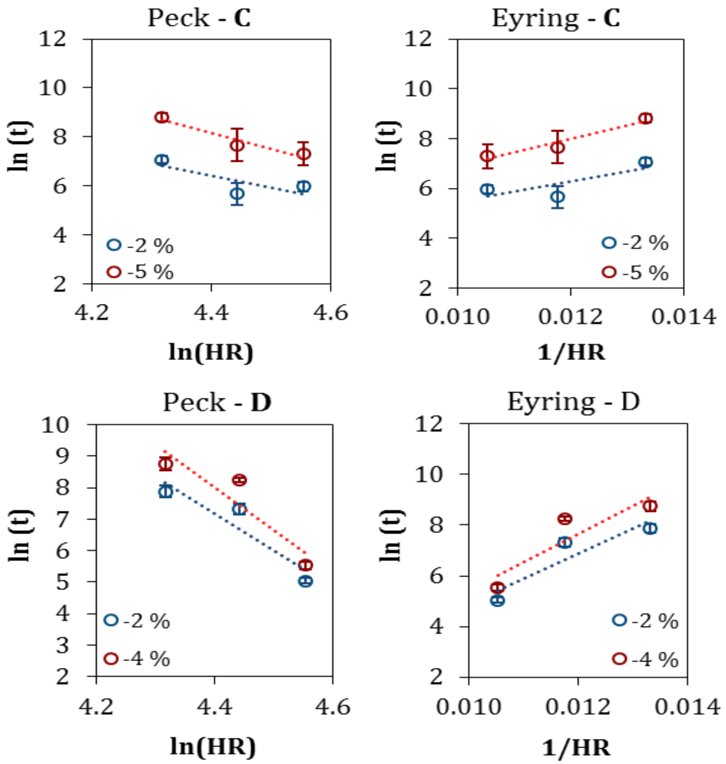
A : Acceleration stress factor
t_s : time on site
t_{test}: time in test
E_a : Activation energy in $J{\cdot}mol^{-1}$
R : perfect gas constant in $J{\cdot}mol^{-1}{\cdot}K^{-1}$
γ : frequency factor in h^{-1}
n : Peck coefficient
HR : relative humidity
T : temperature in K
β : Eyring coefficient
p : Schwarschild's coefficient

C. Avenel, O. Raccurt, J.-L. Gardette, and S. Therias, "Review of accelerated ageing test modelling and its application to solar mirrors," Solar Energy Materials and Solar Cells, vol. 186, pp. 29 – 41, 2018.

Durability modeling method of solar mirrors with a humidity acceleration stress factor:

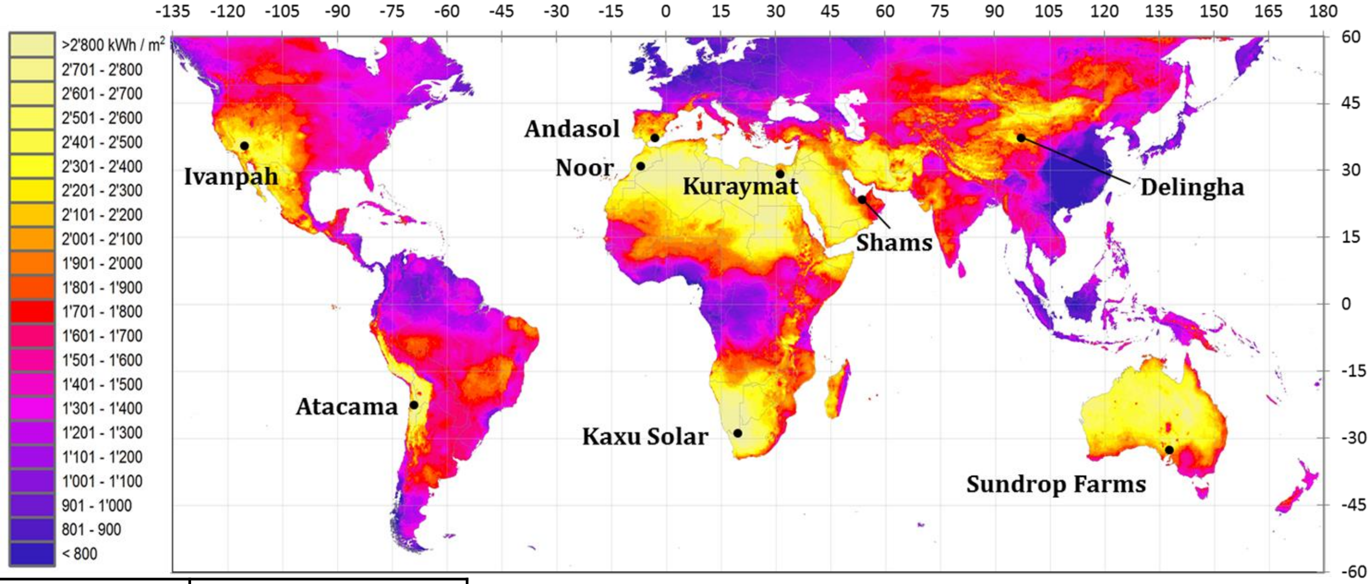
- Determination of the apparent activation energy Ea for **Damp Heat tests**
  - Peck coefficient n $$ln(t\ ) = n.ln(RH) + \left(\frac{E_{a(RH)}}{R.T}\right)$$
  - Eyring coefficient β $$ln(t\ ) = \beta.\frac{1}{RH} + \left(\frac{E_{a(RH)}}{R.T}\right) + ln(C)$$

Graphical method :

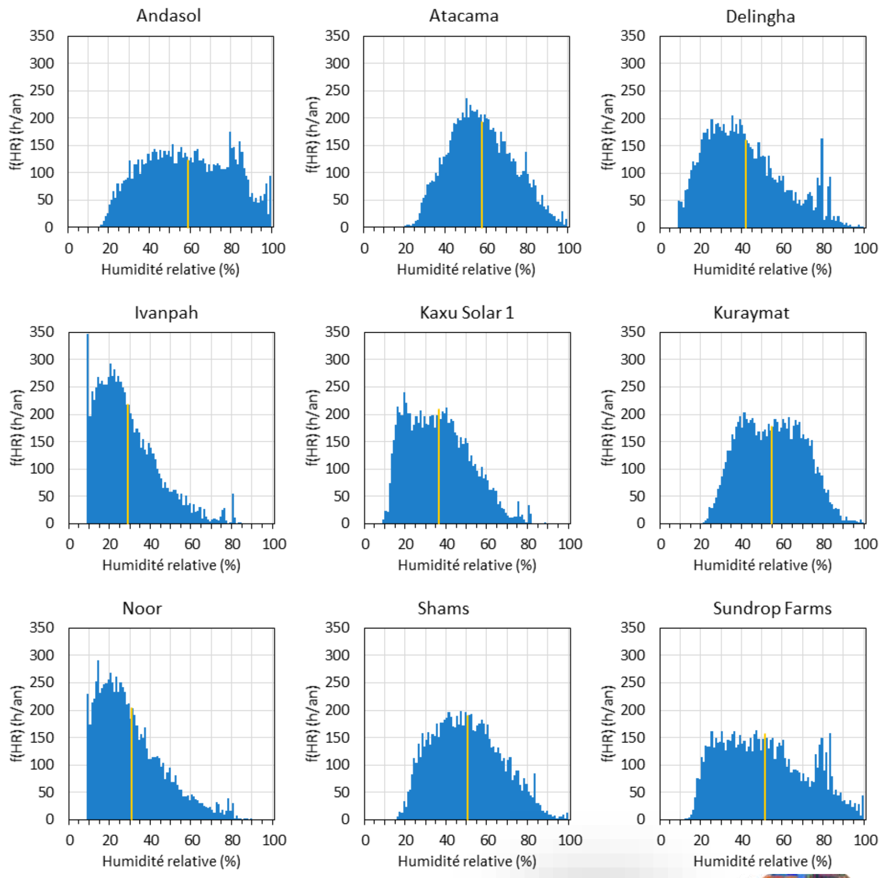


	Mirror	Mean
Ea kJ/mol	C	108
	D	162
n	C	-5.4
	D	-10.9
β %	C	544
	D	926

Durability modeling method of solar mirrors with a humidity acceleration stress factor:



Relative humidity from Meteonorm® 7

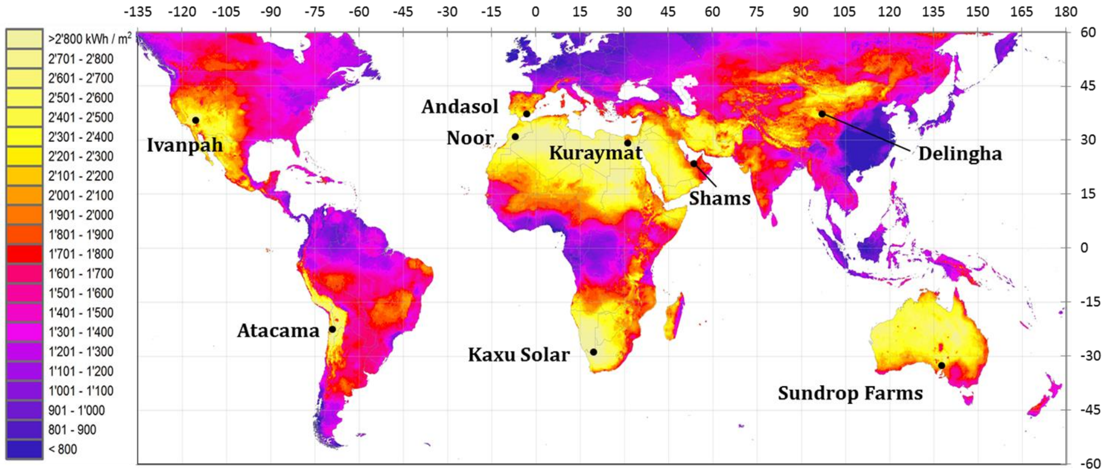


	RH mean %
Andasol	59
Atacama	58
Delingha	42
Ivanpah	29
Kaxu Solar 1	36
Kuraymat	55
Noor	31
Shams	50
Sundrop Farms	51

No effective humidity in the literature
➔ use mean Humidity

E. Le Baron CEA

Durability modeling method of solar mirrors with a humidity acceleration stress factor:



RH$_{test}$ = 85 %

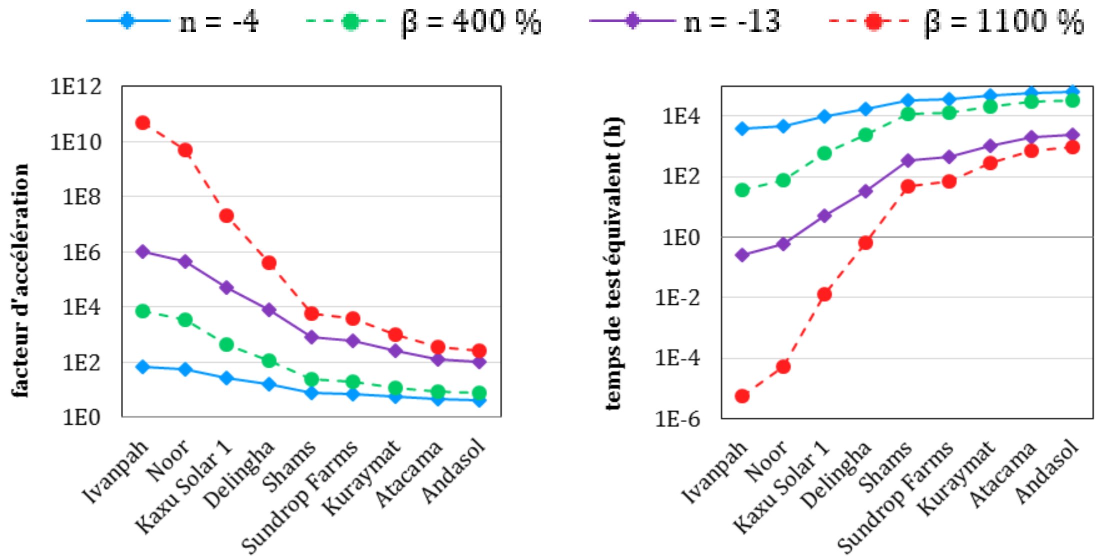
t$_s$ = 30 years

$$t_t = \frac{30\ years}{a_{RH}}$$

Damp Heat tests

Peck $\quad a_{HR} = \left(\frac{HR_{test}}{HR_s}\right)^n$

Eyring $\quad a_{HR} = exp\left[\beta\left(\frac{1}{HR_{test}} - \frac{1}{HR_s}\right)\right]$



- Accelerator stress factor and consistent t$_{test}$ for RHs ≥ 50% (Shams, Sundrop Farms, Kuraymat, Atacama, Andasol)
- Models diverge for RHs < 50%

Durability modeling method of solar mirrors with a humidity acceleration stress factor:

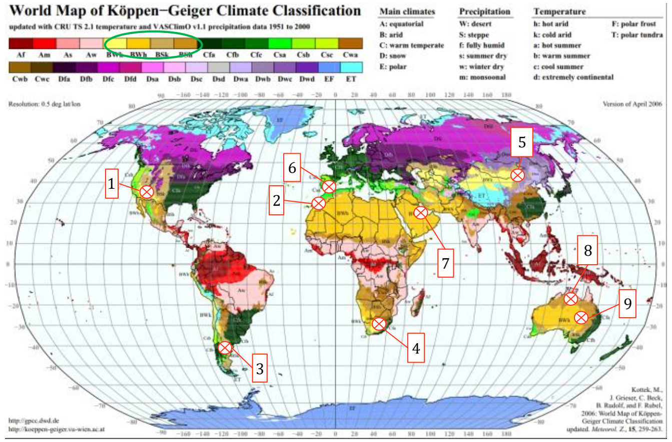
Conclusion of modeling approach to take into account the variation of humidity on sites :

1. 9 Sites selection
2. Meteorological data from Meteonorm® software
3. Activation Energy calculation
4. Modeling Peck /Eyring law using Scilab
5. RH_{mean}%
6. Calculation of time of accelerated test equivalent to 30 years on site

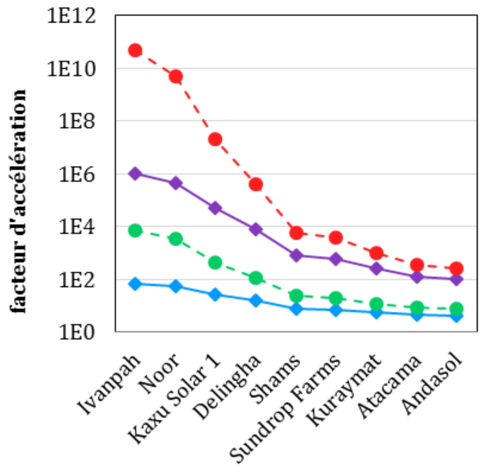
Equivalent testing time to simulate 30 years during accelerated test is :

- dependent on site humidity
- dependent on activation energy

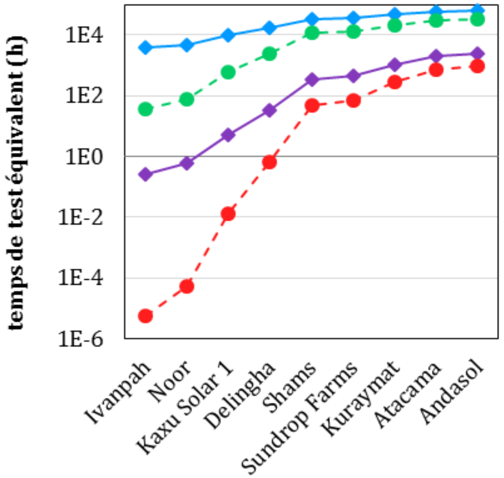
1.



5.



6.



$RH_s > 85\ \%$
$t_s = 30\ years$

"Accelerated aging test modeling applied to solar mirrors", Avenel, C.; Raccurt, O.; Gardette, J.-L.; Therias, S'., in npj 2019'.

Durability modeling method of solar mirrors/absorbers/glass of local solar spectra on sites :

Modeling approach to take into account the variation of local solar spectra on sites :

1. 10 Sites selection
2. Solar performances : ASTM SMARTS vs real local solar spectra AERONET Data

Optical properties

$$P_{S,n} = \frac{\int_{280}^{2500} S(\lambda) \cdot J_n(\lambda) \cdot d\lambda}{\int_{280}^{2500} J_n(\lambda) \cdot d\lambda} \rightarrow \text{Solar performance}$$

Solar spectrum

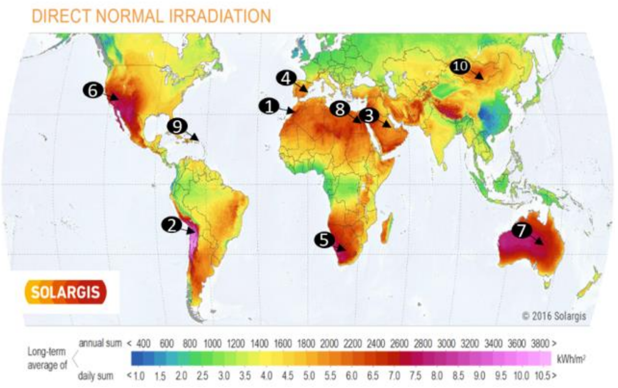
$$P_{S,y} = \frac{\sum_{n=1} I_n \cdot P_{S,n} \cdot \Delta t_n}{\sum_{n=1} I_n \cdot \Delta t_n} \rightarrow \text{Annual solar performance}$$

3. Impact of solar wavelength range

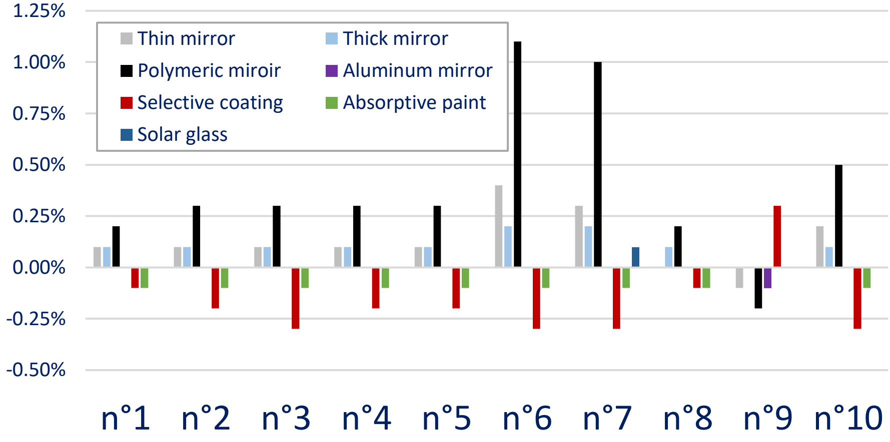
ASTM G173-03 DC solar spectrum is a reliable reference for performance evaluation of CSP components

- Mismatches with the ASTM solar spectrum are mainly due to specific location with high s Precipitable Water : PW (a dryer atmosphere)
- Polymeric mirrors can have difference between local spectra to ASTM up to 1%

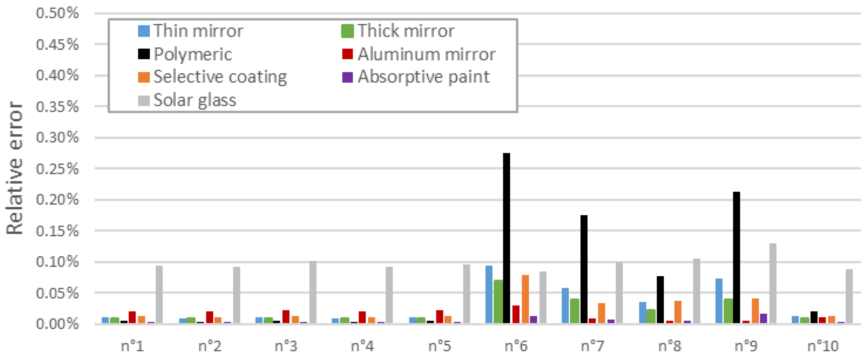
1.



2. real local solar spectra /ASTM G173-03 DC



3.



"Long Time Series Solar Spectra Used for Solar Field Performance Evaluation", A.Grosjean, E. Le Baron, A.C Pescheux et A.Disdier, (2019), in 'Solar PACES 2019'

Example of absorbers :

Durability modeling method and lifetime extrapolation

Durability modeling method of solar absorbers with a thermal acceleration stress factor:

Samples	T_{stab}(°C)*	T_{test} = cste (°C)		
A	430		450	480
B	300	350	400	450
C	300	350	400	450

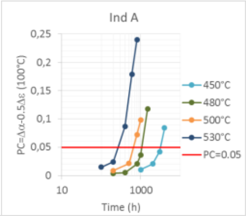
Degradation mechanism = oxidation of the metallic part of CERMET layer

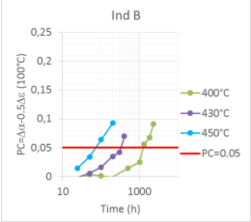
A B C

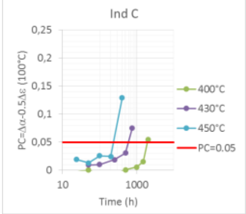
Definition of performance criterion

$$PC = -\Delta\alpha + 0.5\Delta\varepsilon_{100°C} \leq 0.05$$

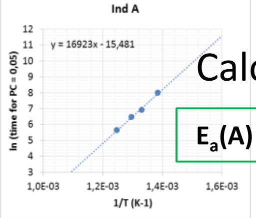
PC=0.05 depending of the accelerate test temperature → **Arrhenius law** → **Tmax for 25 years of operation**



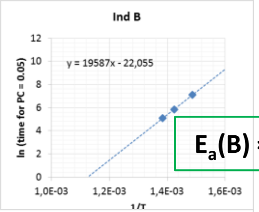




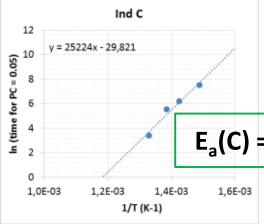
Calculation of Ea



$E_a(A)$ = 140 kJ.mol^{-1}



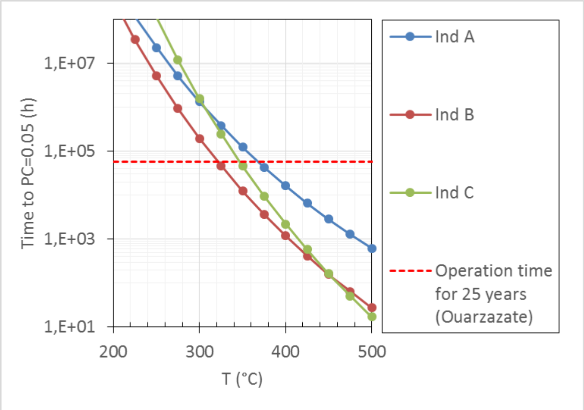
$E_a(B)$ = 160 kJ.mol^{-1}



$E_a(C)$ = 210 kJ.mol^{-1}

$$a_T = \frac{t_{test}}{t_{obj}} = \exp\left[-\left(\frac{E_a}{R}\right).\left(\frac{1}{T_{test}} - \frac{1}{T_{op}}\right)\right]$$

$$ln(t_{test}) = \frac{-E_a}{R}.\frac{1}{T_{test}} + ln(t_{op}) - \frac{E_a}{R.T_{op}}$$



$$\ln(t_{PC=0,05}) = -\frac{E_a}{R} \times \frac{1}{T_{test}} + A$$

Sample	A	B	C
T_{op} max (°C)	375	325	350

Maximum operation temperature for 25 years at Ouarzazate for each absorber

E. Le Baron CEA

"Accelerated Ageing Test for Durability Study of Solar Absorber Coating on Metallic Substrate for Solar Thermal Energy (STE) Application", Raccurt, O. & Disdier, A. (2017), in 'Solar PACES 2017'.

Solar Facilities for the European Research Area

Programme funded by the EUROPEAN UNION

SFERA III: On site Training for Indusry

Le Bourget-du-Lac, June, 8th – 10th 2022

Lifetime extrapolation of reflectors (erosion and corrosion)

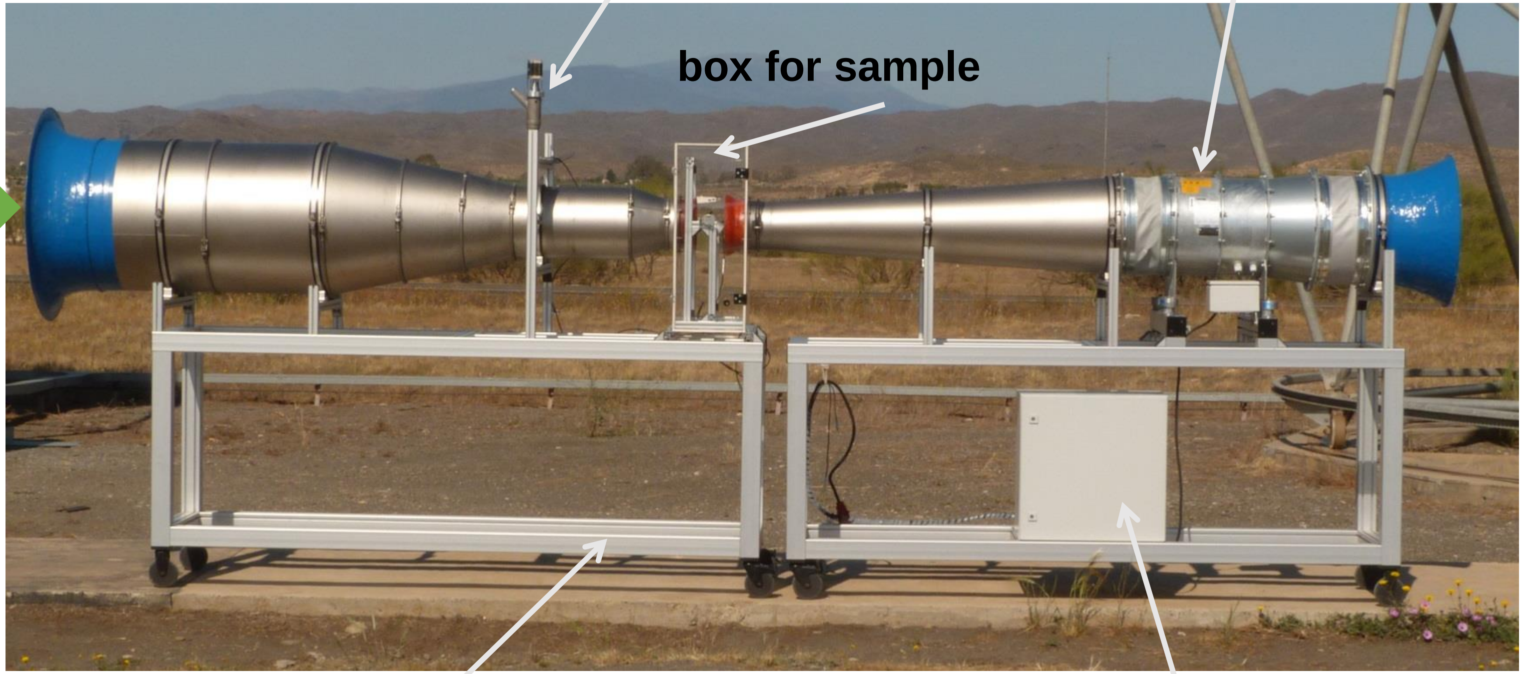
Florian Wiesinger, DLR

DLR Deutsches Zentrum für Luft- und Raumfahrt e.V. in der Helmholtz-Gemeinschaft

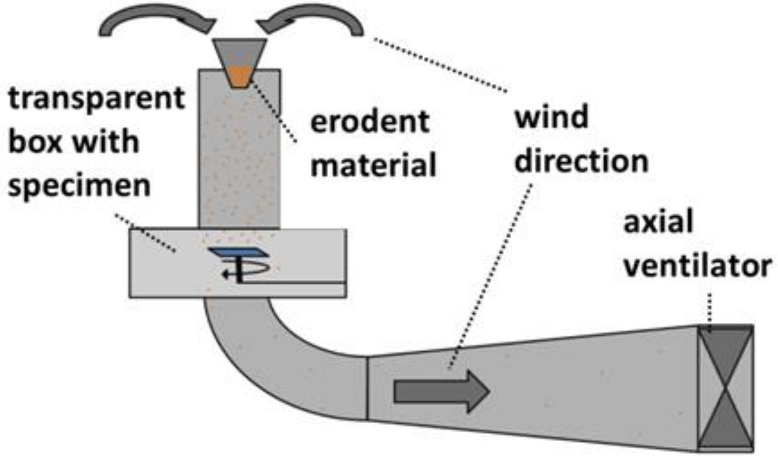
Contents

Erosion Testing- Testloop C

Sand erosion test to simulate sand storms



Erosion Testing- Testloop C



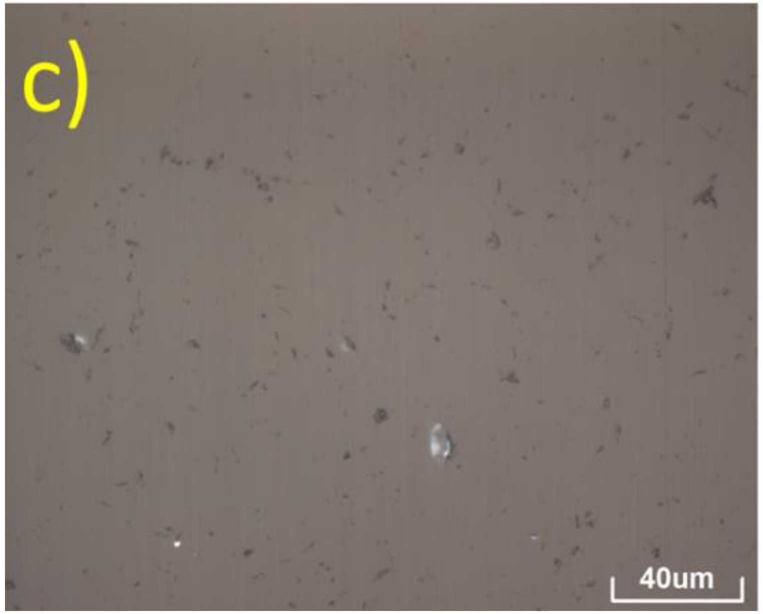
Open loop wind tunnel in suction mode with high variability of input parameters allowed for a comprehensive study of erosion determining influences coming from: **particle velocity, impact angle, erodent material**

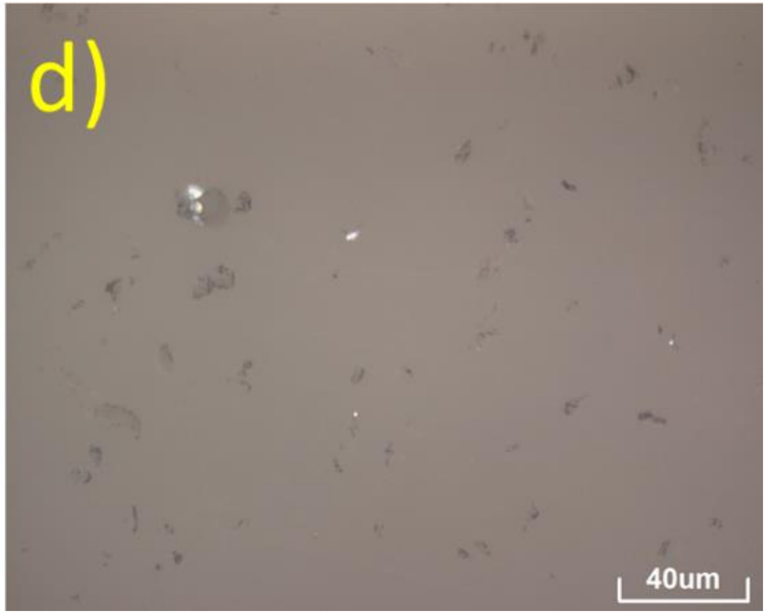
Erosion Testing- Testloop C - velocity

Open loop wind tunnel in suction mode with high variability of input parameters allowed for a comprehensive study of erosion determining influences coming from: **particle velocity**, **impact angle, erodent material**

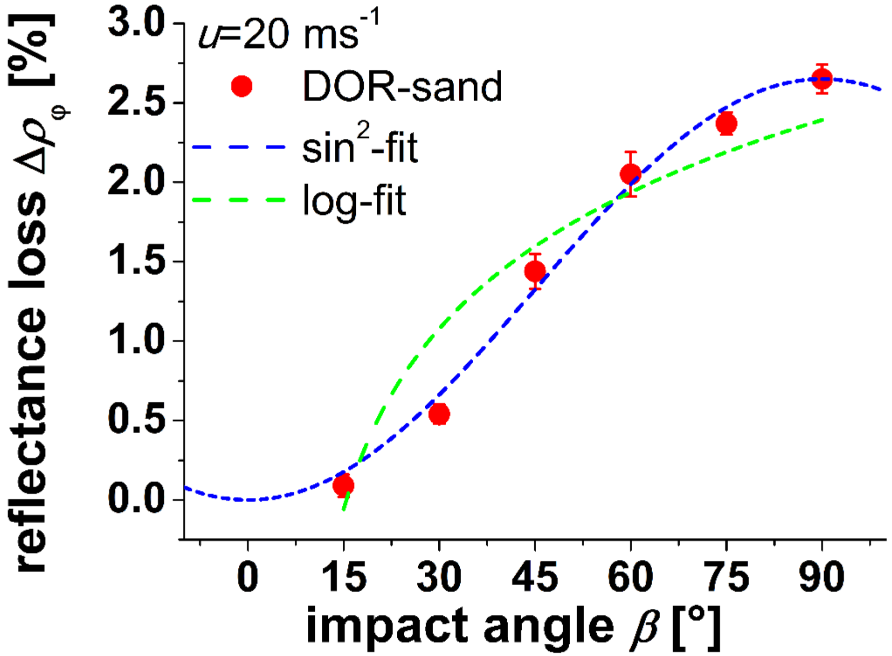
c) MIL-dust: <150µm

d) DOR-sand: 15-300µm

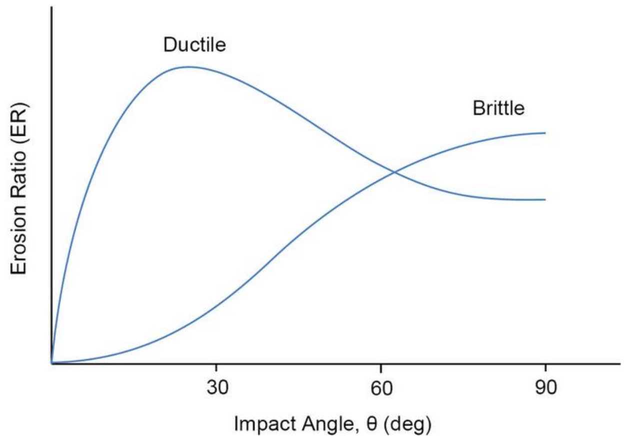




Erosion Testing- Testloop C –



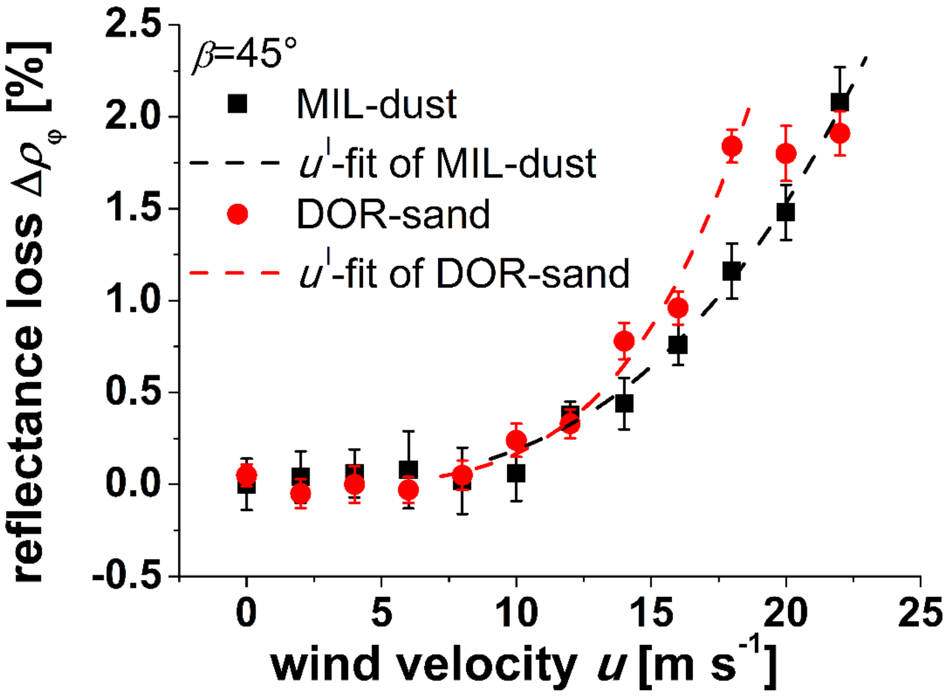
DOR-sand: 15-300µm



- Theory differentiate brittle and ductile materials.
- Fit because $E_g \approx \vec{u}^2 = (u \cdot \sin\beta)^2$

Arabnejad 2015

Erosion Testing- Testloop C - velocity

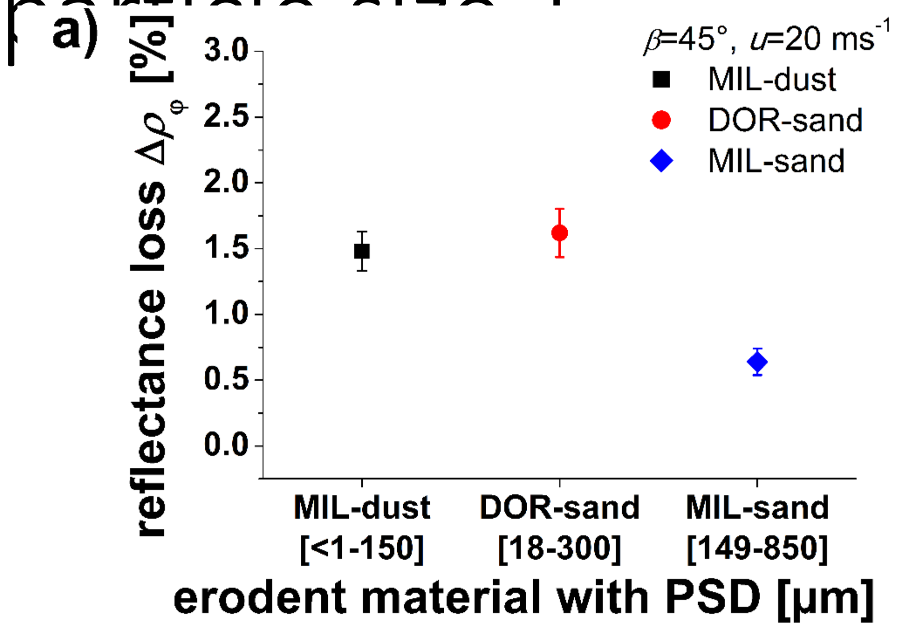


MIL-dust: <150µm

DOR-sand: 15-300µm

- Mechanical wear exhibits minimum threshold; below negligible.
- Relation between impact energy (E_g) and wear can be described as power law.
- For DOR-sand also maximum threshold observed →All particles do maximum damage.

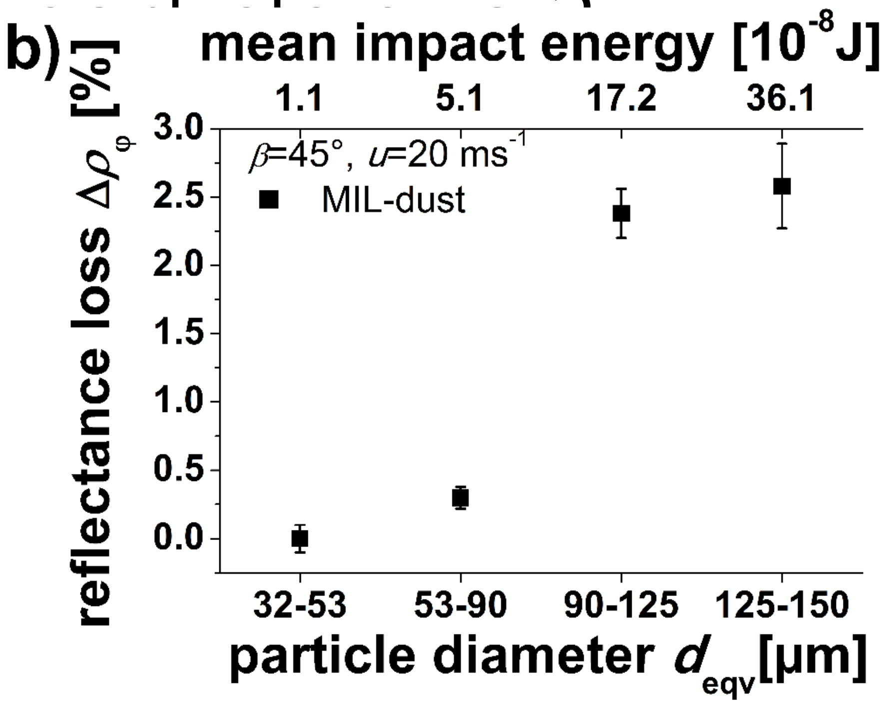
Erosion Testing- Testloop C – particle size 1



MIL-dust: <150µm
DOR-sand: 15-300µm
MIL-sand: 150-850µm

- MIL-sand largest particles and smallest Δρ.
  → Threshold effects and particle number per impact mass.
- Same investigation with higher resolution…

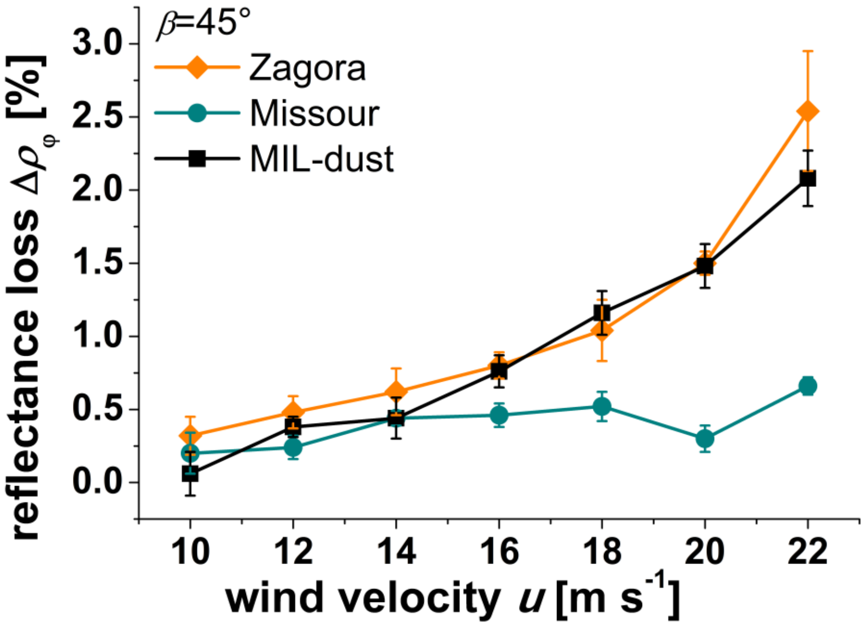
Erosion Testing- Testloop C –



Sieve MIL-sand in four size fractions: see subscript range

→ Aeolian erosion at typical field conditions becomes inefficient for quartz particles smaller than 50µm.

Erosion Testing- Testloop C – natural material

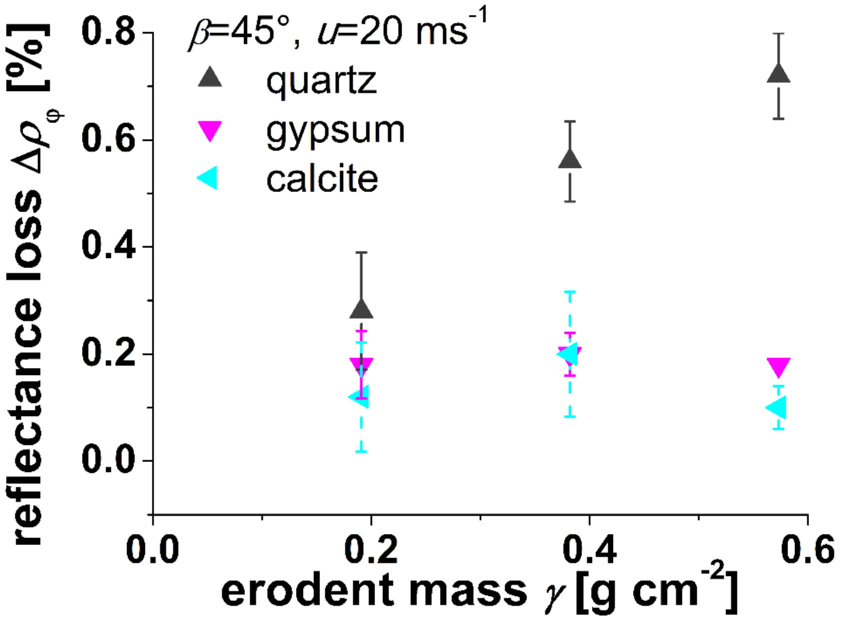


All particle types sieved to same size range.

→ Material from Zagora more aggressive than Missour material.

- Particle characteristics (shape, mineralogy)

Erosion Testing- Testloop C –



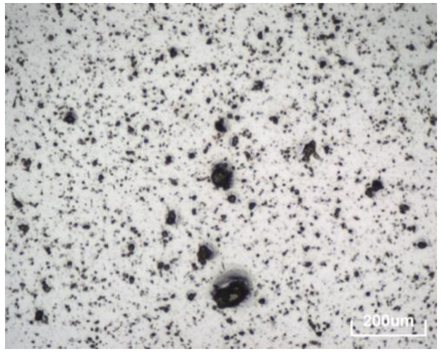
All particle types sieved to same size range.

→ Quartz highest erosion potential, due to its hardness. (quartz 7, gypsum 2, calcite 3)

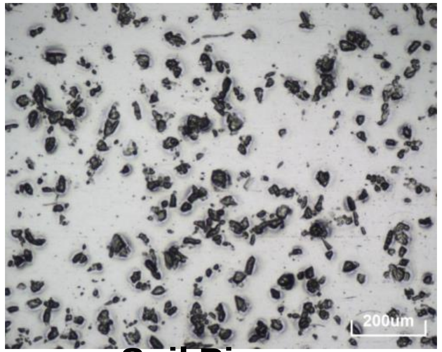
→ Gypsum and calcite contents in natural material not responsible for erosion effects under typical conditions.

Erosion Testing- Standartization

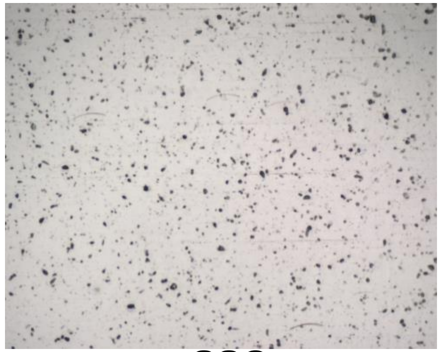
- How to quantify erosion ?
- Reflectance loss ρ not meaningful, since one large defect can cause similar Δρ as a lot of small defects while the consequences might be completely different.
- Instead of ρ use image analysis to obtain *defect size density distribution DSDD*.



Zagora
20
month



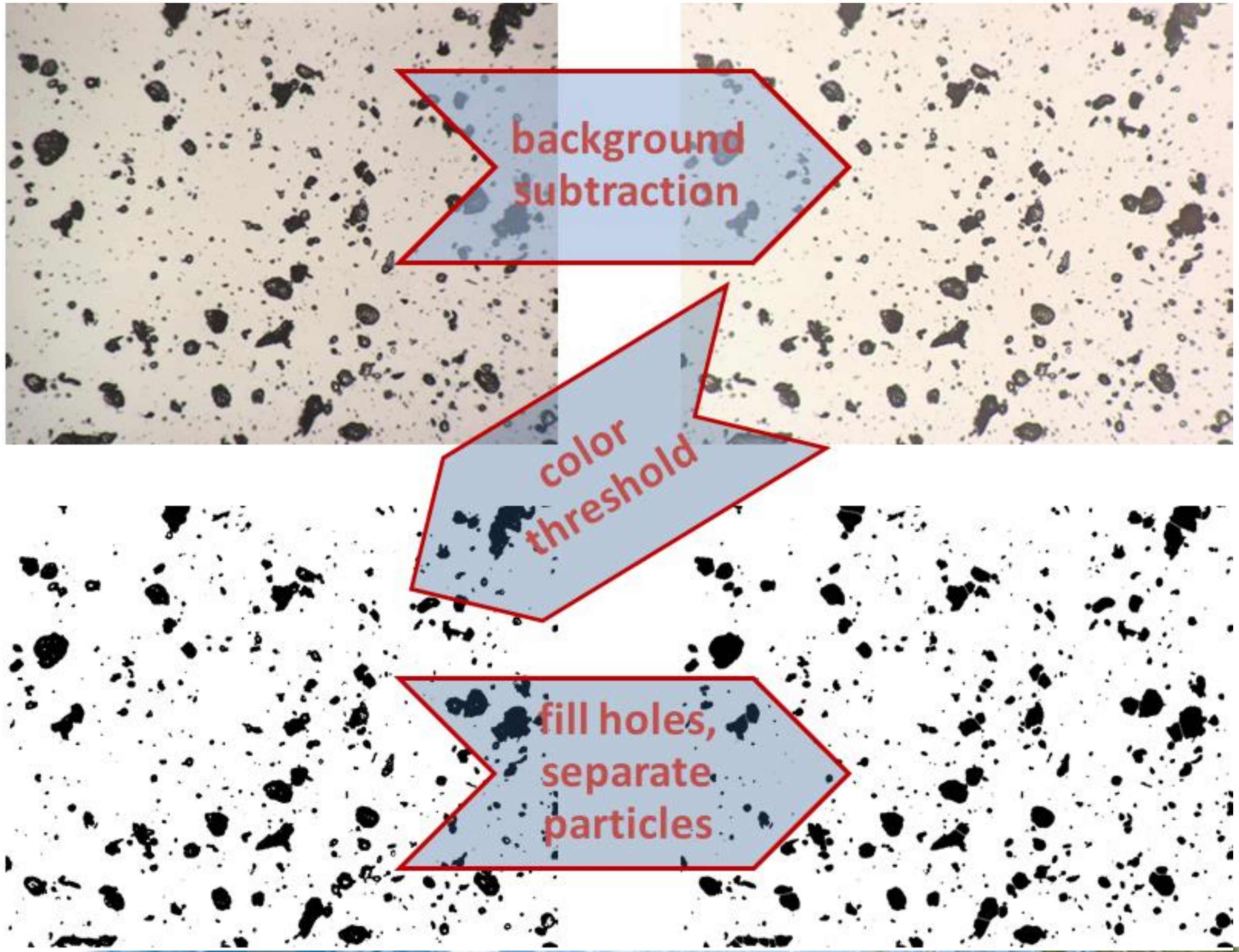
Soil Pipe



SSC

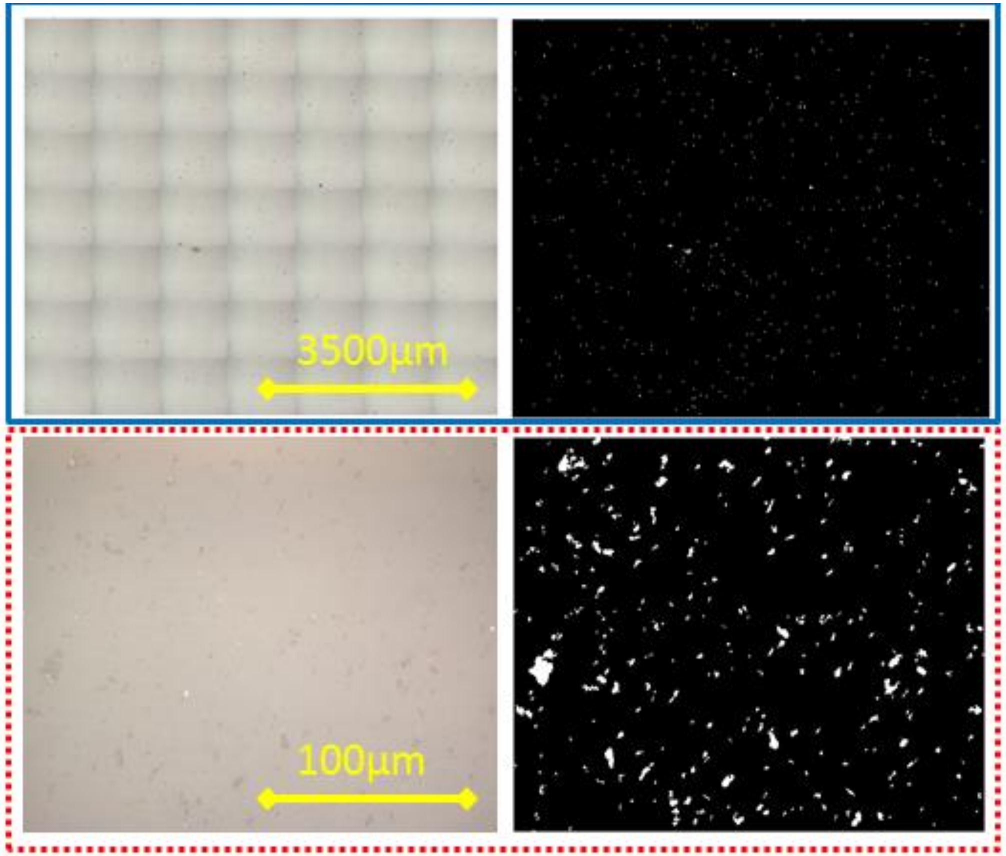
Erosion Testing- Standartization - DSDD

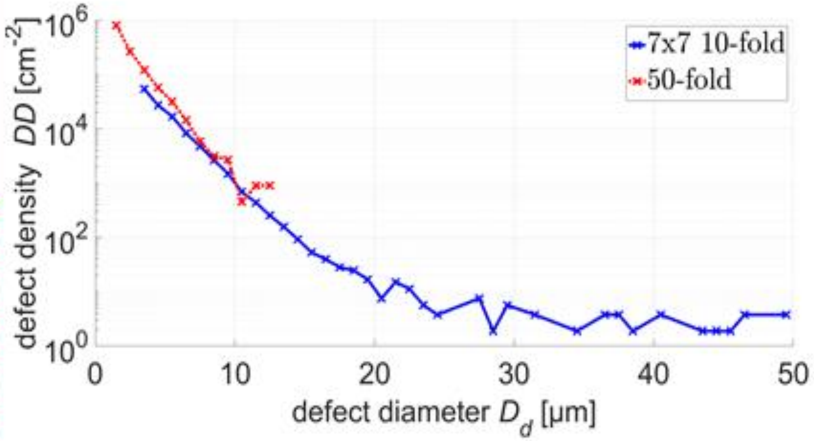
Instead of ρ use image analysis to obtain *defect size density distribution DSDD*.



Erosion Testing- Standartization - DSDD

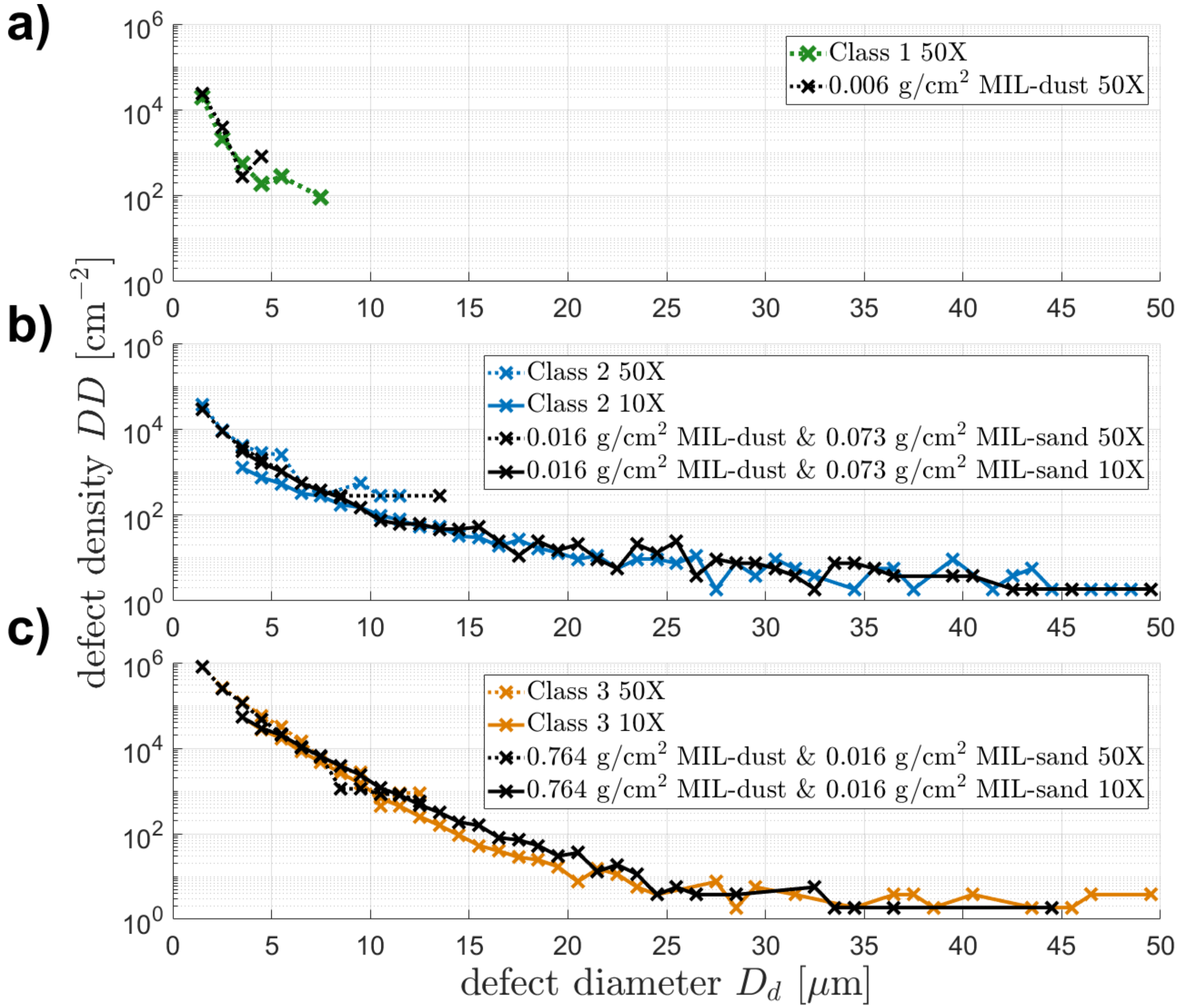
Use two different magnifications of microscope and combine them to account for whole range of defect sizes. Best (100 x 100 with high magnification but kills RAM)



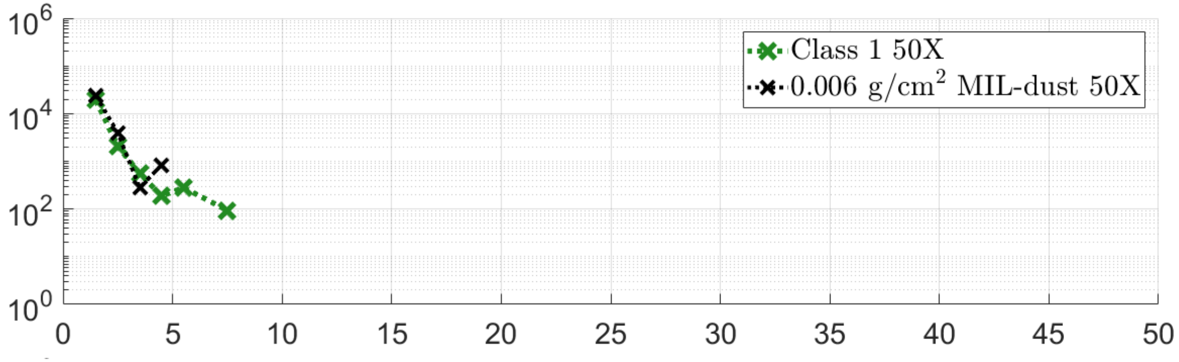


Erosion Testing- Standartization - DSDD

- Rank outdoor sites regarding the observed DSDD in three different erosion classes.
- Find adequate parameters in the testloop C to simulate the same DSDD.



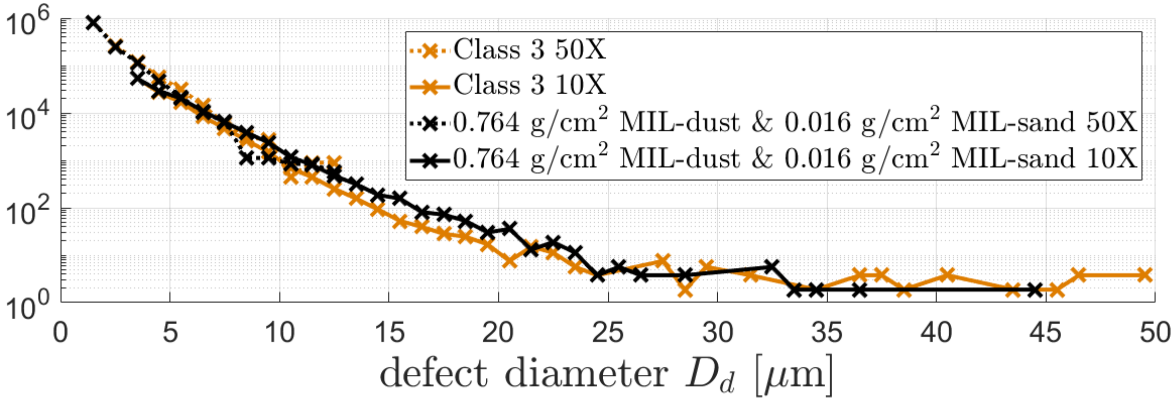
Erosion Testing- Standartization - DSDD



Lifetime assessment:

- Outdoor exposure for X years
- Determine DSDD and find necessary particle mass in artificial aging test to simulate X years.
- Multiply the determined particle mass in order to achieve simulation for e.g. 10 years.
- Class 1 for 10 years, use 0.06g/cm² → Δρ around 2.5% (1 year Δρ ca 0.25%) linear behavior.

Erosion Testing- Standartization - DSDD



Lifetime assessment:

- Class 3 for 10 years Δρ around 38% (1 year Δρ ca 5%) NON-LINEAR behavior.

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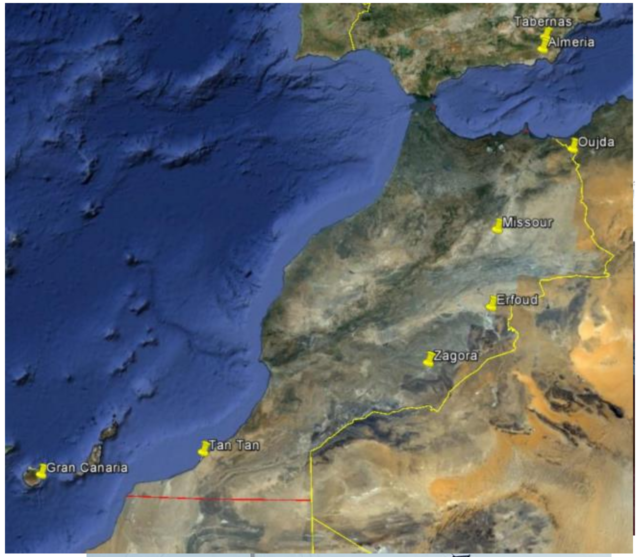
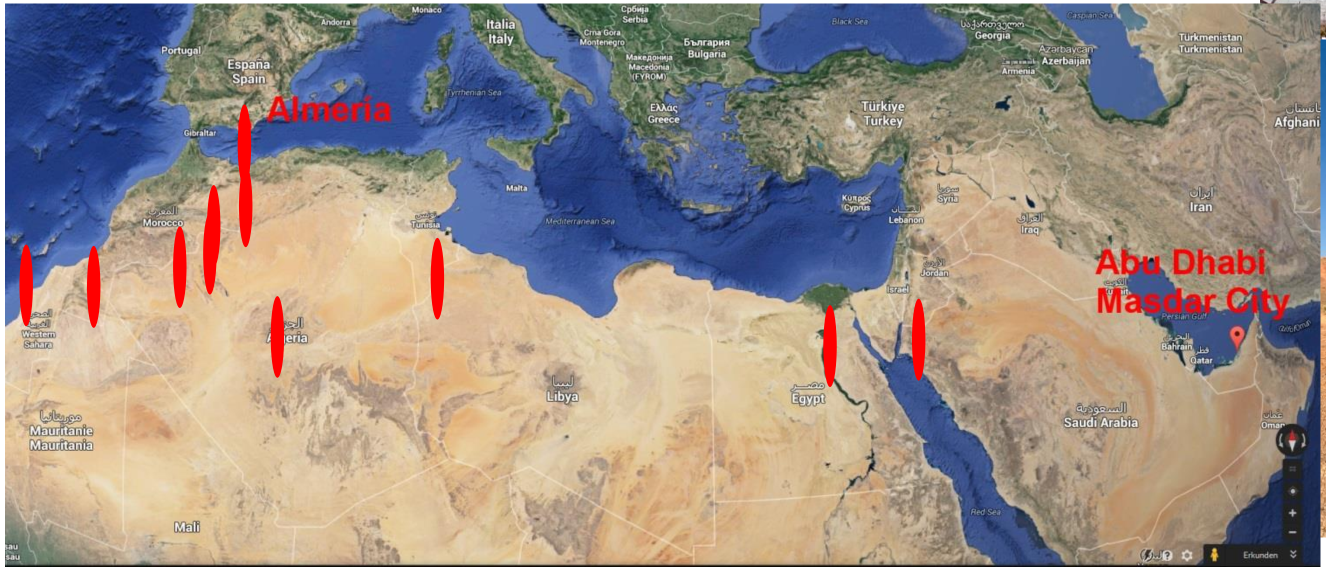
Corrosion Testing

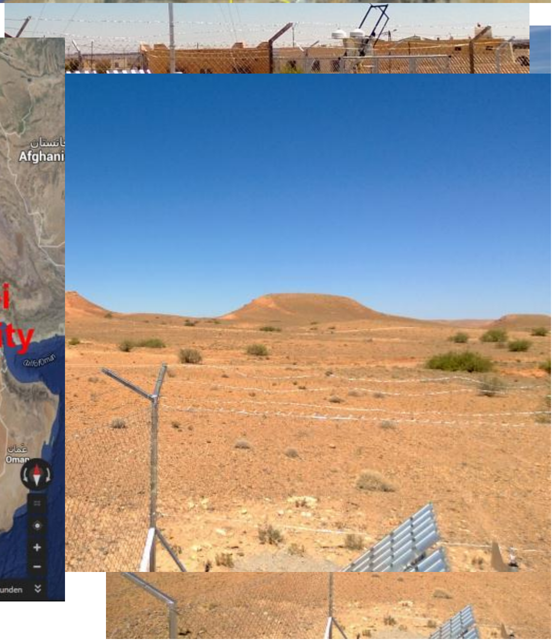
- Extensive outdoor exposure campaign on 13 sites: Almeria, Tabernas, Gran Canaria, Abu Dhabi, Oujda, Missour, Erfoud, Zagora, Tan Tan, Maan, Tatauine, Adrar, Cairo

- Variety of site conditions, from urban over coastal to desert

- On-site measurements of parameters (temperature, wind, irradiation, humidity, particles, etc.)







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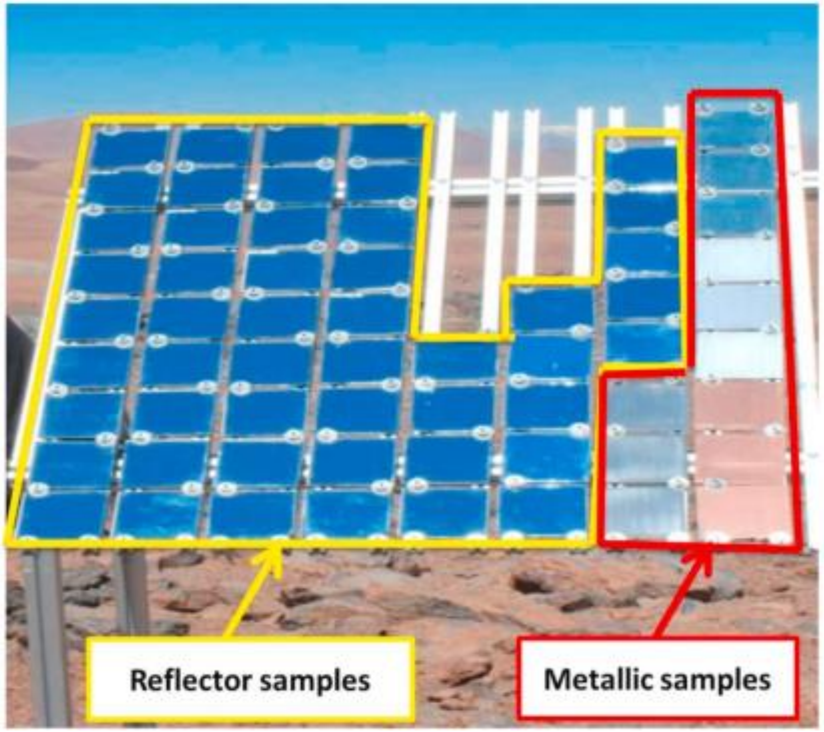
http://sfera3.sollab.eu/

Corrosion Testing

- In order to assess site corrosivity: ISO 9223:2012 standard:
  - 10x10 cm² coupons of steel, copper, zinc and aluminum exposed for 1 year.
  - Afterwards collect, clean and determine weight loss.
  - Classify in 6 categories (C1,…,C5,CX)



Reflector and standard metal samples in outdoor exposure rack.

Buendia 2021

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Corrosion Testing

Site	Average mass loss (g/m^2)				Average corrosivity class
	Zinc	Cooper	Aluminum	Steel	
Almeria	8.78	43.4	1.19	346	**C4**
Tabernas	3.79	15.3	0.45	132	**C3**
Odeillo	3.30	5.61	0.09	8.59	**C2**
Missour	5.05	7.62	0.14	43.4	**C2**
Erfoud	4.01	19.8	0.30	65.7	**C2**
Zagora	2.44	5.15	0.03	28.3	**C2**
Ouarzazate	3.75	7.15	0.47	19.4	**C2**
Temara	398	190	4.83	7769	**CX**
Atacama Desert	5.41	20.5	0.64	210	**C3**
Chajnantor	3.50	6.38	0.27	103	**C2**

Average mass loss per square meter after 1 year outdoor exposure.

In addition to corrosion characterization also reflector exposure

Buendia 2021

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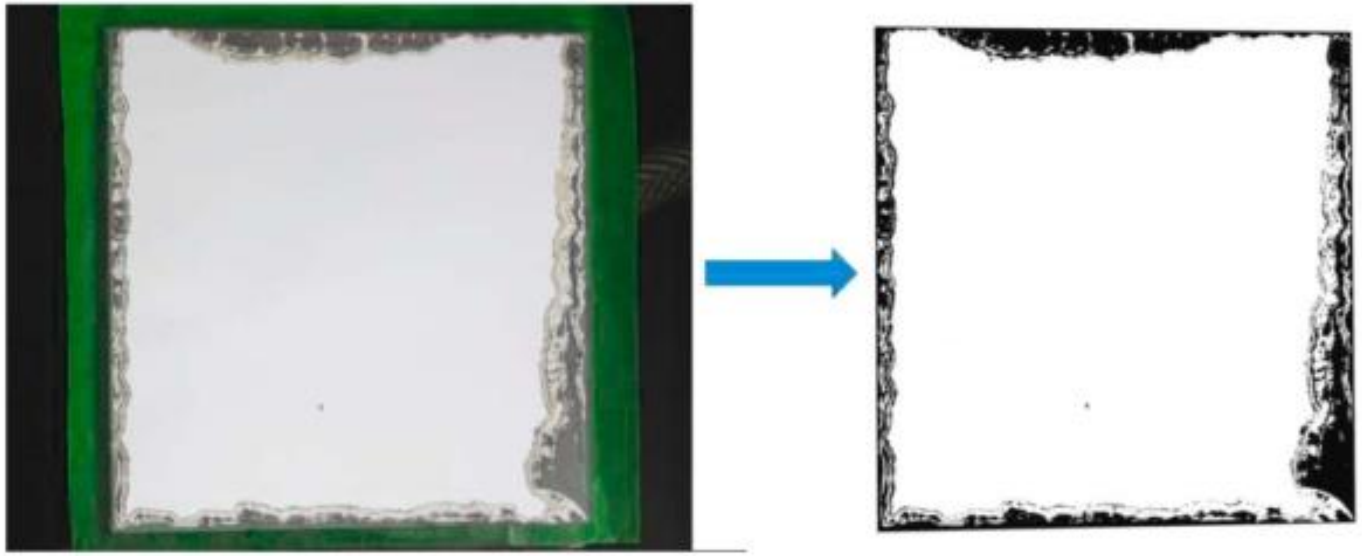
Corrosion Testing - modeling



Analysis via total reflectance: $$\rho = \rho_{NC} \cdot \frac{A_{NC}}{A_{Total}} + \rho_C \cdot \frac{A_C}{A_{Total}}$$

When ρ_C is considered to be negligible → $$\rho = \rho_{NC} \cdot \left(1 - \frac{A_C}{A_{Total}}\right)$$

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Corrosion Testing - modeling

Further correlation approaches

$$\rho = \rho_{NC} \cdot \left(1 - \frac{A_C}{A_{Total}}\right)$$

$$\rho_{NC} = \rho_0 - a \cdot t_{outdoor}$$

$$\frac{A_C}{A_{Total}} = 1 - e^{-b\left(\frac{t_{outdoor}}{a_f}\right)^c}$$

Non corroded area shows linear degradation of reflectance, due to erosion, UV-degradation or soiling deposition

Correlation derived from CASS test. Taking into account the acceleration factor a_f

Buendia 2021

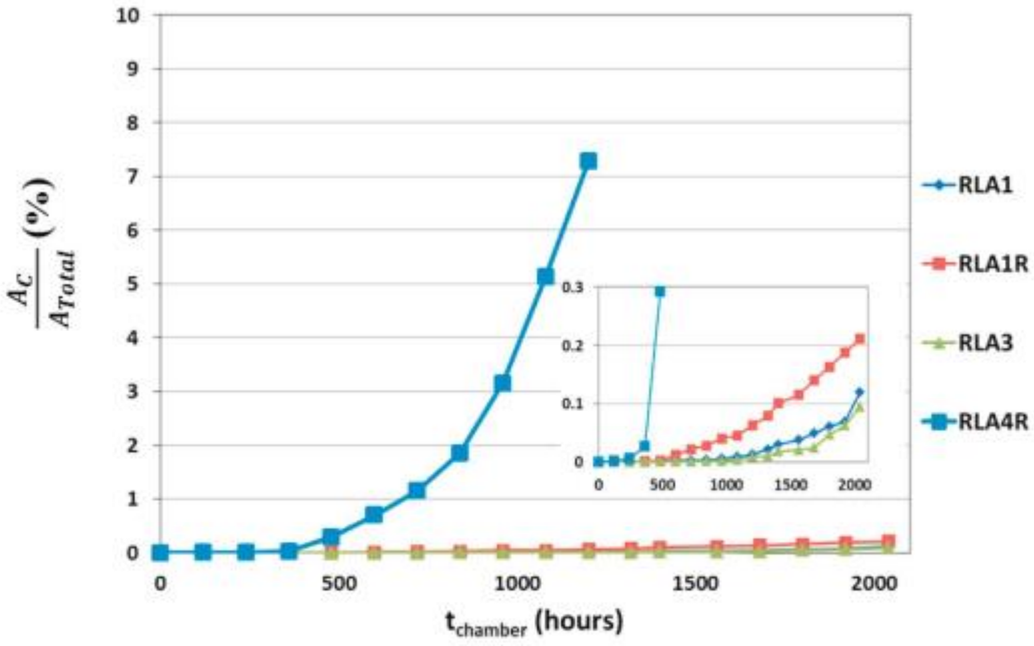
Corrosion Testing - modeling

Further correlation approaches

$$\rho = \rho_{NC} \cdot \left(1 - \frac{A_C}{A_{Total}}\right)$$

$$\frac{A_C}{A_{Total}} = 1 - e^{-b\left(\frac{t_{outdoor}}{a_f}\right)^c}$$

To find reasonable model: CASS test



Acceleration factor a_f derived from comparison of CASS test with outdoor results.

Buendia 2021

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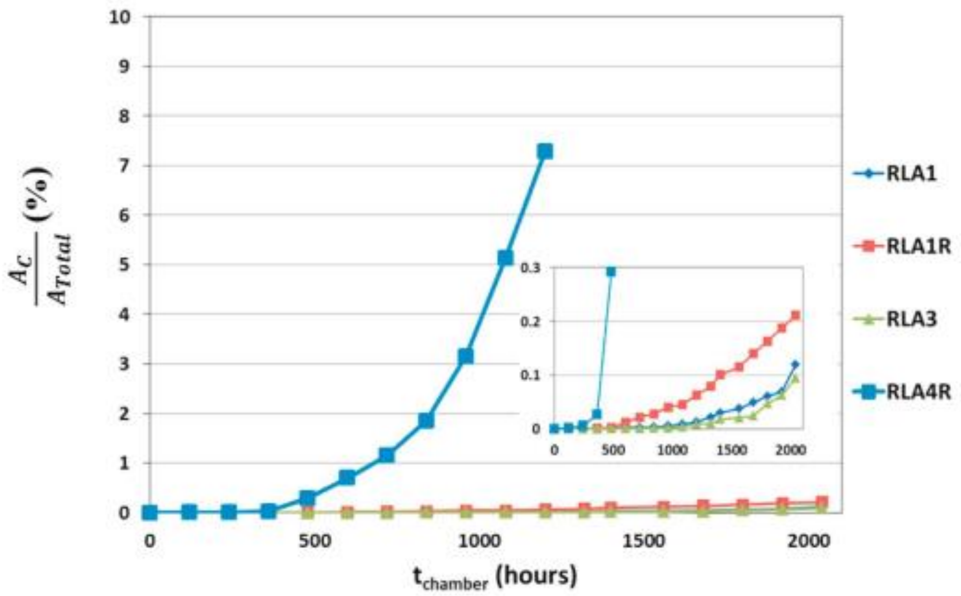
Corrosion Testing - modeling



Find testing time in CASS to reproduce same corrosion area as after 3 years outdoor.

Table 4

Ratio of area corroded by corrosion spots $\left(\frac{A_C}{A_{Total}}\right)$ after approximately 3 years of outdoor exposure, depending on the material and site.

Material	Site (corrosivity class)		
	Almería (C4)	Tabernas (C3)	Atacama Desert (C3)
	$A_C/A_{Total}(-)$	$A_C/A_{Total}(-)$	$A_C/A_{Total}(-)$
RLA1	0.000001	0.000000	0.000000
RLA1R	0.000007	0.000002	0.000002
RLA3	0.000037	0.000004	0.000001
RLA4R	0.000210	0.000021	0.000055

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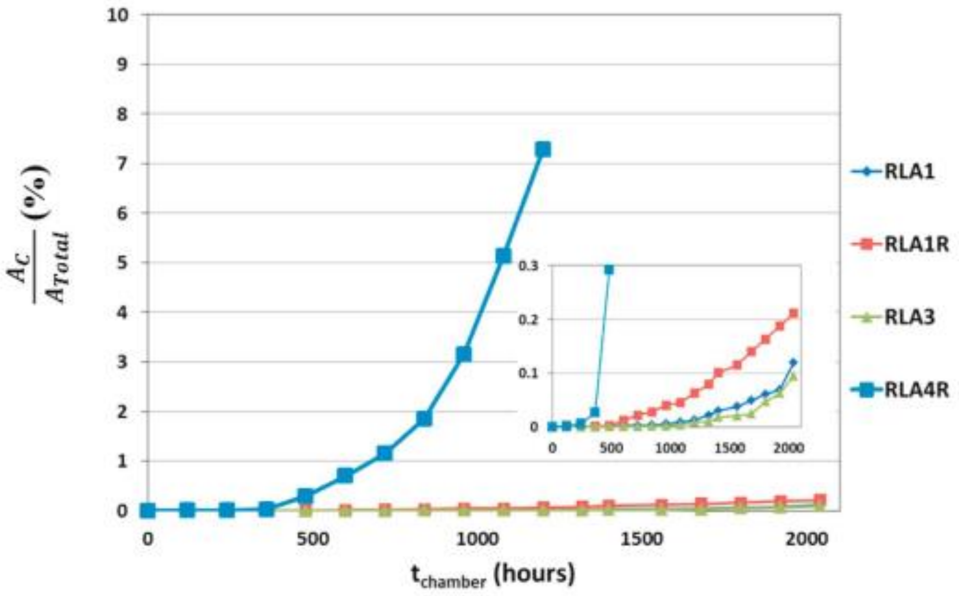
Corrosion Testing - modeling



Acceleration factor a_f derived from comparison of CASS test with outdoor results.

Material	Site (corrosivity class)					
	Almería (C4)		Tabernas (C3)		Atacama Desert (C3)	
	$t_{chamber}$ (h)	a_f (–)	$t_{chamber}$ (h)	a_f (–)	$t_{chamber}$ (h)	a_f (–)
RLA1	234	106	118	204	131	200
RLA1R	230	108	130	185	144	182
RLA3	935	27	493	48	331	79
RLA4R	280	88	157	153	201	131

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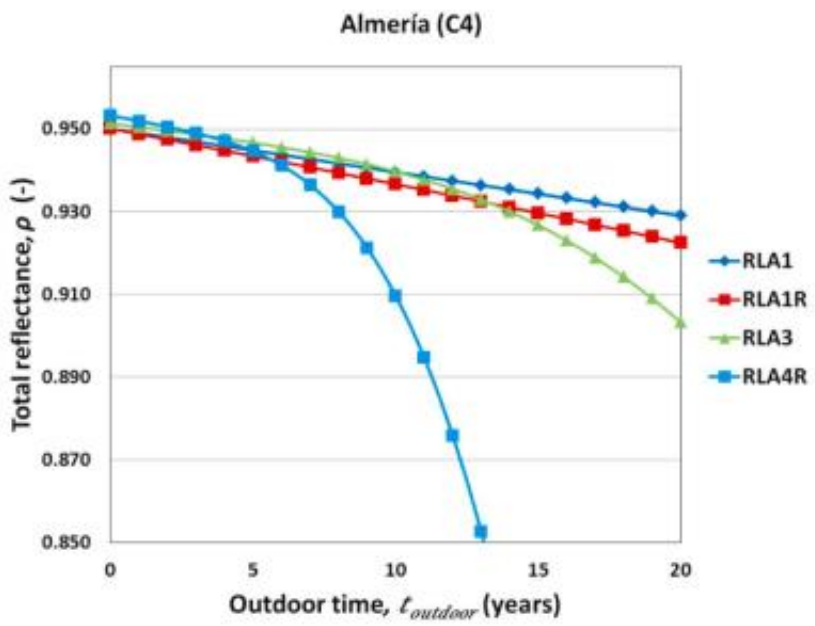
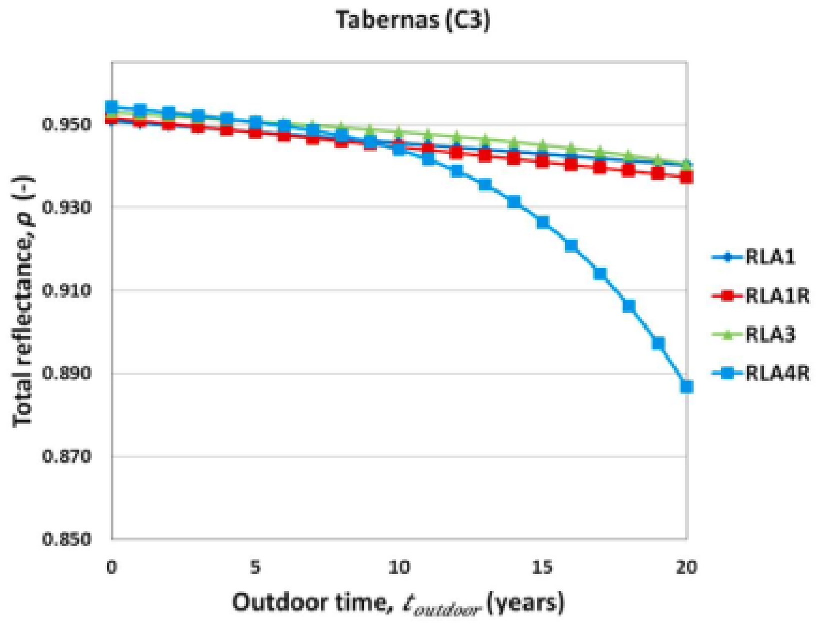
Corrosion Testing - lifeti

Material	Site (corrosivity class)					
	Almería (C4)		Tabernas (C3)		Atacama Desert (C3)	
	$t_{chamber}$ (h)	a_f (–)	$t_{chamber}$ (h)	a_f (–)	$t_{chamber}$ (h)	a_f (–)
RLA1	234	106	118	204	131	200
RLA1 R	230	108	130	185	144	182
RLA3	935	27	493	48	331	79
RLA4R	280	88	157	153	201	131

Using the acceleration factor a_f the lifetime of each reflector type and every site can be calculated.





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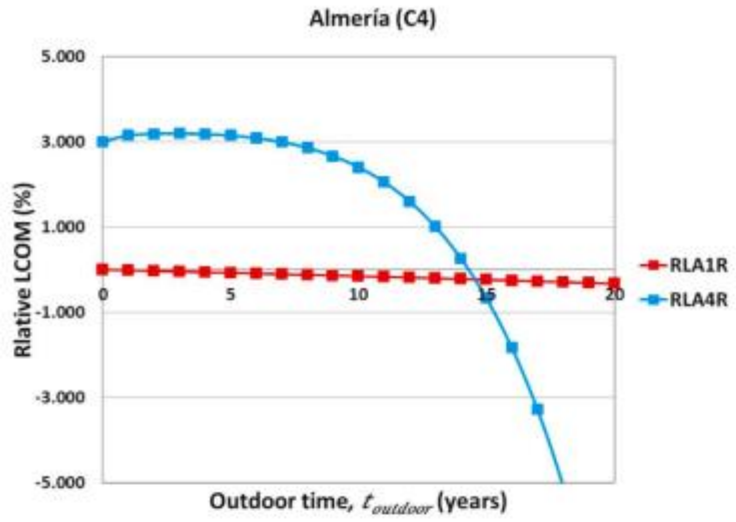
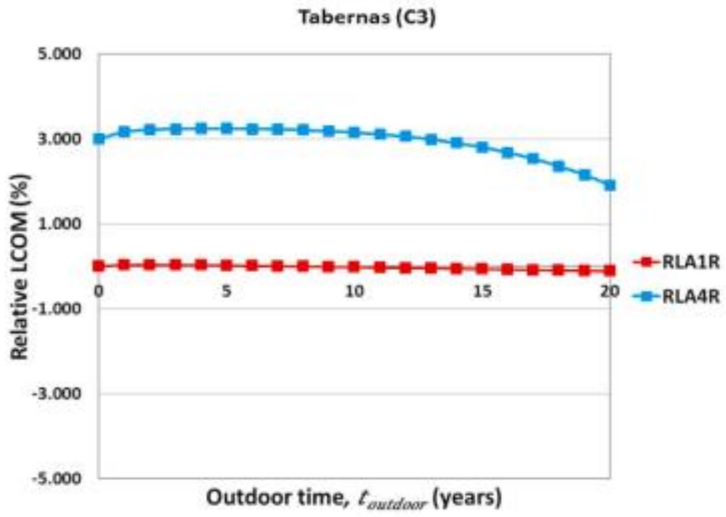
Corrosion Testing – economic analysis

- LCOM of two reflectors RLA1R RLA4R.
- RLA4R is 3% cheaper for initial cost.
- At C4 sites only advisable if lifetime <15 years.





Buendia 2021

Friday, June 10, 2022

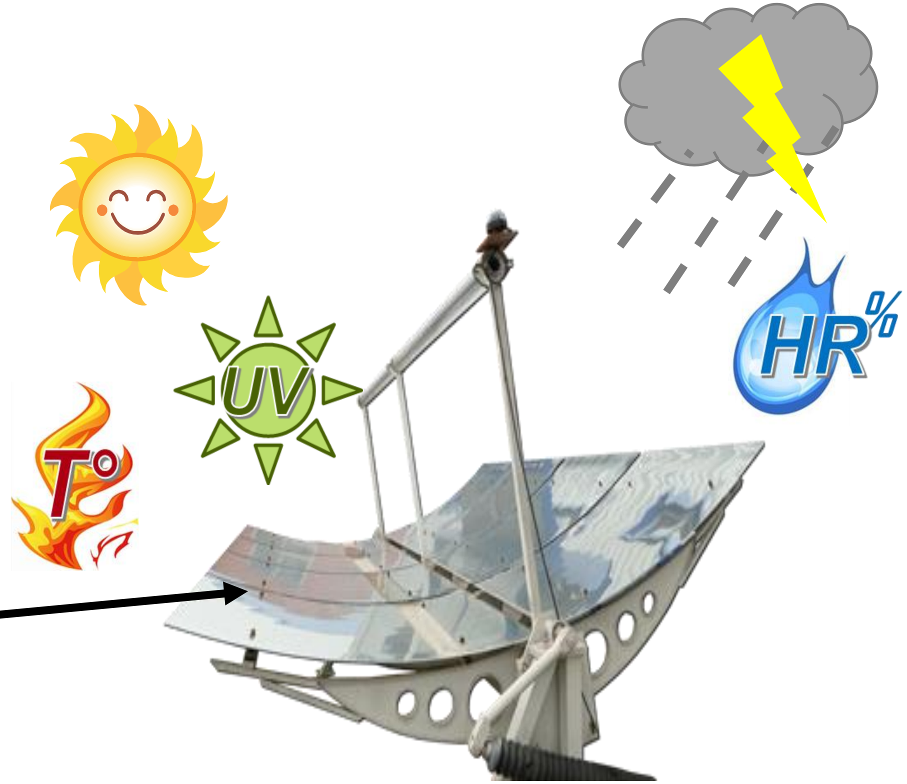
9:15 – 10:15	Coupling stress factors and conclusion on lifetime prediction and durability studies	CEA	60 min
10:15 – 11:15	CEA Optical and mechanical characterization tools	CEA	60 min
11:15 – 11:30	- Coffee break -		15 min
11:30 –12:15	DLR Optical characterization tools	DLR	45 min
12:15 – 13:45	- Lunch break at Restaurant “SUPERNOVA”		90 min
13:45 – 15:45	Experience sharing industrial focus and Feedback	All	120 min
15:45	End of meeting		

Coupling stress factors and conclusion on lifetime prediction and durability studies

E. Le Baron CEA

Coupling several acceleration stress factors:

Example of solar plant



1. Temperature
2. Irradiation, UV
3. Relative Humidity

On site all of these stresses are applied at the same time

➔ We therefore need a coupling accelerated law

Modeling method of solar mirrors by coupling several acceleration stress factors:

Acceleration stress factor : $A = \frac{t_s}{t_{test}}$?

T° HR% UV

No synergy between stress factors [1] $A = a_T \cdot a_{RH} \cdot a_I$

model developed by Jorgensen [2] $\Delta\rho = C \cdot I_{UV} \cdot T^{-n} \cdot e^{-\frac{Ea}{R \cdot T}} e^{RH\left(\beta + \frac{B}{T}\right)}$ based on Eyring's law

model proposed by Lee et al [3] $\Delta\rho = C \cdot I_{UV} \cdot e^{-\frac{Ea}{R \cdot T}} e^{B \cdot RH} \cdot ts)$

A : Acceleration stress factor
t_s : time on site
t_{test}: time in test
E_a : Activation energy in $J \cdot mol^{-1}$
R : perfect gas constant in $J \cdot mol^{-1} \cdot K^{-1}$
γ : frequency factor in h^{-1}
n : Peck coefficient
RH : relative humidity
T : temperature in K
β : Eyring coefficient
p : Schwarschild's coefficient
I_{uv} : Irradiation, in $W \cdot m^{-2}$
B, C : constant

[1] M. Kohl, B. Carlsson, G. Jorgensen, A.W. Czanderna, Performance and Durability Assessment, Optical Ma, 2004
[2] G.J. Jorgensen, and al., "Durability studies of solar reflector materials exposed to environmental stresses", Knowl. Creat. Diffus. Util. (1997)
[3] J. Lee, "Lifetime Prediction for Degradation of Solar Mirrors using Step-Stress Accelerated Testing", (2011)

Modeling method of solar mirrors by coupling several acceleration stress factors:

Three hypotheses from theoretical lifetime models [1]:

$$A = a_T \cdot a_{RH} \cdot a_I$$

T° HR% UV

1. Coupling hypothesis: Accelerating factors multiply each other without synergy
2. Dose assumption: There is a proportional response between the duration of a stress and the degradation mechanisms observed
3. Initialization hypothesis: It states that if a sample undergoes several accelerated tests, the order of the application of these tests is not important.

➔ The three combined stress factors, temperature, relative humidity and irradiation, we conducted accelerated aging tests in three different chambers ➔ Now UV5X commercial unique equipment could produce the elevated level of these three stresses factors

[1] M. Kohl, B. Carlsson, G. Jorgensen, A.W. Czanderna, Performance and Durability Assessment, Optical Ma, 2004

Accelerated aging tests and characterizations of solar mirrors: Comparison of combinations of stress factors on degradation", Grosjean A., Le Baron E., Disdier A., Solar Energy Materials and Solar Cells 220 (2021)

Example of Coupling several acceleration stress factors of reflectors :

3 successive conditions:

Thermal + UV + Humidity tests ➔ 3 conditions of unitary tests + 3 coupling + 3 initialization

Accelerated aging plan :

Week n°	n°1	n°2	n°3	n°4	n°5	n°6	n°7	n°8	n°9	n°10	n°11	n°12
Short Cycle	1st turnover = 3 weeks			2nd turnover = 3 weeks			3th turnover = 3 weeks			4th turnover = 3 weeks		
Start T+HR	T+HR	T+Irr	T	T+HR	T+Irr	T	T+HR	T+Irr	T	T+HR	T+Irr	T
Start T	T	T+HR	T+Irr	T	T+HR	T+Irr	T	T+HR	T+Irr	T	T+HR	T+Irr
Start T+Irr	T+Irr	T	T+HR	T+Irr	T	T+HR	T+Irr	T	T+HR	T+Irr	T	T+HR
Average Cycle	1st turnover = 6 weeks						2nd turnover = 6 weeks					
Start T+HR	T+HR		T+Irr		T		T+HR		T+Irr		T	
Start T	T		T+HR		T+Irr		T		T+HR		T+Irr	
Start T+Irr	T+Irr		T		T+HR		T+Irr		T		T+HR	
Long Cycle	1st turnover = 12 weeks											
Start T+HR	T+HR				T+Irr				T			
Start T	T				T+HR				T+Irr			
Start T+Irr	T+Irr				T				T+HR			

Initialization effect:

- T+HR = 95°C + 85% HR
- T = 95°C
- T+Irr = 95°C + 200W/m²

Coupling effect:

- Short Cycle of one week (168h)
- Average Cycle of two weeks (336h)
- Long Cycle of four weeks (672h)

Total of 12 weeks (2016 h):

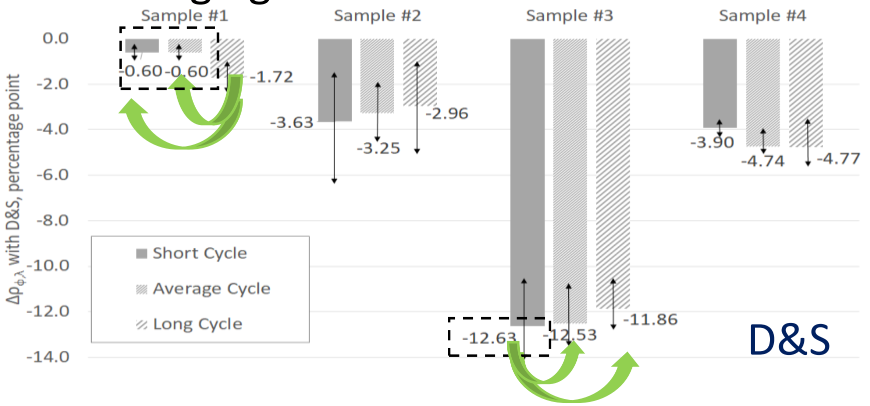
- 4 weeks at a temperature of 95 °C
- 4 weeks at a relative humidity of 85% and a temperature of 95°C
- 4 weeks at 200W/m² UV irradiation and a mirror temperature of 95°C

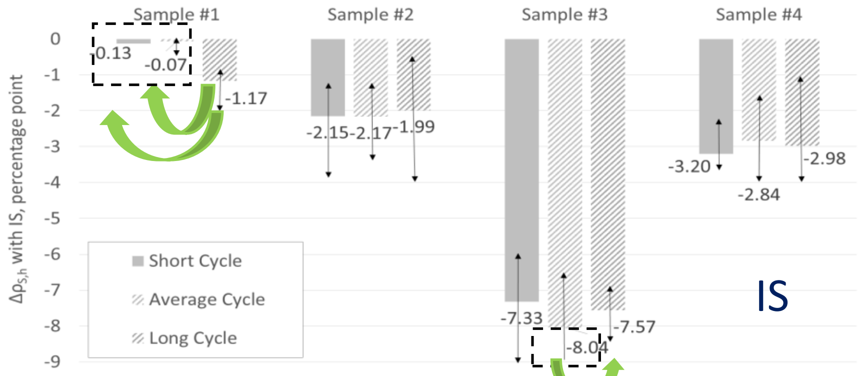
Accelerated aging tests and characterizations of solar mirrors: Comparison of combinations of stress factors on degradation", Grosjean A., Le Baron E., Disdier A., Solar Energy Materials and Solar Cells 220 (2021)

Example of Coupling several acceleration stress factors of reflectors :

Thermal + UV + Humidity tests

- Evolution of specular reflectance ρs and hemispherical reflectance over time t to compare different cycle durations for the same first aging test





Coupling effect:

- Short Cycle of one week (168h)
- Average Cycle of two weeks (336h)
- Long Cycle of four weeks (672h)

- 4 comparisons show a high difference
- 8 comparisons show no difference

- 3 comparisons show a high difference
- 9 comparisons show no difference

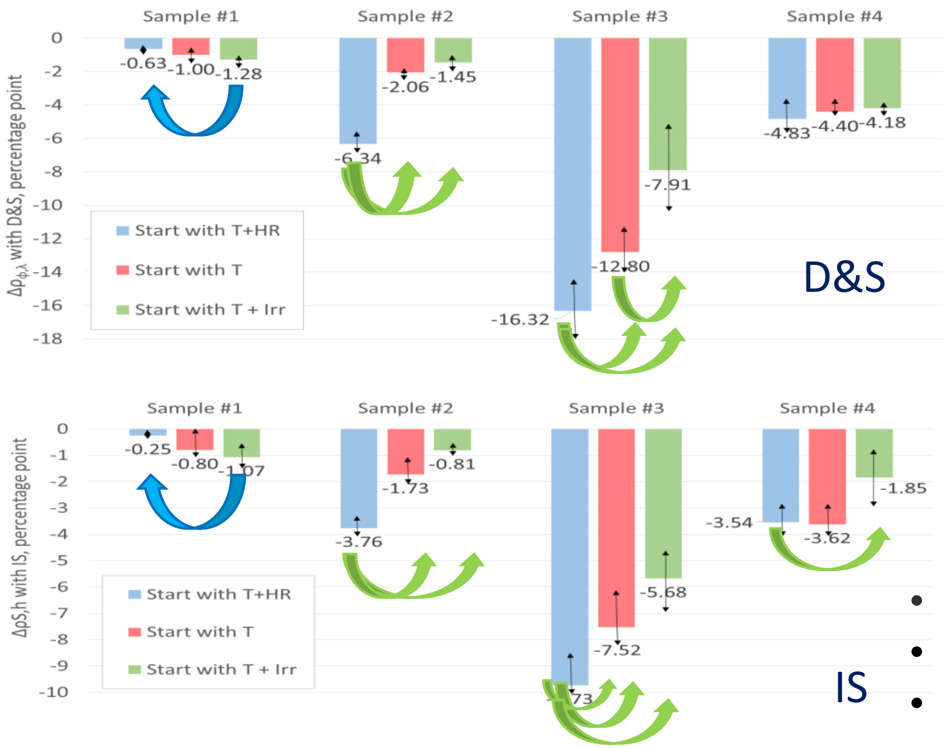
- Samples #1 : minimal specular/hemispherical reflectance loss of 1%
- Samples #3 : significant losses of 12%

Accelerated aging tests and characterizations of solar mirrors: Comparison of combinations of stress factors on degradation", Grosjean A., Le Baron E., Disdier A., Solar Energy Materials and Solar Cells 220 (2021).

Example of Coupling several acceleration stress factors of reflectors :

Thermal + UV + Humidity tests

- Evolution of specular reflectance ρs and hemispherical reflectance over time t to compare different first aging tests for the same cycle duration



Initialization effect: the effect of the 1st stress

- 5 comparisons show high difference
- 1 comparison shows an average difference
- 6 comparisons show no difference

- 7 comparisons show high difference
- 1 comparison shows an average difference
- 4 comparisons show no difference

- Samples #1 : minimal specular/hemispherical reflectance loss of 1%
- Samples #3 : significant losses of 16%
- Samples #2 #3 #4 : T + HR >T >T + Irr test

Accelerated aging tests and characterizations of solar mirrors: Comparison of combinations of stress factors on degradation", Grosjean A., Le Baron E., Disdier A., Solar Energy Materials and Solar Cells 220 (2021)

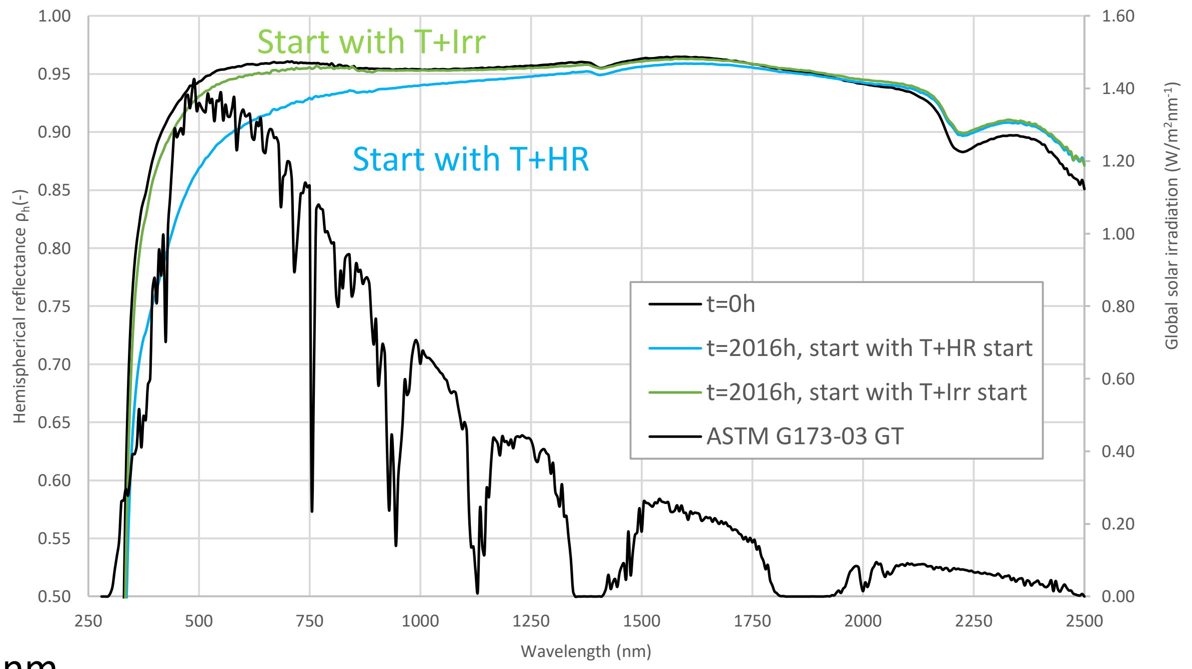
Example of Coupling several acceleration stress factors of reflectors :

Thermal + UV + Humidity tests

- Evolution of spectral hemispherical reflectance over time t at t=0h and after 2016 h of tests :

Initialization effect: the effect of the 1st stress

Samples #3 : T + HR >T >T + Irr test



➔ main difference is between 250-1000 nm

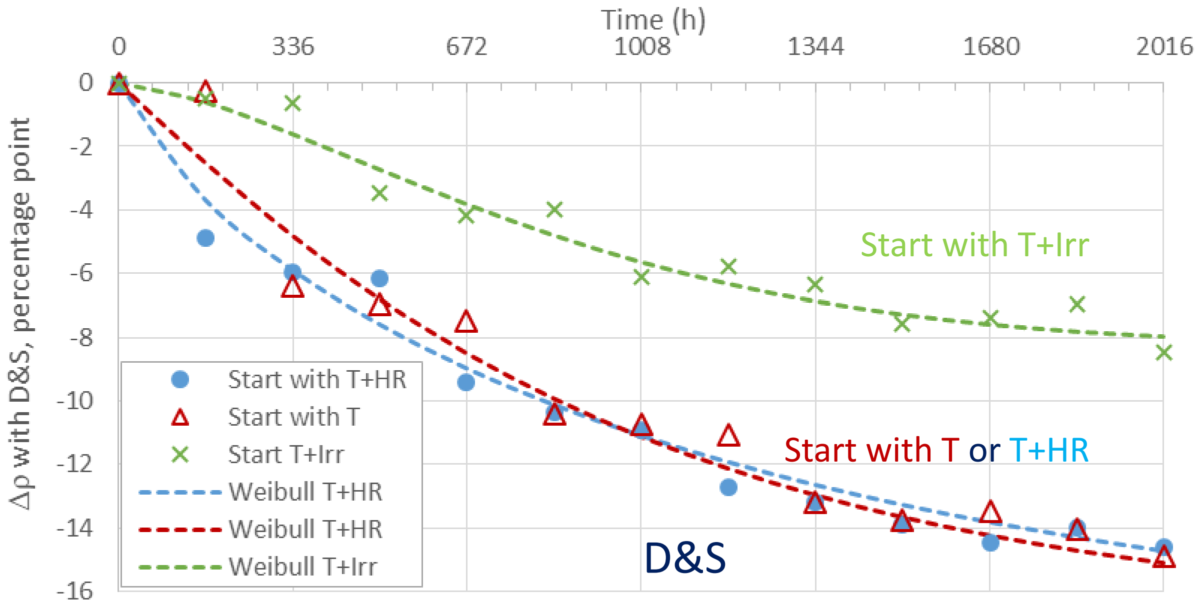
➔ In the NIR spectral area (up to 2 µm), we observe that aged mirrors (green and blue curve) are more reflective than an intact mirror (black curve)

Accelerated aging tests and characterizations of solar mirrors: Comparison of combinations of stress factors on degradation", Grosjean A., Le Baron E., Disdier A., Solar Energy Materials and Solar Cells 220 (2021) 110851. https://doi.org/10.1016/j.solmat.2020.110851

Example of Coupling several acceleration stress factors of reflectors :

Thermal + UV + Humidity tests

- Evolution of specular reflectance ρs over time t



Initialization & dose effects:
Notice the effect of the 1st stress

Samples #3 : T + HR >T >T + Irr test

- Weibull curves with 12 points and -8% <Δρ< -15% with maximal absolute deviation of 0.4%
- Reflectance losses less important for mirrors starting with a temperature and irradiation test (T+Irr)

➔ "protective" effect of UV or polymerization of paints, rendered the paint layers non-permeable to water ?

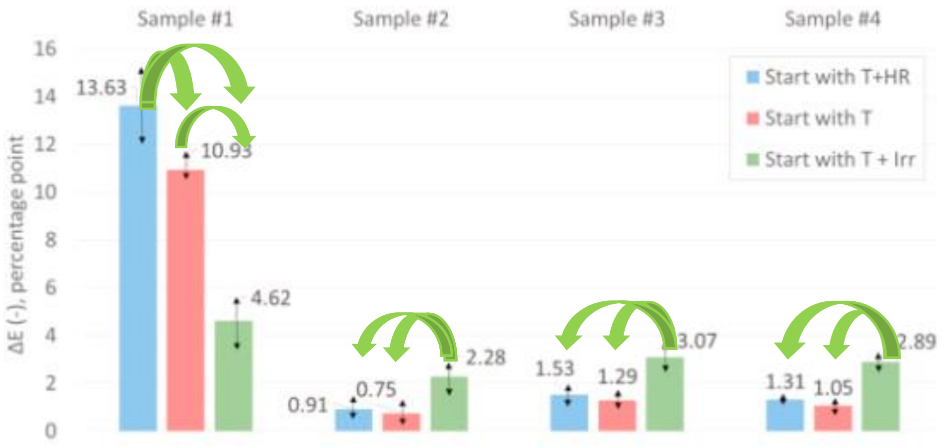
➔ effect of solarization : improve the transmittance of solar glass due to UV radiation

Accelerated aging tests and characterizations of solar mirrors: Comparison of combinations of stress factors on degradation", Grosjean A., Le Baron E., Disdier A., Solar Energy Materials and Solar Cells 220 (2021)

Example of Coupling several acceleration stress factors of reflectors :

Thermal + UV + Humidity tests

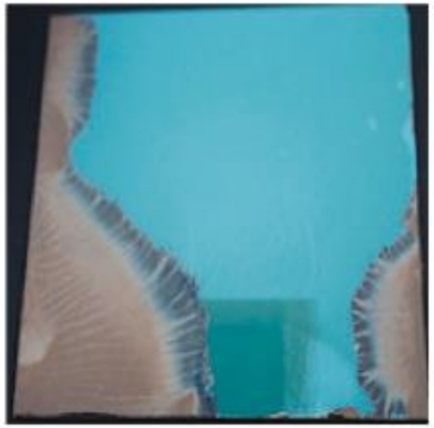
- Evolution of Colorimetric degradation (ΔE) over time t to compare different first aging tests for the same cycle duration



Initialization effect: the effect of the 1st stress

- 9 comparisons show high difference
- 3 comparisons show no difference

Samples #1 :



- Samples #1 : significant discoloration of 13% T + HR >T >T + Irr
- Samples #2, #3, # 4 : minimal discoloration of 3% and T + Irr >T >T + HR

Conclusion is the opposite of the one formulated for reflectance losses

Accelerated aging tests and characterizations of solar mirrors: Comparison of combinations of stress factors on degradation", Grosjean A., Le Baron E., Disdier A., Solar Energy Materials and Solar Cells 220 (2021)

Example of Coupling several acceleration stress factors of reflectors :

Thermal + UV + Humidity tests

Conclusion :

We have studied the coupling of temperature, humidity and UV irradiation stresses on solar mirrors during 12 weeks (2016 h) of accelerated ageing tests. We have chosen 4 different manufacturers of silvered glass mirrors to provide a total of 120 samples.

The hypotheses used by default in multi-factor aging tests were shown to be fallible :

1. The first moment of the mirror's life is decisive for the rest of its life
2. Each sample was subjected to the same duration of each stress (4 weeks in each climate chamber), the first stress and the turnover (1, 2 or 3 weeks) were different
3. We have shown that this difference is not a coincidence because the loss of reflectance is not negligible
4. One of the most surprising result of aging tests is the lifespan longer of mirrors (Samples #2 #3 #4) that underwent firstly UV irradiation stress : hypothesis of "protective" effect of UV or curing the paints

➔ It is necessary to propose a durability model taking into account the synergy and the order of application of the stresses.

➔ impact of three simultaneous stress factors in an appropriate climate Thermal + UV + Humidity tests chamber ?

it is not possible to substitute the combination of three stress factors by several climate chambers with one or two stresses

Accelerated aging tests and characterizations of solar mirrors: Comparison of combinations of stress factors on degradation", Grosjean A., Le Baron E., Disdier A., Solar Energy Materials and Solar Cells 220 (2021) 110851. https://doi.org/10.1016/j.solmat.2020.110851

Conclusion on lifetime prediction and durability studies :

<u>On models :</u>

- One stress factor : Temperature of tests used are suitable to determine the thermal resistance of components and calculation of activation energy. We can calculate the maximum temperature for lifetime operation by Arrhenius law
- Using T_{eff} instead of T_{mean} is necessary → importance of T_{eff} calculation for solar mirrors
- Model for one acceleration stress factors are validated but realistic need REX from kinetic results on CSP plants
- Difficulty to substitute the combination of several stress factors by several climate chambers with one or two stresses
- Need a model taking into account the synergy and the order of the coupling of several acceleration stress factors of tests

<u>On annual performance of solar spectra :</u>

- A slight difference between local spectra with Aeronet® software and the reference spectrum (AM 1.5) for CSP sites

<u>On lifetime prediction :</u>

- Need microclimat results (soiling, erosion, wind levels …) + coupling laws + measurement results on CSP plants during operation (mechanical and geometrical stress, cleaning frequency…)

<u>Role of paintings :</u>

- The paint on the back side of the mirrors and coatings on glasses and absorbers play a key role in the durability of these components (binder photo degradation, pigments loss and blistering phenomenon)
-

"Prediction is very difficult, especially if it's about the future!" N.Bohr

Optical and Mechanical Characterization Tools

Goal :

- determine the real shape of a curved mirror
- Intercept factor evaluation

Either :

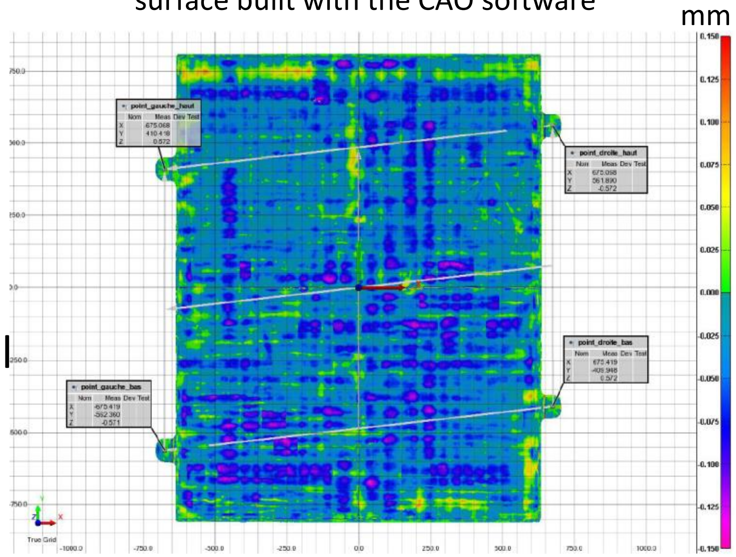
- points coordinates are measured
- Surface is built thanks to a CAO software
- CAO surface is imported into a raytracing model
- The intercept factor is determined

Or :

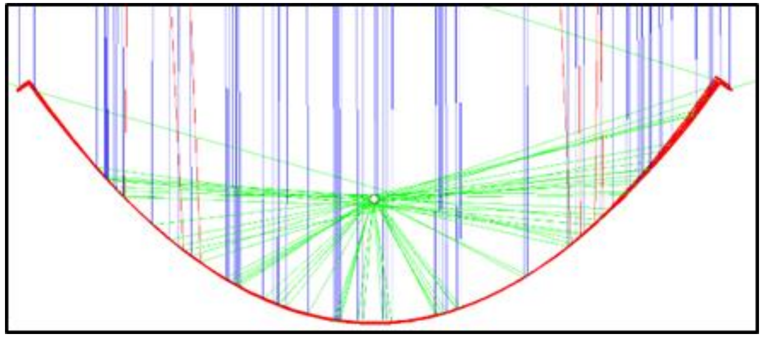
- Slope (or slope errors) are measured
- Knowing thanks to the model the intercept factor decrease with the slope errors, you can assess directly the intercept factor

Performance depends on the slope errors

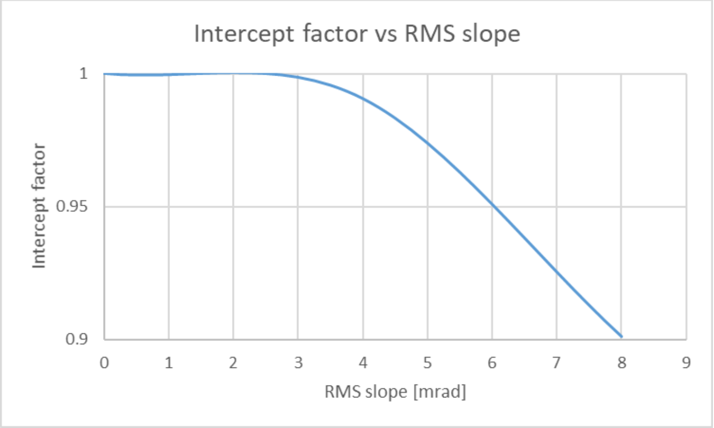
Altitude error map between measured points and surface built with the CAO software



=> Up to 0.15 mm



Example : PTC, C_geo = 19, rim angle : 110°, sun : on-axis



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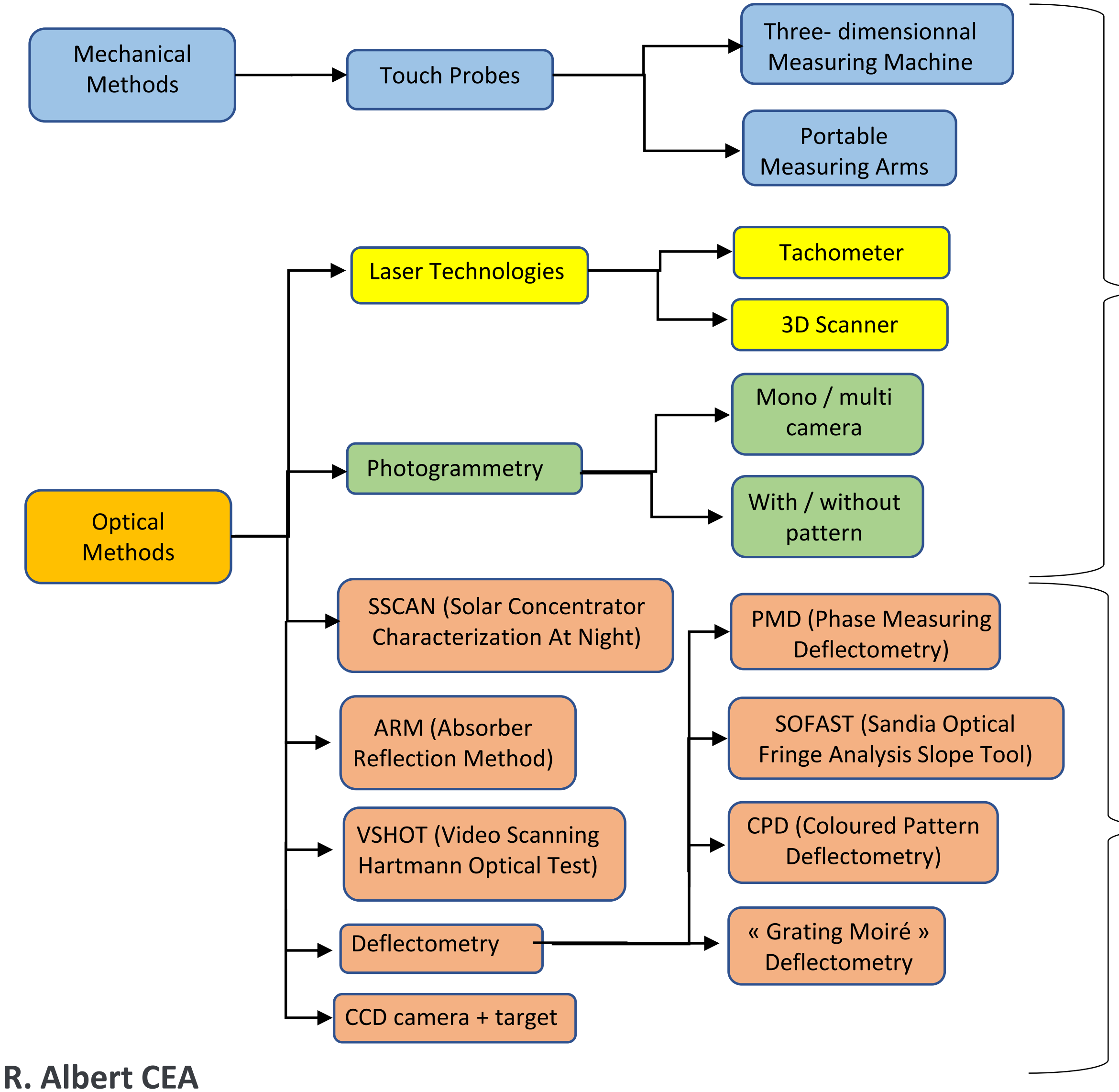


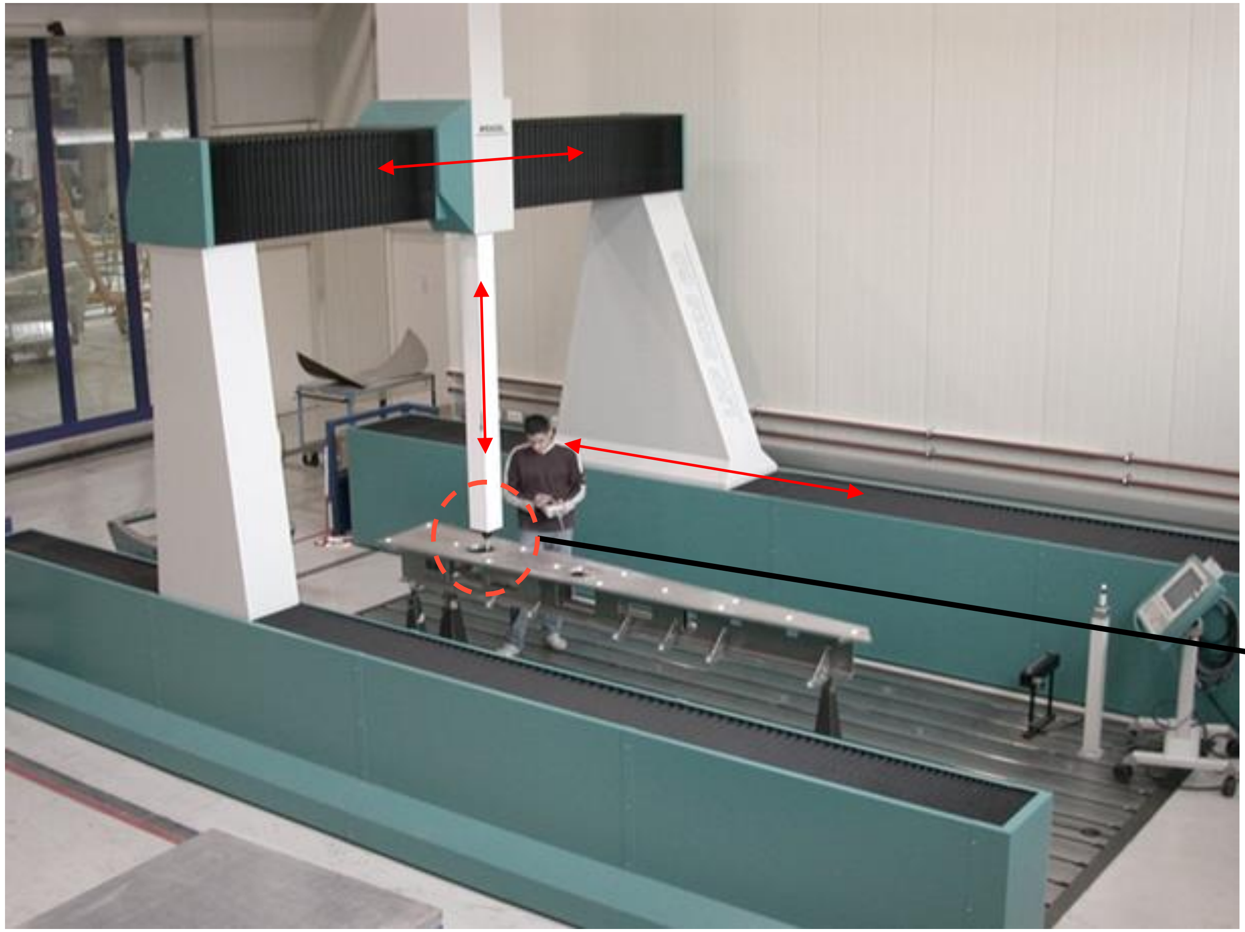
- Points coordinates measurement
- Commercial software available

=> More difficult to make those measurement outside (T°C, wind, sun reflects)

- Slope errors Measurement
- No commercial software available
- Except for Deflectometry, methods developed for CSP

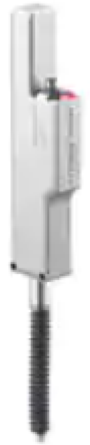
R. Albert CEA

Mechanical method : Touch probes : 3D measuring machine



Automatic measurements
Dimensions : up to 10 m
Accuracy < 0.1 mm :
- Error on the position of the probe (optical sensors on 3 axis)
- Error of the probe

Touch probe



Mechanical method : Touch probes : Portable Measuring Arms

VOLUME DE MESURE (m)

	1,2 M	1,8 M	2,4 M	2,7 M	3 M	3,7 M
Edge		0,024		0,029		0,064
Prime	0,016	0,019	0,024		0,042	0,060
Fusion		0,036	0,043		0,074	0,104

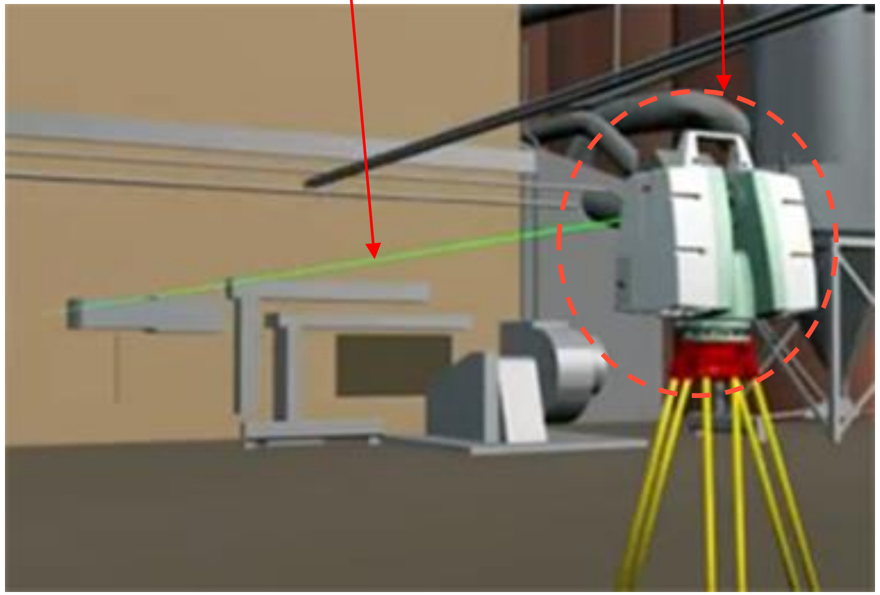
REPETABILITE (mm)

Very good accuracy (<0.1 mm)
Manual measurements
Size < 4 m

Laser technologies : Tachometer (or total station)

laser

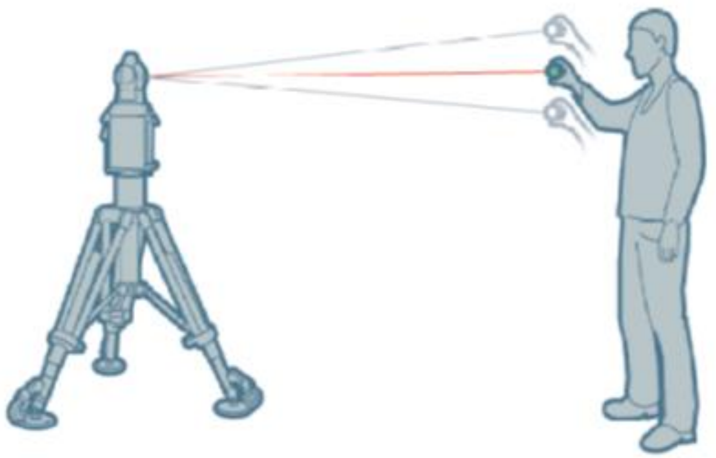
2 rotation axis



Laser emmitter + receiver : distance measurement (Dopler effect) : accuracy : 1 mm
Direction : optical sensors on both axis : accuracy : 0.1 mrad (1 mm at 10 m)
Scan the environnement moving on the 2 axis =>high spatial resolution
Not adapted to measure mirror :

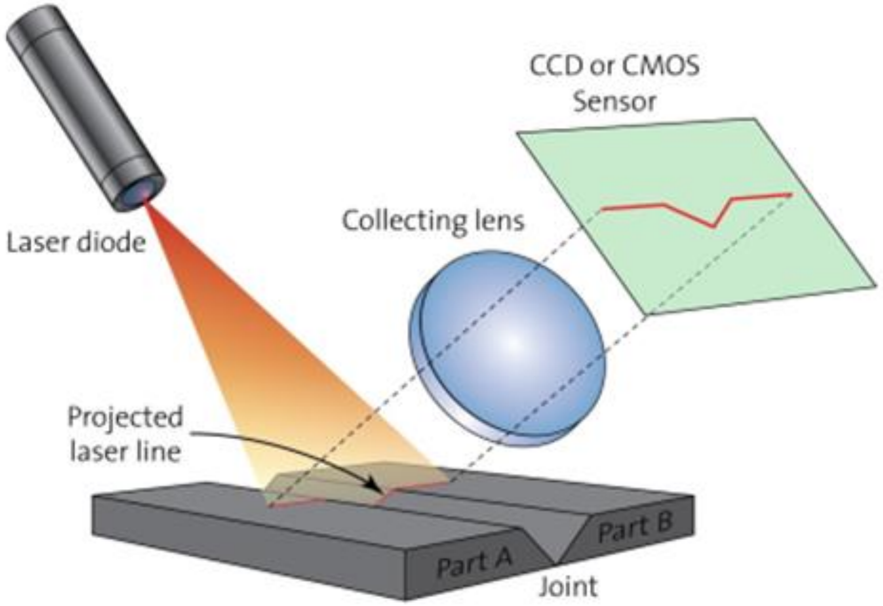
- dedicated white powder to apply or
- use of a tracker + retro-reflective sphere

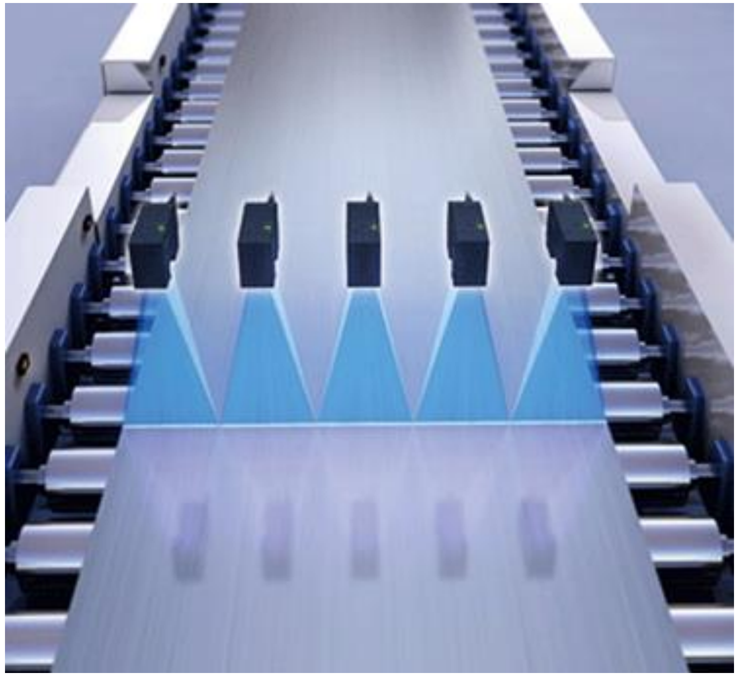
Laser technologies : Tachometer (or total station) + laser tracker + retro-reflective sphere



The tachometer tracks its target (retro-reflective sphere)
Point measurement one by one and by hand, moving the retro-reflective sphere on the surface to measure

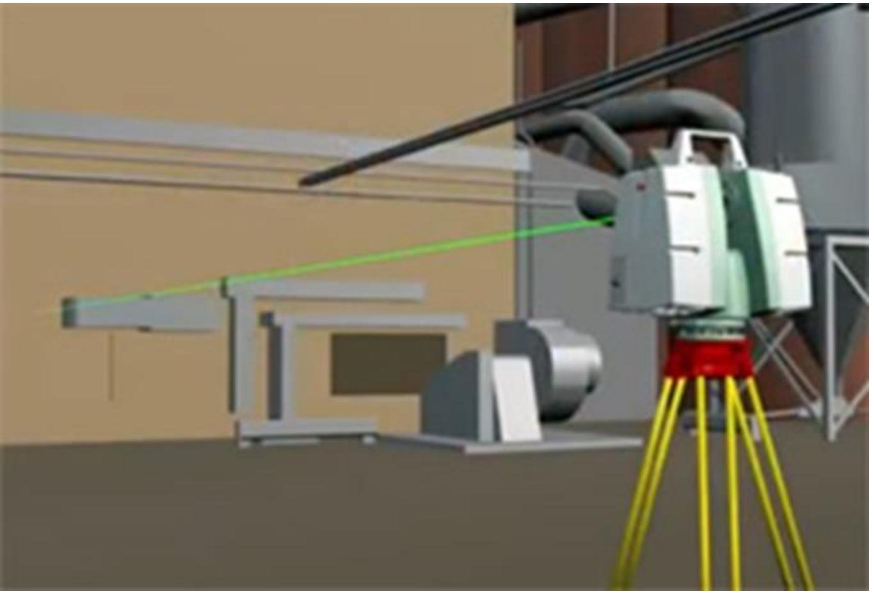
Laser technologies : 2D scanner

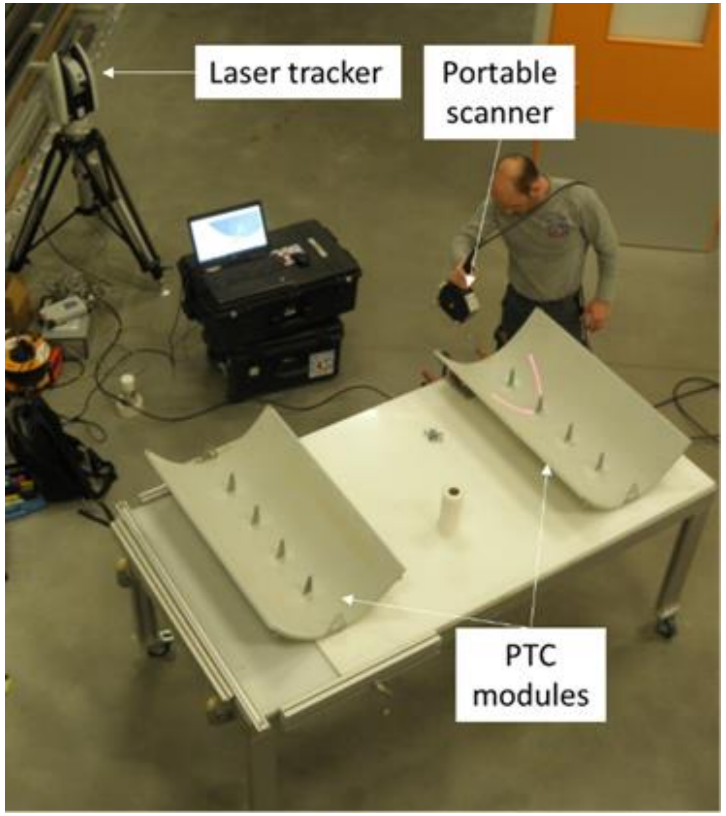




Measurement of the profile thanks to triangulation (incident angle needed)
Not adapted to measure mirrors :
- dedicated white powder to apply

Laser technologies : tachometer tracks the portable 2D scanner

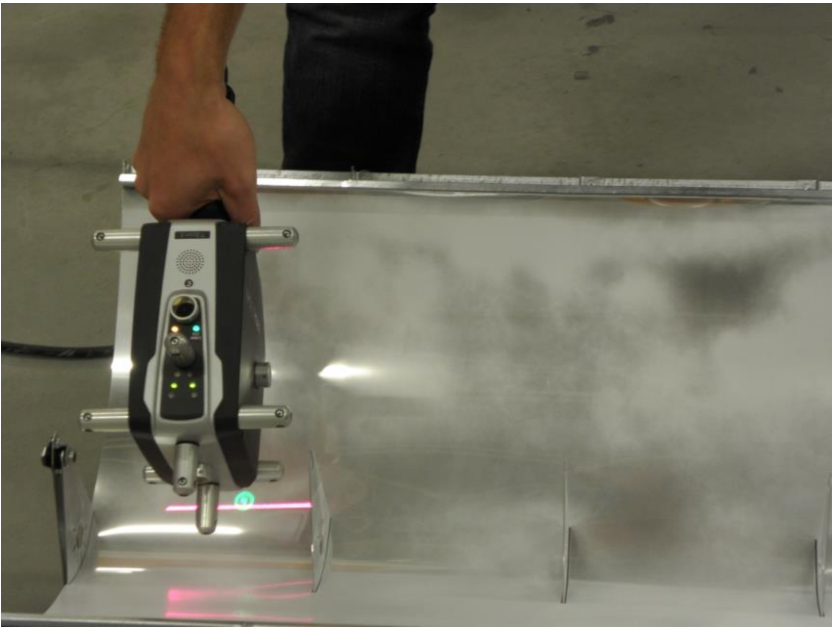


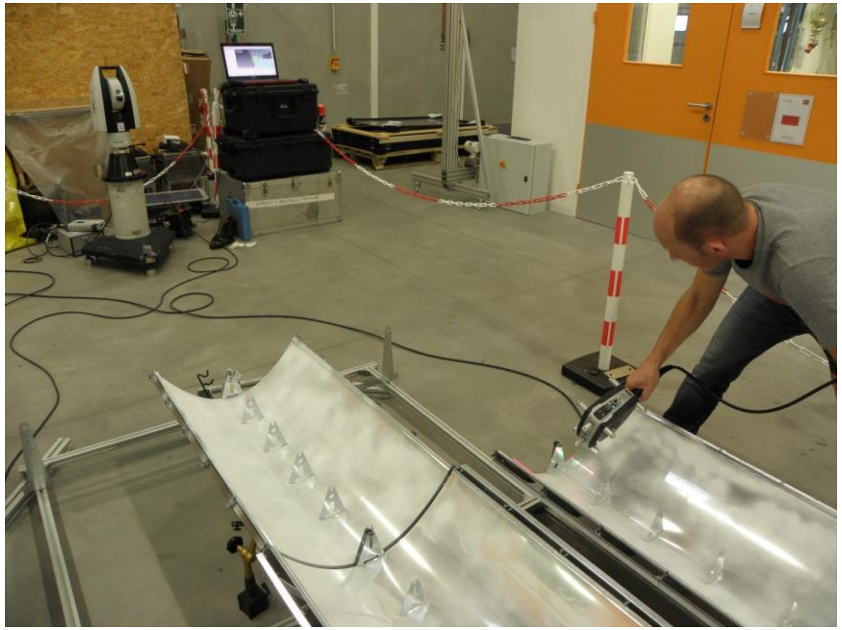


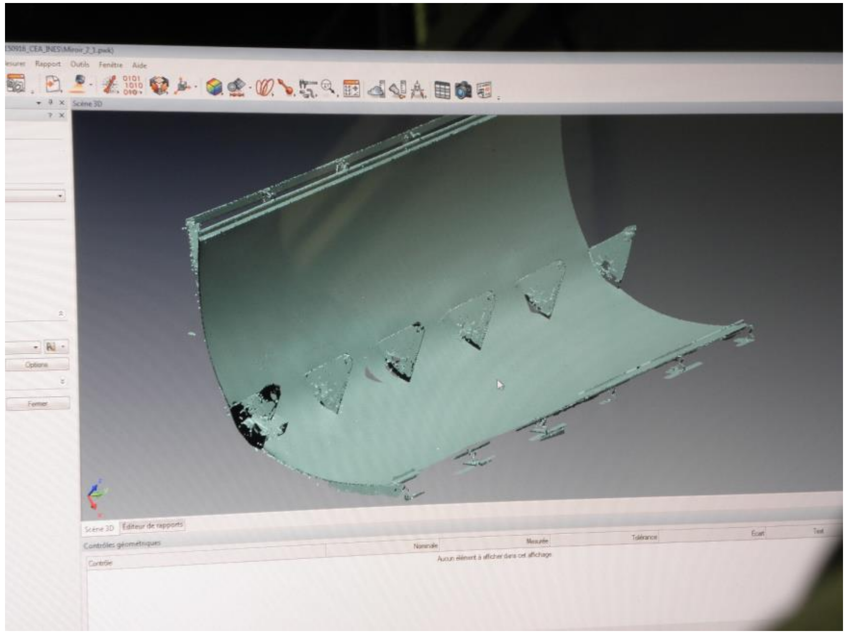
AT960 LR + T-SCAN 5 (LEICA) :

- Spatial resolution : 0.07 x 0.07 mm to 2 x 2 mm
- Accuracy : 80 µm + 3 µm/m

Laser technologies : tachometer tracks the portable 2D scanner





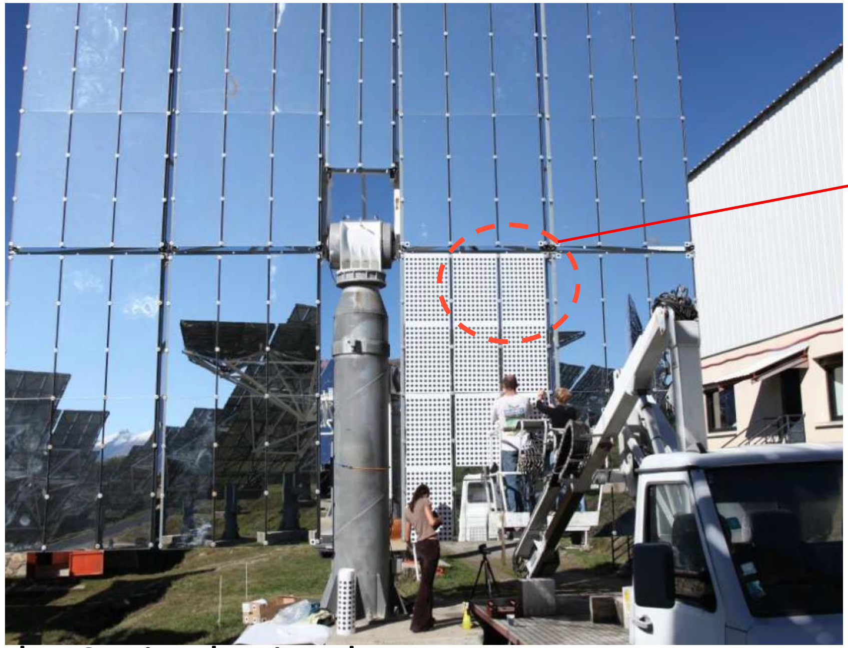


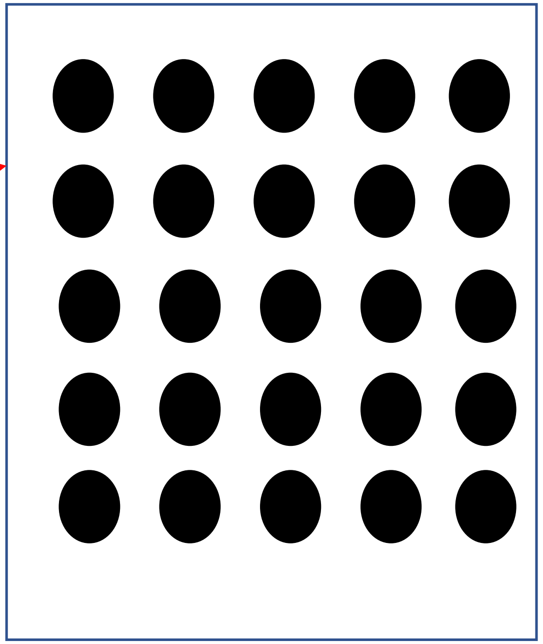
Touch probes associated with laser technology

Portable Measuring Arms + scan 3D

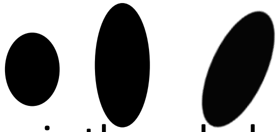
Portable touch probe + tachometer

Photogrammetry



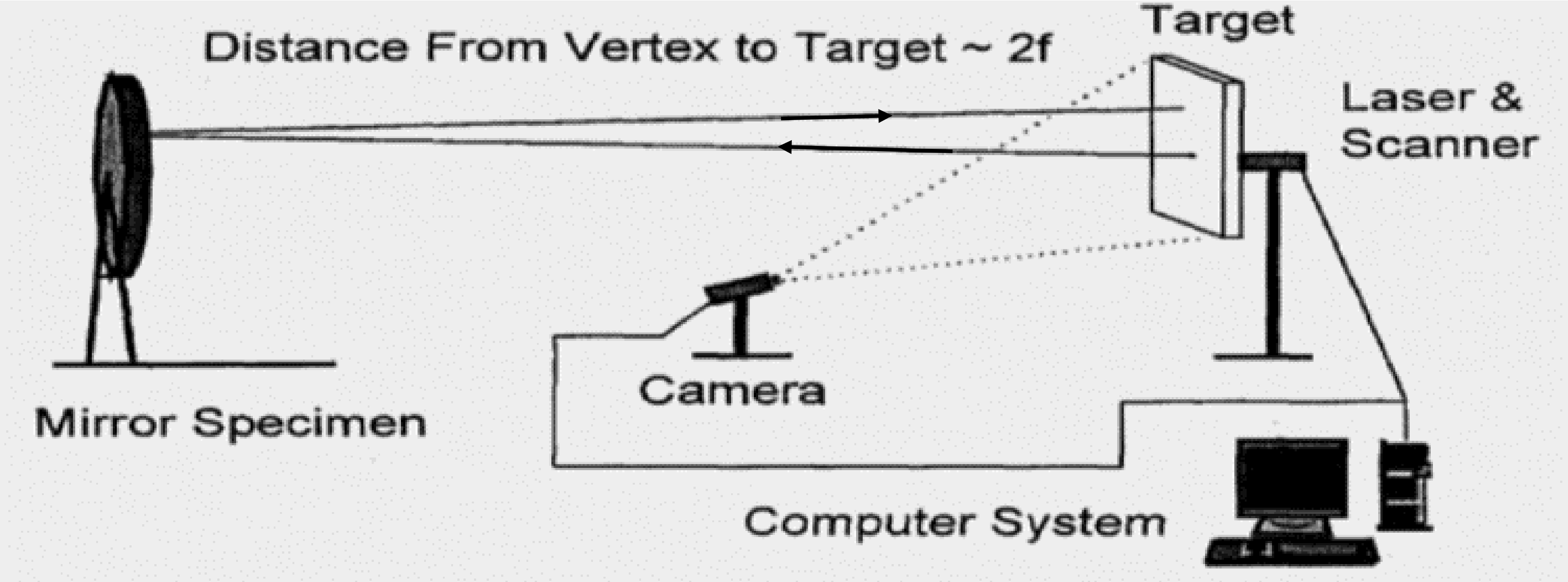


Thanks to several pictures of the same object, the 3D is obtained
4 corners location are deduced without any pattern
Several pictures with one camera or several cameras
Circles are seen deformed according to the location of the camera



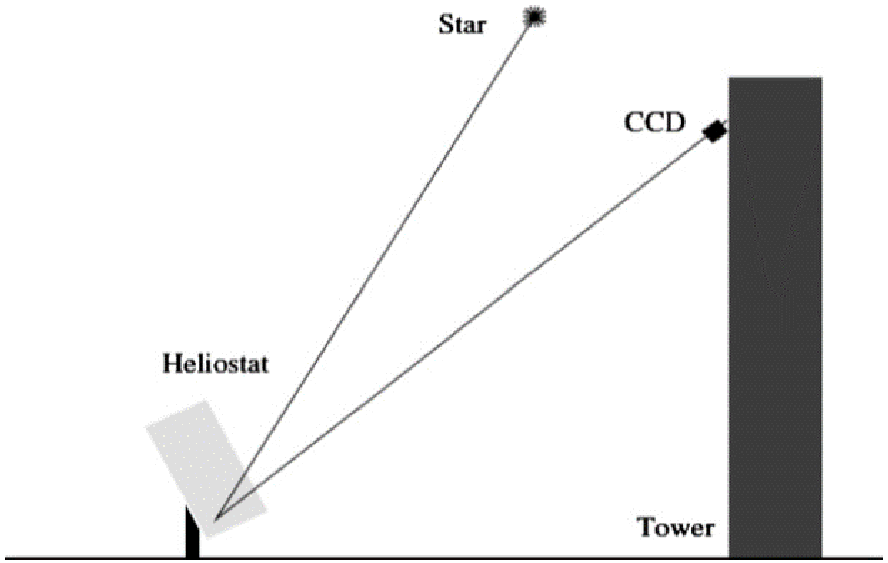
In the software, you indicate the 4 corners, the center of each black circles is then deduced
(Camera location is deduced)
Accuracy depends on the quality of the pictures, spatial resolution limited

VSHOT (Video Scanning Hartmann Optical Test)

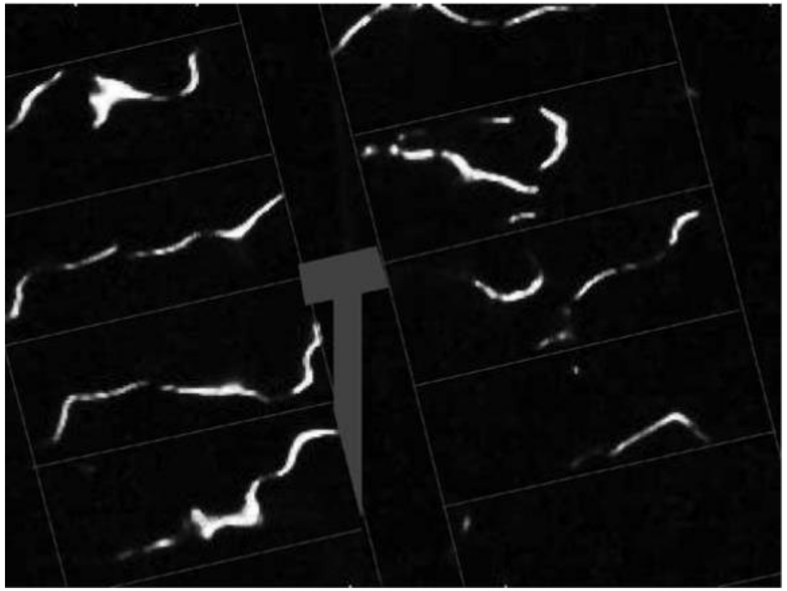


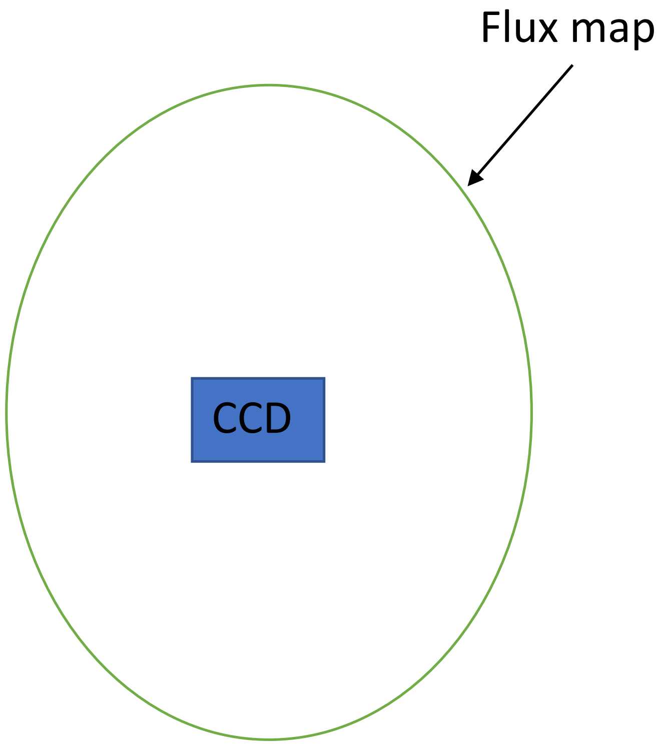
Slope measurement thanks to the location of the reflected spot on the target

SSCAN (Solar Concentrator Characterization At Night)



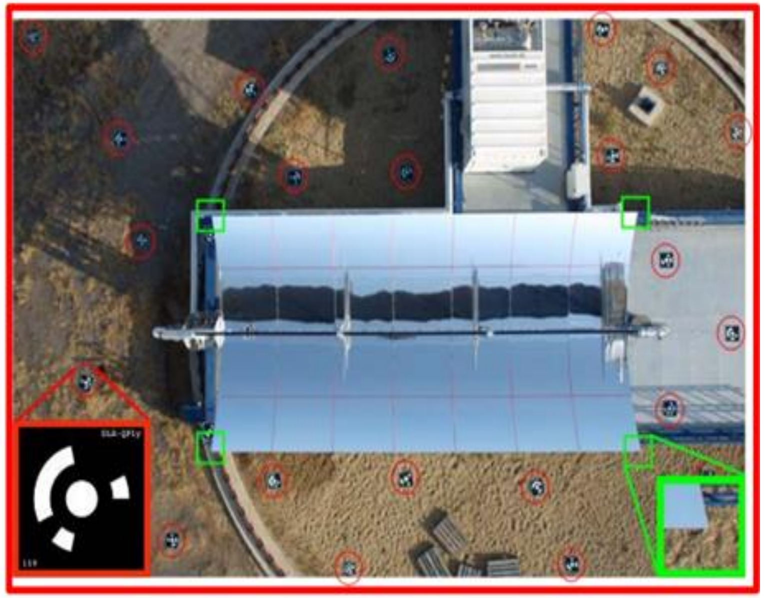
Star seen trough the heliostat, from the CCD camera

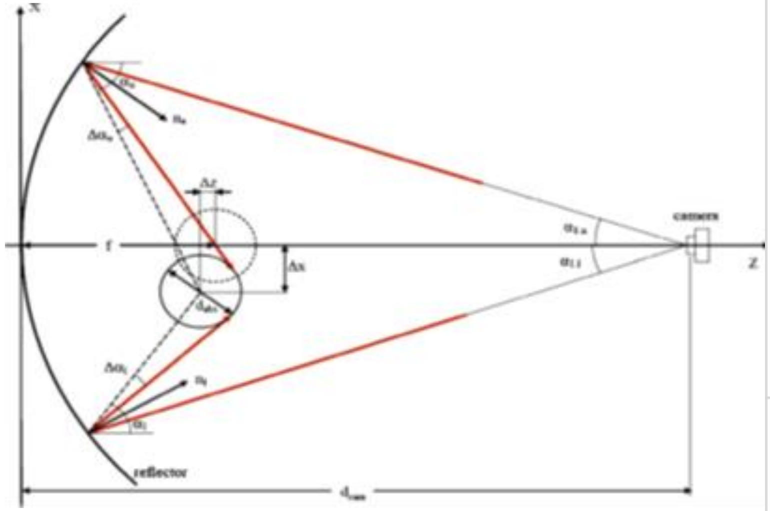


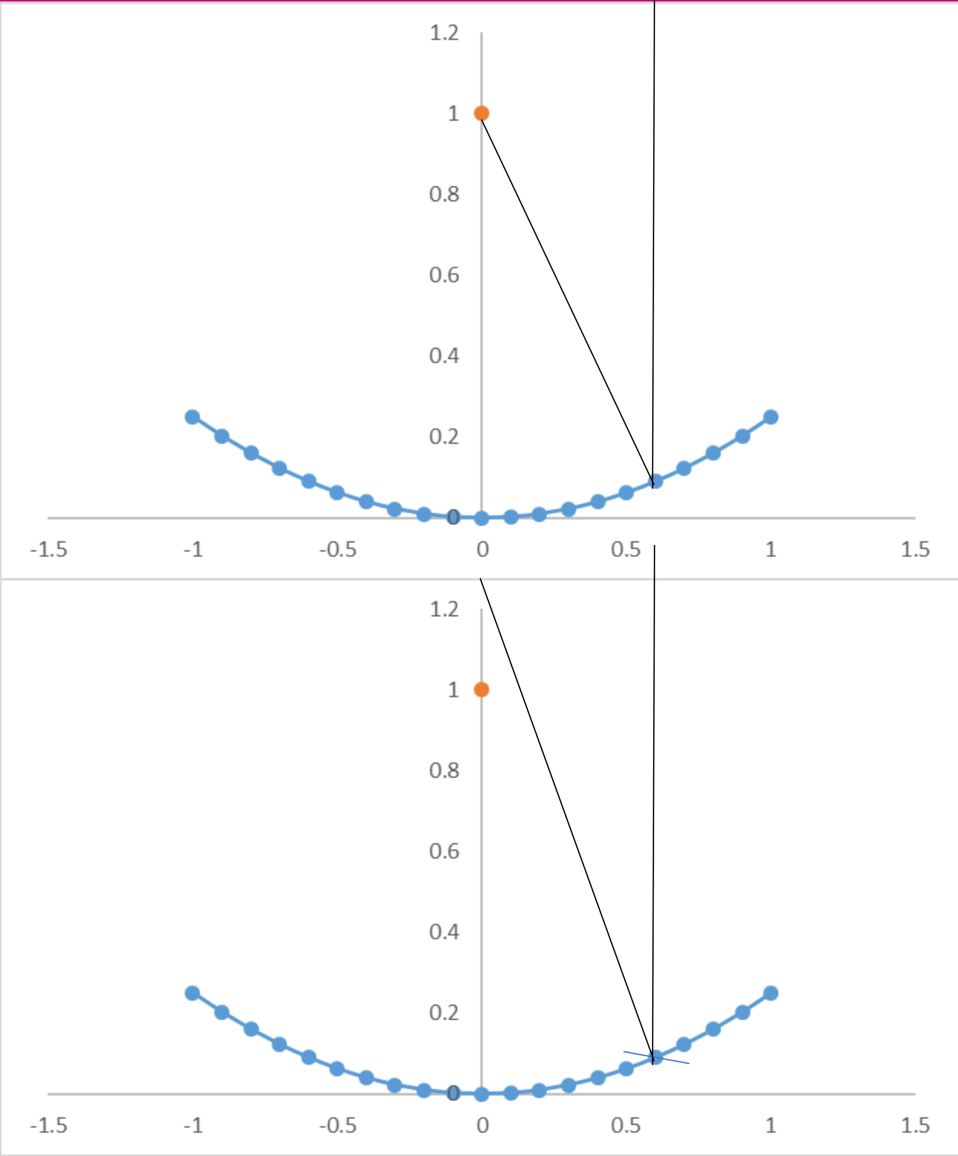


The heliostat tracks a star and aims at a CCD camera at the top of the tower
From the CCD camera, the star is seen at several location onto the heliostat
Need to sweep the heliostat (or the CCD camera) so that all the reflected spot goes to the camera
Slope errors are deduced comparing where the star is seen with where it should be seen (optical model)

ARM (Absorber Reflection Method)

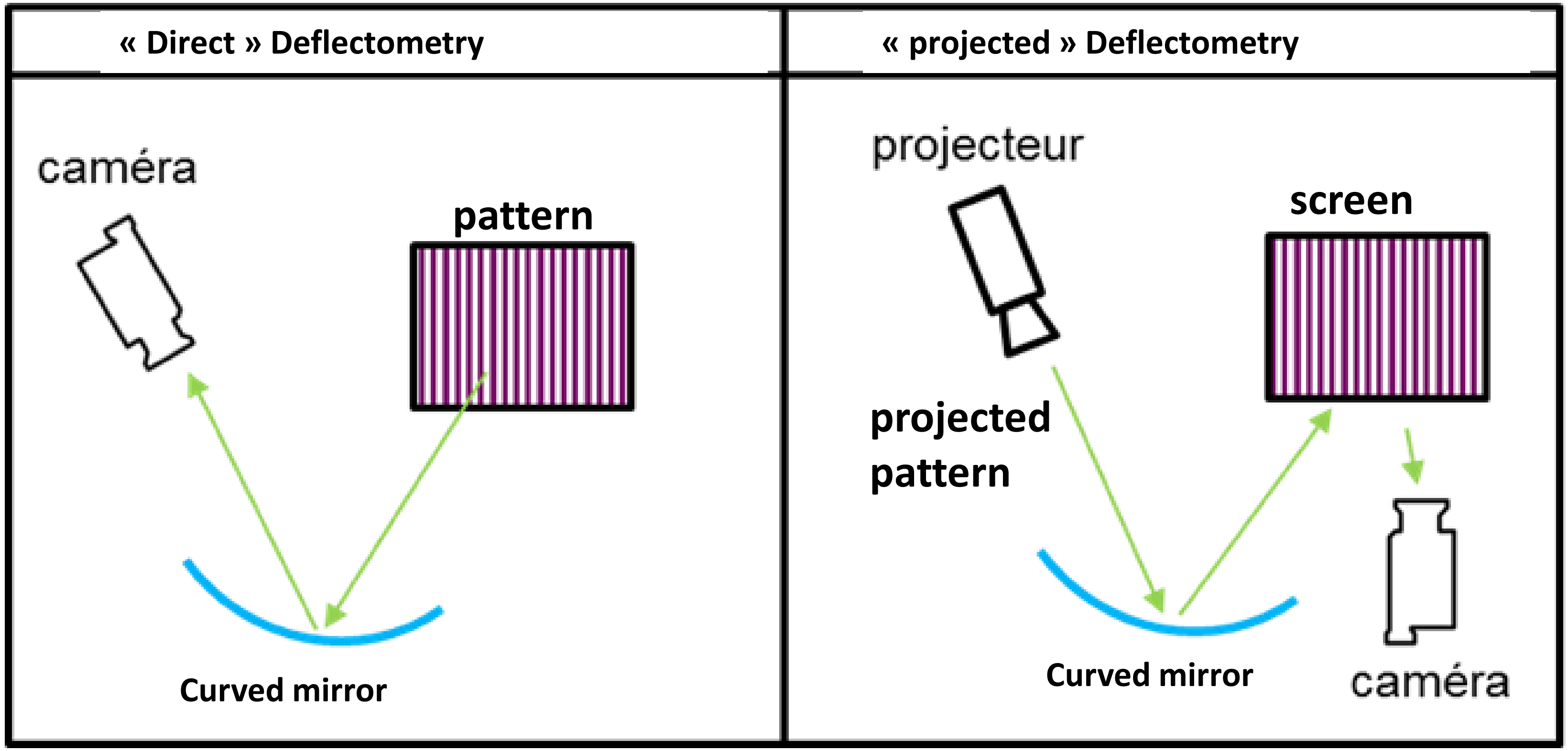






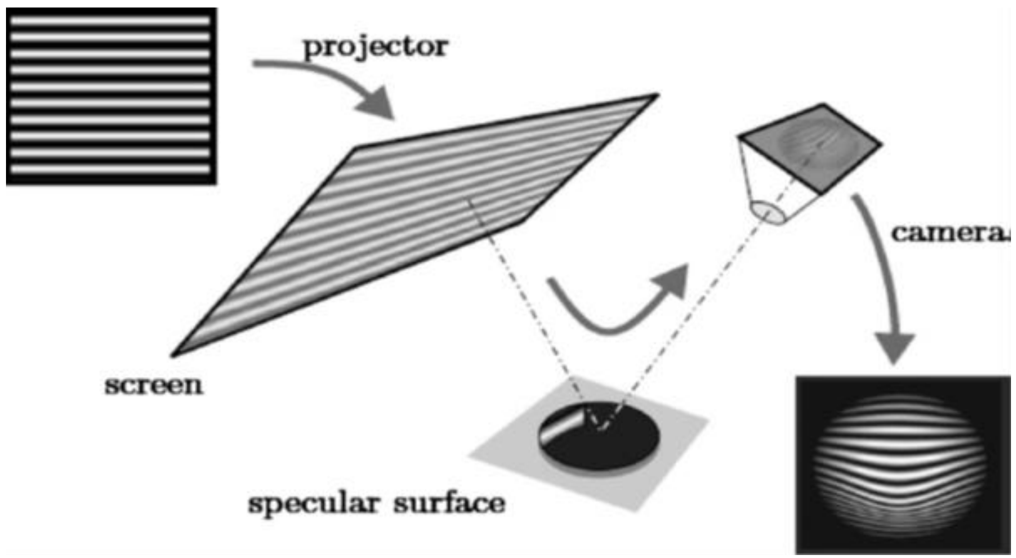
Camera is moving along the aperture
According to where the tube is seen, slope error is deduced

Deflectometry



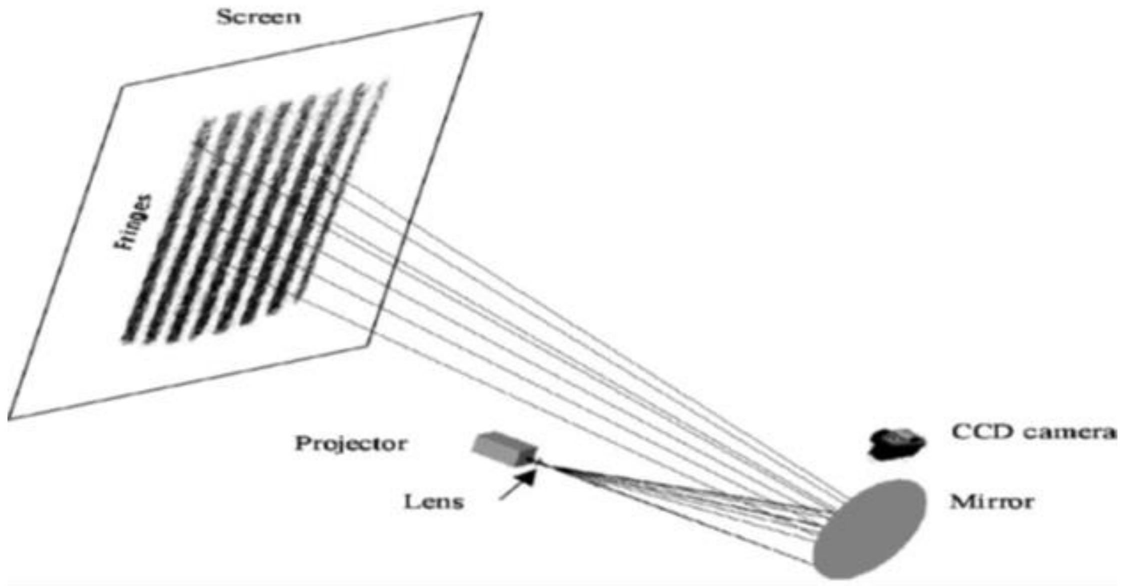
Fast
Accuracy : 0.1 mrad
High spatial resolution
No commercial software

Deflectometry : Phase Measuring Deflectometry (PMD)



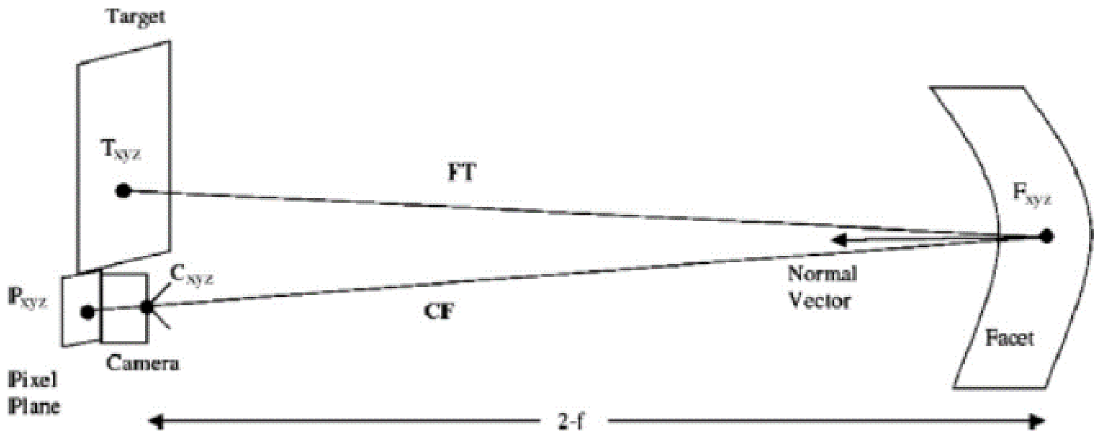
« Direct » Deflectometry
Use of the contrast (black to white according to a sinus)
Size of the fringe are moving

Grating Moiré Method



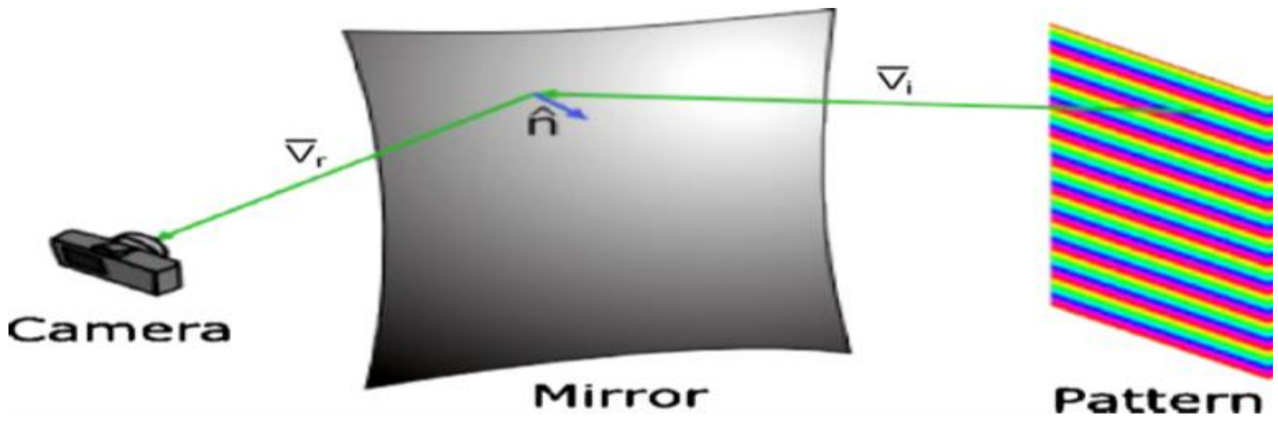
« projected » Deflectometry

Deflectometry : SOFAST
(Sandia Optical Fringe Analysis Slope Tool)



« Direct » Deflectometry
LCD screen : pattern can vary

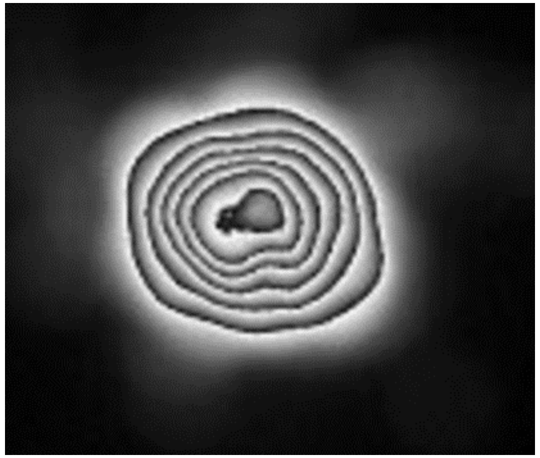
Coloured Pattern Deflectommetry (CPD)



« direct » Deflectometry

CCD Camera + Target

« grey » image from CCD camera



Slope errors are deduced indirectly comparing the measured and the simulated flux map
Need for a flux calibration

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KEYENCE, https://www.keyence.fr/products/measure/laser-1d/lk-g3000/index.jsp.

SFERA III: On site Training for Indusry

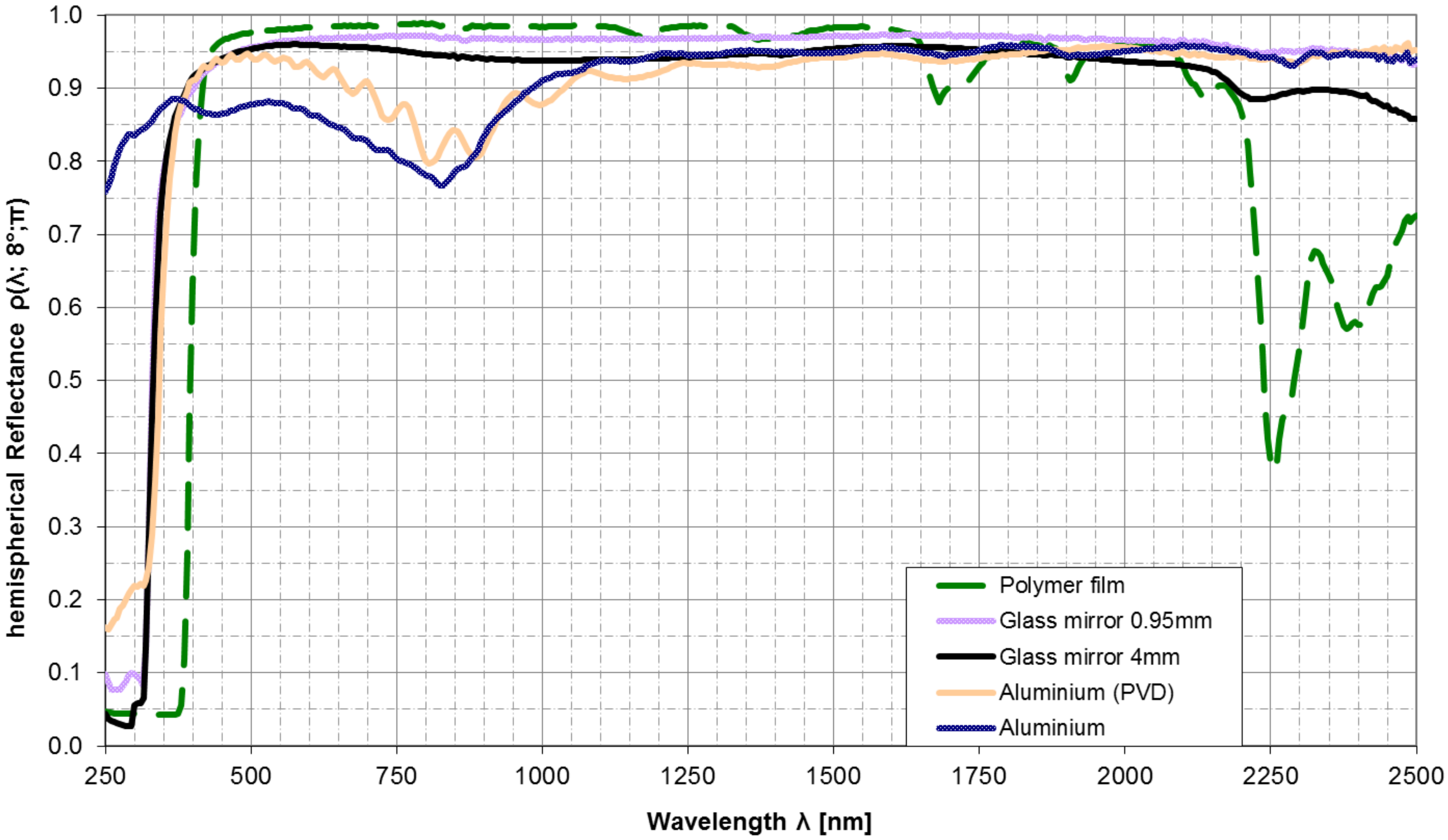
Le Bourget-du-Lac, June, 8th – 10th 2022

Optical characterization tools

Florian Wiesinger, DLR

Deutsches Zentrum
für Luft- und Raumfahrt e.V.
in der Helmholtz-Gemeinschaft

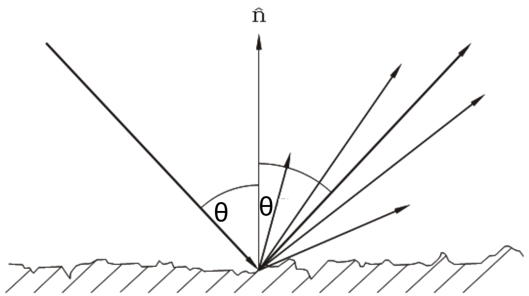
Materials – reflectance properties

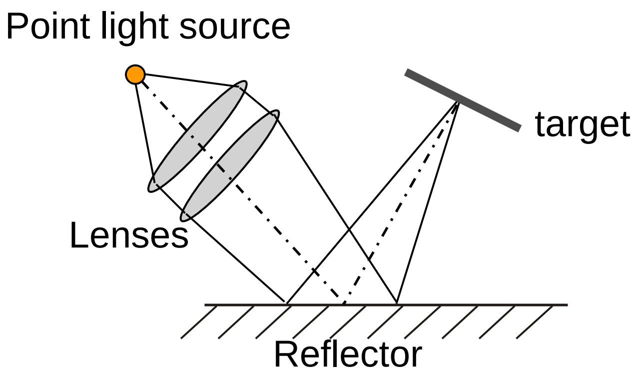


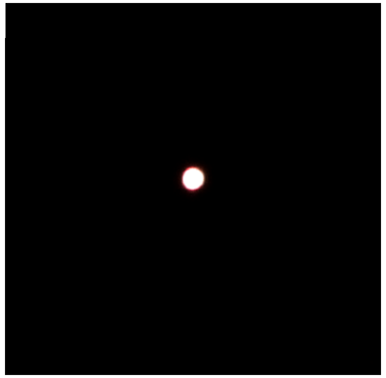
Materials – reflectance properties

	ρ(SW; 8º;h)	ρ(660nm; 8º;h)	ρ(660nm; 15º;12.5mrad)	ρ(SW; 15º;12.5mrad)
Glass mirror 0.95 mm	95.7	96.9	96.3	95.1
Glass mirror 4 mm	94.1	95.7	95.6	94.0
Polymer film	93.9	98.5	95.5	91.0
Aluminum (PVD)	90.0	90.6	85.1	84.5
Aluminum	87.2	84.2	79.6	82.4

Materials - scattering





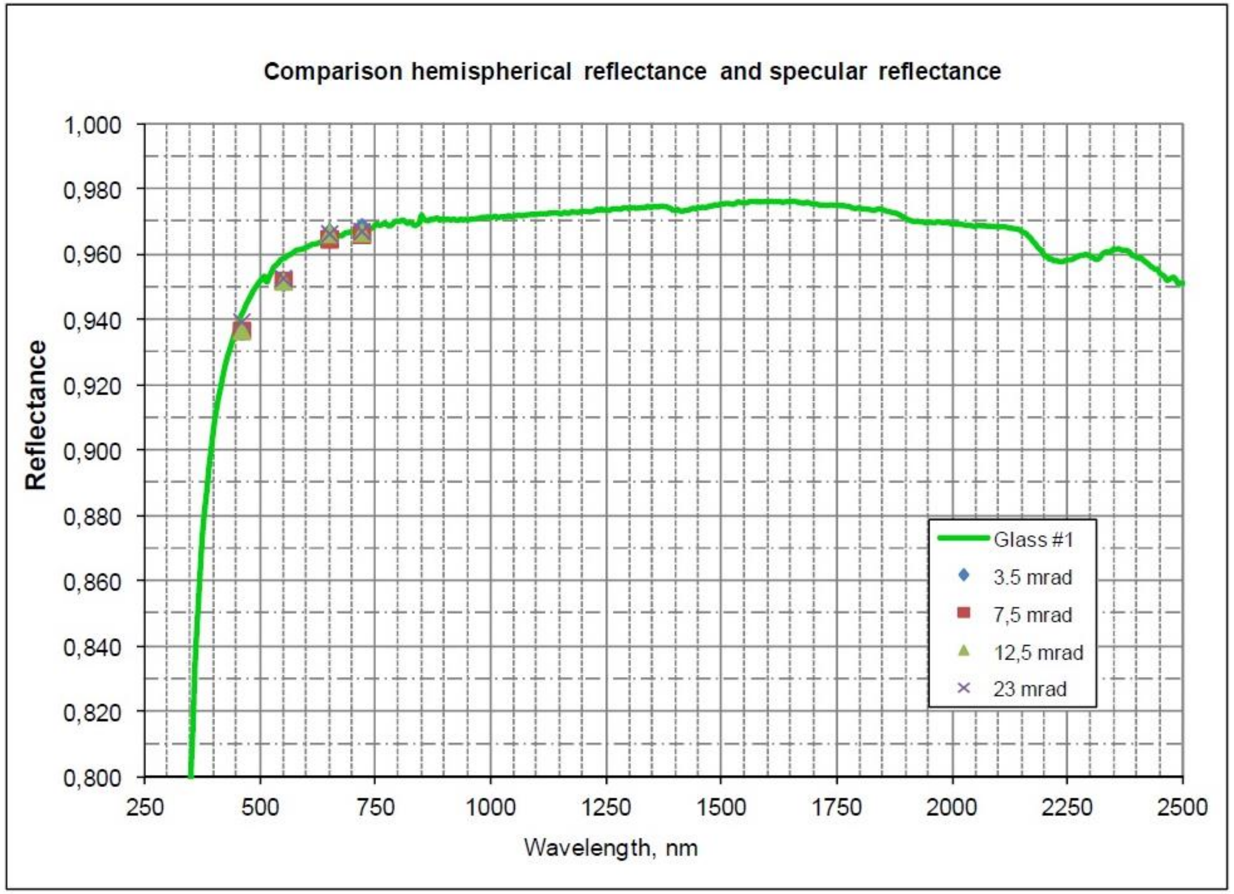


0.95mm Glass

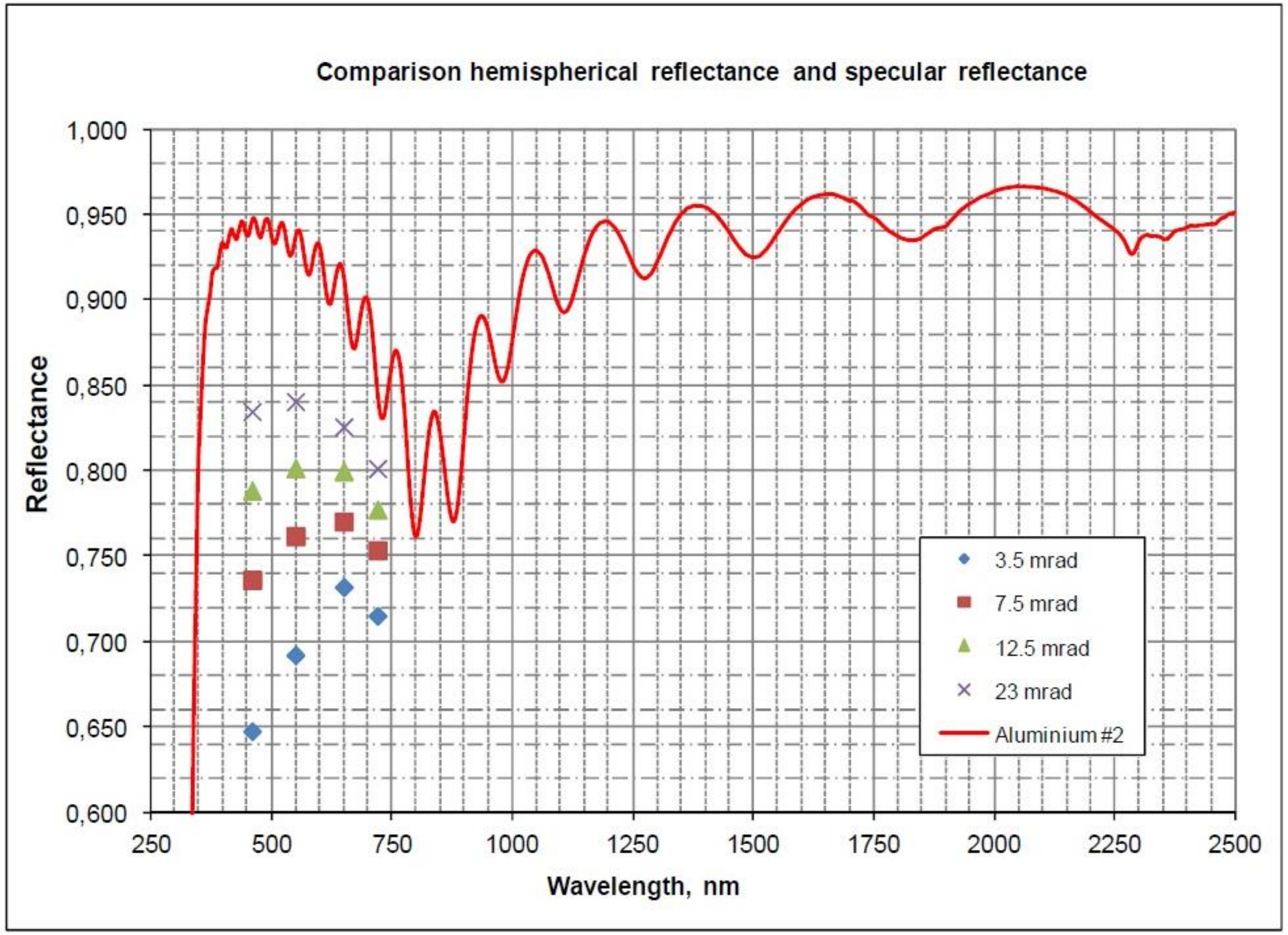
Polymer film

Aluminum (PVD)

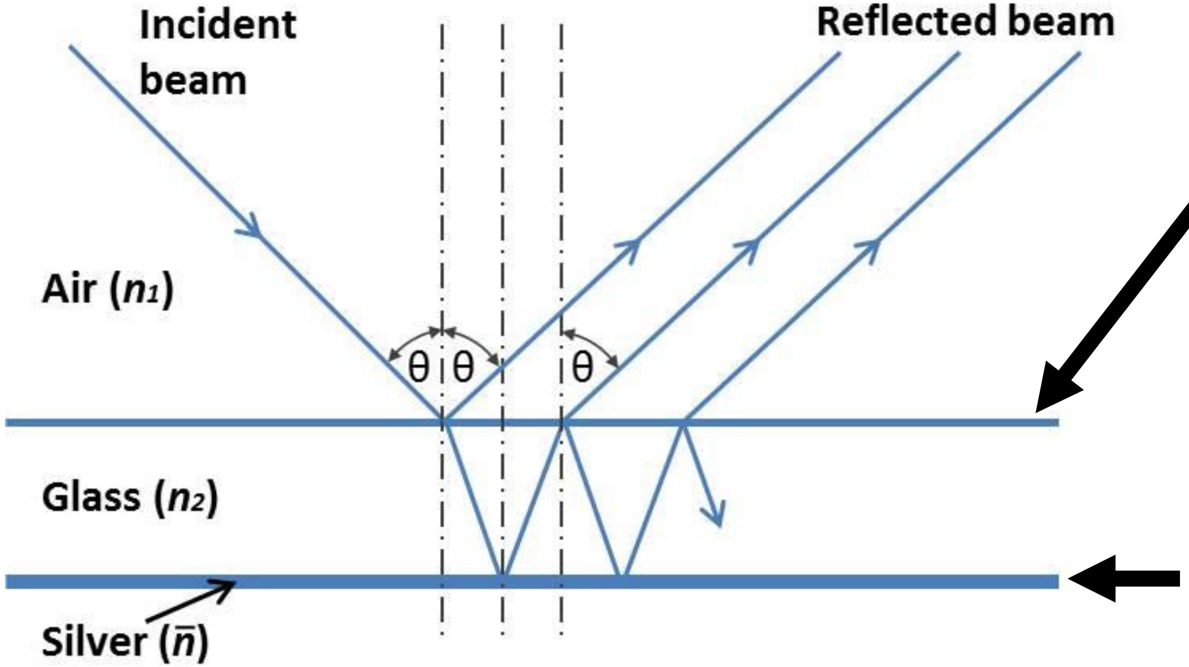
Materials - scattering

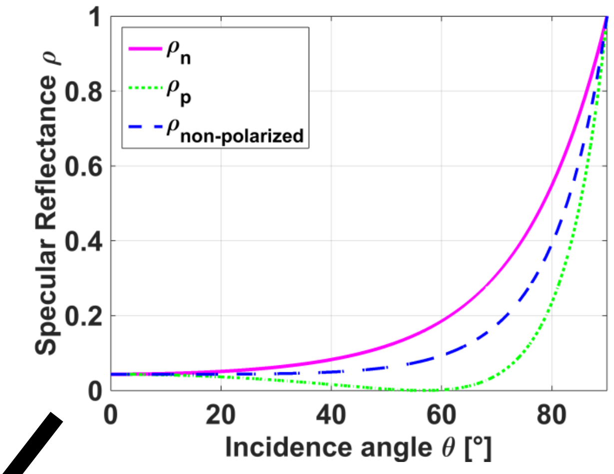


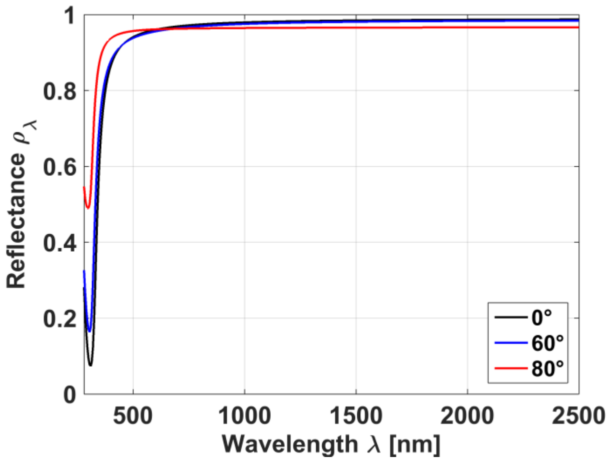
Materials - scattering



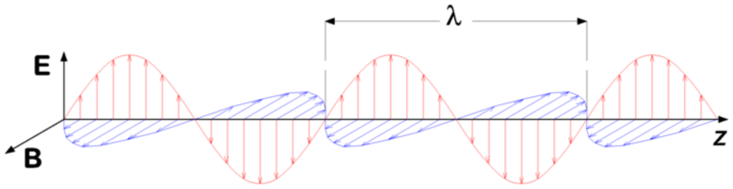
Materials – reflectance properties







Materials – reflectance properties



Fresnel formulae

Parallel polarized light

$$\rho_p = \left| \frac{n_2^2 cos(\theta) - n_1 \sqrt{n_2^2 - n_1^2 \, sin^2(\theta)}}{n_2^2 cos(\theta) + n_1 \sqrt{n_2^2 - n_1^2 \, sin^2(\theta)}} \right|^2$$

Perpendicular polarized light

$$\rho_s = \left| \frac{n_1 \, cos(\theta) - \sqrt{n_2^2 - n_1^2 \, sin^2(\theta)}}{n_1 \, cos(\theta) + \sqrt{n_2^2 - n_1^2 \, sin^2(\theta)}} \right|^2$$

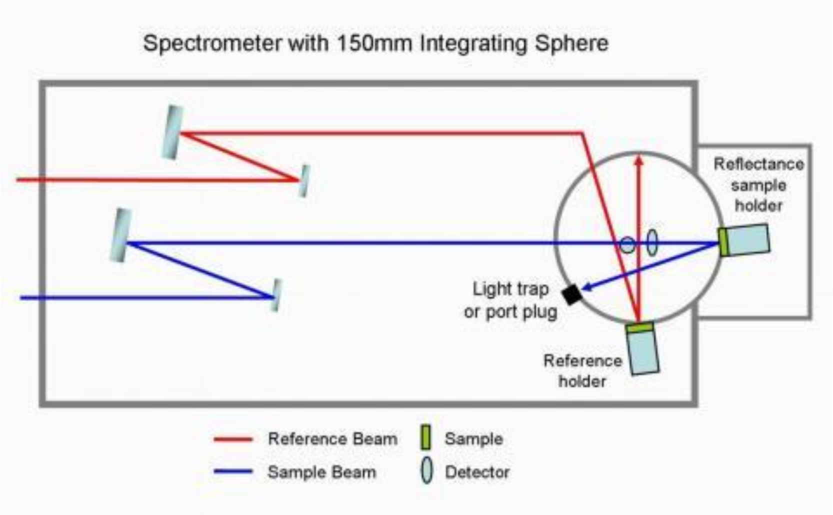
$$\rho_{non-polarized} = \frac{1}{2}(\rho_p + \rho_s)$$

Refractive index for metals is complex.

Perkin Elmer Lambda 1050 spectrophotometer

- Top class instrument
- Measures hemispherical reflectance, transmittance or absorptance
- Wavelength of light source: λ= 250 - 2500 nm
- Incidence angle θ =8°
- High repeatability (<0.2%)

Disadvantages:
- Max. measurement spot 9x17mm²
- No specular measurements



Materials – reflectance properties

D&S (various)

Condor

SOC 410 Solar

Konica Minolta

pFlex

Materials – reflectance properties

D&S (various)

- Monochromatic specular reflectance at selected acceptance angles
- Incidence angle θ =15°
- Beam spot diameter 10mm
- multi wavelength model with 460, 550, 650, 720 nm
- (Half) acceptance angles φ 2.3, 3.5, 7.5, 12.5 and 23.0 mrad
- Curved mirrors

Materials – reflectance properties

Condor – Aragon Photonics

- 6 different beam sources and 6 detectors
- Monochromatic specular and solar-weighted specular (from 6 wavelengths)
- Incidence angle θ =12°
- 6 spots are aligned (mirror thickness & curvature) and cover 230mm² area
- Wavelengths: 435, 525, 650, 780, 940 and 1050nm
- (Half) acceptance angles φ 145 mrad

Materials – reflectance properties

SOC 410 Solar – Surface Optics

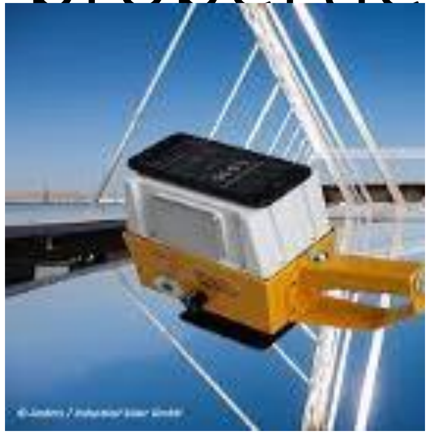
- Integrating sphere where specular port can be opened →hemispherical and diffuse, specular calculated
- Incidence angle θ =20°
- Beam spot diameter 6.35mm
- Wavelength at seven bands between 300 and 2500nm
- (Half) acceptance angles φ 52.4mrad

Materials – reflectance properties

CM700d/600d – Konica Minolta

- Integrating sphere where specular port can be opened →hemispherical and diffuse
- Incidence angle θ =8°
- Beam spot diameter depending on model between 3 and 8mm
- Wavelength in 10nm steps between 400 and 700nm

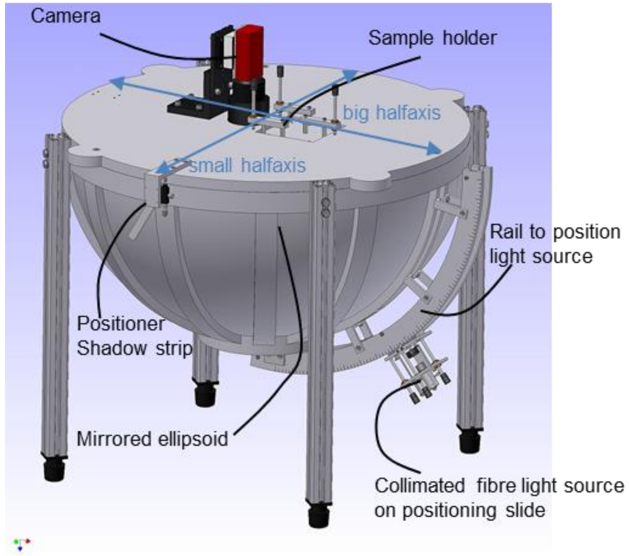
Materials – reflectance properties

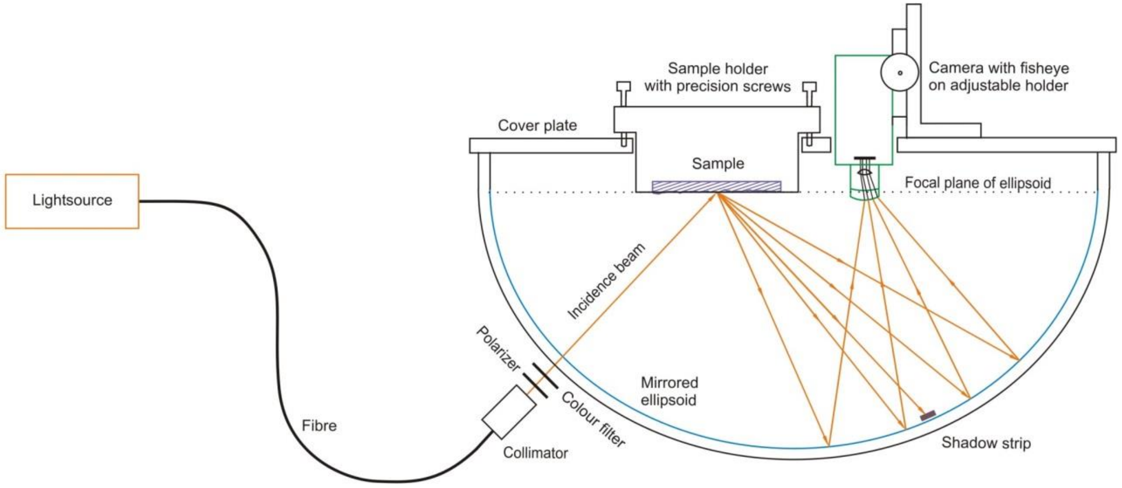


pFlex – Frauenhofer ISE

- 3 light sources with different λ and 1 detector
- Incidence angle θ =8°
- Beam spot diameter 10mm
- Wavelengths 470, 525 and 625nm
- (Half) acceptance angles φ 67mrad

Prototypes – MIRA

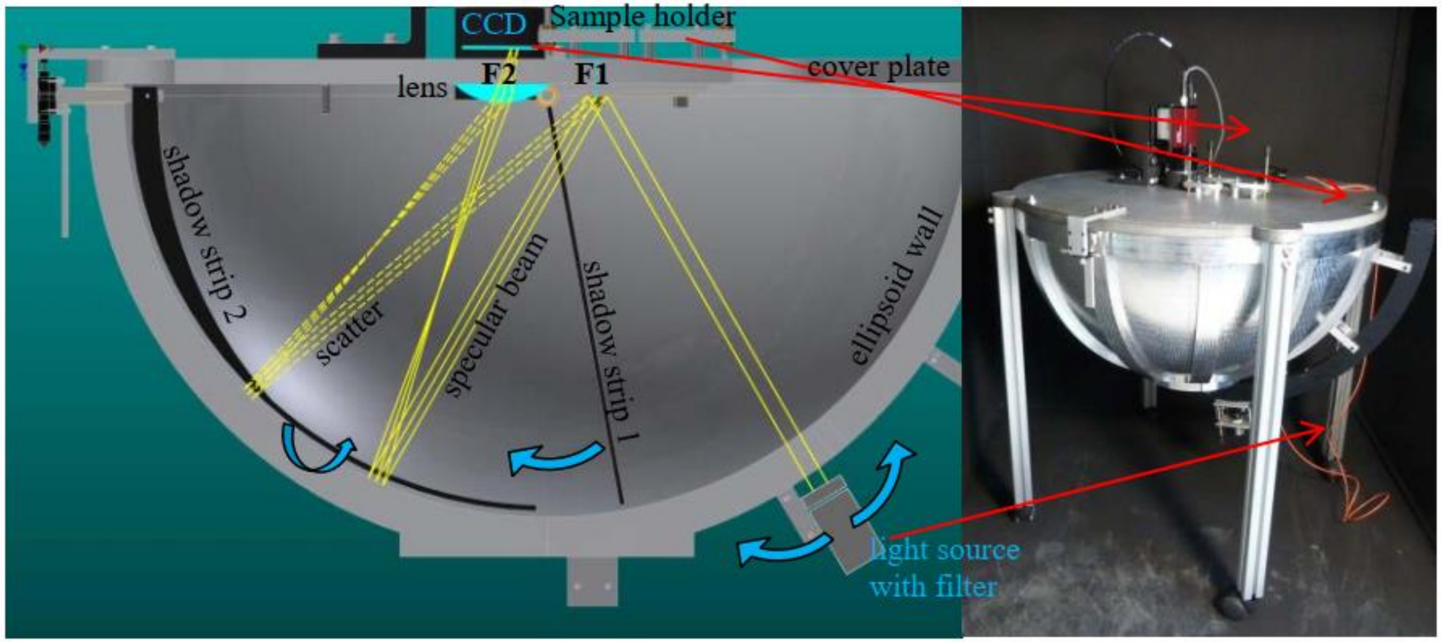




- Measurement of complete BRDF
- Allows to compute reflectance as function of φ
- Variable incidence angle θ = 6°- 60°
- White light or λ = 450, 500, 550, 650, 700, 850, 940 nm

Meyen 2014

Prototypes – MIRA



- Measurement of complete BRDF
- Allows to compute reflectance as function of φ
- Variable incidence angle θ = 6°- 60°
- White light or λ = 450, 500, 550, 650, 700, 850, 940 nm

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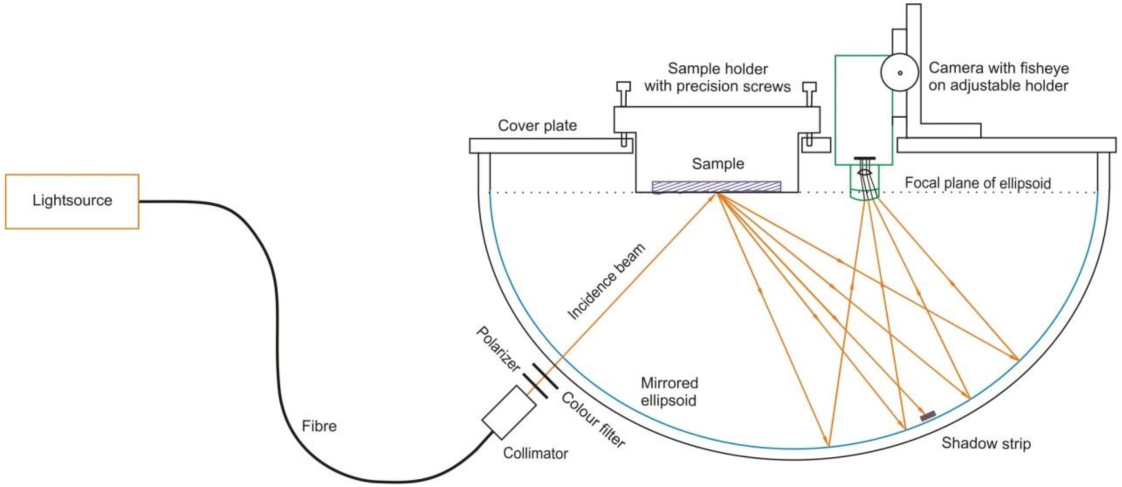
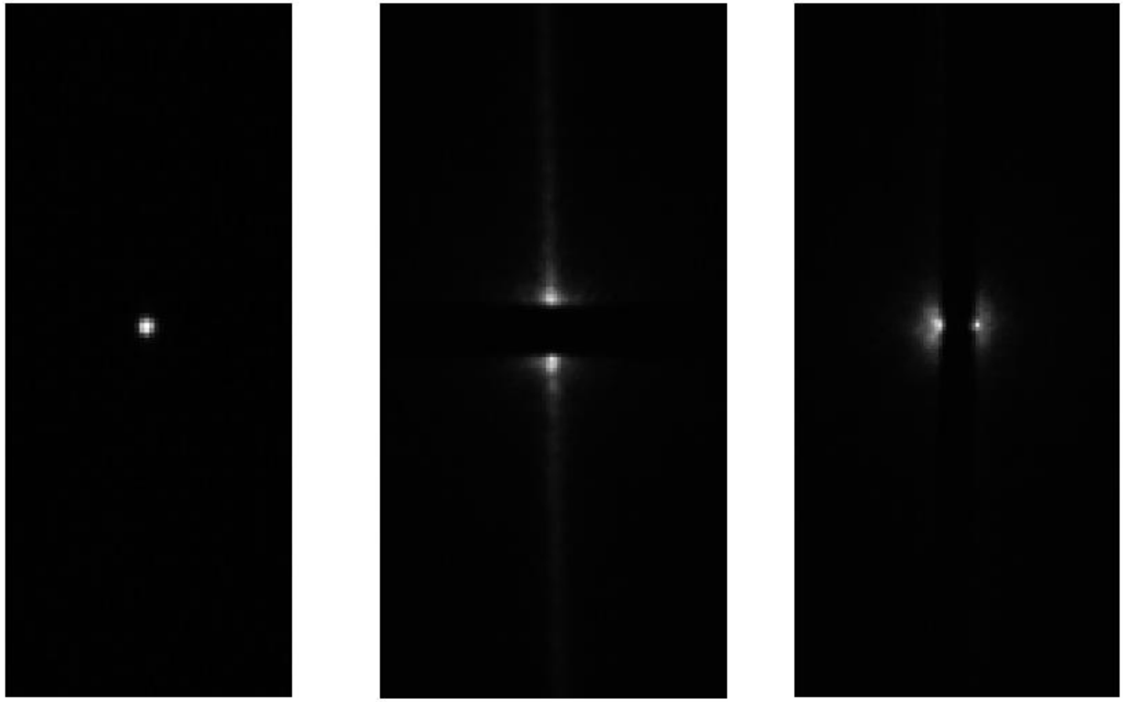
Prototypes – M





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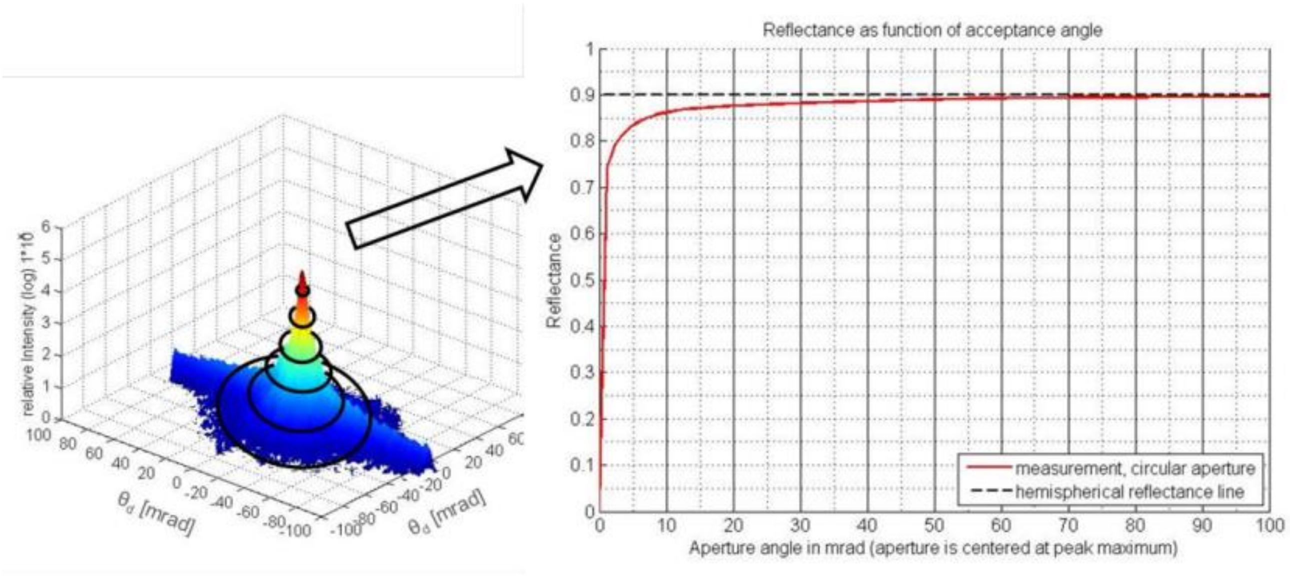
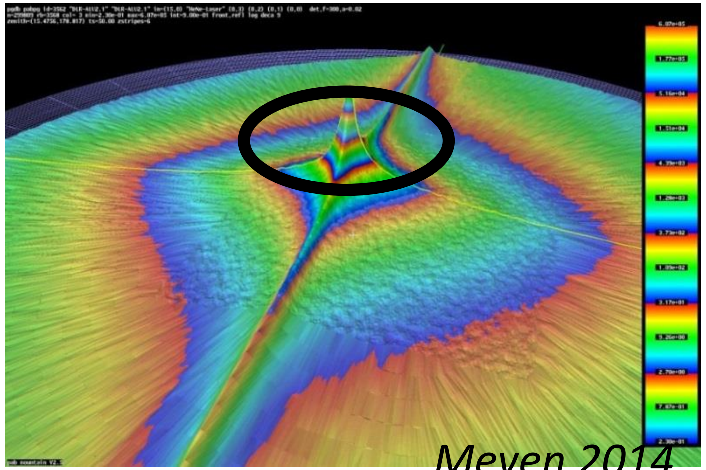
Prototypes – MIRA



- Measurement of complete BRDF
- Allows to compute reflectance as function of φ
- Variable incidence angle θ = 6°- 60°
- White light or λ = 450, 500, 550, 650, 700, 850, 940 nm



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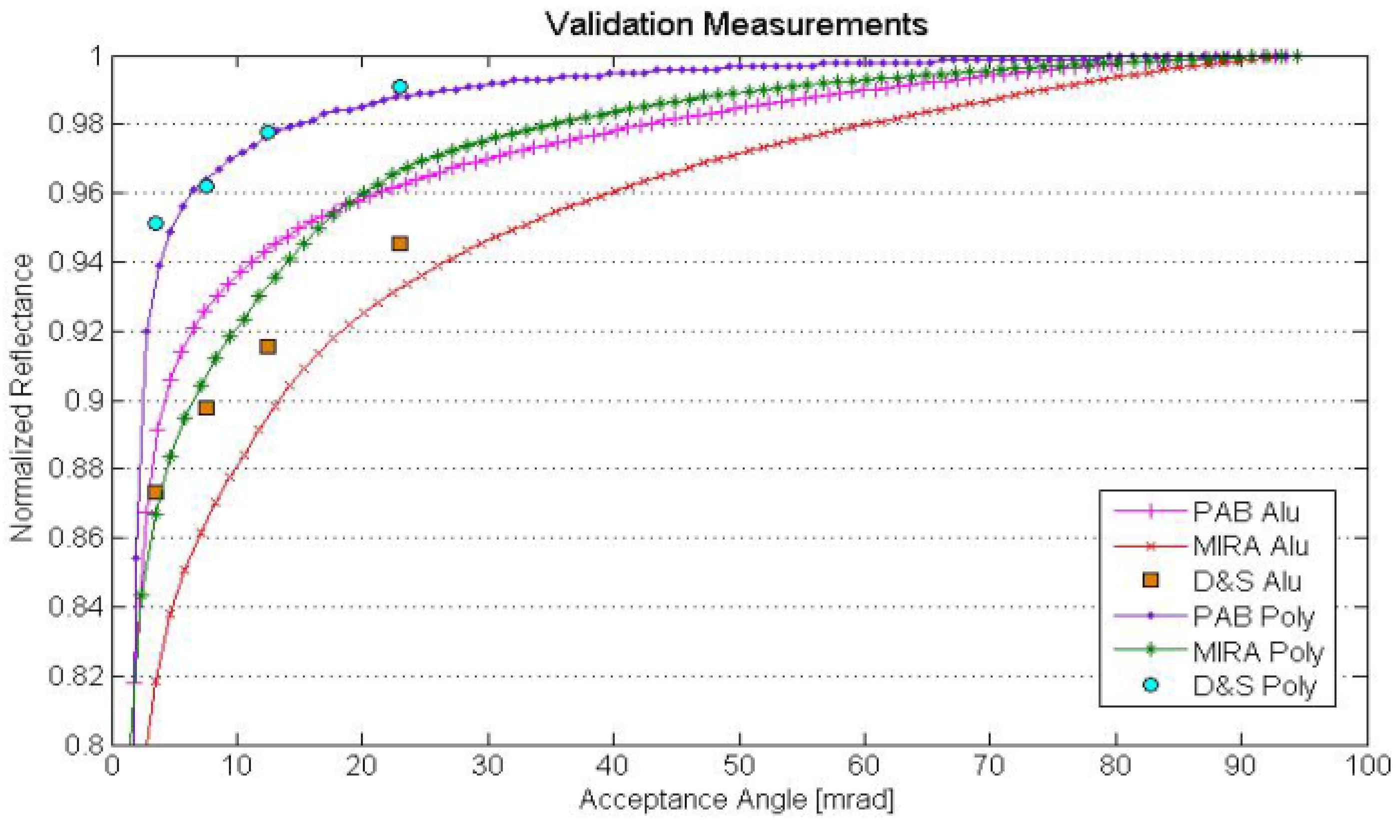
Prototypes – MIRA



D&S measurements at slightly different wavelength

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THANK YOU FOR YOUR ATTENTION!
ANY QUESTIONS?