D8.5: Report on the methodology of accelerated erosion testing for reflectors and absorbers

Performance of CSP components in desert environment

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Partner responsible	DLR, CRANFIELD, TEKNIKER, TECNALIA, CEA
Person responsible	F. Sutter (DLR)
Author(s) /Contributions:	Florian Wiesinger (DLR), Peter King (Cranfield), Francesco Pagano (Tekniker), Raquel Bayon (Tekniker), Gorka Imbuluzqueta (Tecnalia), Anne-Claire Pescheux (CEA)
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1 Introduction

In order to perform a reasonable yield analysis for concentrating solar power (CSP) plants, it is of crucial importance to determine all the relevant parameters that are affecting the electrical energy output. Energy conversion processes are limited in their efficiency due to several constraints and losses can be of optical nature, because of heat losses, or further effects like operation strategy or parasitic energy. For example, the peak optical efficiency of a parabolic trough collector can be written as:

$$\eta_{opt,0} = \rho \cdot \tau \cdot \alpha \cdot \gamma_{IC} \cdot \eta_{mech} \tag{1}$$

Where ρ, τ and α are the mirror reflectance, the glass envelope tube transmittance and the receiver absorptance, respectively. γ_{IC} is the geometric intercept factor and η_{mech} stands for mechanical imperfections like tracking or structural torsion [1]. It is important to note, that all those variables can change over time and thereby have a significant impact on the annual electricity yield of a CSP plant. Performance forecasts over the complete component lifetime are necessary in order to assess the economic benefit of the system as a whole. Typically the components, that are going to be used for CSP installations are subjected to accelerated aging tests which are especially tailored to meet the conditions to be expected during their lifetime. Many of those testing procedures are already formulated as standards; however a testing methodology to simulate the effects during sand and duststorms (SDS) is not available yet.

2 Scope

This guideline is dedicated to present the methodology to be applied if components are to be tested with respect to their resistance towards SDS erosion. It is important to note, that SDS can be very different around the world and meteorological measurements to determine all their physical properties in a temporal resolution are almost impossible to conduct. However various field campaigns from literature and the participating institutes provided enough knowledge to formulate this guideline. For example a three year outdoor exposure testing campaign in various sites in Morocco. Some of the exposed reflector samples have been found to be almost completely unaffected from erosion effects while at specific sites, especially in Zagora (Morocco), the specular reflectance has been significantly reduced after exposure.

This document depicts how tests should be designed and gives the most important parameter ranges in which representative tests should be conducted to simulate severe sandstorm conditions. Still it is highly recommended to confirm and optimize the testing conditions by the outdoor exposure of sample specimen at the respective site. Samples to be tested can be all possible optical components of CSP plants.

3 Specimen handling

The samples shall be handled with care. The cleaning is a very important issue for the comparability of the results. The samples must be carefully cleaned before optical characterization. Due to the nature of this aging experiment there will be a substantial amount of dust adhering to the sample surface. The removal of this dust should be carried out as reproducible as possible. The dust needs to be removed completely before performing optical measurements. However it should be avoided to cause more damage by the cleaning.

Samples should be cleaned under extensive demineralized water flow directly after testing to remove loose adhering dust. Still under water flow, the back side should be cleaned first with a soft tissue. When the backside is clean, the sample is turned and with only very little pressure and a new tissue the front side is cleaned under water flow. After some strokes, the tissue should be changed for a new one and slightly more force should be applied to the cleaning action. After the cleaning process the use of oil-free pressurized air is recommended to blow the sample dry.

4 Optical characterization

The severeness of erosion testing with different parameters should be evaluated and compared by the use of optical measurement techniques as specified in the SolarPACES Reflectance Guideline Version 2.5 [2]. A full characterization shall be performed before the first and after each accelerated erosion test run.

4.1. Measurement of the hemispherical reflectance, the transmittance and the absorptance

The hemispherical reflectance $\rho_{s,h}(\lambda,\theta,h)$ will be measured using a commercial laboratory instrument with an integrating sphere of minimum 150 mm diameter over the relevant solar spectrum from 300 nm to 2500 nm. The $\rho_{s,h}(\lambda,\theta,h)$ is measured at near normal angles of incidence, typically $\theta \leq 15°$ and preferably at 8°. The sample shall be measured three times and be rotated after each measurement by 90° (to obtain measurements at 0°, 90° and 180°, see Fig.1). The solar weighed hemispherical reflectance $\rho_{s,h}([300\text{-}2500\text{nm}],\theta,h)$ is calculated by integration of the reflectance spectrum with the solar spectrum ASTM G173 [3] as below

$$\rho_{s,h}(SW,\theta,h) = \frac{\sum_{i=300}^{2500} \rho(\lambda_i) E_\lambda(\lambda_i) \Delta\lambda_i}{\sum_{i=300}^{2500} E_\lambda(\lambda_i) \Delta\lambda_i} \quad (2)$$

The solar weighted transmittance is measured analogously. For the determination of solar weighted absorptance, $\rho_{s,h}(SW,\theta,h)$ is measured and subtracted from 1, to convert reflectance in absorptance.

4.2. Measurement of the specular reflectance

The specular reflectance $\rho_{\lambda,\varphi}(\lambda,\theta,\varphi)$ will be ideally measured at three narrow wavelengths with an acceptance half angle $\varphi \leq 20$ mrad and an incidence angle $\theta \leq 20°$. If the instrumentation available does not permit to measure at 3 λ, the measurement will be done at only one λ. If available, the specular reflectance will be measured with the portable reflectometer D&S with $\varphi = 12.5$ mrad and $\theta = 15°$.

At least three measurements on different local spots should be performed per sample (see Fig.1). The average should be given as a result together with its standard deviation. This is particularly important since erosion simulation can present considerable inhomogeneity over the eroded surface area. To perform this task, larger samples eroded in an area of e.g. 6 x 6 cm² or 10 x 10 cm² are advantageous since they offer more area to measure on. For specimens that are eroded on the minimum circular area of 2.5 cm diameter, measurement spots might probably overlap partially but great care needs to be taken not to measure outside of the eroded area (make use of a suitable mask).

Figure 1: Illustration of the positioning of the measurement spots on a reflector sample. The grey circle represents the minimum area of the erosion experiment (2.5 cm diameter), the red circles stand for the D&S measurement spots (1 cm diameter with allowed overlap) and the green rectangle for the measurement spot of a Lambda 1050 spectrophotometer from Perkin Elmer (17 x 9 mm²) in the 0° measurement position. This spot shall be rotated two times by 90°.

4.3. Further evaluation

Microscope pictures of the samples should be taken in the initial state and after every conducted erosion test run (samples have to be cleaned first). This not only helps to understand the development of erosion effects, but it also facilitates the detection of remaining dust on the sample. Therefore it is recommended to first perform microscope analysis and then reflectance measurements. In case there is any dust left, the sample can be cleaned again before determination of reflectance values. It is suggested to observe the development of three different spots on the sample. To perform this monitoring, a microscope with an internal coordinate system is useful so that the same spots on the sample surface can be easily found again.

SEM analysis can be done for all tested samples additionally, to detect the average defect density and maximal depth of the defects.

5 Erosion testing

The testing method presented in the following paragraph can principally be used for any kind of component that should be tested for sandblasting. The parameters are given in order to meet actual field conditions of optical CSP parts, though. Those values have been obtained during meteorological and geological field campaigns which took place in cooperation with the enerMENA meteorological network [4, 5] in Zagora (30°19´50´´ N, 5°50´17´´ W), Missour (32°53´46´´ N, 4°06´37´´ W), both in Morocco and Tabernas (37°01´16´´ N, 2°27´59´´ W), Spain. The obtained particle concentrations represent the worst possible site specific case, as the particles have been measured in an open environment, while as in real CSP plants the components may be partly protected by dust fences.

It should be emphasized, that in order to achieve realistic results representative for a distinct outdoor site, a field campaign and the following adjustment of testing parameters is indispensable.

The testing procedure will be the same for reflector samples, glass envelope tubes and absorber coatings. The area on the specimen to be eroded needs to be at least a **circle of 2.5 cm in diameter**.

5.1. Test setup

Possible setups to perform SDS simulation experiments can be based on pressurized air tanks or wind tunnels driven by ventilators. An erosion rig operated with pressurized air in which a stream of particles (the erodent) becomes injected can be seen in Fig.1a. Typically the nozzle diameter is in the range of some centimetres. The wind tunnel solution can be either facilitated by open- or closed loop channels (for open loop example see Fig.1b). Here the tube diameters can be larger and still sufficiently high air flow velocities can be achieved at the sample. Independent of the setup, various parameters have to be controlled. It needs to be mentioned that the necessity of a homogeneous particle flux over the test area is inevitable for comparable and repeatable results.

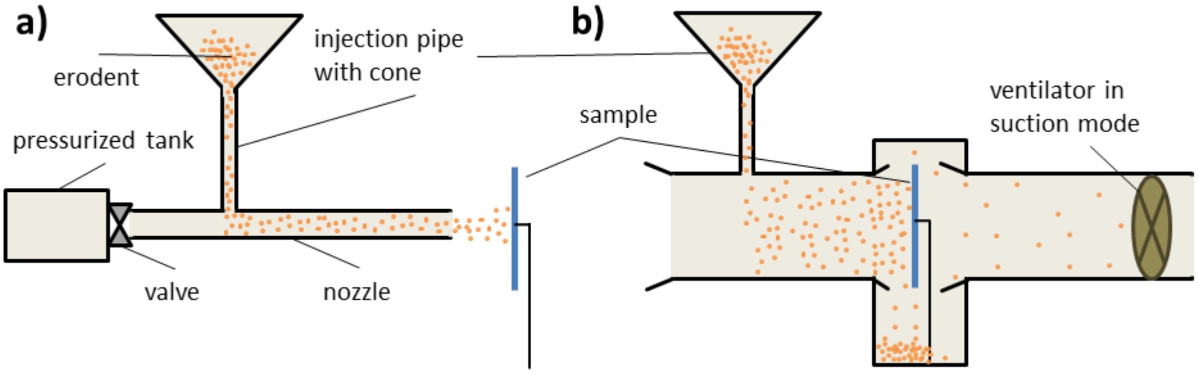


Figure 1: proposed setups for erosion experiments; a) pressurized sand blasting and b) open wind tunnel in suction mode.

5.2. Test parameters

- Impact velocity: Since it is hard to directly determine the velocity of the particles impacting on the specimen, it is proposed to measure the wind speed at the point of the test specimen. For some setups this means that the sample holder needs to be removed and exchanged with an anemometer. The wind speed to be applied during the accelerated testing should be chosen in accordance with field measurements conducted at the sites, the samples should be tested for. If no wind speed data are available, representative set values for the wind speed are: 10, 15, 20 and 25 m/s. It is necessary to determine the velocity within an uncertainty of not more than 0.5 m/s in order to achieve a meaningful reproducibility for erosion testing. The particles should be injected into the flow at a sufficient distance to the specimen, so that they have reached their final velocity within the flow before impacting on the specimen.

- Impact angle: The impact angle β spans between the particle trajectory and the sample surface plane. Therefore a particle impact with β=90° stands for a perpendicular impact on the sample. In order to achieve the most realistic testing conditions, β should be chosen in accordance with typical outdoor impact angles. Obviously those angles vary quite strongly with power plant concept (parabolic trough, solar tower, etc.), plant orientation and wind direction and are therefore impossible to be determined for every reflector in a power plant over the year. If no other circumstances justifies testing at a different angle, β should be kept fixed at 90° with a deviation smaller than ±3°.

- Physical properties of the erodent: The mechanical properties of sand and dust can be completely different from one site to another. The variation can be present over a great number of parameters. The particle size distribution (PSD), the hardness, the toughness and the shape are the most important ones to be mentioned. Therefore it is recommended to use natural dust from the site to be tested for, for the most representative results. If no such sand samples are available or it is only aimed for a comparative performance study, artificial sand can be taken as erodent material.

- Total erodent mass: This parameter represents the natural frequency and typical duration of SDS. It should be chosen in accordance with site specific data. However very often there is a lack of such data. The following paragraph is dedicated to present a possible way to achieve useful field quantities in order to classify outdoor sites regarding the total sand mass density which is estimated to impact upon exposed reflectors.

  Evaluation of Outdoor campaign: From literature like Zhao et al.[6], it became clear that a total suspended particle (TSP) concentration in the range of 0.1 g/m³ is possible during SDS events. Typical wind speed values of 10 m/s give mass flux values of 0.0001 g/(cm² s). Assuming durations of SDS of around 4 hours leads to a total impact mass of 1.44 gram per square centimetre reflector area and sand storm event (see Sansom et al. [7]). However, to end up with a value for this parameter for a CSP specific erosion guideline the reliance on naked literature values with no given uncertainties and some unknown parameters, like the connection of the meteorological to mechanical erosion data is regarded to be inaccurate. Within the STAGE-STE project reflector samples as well as an EDM 164 particle counter from GRIMM Aerosol Technik GmbH &Co.KG (Ainring/Germany) have been exposed at three different outdoor sites. The detected TSP concentrations have been evaluated to the annual total impact mass per square centimetre for different wind velocity ranges (see Tab.1). It can be seen that the annual total impact mass density for Zagora lies very close to the total impact mass calculated for a 4-hour SDS with values taken from [6]. Still, all of these meteorological values should be considered critically since major uncertainties were involved in their determination, like the poor sampling efficiency of the EDM 164 for larger particles [8] and the short data acquisition interval (in Zagora it was only 3 month, the values are going to be updated soon).

Table 1: Extrapolated annual total impact mass density for different wind velocity ranges obtained from field campaigns at Zagora, Missour and Tabernas. Wind velocity was measured in 10 m above ground and particle concentration was obtained from an EDM 164 particle counter mounted at around 1.5 m above ground. The last line shows the average annual loss in specular reflectance of a glass reflector exposed on site 1.5m above ground.

wind velocity v [m/s]	Zagora	Missour	Tabernas
10<v<15	1.258 g/cm²	0.128 g/cm²	0.012 g/cm²
15<v<20	1.957 g/cm²	0.092 g/cm²	0.008 g/cm²
v>20	0.033 g/cm²	-	-
Annual loss in $\rho_{\lambda,\varphi}$(660 nm,15°,12.5 mrad)	1.4%	0.4%	0.1%

In order to perform the laboratory erosion simulation as realistic as possible, the respective sand masses of Table 1 should be used at the various wind speeds. Additionally the usage of the natural sands would be necessary. However the application of the complete particle size range of the natural sand, like it can be found in the soil, would also lead to erroneous erosion results since barely soil particles of all sizes become airborne during sandstorms. It has been pointed out, that a complete acquisition of the natural parameters and their successive translation to the laboratory is quite complex and a more simplified procedure is suggested in paragraph 5.3 with the intention to provide a comparable method which is not far away from reality.

5.3. Simplified procedure

Since the parameters from paragraph 5.2. are general and can lead to completely different actual testing conditions for different outdoor sites, a more concrete basis of testing parameters shall be given within this paragraph. This testing procedure is proposed to meet the actual field conditions in Zagora, Missour and Tabernas as an example and can be used to compare different materials.

- The wind velocity *v* for the test shall be fixed at 20 m/s due to simplicity and also to test for the worst case scenario.
- The impact angle *β* shall be fixed at 90° in order to test for the worst possible sandstorm effects on the reflectors.
- The pure quartz sand **esqua DOR 0.06-0.3** (see Appendix 1) from KSL Staubtechnik GmbH

(Lauingen/Germany) is recommended to be taken as a standard sand type. The PSD is in a reasonable range and particles with diameter smaller than 50 µm are almost completely absent. By this, problems with the injection mechanism of the setup can be avoided. Furthermore scholars like Hutchings [9] suggest that a threshold exists for the erosion determining parameters like the particle size and it's reasonable to assume it in this order of magnitude for the diameter.

- The total impact mass densities given in Tab 1. are a rough estimation due to the poor sampling efficiency of the used instrument for particles with diameters larger than 20 µm [8]. Therefore, the determination of the total impact mass density shall be conducted by the comparison with the annual reflectance loss observed in the field. This quantity is given in Tab. 1, as well as in Fig. 2, where a correlation between the impacting mass density used in the open loop erosion tunnel (OLET) of DLR and the resulting specular reflectance loss is displayed. By a linear fit of the three data points and the measured $\rho_{\lambda\varphi}$-losses from outdoor experiments, the necessary impact mass density for the simulation experiments could be fixed at 0.37 and 0.11 g/cm² for Zagora and Missour, respectively.

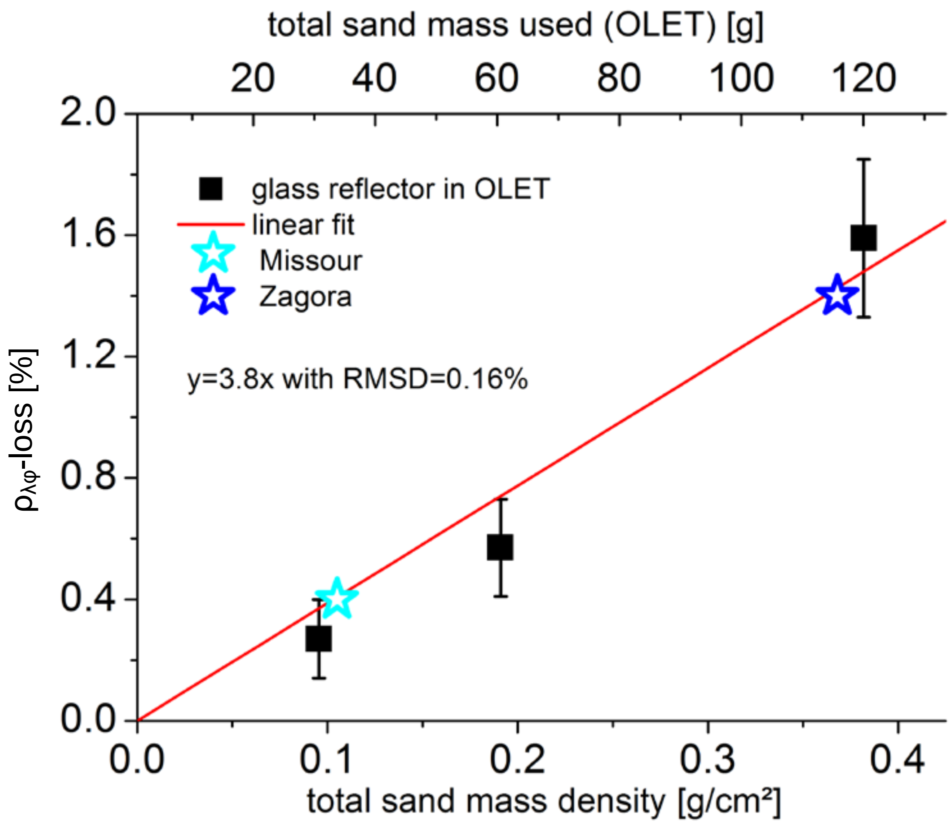


Figure 2: Specular reflectance loss $\rho_{\lambda\varphi}$ of a glass reflector sample after progressive sandstorm testing in the OLET at 20 m/s. A linear fit has been applied to the data and respective $\rho_{\lambda\varphi}$-losses from outdoor sites are displayed.

The selection of the chosen parameters leads to realistic erosion results (see Fig. 3). A naturally and an artificially eroded sample is compared via microscope pictures of the glass surface of the reflector samples. The reflector in Fig. 3a) was exposed in Zagora for three and a half years where a specular reflectance loss of 4.9% could be detected. In Fig. 3b) a similar glass sample has been artificially eroded with 0.4 g/cm² at 20m/s, resulting in a loss in specular reflectance of 1.6%. Therefore, it is possible to finally fix the value per test run to **0.37 g/cm² at 20 m/s** which should simulate **one year of outdoor exposure in Zagora**. The simulation of more years is simply facilitated by repeating the procedure and other sites shall be simulated by adopting the mass density to a reasonable value. E.g. to **simulate one year in Missour**, a mass density of **0.11 g/cm² shall be used at 20 m/s**. The outdoor exposure campaign in Tabernas lead to the conclusion that no severe SDS events have been present because no significant drop of specular reflectance could be measured after an exposure time of four years.

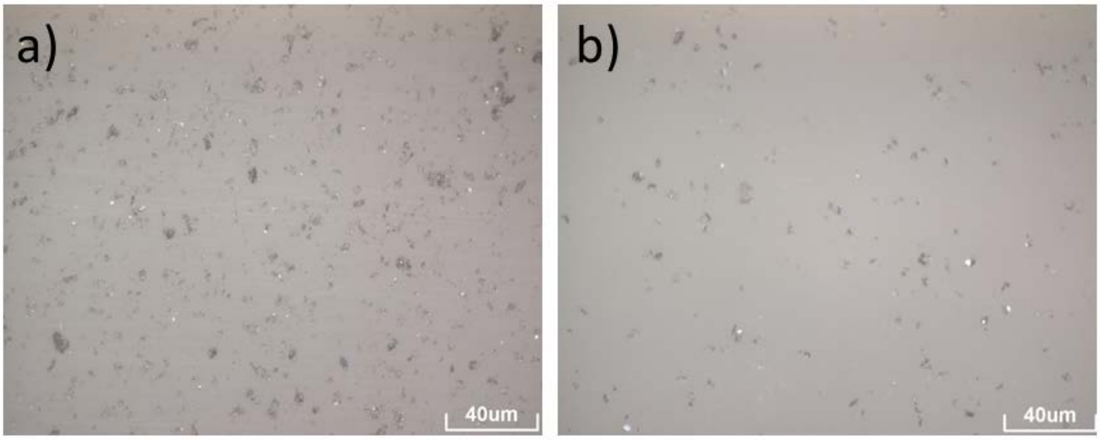


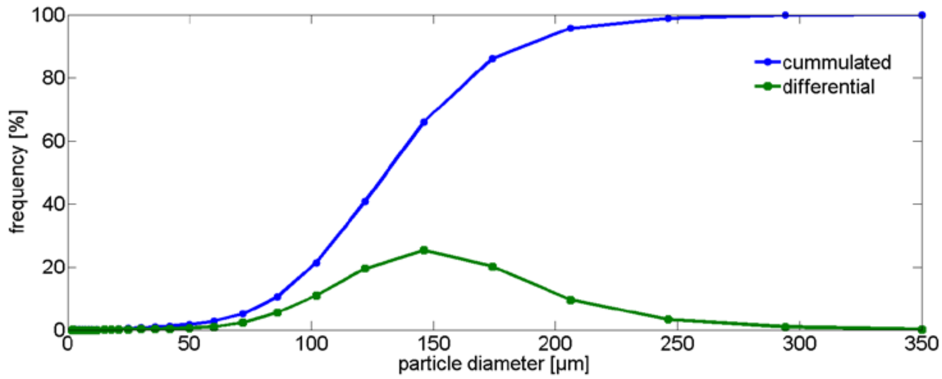
Figure 3: Glass sample after erosion. a) exposed to Zagora for 3.5 years showing a loss in $\rho_{\lambda\varphi}$(660 nm,15°,12.5 mrad) of 4.9% and b) simulated erosion with 0.4 g/cm² at 20 m/s showing a loss in $\rho_{\lambda\varphi}$(660 nm,15°,12.5 mrad) of 1.6%.

6 Report

The test report shall at least contain:

- A reference to this guideline.
- All information on the testing parameters.
- All measured optical characteristics from section 4 (before and after the erosion testing).
- Description of used equipment with related uncertainties.
- Critical assessment of result influencing circumstances.

7 Appendix



Appendix 1: Particle size distribution of esqua DOR 0.06-0.3 standard test dust.

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