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Guideline for accelerated ageing testing of reflectors for CSP

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Foreword

The creation of this guideline has been funded by the European Commission within the FP7 Programme under the grant agreement number 609837 (STAGE-STE project). The work of comparative accelerated aging testing has been conducted in close collaboration with the Spanish standardization entity AENOR, within the sub-committee AEN/CTN 206/SC117. Contributions to this sub-committee from the companies of Rioglass, Guardian and Sener are gratefully acknowledged. Publication of the Spanish standard “Reflector Panels for Concentrating Solar Technologies” is foreseen by AENOR in 2018. This deliverable summarizes some key aspects for comparative durability testing of reflector materials for CSP.

The German Federal Ministry for Economic Affairs and Energy funded the development of a specific guideline for aluminum reflectors under the grant agreement number 0325420 (Alumir project), permitting to make service life-time estimations based on accelerated test results. The aluminum reflector guideline has been published in the SolarPACES Task III “Solar Technology and Advances Applications” and is available online [1]. We are thankful for the contributions of the companies of Alanod, Almeco and Constellium as well as from the MASDAR Institute.

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1 Introduction and background of the guidelines

The reflectors used in CSP are expected to withstand harsh environmental conditions during their lifetime of more than 20 years without a significant specular reflectance loss. Accelerated aging uses intensified conditions of humidity, radiation, temperature, mechanical erosion, exposure to environmental pollutants, etc. to speed up the natural aging processes of materials. Accelerated aging testing is used for several purposes:

- Comparative testing: to compare different materials and rank their durability, helping to select the most durable materials for the environmental conditions at the site of operation.
- Quality control: to monitor the quality of running production and to detect eventual issues in the coating lines.
- Material development: to achieve rapid responses regarding the durability of materials of which actual lifespan data is unavailable. Accelerated aging can be employed as an evaluation tool when the chemistry of coatings or manufacturing parameters are to be optimized.
- Product qualification: to obtain in a short period of time in fairly good agreement with what obtained for longer time periods under real conditions.
- Lifetime Prediction: to estimate the lifetime in-service under different climatic conditions.

The latter point requires reliable correlations concerning the degradation kinetics between outdoor exposure and accelerated testing. So far, this has only been achieved for aluminum reflectors, applying the methodology depicted in Figure 1a. By means of a systematic comparison of the degradation mechanisms under accelerated aging and during outdoor exposure (see Figure 1 b) a guideline has been developed, which enables to simulate the degradation caused at three reference sites: a coastal site, a desert site and a desert site with severe dust and sandstorm events. The guideline details the testing sequence, which needs to be followed to reproduce each one of the observed degradation modes from outdoors. The testing method has been validated with outdoor exposure data up to 3 years. Testing parameters to derive lifetime estimations up to 10 years of exposure have been derived based on extrapolating the data collected from the outdoor exposure. The guideline is described in chapter 4 “Accelerated ageing guideline to predict the service lifetime of aluminum reflectors”. It has also been published on the SolarPACES Task III website [1]. Further information can be found in [2-4].

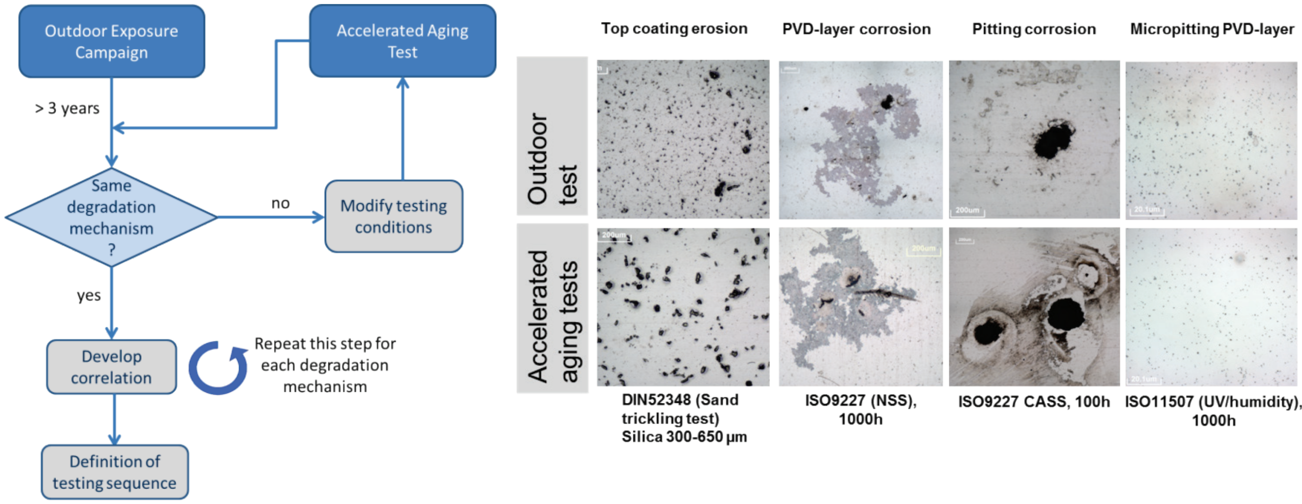

Figure 1 a) methodology to derive an accelerated testing procedure to be used for service lifetime estimation [5] b) Comparison of degradation mechanisms under accelerated aging and outdoor testing for aluminum mirrors

The application of the methodology in Fig. 1a to silvered-glass mirrors is more complex, since glass mirrors proved to be much more durable than aluminum reflectors, requiring long outdoor exposure times until significant degradation results can be obtained for reference. Within STAGE-STE, more than 130 silvered-glass mirror samples have been exposed outdoors at 12 sites of different climatic conditions, reaching a exposure time of nearly 4 years. However, the database on degradation of outdoor samples is still very limited. Main cause for the drop in reflectance in the desertic sites of Morocco was determined to be erosion. Only on the coastal sites considerable degradation due to corrosion was detected. The corrosion was not strong enough to lead to a drop in reflectance. Facets which were in-service at Spanish CSP plants showed only very slight degradation, with negligible reflectance decay after 3 to 4 years. In Portugal, samples set in a marine test site with very high/extreme corrosivity also showed little reflectance decay. The limited degradation on the silvered-glass samples did not allow to derive reliable correlations to accelerated aging yet, however some relevant aging tests have been screened, which show to reproduce realistic degradation mechanisms (see Figure 2). A testing procedure to successfully simulate the erosion damage caused during outdoor exposure in Zagora Morocco has been developed in Deliverable 8.5 within STAGE-STE. On the other hand, attempts to derive correlations of the silver corrosion between outdoor exposure in Abu Dhabi and accelerated testing failed so far [6]. For this reason, for silvered-glass mirrors only the comparative testing method, which is described in chapter 3 “Accelerated aging guideline for comparative testing” and will be published by AENOR, is applicable. A Round Robin test of the comparative accelerated aging method has been performed among 4 laboratories within STAGE-STE. The results are detailed in [7].

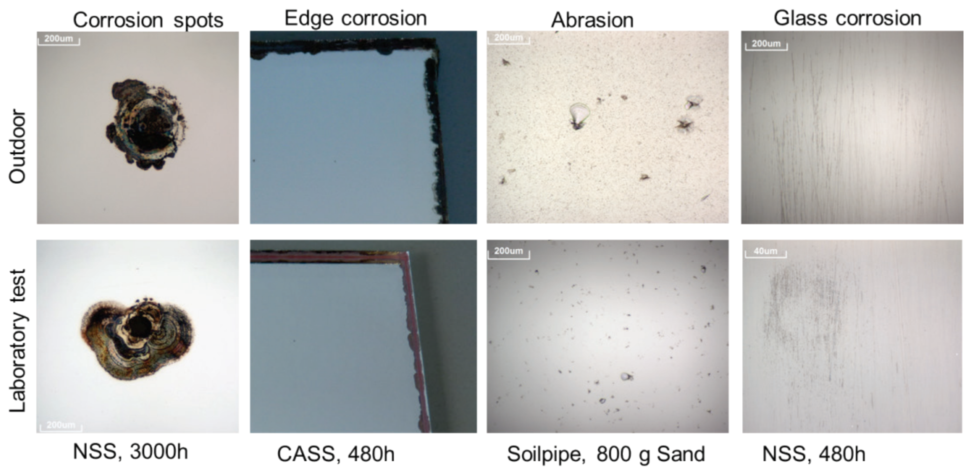

Figure 2 Comparison of degradation mechanisms under accelerated aging and outdoor testing for silvered-glass mirrors

2 Normative references

The following referenced documents are necessary for the application of this guideline. The references are undated; the latest edition of the referenced document (including any amendments) applies:

- ISO 9488 Solar energy – Vocabulary
- ISO 9227: Corrosion tests in artificial atmospheres - Salt spray tests
- ISO 6270-2: Paints and varnishes - Determination of resistance to humidity - Part 2: Procedure for exposing test specimens in condensation-water atmospheres
- ISO 16474-3: Paints and varnishes - Methods of exposure to laboratory light sources - Part 3: Fluorescent UV lamps
- ISO 9806: Solar energy - Solar thermal collectors - Test methods
- DIN 52348: Testing of glass and plastics; abrasion test; sand trickling method

3 Accelerated aging guideline for comparative testing (applicable to all reflector types, to be published by AENOR)

At least three reflector samples shall be tested in each test. The samples shall come from the same manufacturing batch to assure the inter-comparison of the results.

First surface reflectors (where degradation of the reflective layer happens from the front side) shall be all tested with the reflective surface facing upwards. This is applicable to all climate chambers.

Second surface reflectors (where degradation may occur through the protective paint layers from the backside) shall be positioned the following way in the chambers, if not indicated differently: two of the samples should be tested with the protective paint side facing upwards and one sample with the reflective side upwards.

If longer testing times are performed than the ones described in Table 1 or if materials are tested, which may suffer from glass corrosion, it is recommended to test at least one additional sample with a protective tape on the glass surface, so that the reflectance measurement of the reflective layer is not influenced by glass corrosion. The sample should be placed with the protective paint side facing upwards in the chamber. Reflectance values of protected and unprotected samples shall be compared after the durability test. This is applicable to all climate chambers.

3.1 Sample preparation (for all accelerated ageing tests)

The samples tested shall have the same composition, production process, and surface and edge finishes as the reflector to be installed in the solar field. As a minimum requirement, the samples shall contain at least one original edge. Non-original edges shall be sealed using the same process as in the manufacturing line before testing or corrosion effects related to non-original edges shall be ignored for analysis of the results. A sample size of 100 mm x 100 mm is recommended. Other sizes may be used as long as they are larger than 100 mm x 100 mm and it is explicitly stated in the test report. Manufacturers of tempered glass mirrors, who provide non-tempered samples, shall be able to demonstrate that the durability of non-tempered glass mirrors is representative for their final product upon request.

Before testing, any prior defect in the samples such as blisters, scratches, degraded borders, glue, etc. shall be recorded.

The samples must be carefully cleaned before testing. Only compressed air (free of particles or oil) will be preferably applied. In case of remaining dust or soil, demineralized water and a very soft tissue will be employed. Abrasive or dissolvent agents that may change the properties of the sample shall never be employed. In addition, special care must be taken to avoid any contamination after the cleaning due to a negligent manipulation. Gloves shall be used to handle the samples and to avoid fingerprints on them.

Foil material or flexible films need to be prepared on solid supporting material. The tested sample must be prepared in the same way than in the real CSP plant. The preparation of the sample (film + substrate) must be made by the manufacturer of the film or the manufacturer of the CSP technology.

Reflectance measurement of all samples shall be performed before and after testing.

3.2 Post-test sample treatment

Sample treatment after testing shall be done following the procedure of the ISO 9227 standard. If after this treatment the samples still have residues or deposits, demineralized water and a soft cloth and/or pressurized air (free of particles and oil) shall be used to clean them. If dirtiness still remains on the front surface of the sample, a non-aggressive dissolvent with a soft tissue shall be used, avoiding the contact with the backside of the sample.

3.3 Final inspection of sample

After finishing the accelerated ageing test, the samples shall be analyzed according to the following evaluation criteria:

- Type, number and size of damage appearing on the protective layers including delamination, peeling, blisters, discontinuities, discoloration or any other change regarding the original aspect of the sample.
- Type, number and size of any damage to the reflective layer, including corrosion (on the edges or the surface) or discoloration.
- Reflectance measurement before and after testing according to the actual SolarPACES guideline [8].
- Edge corrosion penetration length or affected area, distinguishing between originally sealed edges, protected edges and unprotected edges.
- Density of degradation spots in the reflective surface with a diameter larger than 200 µm. The spot diameter will be measured with an optical microscope and corresponds to the maximum circumference enveloping the degraded area. Density will be calculated as the number of spots larger than 200 µm divided by the area of the tested sample.

3.4 Accelerated aging

Table 1 shows the accelerated aging tests to be performed. New reflector samples shall be employed for each test. Further details regarding the testing conditions can be found in the corresponding standards or the AENOR standard to be published in 2018.

Table 1: Overview of accelerated ageing tests to be conducted (*T*= Temperature, *RH*= relative humidity)

Test	Duration	Summary of testing conditions
Neutral Salt Spray (NSS) ISO 9227	480 h	T=35±2 ºC, pH=[6.5-7.2] at T=25±2 ºC Sprayed NaCl solution of 50 ± 5 g/l with condensation rate of 1.5 ± 0.5 ml/h on a surface of 80 cm²
Copper-accelerated acetic acid salt spray (CASS) ISO 9227	120 h	T=50±2 °C, pH=[3.1-3.3] at T=25±2 ºC Sprayed NaCl solution of 50 ± 5 g/l and 0.26 ± 0.02 g/l of $CuCl_2$ Condensation rate of 1.5 ± 0.5 ml/h on a surface of 80 cm²
Condensation ISO 6270-2 CH	480 h	T=40±3 °C RH=100%, with condensation on the samples
Combined thermal cycling and humidity	10 cycles (240 h)	4 h at T=85±2 °C, 4 h at T=-40±2 °C, Method A: 16 h at T=-40±2 °C and RH=97±3%

		Method B1: 16 h at T=85±2 °C and RH=85±3% Method B2: 40 h at T=65±2 °C and RH=85±3%
UV and humidity ISO 16474-3	2000 h	1 cycle: 4h at UV exposure at T=60±3 °C followed by 4h at RH=100% at T=50±3 °C

3.5 Reporting

At least the following characteristics shall appear in the report:

- a title
- name and address of the test laboratory and location where the tests were carried out
- unique identification report and of each page
- name and address of client, where appropriate
- a reference to the standard
- description and identification of the item tested, including mirror type, thickness and dimensions, reflective layer type, protective coating type and number of coats, production dates, name of manufacturer, serial number, sample label
- number of samples representing each material or product subjected to testing
- characterization and condition of the test item, marking any pre-existing defects
- preparation and preconditioning of samples
- date of receipt of test item and date(s) of test, where appropriate
- identification of test method (e.g. in the cyclical exposure to temperature and humidity test) used
- reference to sampling procedure, if applicable
- any deviations, additions or exclusions from the test method, and any other information relevant to specific tests, such as environmental conditions
- measurements, examinations and derived results supported by tables, graphs, sketches and after all of the tests, and any failures observed
- estimated uncertainty of the test results (where relevant)
- a signature, or equivalent identification of the person(s) accepting responsibility for the content of the certificate or report, and the date of issue
- where relevant, a statement to the effect that the results relate only to the items tested
- a statement that the report shall not be reproduced except in full, without the written approval of the laboratory
- Angle of inclination of the samples tested and arrangement of the samples within the chambers
- Test procedure, including (if applicable)
    - the temperature and humidity recorded throughout the test
    - the type and purity of chemicals (e.g. sodium chloride or copper chloride) and water
    - volume of collected solution
    - the pH of the test solution and the solution collected
    - the salt concentration or density of the solution collected
    - result of chamber corrosivity
    - Total UVA Radiation (from 320 nm to 400 nm)
    - Total UV Radiation (from 295 nm to 400 nm)
- Total duration of test and any incidents during testing
- Method used to clean test specimens after the test
- Description or photo of samples after completing the test

- Type, number and size of damage appearing on the protective layers including delamination, peeling, blisters, discontinuities, discoloration or any other change regarding the original aspect of the sample
- Type, number and size of any damage to the reflective layer, including corrosion (on the edges or the surface) or discoloration
- Reflectance measurement before and after testing to determine the optical degradation of the material
- Edge corrosion length of edges, distinguishing between originally sealed edges, protected edges and unprotected edges
- Density of degradation spots in the reflective surface with a diameter larger than 200 µm

4 Accelerated aging guideline to predict the service lifetime of aluminum reflectors (published in SolarPACES)

4.1 Scope

The aluminum reflector testing guideline specifies the recommended accelerated aging conditions to reproduce realistic degradation mechanisms on aluminum reflectors, which have been observed during a 3 year outdoor exposure testing campaign at 9 exposure sites with 9 different aluminum reflector types (7 of them protected with a SiO_2 based sol-gel coating, 2 of them protected by a polymeric coating). Accelerated aging parameters have been derived to simulate the exposure after 3 and 10 years at three reference outdoor scenarios: “extreme desert”, “desert” and “coastal”.

The parameters have been achieved by averaging the 9 tested material types. However, if the material to be tested deviates significantly in its chemical composition, it is likely that other degradation mechanisms will be accelerated and the correlation to the outdoor reference scenarios will not apply. Figure 3 shows the materials to be tested under the scope of this guideline. In any case, the indicated correlation to the outdoor reference scenarios can only be considered as an estimate. For some of the 9 tested materials the correlation applied better than for others. The expected uncertainty is 4.4 % (pp) specular reflectance, ρ, at a wavelength, λ, of 660 nm, an incidence angle, θ_i, of 15° and an acceptance angle, φ, of 12.5 mrad to simulate 3 years of exposure on the desert and coastal sites. For the “extreme desert” site the expected uncertainty is considerably higher because of the strong dependence on specific abrasion effects on site. The simulation of 10 years of exposure is based on extrapolation of the available outdoor data after 3 years.

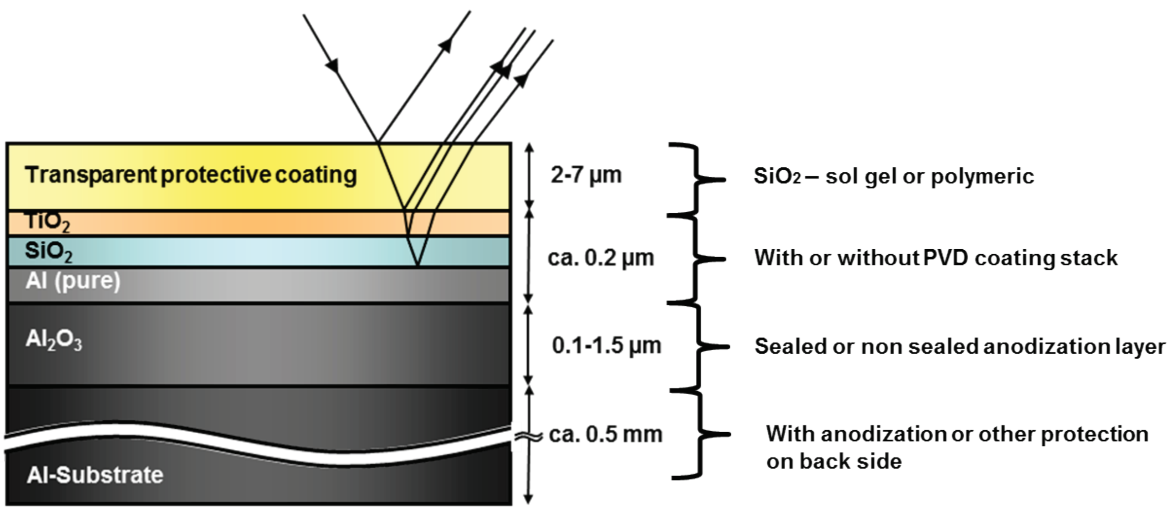

Figure 3: Materials to be tested within the scope of the aluminum reflector guideline

4.2 Terms and definitions

The herein named “extreme desert”, “desert” and “coastal” exposure reference sites refer to the conditions shown in Table 2. The sites are not located closely to industrial factories, mines or similar facilities releasing industrial pollutants. They represent exposure conditions of relevant North African and South of Iberian Peninsula CSP sites.

The Time of Wetness (TOW) refers to annual percentage of time, in which the temperature is above 0 °C and the relative humidity is above 80 % (as according to ISO 9223).

The minimum and maximum values of the presented irradiance data in Table 2 are absolute values per area (W/m²). Instead of the average value, the annual irradiance per area (kWh/m²/a) is given.

Table 2: Conditions of the reference sites

Meteorological parameter		Temperature [°C]	Wind speed [m/s]	Relative humidity (RH) [%]	Time of Wetness (TOW) [%]	Direct Normal Irradiance (DNI)	Global Horizontal Irradiance (GHI)	Comments
Extreme Desert	Avg.	23.9	3.8	23.4	0.9	2133 kWh/m²/a	2174 kWh/m²/a	Frequent occurrence of sand storms
	Min.	-1	0	2	-	-	-	
	Max.	45	19	98	-	1090 W/m²	1241 W/m²	
Desert	Avg.	19.5	3.3	45.9	9.5	2141 kWh/m²/a	1965 kWh/m²/a	-
	Min.	-4	0	3	-	-	-	
	Max.	44	21	100	-	1084 W/m²	1173 W/m²	
Coastal	Avg.	19.7	5.3	71.3	71.5	1360 kWh/m²/a	1925 kWh/m²/a	Distance to coast < 5 km
	Min.	9	0	12	-	-	-	
	Max.	33	15	100	-	984 W/m²	1107 W/m²	

4.3 Sample preparation

The tested samples should be representative for the manufacturing line. Small samples (e.g. 100x100 mm²) can be cut out of the final product from running production and used for testing. If the edges are protected in operation outdoors, then the same edge sealing shall be applied on the samples.

The samples shall be handled with care. The surface may only be touched with gloves. Before optical characterization, the sample shall be cleaned with demineralized water and a soft tissue. After drying, remaining dust particles shall be removed with compressed air (filtered to remove particles larger than 5µm and any traces of compressor lubricants). During measurements contact between the sample surface and sharp and hard parts of the testing equipment (e.g. reflectometer support screws) shall be minimized, for example by covering the respective parts with a suitable mask.

4.4 Sample characterization

The following parameters shall be reported after the accelerated aging sequence:

Reflectance loss:

- Solar weighted hemispherical loss $\Delta\rho_s([300,2500],\theta_i,h)$
- Monochromatic hemispherical loss $\Delta\rho_\lambda(\lambda,\theta_i,h)$
- Monochromatic specular loss $\Delta\rho_\lambda(\lambda,\theta_i,\theta_r,\varphi)$ (at the same wavelength as for $\Delta\rho_\lambda(\lambda,\theta_i,h)$)

Degradation results:

- Maximum edge corrosion penetration (mm)
- Number of pits
- Number of localized corrosion spots in the reflective aluminum layer >200µm per tested area
- Number of visible localized blisters (if applicable) in the protective coating per tested area
- % area affected by corrosion/erosion

A full characterization shall be performed before the first and after the last accelerated aging test of the testing sequence described in chapter 6. Specular and hemispherical reflectance shall be measured according to the actual version of the SolarPACES reflectance guideline [8]. The standard deviations of the measurements and uncertainties of the used reflectometer and spectrophotometer shall be reported. The samples shall be measured in the exact same positions before and after the accelerated aging tests. As a minimum, 5 monochromatic specular measurements and 3 spectral hemispherical measurements shall be taken on a 100x100 mm² sample. The 5 monochromatic measurements obtained with a reflectometer shall be taken in the center of the sample and close to the 4 corners of the sample. The measurement shall not be taken closer than 10 mm to the sample edge or areas that have not been exposed to the testing conditions (e.g. due to the sample holder). The spectral hemispherical measurements obtained with a spectrophotometer shall be taken in the center of the sample. The sample shall be rotated after each measurement by 90° (to obtain measurements at 0°, 90° and 180°). Alternatively, the sample may be moved 1-2cm between the measurements to measure in different spots, as long as it is assured that the same spots and orientations are measured before and after aging.

Figure 4 shows an example of the measurements taken on a 120x120 mm² sample. The herein used reflectometer and spectrophotometer have a measurement spot of 10 mm diameter and 9 x 17 mm², respectively.

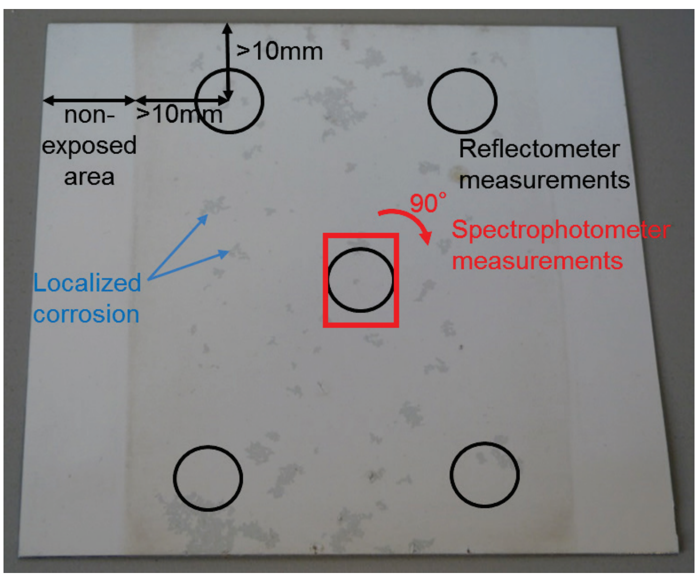

Figure 4: Exemplary measurements taken on a 120x120 mm² sample with localized corrosion spots

The appearing edge corrosion penetration or number of localized corrosion spots after the durability tests can be evaluated by optical microscopy or image processing tools.

Intermediate analysis (e.g. after each step in the testing sequence) provides additional information on the failure mechanism and is recommended.

4.5 Accelerated aging sequence

Table 3 shows the testing parameters to simulate 3 or 10 years of exposure at the “extreme desert”, “desert” or “coastal” reference scenario.

The sample shall be tested as-received from the manufacturing line in the first test, and then subsequently undergo the following tests of the sequence indicated in Table 3.

The sample shall be cleaned with demineralized water and a soft tissue after each test. Remaining sand particles from the erosion test and corrosion products shall be removed. The samples shall be cleaned immediately after the corrosion test, to prevent further corrosion trough condensed salt solution on the surface.

Additionally, after the final test the surface shall be carefully cleaned with a 9 % vol. HCl solution and rinsed with an ethanol-water solution (50 %/50 % v/v) followed by demineralized water immediately afterwards.

All tests are performed according to the standards cited in section 2, except two amendments for the sand trickling test DIN 52348: the used test sand shall be synthetic silica with a particle size between 300 and 625µm (instead of 500 to 710µm) and the impact angle shall be 30° (instead of 45°).

Table 3: Accelerated ageing testing sequence for aluminum reflectors

	Accelerated aging step		1	2	3	4
Method code	**Simulated reference site**	**Simulated Years**	**ISO9227: CASS Test [testing time in h]**	**DIN 52348: Sand trickling [sand mass in g]**	**ISO9227: CASS Test [testing time in h]**	**ISO 16474-3, Method A, cycle No. 1 [testing time in h]**
A1	Extreme Desert	2-3	-	180	2	480
A2		6-14	-	600	8	480
B1	Desert	2-3	-	5	8	480
B2		6-14	-	15	24	480
C1	Coastal	2-3	96	5	8	480

C2		6-14	312	15	24	480

4.6 Reporting

The test report shall contain:

- A reference to this Guideline
- An information on the testing sequence applied (Method A1…C2)
- All measured parameters from section 4.4 (before and after accelerated aging)
- Used equipment with corresponding uncertainties
- The required parameters to be reported from the corresponding standards of the individual tests

5 Conclusions and Outlook

This document presented two accelerated aging guidelines for different purposes. While the comparative testing guideline is applicable to all reflector types, it does not allow for service lifetime prediction. On the other hand, the aluminum guideline is only applicable to first-surface aluminum based reflectors. Its testing sequence has been tailored to reproduce the degradation mechanisms observed during outdoor exposure and can be used to estimate the expected reflectance losses after 3 and 10 years at three references sites with different climatic conditions.

It is foreseen that AENOR will publish the comparative testing method in 2018. In addition, further research needs to be conducted to derive a testing guideline capable to allow service lifetime predictions for silvered-glass mirrors. More complex test procedures combining more stress factors need to be investigated either in form of cyclic tests or by conducting a series of tests. Preliminary tests conducted by LNEG, which combine UV radiation, salt spray and a corrosive gas atmosphere (with NO_2 and SO_2) show promising results and will be presented and published in 2018 [9]. The testing of silvered-glass mirrors, which are known to show degradation during outdoor exposure, is a suitable method to verify newly proposed testing procedures.

6 Literature

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