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ScienceDirect

Energy Procedia 49 (2014) 1718 – 1727

Energy Procedia

SolarPACES 2013

Comparison and evaluation of accelerated aging tests for reflectors

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Abstract

Accelerated aging testing is used in several industries to estimate the lifetime of products and components. Manufacturers of solar reflector materials usually test the durability of their products following standards from automotive and photovoltaic industry. The testing time and the "pass" or "fail" criteria differ from manufacturer to manufacturer which makes it hard for customers to compare the available mirrors on the market and to select the most durable product based on the data sheets.
This paper gives an extensive review of the state of the art of currently applied accelerated aging tests for solar reflectors. The testing conditions of relevant tests are summarized. Based on the experience gained over the last years in the aging laboratory of CIEMAT and DLR, a typical testing program to qualify the durability of reflector materials is being proposed. The appearing degradation of glass and aluminum mirrors under accelerated aging is analyzed and compared to outdoor exposure results.

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Selection and peer review by the scientific conference committee of SolarPACES 2013 under responsibility of PSE AG.
Final manuscript published as received without editorial corrections.

Keywords: Solar reflector; durability; accelerated aging; outdoor weathering; specular reflectance, coating defects, pinholes, corrosion

1. Standardized accelerated aging testing

This paper gives an extensive review of the state of the art of currently applied accelerated aging tests. The testing conditions of relevant tests are summarized. The most widely used accelerated aging tests for reflectors are briefly described in the following paragraphs.

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Selection and peer review by the scientific conference committee of SolarPACES 2013 under responsibility of PSE AG.
Final manuscript published as received without editorial corrections.
doi:10.1016/j.egypro.2014.03.181

1.1. Damp Heat Test IEC 62108, Test 10.7 a or b, or Test IEC 61215, Test 10.13

The damp heat test is used to test the resistance against penetration of humidity through the paint coatings at relatively high temperatures. There are two options to perform the test. In both cases the samples are subjected to a constant climate of 85 ± 5% relative humidity in a climatic chamber. In Test 10.7a the operating temperature is 85 ± 2°C and the testing time is 1000 hours. Test 10.7b operates at a lower temperature of 65 ± 2°C but the testing time is higher (2000 hours) [1]. Test 10.7a is similar to test 10.13 from IEC 61215 [2].

1.2. Condensation Test ISO 6270-2

The resistance to condensation water is tested by exposing the samples to constant conditions of 40°C with 100% relative humidity. Several climatic chambers are available on the market to perform this test. The commonly performed testing time is 480 hours [3].

1.3. UV+Water Test ISO 11507

The UV+Water test consists of the following cycle: in the beginning, samples are exposed during 4 hours at 60 ºC to UV-radiation in a specific testing chamber (see Fig. 1). For solar reflectors the lamp type II is recommended. It emits radiation in the wavelength-range of 290-400 nm with a peak emission at 340 nm. The lamp power matches one sun. Afterwards, the samples are exposed during 4 hours at 50 ºC to condensation (100% relative humidity without irradiation) [4]. The total duration of one cycle is 8 hours (see Fig. 2). It is recommended to expose both, the front and back side of different reflector samples to the interior of the testing chamber. The commonly performed testing time is 2000 hours.

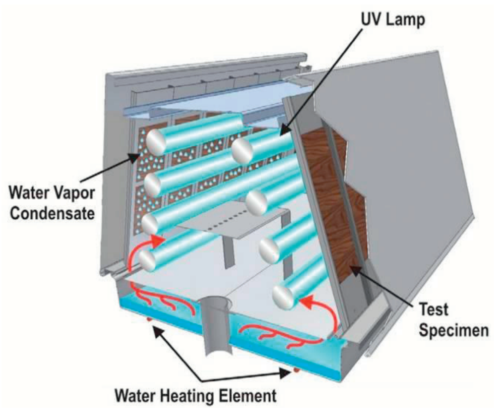


Fig. 1: UV+water testing chamber [5]

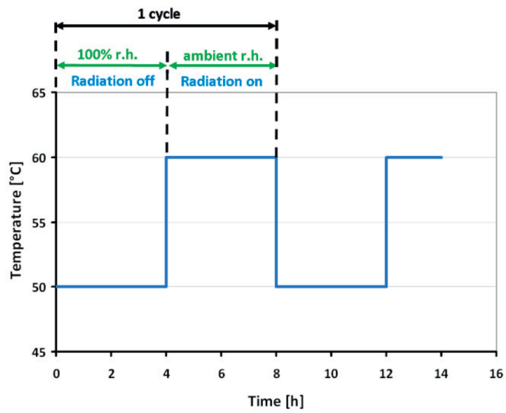


Fig. 2: UV+water testing cycle.

1.4. Neutral Salt Spray Test (NSS) ISO 9227

The NSS-test is a widely used corrosion test to simulate coastal environments. Samples are exposed to constant conditions of 35°C with a spray of a NaCl solution (50 ± 5 g/l, pH = 6.5-7.2) at 100% humidity. The samples should be positioned with a tilt angle of 20 ± 5° respect to the vertical within the salt spray chamber (see Fig. 3). The amount of the sprayed solution should be adjusted to obtain a condensation rate of 1.5 ± 0.5 ml/h on a surface of 80 cm² [6]. The condensation rates should be checked at various locations within the chamber to assure of homogeneous distribution of the salt fog. A circular chamber design usually leads to higher reproducibility of test results of samples tested in different positions within the chamber. The commonly performed testing time is 480 hours.

Fig. 3: Salt spray chamber for NSS or CASS tests.

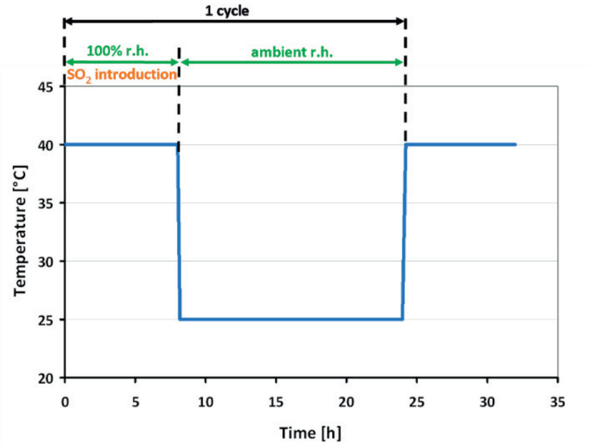


Fig. 4: Kesternich testing cycle

1.5. Copper Accelerated Salt Spray Test (CASS) ISO 9227

Further acceleration compared to NSS can be achieved with CASS. Samples are exposed to 50 °C and 100% relative humidity with a constant spray of demineralized water containing 50 ± 5 g/l NaCl. Additionally the solution contains 0.26 ± 0.02 g/l of copper chloride ($CuCl_2$). The pH of the sprayed solution lies between 3.1-3.3 and is adjusted using hydrochloric acid (HCl), sodium hydroxide (NaOH) or sodium bicarbonate ($NaHCO_3$) [6]. The salt spray chamber can be used for both NSS and CASS. However, once a CASS test has been performed within the chamber it is not recommended to perform later NSS experiments due to the chemical contamination of the chamber interior which will lead to modified test results. The commonly performed testing time is 120 hours.

1.6. Kesternich Test DIN 50018

The Kesternich test is used to simulate aggressive industrially polluted environments. During the first 8 hours of this cyclic test the samples are exposed in a climatic chamber to 40 ± 3 °C and 100% relative humidity. Additionally, 0.33 or alternatively 0.67% of the volume of the testing chamber is charged with sulfur dioxide gas (SO_2). During the following dry phase of 16 hours, the samples are exposed to the ambient conditions of temperature and humidity [7]. The duration of 1 cycle is 24 hours (see Fig. 4). There is no agreement about the number of cycles yet.

1.7. Thermal Cycling Test IEC 61215, Test 10.11 or IEC 62108, Test 10.6

The resistance to formation of cracks or delamination due to thermal influence is tested with thermal cycling tests. In IEC 62108, Test 10.6 (Option TCA 3) the samples are subjected to 2000 cycles from -40°C to 65°C. A dwell time of at least 10 min within ±3 °C of the high and low temperatures is required (see Fig. 7a) [8]. The procedure defined in IEC 62108, Test 10.6 (Option TCA 1) works in the exact same manner, but the maximum temperature is increased up to 85°C (see Fig. 5). The number of cycles is 1000. The thermal cycling test defined in IEC 61215, Test 10.11 is identical to IEC 62108, Test 10.6 (Option TCA 1) but the cycle number is reduced to 200 cycles [11].

1.8. Thermal Cycling combined with Condensation ISO 6270-2

Several years ago a mirror manufacturer defined a modified test combining thermal cycling and the constant exposure to condensation according to ISO 6270-2. This seems reasonable because eventually appearing cracks in the paint system due to different thermal expansion coefficients of the layers will allow the penetration of humidity during the condensation phase. This will result in severe coating cracking once the penetrated water freezes during the exposure to -40 °C during 4 hours. The testing cycle is shown in Fig. 6. 10 cycles are usually performed.

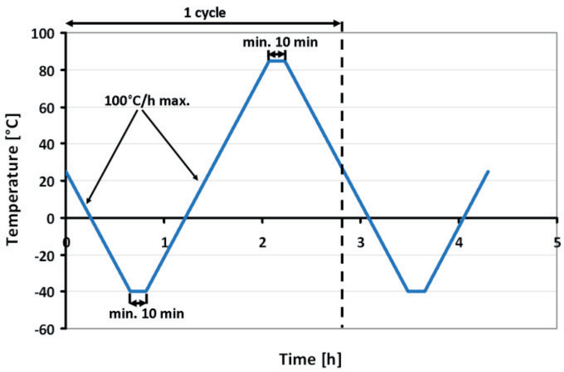


Fig. 5: Thermal cycling according to IEC 61215, 10.11 or IEC 62108, Test 10.6 (Option TCA 1).

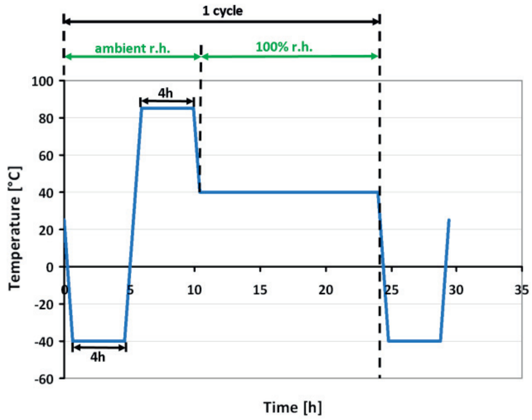


Fig. 6: Thermal cycling and humidity test ISO6270-2.

1.9. Humidity Freeze Test IEC 62108, Test 10.8

A similar test to the one described in 1.8 is the humidity freeze test. It is used to check the coating resistance to formation of cracks or delamination due to thermal influence in combination with humidity. In difference to the previously described test, the humidity freeze is performed in two steps. At first, the samples are subjected to 400 cycles from -40 °C to 65 °C. A dwell time of at least 10 min within ±3 °C of the high and low temperatures is required (see Fig. 7a). The cycling frequency should be 10 to 18 cycles per day. In the second step the samples are subjected 40 times to the humidity freeze cycle shown in Fig. 7b. The total duration of the test is approximately 1500 hours.

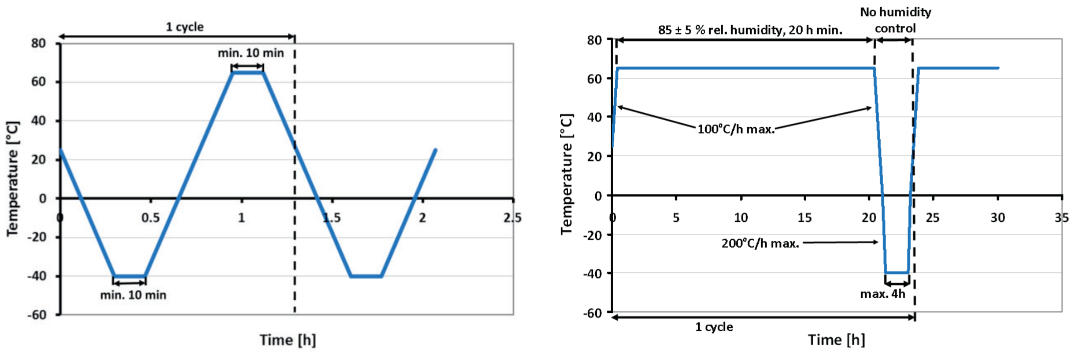


Fig. 7: a) Thermal cycling IEC 62108, Test 10.8 (Option TCA 3), 400 cycles, b) Humidity freeze cycle, IEC 62108, Test 10.8, 40 cycles.

1.10. Abrasion tests

Several standards are used to test the abrasion resistance of paints and varnishes. For example, ISO 11998 defines a procedure to determine the wet-scrub resistance and cleanability of coatings [9]. Alternative accelerated abrasion tests involve testing with the Taber Abrasor scrub resistance tester or a similar device, according to ISO 9211-4, in which the surface is exposed to repetitive wiping with a defined abrader [10]. The normal force of the abrader on the sample can be controlled and modified which leads to more reproducible results compared to other abrasion tests.

MIL-STD-810G defines a dust and sand test to determine resistance against particle abrasion in desert regions [11]. Such tests need to be carried out in sophisticated sand storm simulating chambers able to control wind velocities and particle concentrations. From the experiences gained so far, both the sand and dust test defined in MIL-STD-810G are too aggressive for reflective materials and the testing conditions need to be modified.

1.11. Pass / fail criteria

The above described standards originate from automotive and photovoltaic industry and, as a consequence, the defined pass / fail criteria cannot always be applied to solar reflectors. IEC 62108 for example demands "no major visual defects" which leads to a certain range of interpretation depending on the operator who inspects the samples after the test.

For the future, it would make sense to establish quantitative pass criteria taking into account several factors: specular and hemispherical reflectance loss, number of corrosion pits, size of corrosion pits, and edge corrosion penetration length.

2. Accelerated aging testing of different reflector types

In order to determine the durability of solar reflective materials ever since the following questions arise: Which accelerated aging tests should be performed? For how long / how many cycles? How do the test results correlate to outdoor exposure sites? Due to the complexity of the material degradation, the increased variety of reflector materials and the high number of relevant environmental parameters that influence this process, none of these questions can be answered easily. In order to derive a correlation to outdoors, samples from accelerated aging tests need to be compared to samples from outdoor exposure tests. Such correlations are generally material and site dependent and often it is not valid to extrapolate derived correlations to a new material type. Especially when it comes to test new materials, where no outdoor reference sample is available, the possible degradation mechanisms are completely unknown. Thus, a wide testing program should be applied to such materials in order to screen different failure modes. One of the goals of the OPAC (Optical Aging Characterization) Laboratory at the Plataforma Solar de Almería is to define such a standard test method with its corresponding pass/fail criteria to be able to predict possible material failure in the field.

2.1. The preliminary testing program

In order to set up a representative testing program, the following approach is being followed: a silvered thick glass and a silvered thin glass mirror, which have proven to be durable in European outdoor applications, are selected. A set of accelerated aging tests is being performed for a much higher amount of time than stated in most of the data sheets from the manufacturers. New materials to be tested can then be benchmarked with the proven thick and thin glass mirrors. Additionally, the obtained test results will be compared to a type of aluminum reflector whose failure and degradation kinetics are well known [12].

Real degradation processes outdoors happen through a combination of several parameters: radiation (especially UV-A, UV-B), mechanical stresses (due to wind loads or mounting), environmental pollutants (originating from soil or aerosols, industrial or coastal proximity), abrasion (due to cleaning, or airborne dust and sand), humidity (ambient humidity, condensation cycles, rain), temperature (cyclic day/night temperature changes, frost). Therefore it does not seem reasonable to perform the described standardized tests in section 1 individually. It would rather make sense to define testing sequences in which the samples need to run through a certain set of aging tests. Following considerations were made in order to set up the selected testing sequence:

1st step: Abrasion test. The testing sequence should start with an abrasion test because the observed degradation outdoors showed to start from defects in the protective coating (both front or back). It would not make sense to perform the abrasion test after the corrosion test because the coating defects brought in by abrasion will accelerate the corrosive attack. However, at the current state of the art it is very difficult to define realistic abrasion conditions that simulate service life times of 30 years. Therefore, for this study the worst case scenario was simulated. The worst case happens when the coating system is damaged down to the silver or aluminum layer. This can be simulated by scratching the protective coatings with a standardized scratching tool (e.g. according to [13]). If the tested samples were cut out from a larger piece of reflector and at least 2 non-original edges are present it is not considered to be necessary to scratch the sample. Ideally the tested samples should contain two originally sealed edges and two cut edges (minimum one original edge). The selected thick, thin and aluminum reflector samples met this criterion; therefore they were not scratched before the test.

2nd step: Thermal cycling. The samples should be thermally cycled in order to check their resistance against micro crack formation. 100 thermal cycles from -40°C to 85°C (IEC 61215, Test 10.11) were selected for this program before the regular climatic tests are performed.

3rd step: Corrosion test. The most meaningful corrosion tests, the Damp Heat test, the NSS and the UV+water test, were included in the program. Furthermore, a cyclic test modification has been defined combining the NSS and the UV+water test. The samples were manually changed once a week from the NSS to the UV+water chamber and backwards. Experiments made with aluminum reflectors did show some evidence that such a practice may lead to more realistic degradation results.

To determine the influence of the thermal cycling, additionally two samples from each material have been tested that have not been thermally cycled prior to the corrosion tests. An overview of the selected testing program is shown in Fig. 8. In total 16 samples per material have been tested (8 samples with thermal cycling, 8 samples without thermal cycling).

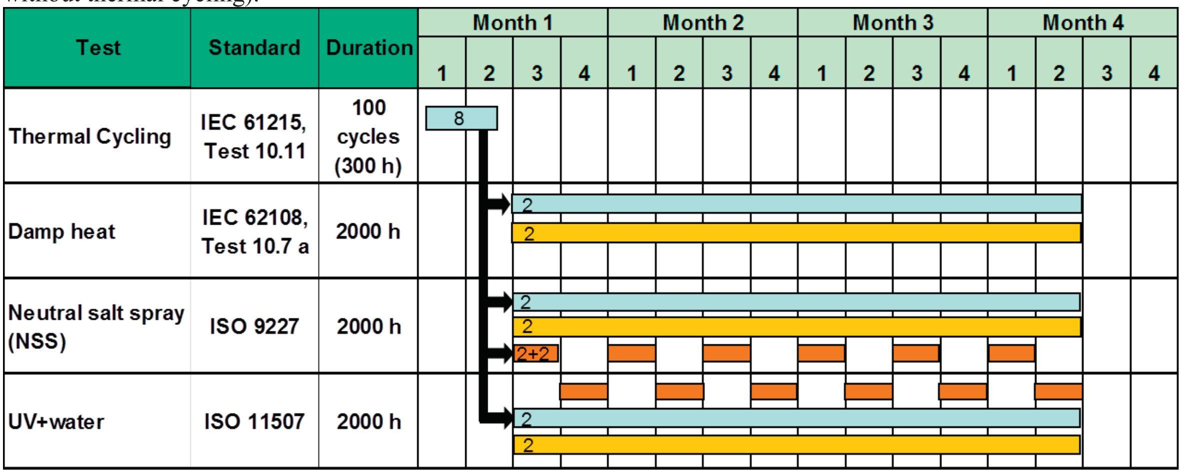


Fig. 8: Testing plan. 16 samples of each material have been tested. 8 samples have been previously cycled 100 times according to IEC 61215, Test 10.11.

2.2. Results

The samples have been microscopically evaluated every 500 hours with the microscope Axio CSM 700 by Zeiss. The different appearing degradation effects are shown in Table 1, 2 and 3.The decay of the monochromatic specular reflectance ρ_s*(660nm; 12.5mrad; 15°)* over time for each material is shown in Fig. 9, 10 and 11. This value was measured with the portable specular reflectometer 15R-USB by Devices and Sevices.

Significant edge corrosion was found at the cut edges of the tested thick glass mirrors. The thin glass and the aluminum mirrors showed almost no edge corrosion. The maximum edge corrosion length after 1500 hours of testing of the thick glass mirrors was 6 mm in NSS, 5.5 mm in Damp Heat, 5 mm in NSS / UV+water and 3.5 mm in the UV+water test.

Table 1: Microscopic degradation analysis of the thick glass mirrors in different accelerated aging tests (samples were previously thermally cycled 100 times according to IEC 61215, Test 10.11).

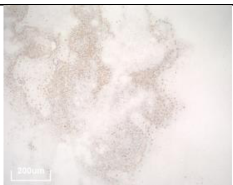
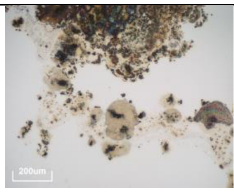
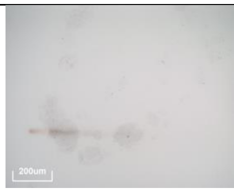
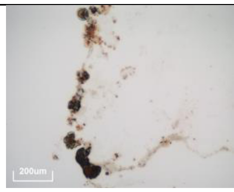
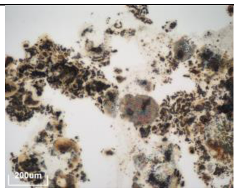
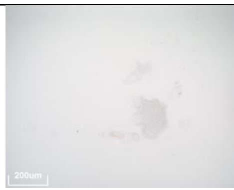
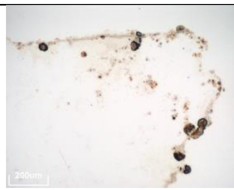
	Damp Heat	NSS	UV+water	NSS / UV+water
500 hours				
1000 hours				
1500 hours				

Table 2: Microscopic degradation analysis of an aluminum mirror in different accelerated aging tests.

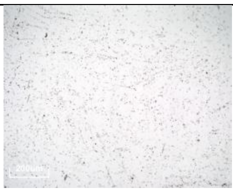
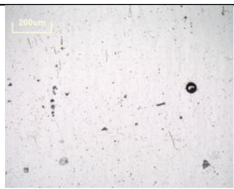
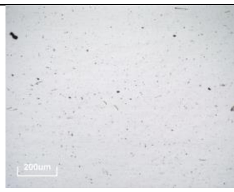
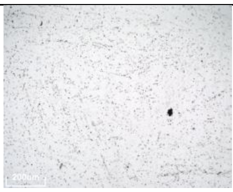
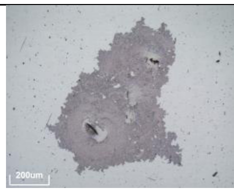
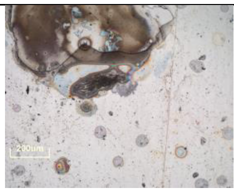
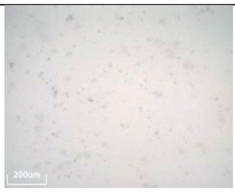
	Damp Heat	NSS	UV+water	NSS / UV+water
500 hours				
1000 hours				
2000 hours				

Table 3: Microscopic degradation analysis of the thin glass mirrors in different accelerated aging tests (samples were previously thermally cycled 100 times according to IEC 61215, Test 10.11). The microscope images for 500 and 1000 hours are very similar to the ones shown at 1500 hours.

	Damp Heat	NSS	UV+water	NSS / UV+water
1500 hours				

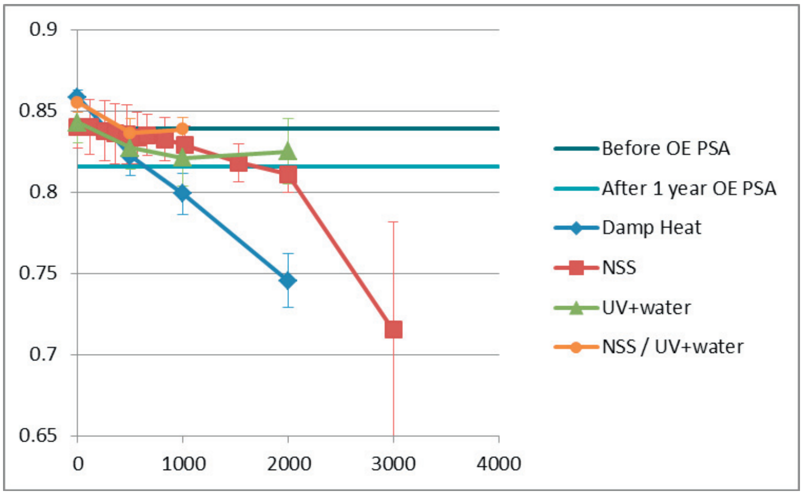


Fig. 9: Specular reflectance ρ_s*(660nm; 12.5mrad; 15°)* during accelerated aging testing of an aluminum mirror compared to outdoor degradation after 12 months of outdoor exposure (OE) at the Plataforma Solar in Almeria (PSA), Spain. The specular reflectance loss due to outdoor exposure after 1 year was in the range of 1.9 ± 0.4 %.

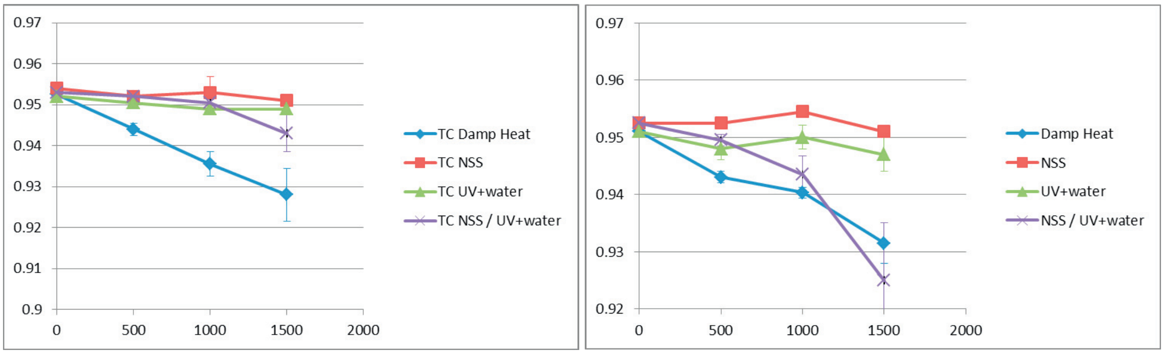
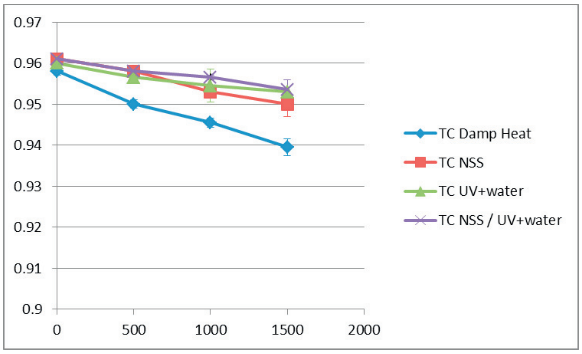


Fig. 10: Specular reflectance ρ_s*(660nm; 12.5mrad; 15°)* during accelerated aging testing of thick glass mirrors, a) samples were previously thermally cycled 100 times according to IEC 61215, Test 10.11, b) samples were not thermally cycled before testing.



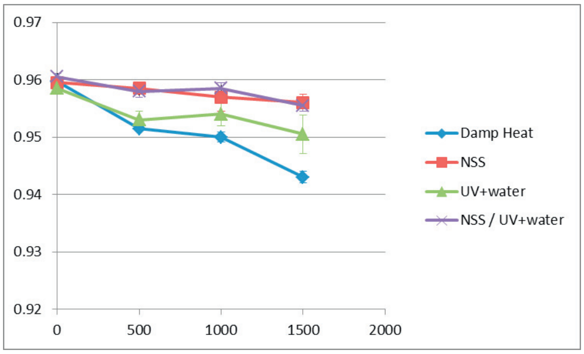


Fig. 11: Specular reflectance ρ_s*(660nm; 12.5mrad; 15°)* during accelerated aging testing of thin glass mirrors, a) samples were previously thermally cycled 100 times according to IEC 61215, Test 10.11, b) samples were not thermally cycled before testing.

3. Discussion

The different tests are evaluated regarding their ability to reproduce the observed outdoor degradation. Fig: 12 shows typical failures of aluminum, thick and thin glass mirrors during their service life time. Besides the classical corrosion originating from coating defects on aluminum reflectors described in [12] (see Fig: 12a), another degradation mechanism for aluminum reflectors has been observed. It seems that humidity is capable to diffuse through the protective coating and causing locally a high number of small corrosion pits (see Fig: 12b). The available outdoor data for thick and thin glass mirrors is reduced compared to aluminum. Also, the degradation mechanisms have not been studied in such detail. Fig: 12c and d show typical outdoor defects for these material types.

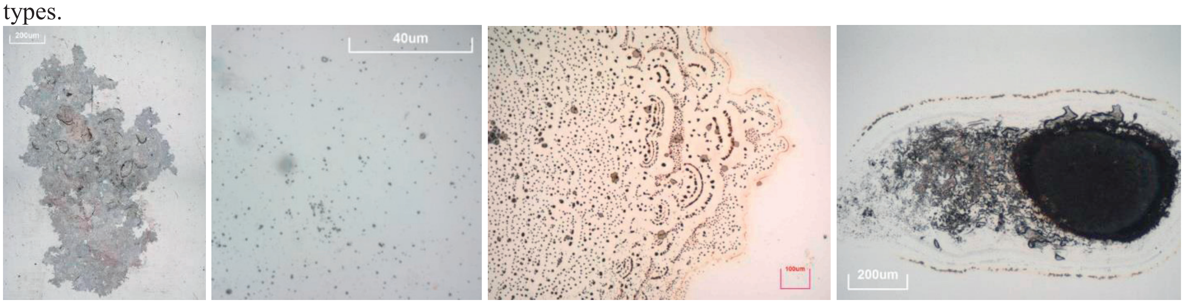


Fig: 12: Observed outdoor degradation a) local corrosion of an alumnium reflector starting from coating defects (scale: 200µm), b) small corrosion pits of an aluminum reflector originating through humidity penetration (scale: 40µm), c) edge corrosion of a not perfectly sealed thin glass reflector (scale: 100µm), d) corrosion pit of a thick glass reflector (scale: 200µm).

The Damp Heat test showed to lead to the fastest drop in reflectance compared to the other tests. However, the appearing degradation effects neither seem realistic for aluminum nor glass mirrors. The reason might be that the test operates at unrealistically high temperatures of 85°C. Therefore it seems more convenient to perform the Damp Heat test according to IEC 62108, Test 10.7 b, where the maximum temperature is reduced to 65°C.

The NSS is considered one of the most meaningful corrosion tests for reflectors. For aluminum, the NSS showed to be able to reproduce local corrosion spots originating from coating defects (see Fig: 12a). The usually performed testing time by the manufacturers of 480 hours showed to be insufficient as materials that failed in the field passed these conditions. Aluminum mirrors for example, usually do withstand 480 hours of NSS showing almost no corrosion. However, especially at coastal regions corrosive attack can be observed already after six months of exposure. Therefore useful testing times are considered to be more than 1500 hours.

For all of the tested materials, the UV+water test showed to lead to less visible degradation spots than the other tests. For some aluminum materials after 2000 hours of testing, some coating cracks appeared that have not been found so far on the outdoor exposed samples. The test seems well suited to reproduce the small corrosion pits shown in Fig: 12b.

It seems reasonable to combine the NSS test with the UV+water test in order increase the realism of the environmentally simulated parameters. For aluminum reflectors, the NSS cycle reproduces local corrosion at coating defects and the UV+water cycle reproduces small corrosion pits that appear through diffusion processes. It still needs to be proven if this combination of tests is also useful for glass mirrors.

The influence of thermal cycling is considered rather low. Neither a higher reflectance drop nor increased microscopically degradation has been observed at the samples that were previously cycled. However, thermal cycling tests are still considered useful and relevant for newly developed coating systems.

4. Conclusions and Outlook

This paper described commonly performed accelerated aging tests for solar reflectors. It is recommended to define testing procedures in which the specimens pass subsequently different standardized tests to cover most of the environmental relevant parameters. In this paper a testing procedure was defined which consisted in performing 100 thermal cycles from -40 to 85°C and afterwards altering between the Neutral Salt Spray and the UV+water test every 168 hours. This approach showed to lead to more realistic accelerated degradation results for aluminum reflectors. For glass mirrors the available outdoor data is not broad enough to draw trust worth conclusions. The gained accelerated aging data from the tested materials which proofed to be suitable at European outdoor application can be used to benchmark newly developed reflective materials. Outdoor exposure of thick and thin glass mirrors begun at several North African sites and in a couple of years the appearing degradation mechanisms from accelerated and natural aging shall be compared. A parameter to be investigated more in detail is the influence of the local dust composition that might lead to aggressive electrolytes in combination with water. The effect of different dust and sand types from North African desert regions on the reflectors durability shall be examined in future accelerated aging tests.

Acknowledgements

The authors want to thank Lucía Martinez from the Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT) and Stephanie Meyen from Deutsches Zentrum für Luft- und Raumfahrt (DLR).

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