

Correlating Outdoor Exposure with Accelerated Aging Tests for Aluminum Solar Reflectors

Johannes Wette^{1, a)}, Florian Sutter^{1, b)} and Aránzazu Fernández-García^{2, c)}

¹*DLR, German Aerospace Center, Institute of Solar Research, Plataforma Solar de Almería, Ctra. Senés Km. 4, P.O. Box 39, E04200, Tabernas, Almería (Spain)*

²*CIEMAT Plataforma Solar de Almería, Ctra. Senés Km. 4, P.O. Box 22, E04200, Tabernas, Almería (Spain)*

^{a)}Corresponding author: johannes.wette@dlr.de

^{b)}florian.sutter@dlr.de

^{c)}arantxa.fernandez@psa.es

Abstract. Guaranteeing the durability of concentrated solar power (CSP) components is crucial for the success of the technology. The reflectors of the solar field are a key component of CSP plants, requiring reliable methods for service lifetime prediction. So far, no proven correlations exist to relate accelerated aging test results in climate chambers with relevant CSP exposure sites. In this work, correlations have been derived for selected testing conditions that excite the same degradation mechanisms as for outdoor exposure. Those testing conditions have been identified by performing an extensive microscopic comparison of the appearing degradation mechanisms on reference samples that have been weathered outdoors with samples that underwent a high variety of accelerated aging experiments. The herein developed methodology is derived for aluminum reflectors and future work will study the applicability to silvered-glass mirrors.

INTRODUCTION

Nowadays several alternatives to the thick glass mirrors mainly used in CSP plants are discussed [1] which could present advantages concerning price and flexibility in fabrication and installation. Besides polymer reflector foils one important group of materials is rolled aluminum sheets with enhanced reflective and protective coatings. The main advantages of these aluminum reflectors are their light weight and very good formability which also leads to an impossibility of breakage.

The structure of the reflector materials included in this work is shown in Fig. 1. The reflectors consist of the anodized aluminum sheet substrate on which several protective layers are deposited. These protective layers comprise either a SiO₂ based sol-gel coating or a polymer based coating. Some of the materials also possess several very thin reflectance enhancing layers applied by physical vapor deposition (PVD). The PVD layer system consists of a very pure aluminum layer followed by SiO₂ and TiO₂ layers to use positive interference for reflection enhancement.

As the experience with the performance of these reflector materials is very limited it is of strongest concern to gain information about their degradation behavior [2]. The goal of the ALUMIR project is the development of a method for accelerated aging and lifetime estimation of the aluminum reflectors. For this purpose a wide outdoor testing campaign as well as a campaign for accelerated aging in the laboratory has been conducted. Microscopic comparison of the excited degradation mechanisms outdoors and under accelerated aging permitted to select the most suited tests to realistically age the materials. In this paper the correlation between outdoor exposure and lab testing for selected degradation mechanisms is presented.

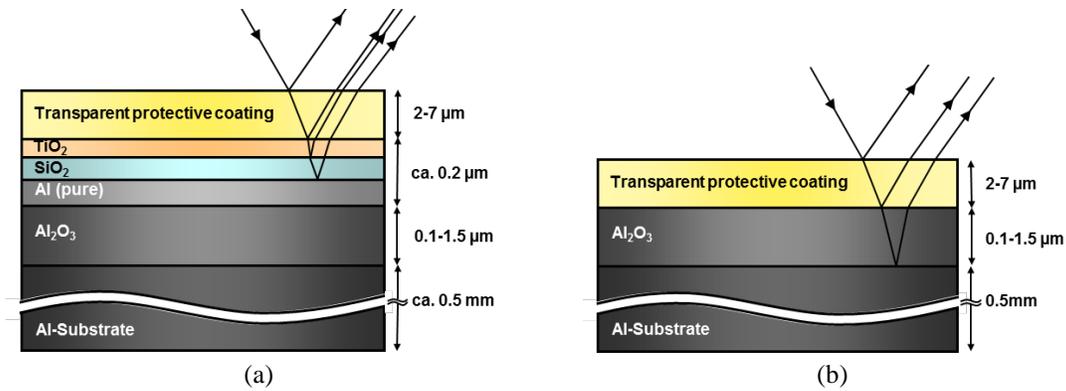


FIGURE 1. Structure of the aluminum reflectors with (a) and without (b) reflectance enhancing layers

METHODOLOGY

Outdoor Testing Campaign

In the course of the ALUMIR project an extensive outdoor testing program is conducted. Nine testing sites in Spain, Morocco and United Arab Emirates are selected to represent a wide range of conditions from coastal over urban to desert sites. In Fig. 2 (a) a map with the sites can be seen. In the Table 1 the exact location of the sites with their corresponding main characteristics can be seen.

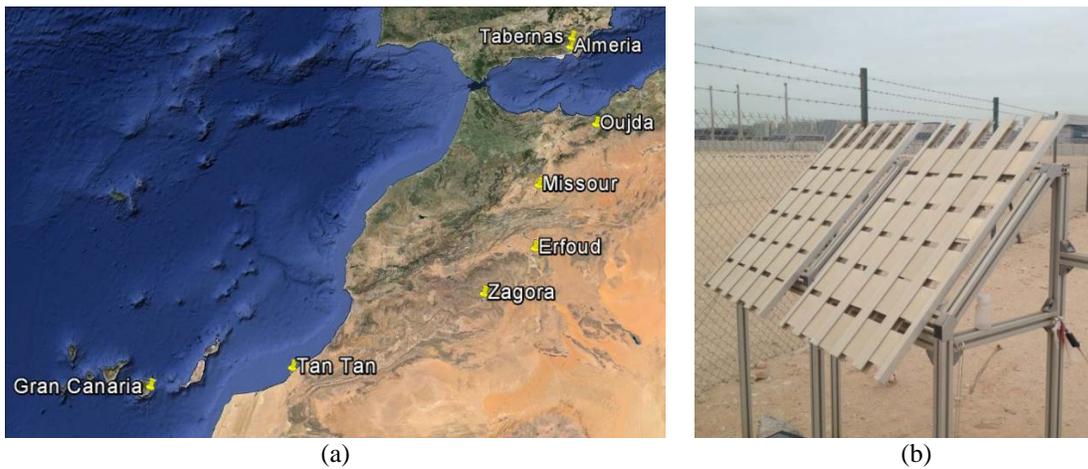


FIGURE 2. (a) Eight of the nine outdoor sites, excluding Abu Dhabi, (b) Outdoor exposure rack with reflector samples

On each site nine differently coated aluminum reflector materials (named from A to I) from three manufacturers are exposed. Samples are collected every six months from every material and site and analyzed in the Optical Aging Characterization (OPAC) laboratory of the Plataforma Solar de Almería (PSA). The reflectance of the samples is measured before and after exposure and a detailed analysis with a light and in special cases with a scanning electron microscope (SEM) is done. The total duration of available outdoor data for the different sites is also included in Table 1.

TABLE 1. Outdoor exposure sites with their locations and main characteristics

Location	Latitude	Longitude	Characteristics	Exposure time (months)
Almeria	36.85° N	-2.36°E	Coastal, urban	30
Tabernas	37.1°N	-2.35°E	Desertic	30
Oujda	34.65°N	-1.9°E	Urban, desertic	18
Missour	32.86°N	-4.11°E	Desertic	20
Erfoud	31.49°N	-4.22°E	Desertic	20
Zagora	30.27°N	-5.85°E	Desertic	20
Tan Tan	28.5°N	-11.32°E	Coastal	20
Gran Canaria	27.92°N	-15.39°E	Coastal	30
Abu Dhabi	24.44°N	54.62°E	Coastal, urban	30

Accelerated Laboratory Testing

To reproduce the effects on the samples found outdoors, an accelerated testing campaign was conducted in the laboratory. The accelerated testing program included common standardized tests (salt spray according to ISO9227, UV/humidity ISO11505, damp heat IEC 62108 test 10.7b, humidity freeze IEC 62108 test 10.8, condensation ISO6270-2 (CH) and thermal cycling with condensation) as well as less frequently used tests (Machu and Kesternich DIN50018) and also especially designed tests (combinations of tests, testing of soiled samples, etc.). The tests that were chosen to reproduce the different mechanisms are presented in more detail.

The copper accelerated acetic acid salt spray (CASS) test [3] is a fast corrosion test to simulate exposure to aggressive climates with the presence of chlorides. The test is based on the well-known neutral salt spray test (NSS) and consists of the exposure to the mist of a salty solution. The solution contains sodium chloride and copper chloride ($[\text{NaCl}]=50\pm 5 \text{ g/l}$; $[\text{CuCl}_2]=0.26\pm 0.02 \text{ g/l}$). The temperature in the chamber is $50\pm 2^\circ\text{C}$ and the pH lies between 3.1-3.3. These conditions make the test far more aggressive than the standard NSS test.

The UV/humidity test [4] is a cyclic test in which the samples are exposed to high humidity and UV radiation. One cycle consists of four hours of humidity (100% r.h. at 50°C) and four hours of exposure to UV radiation (60°C , UVA lamp with peak of $0.77 \text{ W/m}^2/\text{nm}$ at 340 nm). The cycles are repeated until the total test time is completed.

For the abrasion test a soil pipe was used based on DIN 52348 [5]. It basically consists of a 1.625 m long vertical pipe with a diameter of 15 cm and an inlet funnel and two meshes for particle homogenization. At the lower end of the pipe the samples are fixed to a holder that is tilted 30° to the horizontal and turning with a velocity of 250 rpm. During the test a defined mass of sand is trickled on revolving samples. The sand used for the experiment was synthetic quartz sand with particle diameters between 300 and 625 μm . A detailed description of the setup and conducted tests can be found in [6]. Images of the laboratory chambers are presented in Fig. 3.

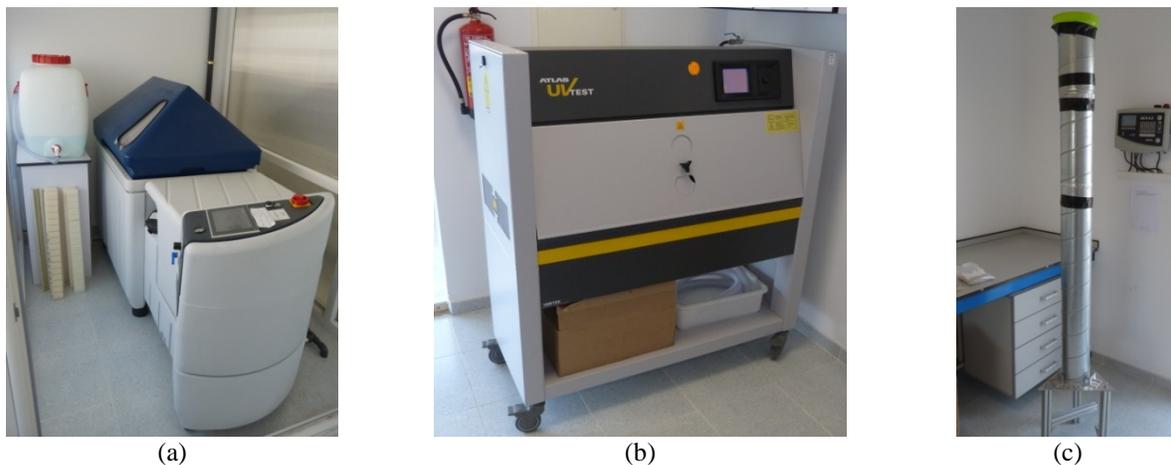


FIGURE 3. The laboratory test chambers used for the tests, (a) Salt spray chamber, (b) UV/humidity chamber, (c) Soil pipe

Correlation Analysis

To be able to make a prediction of the lifetime of reflectors, not only the degradation mechanisms have to be reproduced but also the amount and degree of degradation has to be known for the outdoor and the accelerated tests. The degradation mechanisms were analyzed and quantified separately. This way a correlation between laboratory testing and outdoor exposition is developed for each degradation mechanism individually.

The reflectance of the material is in the end the most important factor to decide if a reflector is suited for the corresponding application. However, the reflectance showed not to be a well suited parameter to derive correlations. First because the influence of a certain degradation mechanism cannot be separated from other degradation mechanisms because they appear combined, especially outdoors. Secondly the reflectance is only measured punctually and not covering the whole reflector surface. The degradation on the other hand, although very visible, often only covers a small part of the surface and is thus hard to represent with punctual measurements. Consequently, the degradation analysis is performed by microscopic techniques to really focus on every defect type identified, covering the sample surface in detail. In the end, for every mechanism a special parameter was selected to derive the correlation. The corresponding methods are explained in the result section below.

RESULTS

The samples that return from the outdoor sites show, depending on the type of site, strong signs of degradation already after 6 months. The degradation is usually stronger on sites close to the coast where the humidity is high. One desert site (Zagora) showed some unique defects in form of massive abrasion of the top coating that covers the entire surface.

In Fig. 4 the loss of specular reflectance is displayed. It can be seen that the materials and sites show strong differences in the degradation. The very high loss in Zagora can be explained by the before mentioned strong abrasion.

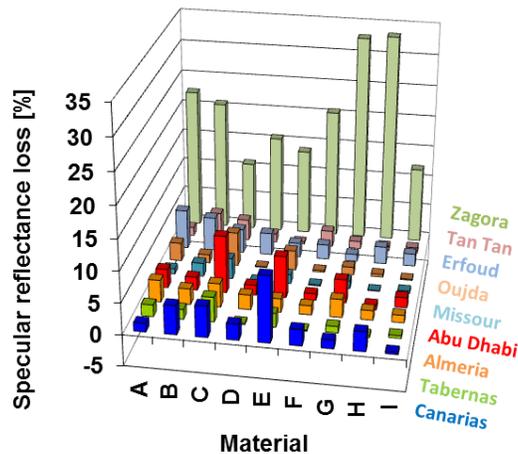


FIGURE 4. Specular reflectance loss for all materials and sites after 18 months of exposure

Five main degradation mechanisms were identified on the outdoor exposed samples: corrosion of the aluminum PVD layer, micropitting of the PVD layer, pitting corrosion reaching the substrate, non-removable deposits on the surface and defects on the protective top coating caused by abrasion through airborne particles. Although no single accelerated aging test was found to reproduce all the mechanisms, it was possible to reproduce all of them in different tests (see Fig. 5). For three of five of these mechanisms the correlation between outdoor and selected accelerated tests is presented in the following.

Details of the PVD corrosion mechanism were already discussed in previous works [7] and will not be addressed in this work. The permanent soiling through deposits is a mechanism that is important but is also excluded in this work because the outdoor exposed samples were not cleaned during exposure. In every commercial application some form of regular cleaning procedure is always applied though. That is why an exposure campaign concerning soiling has to include such a procedure as well to produce realistic results.

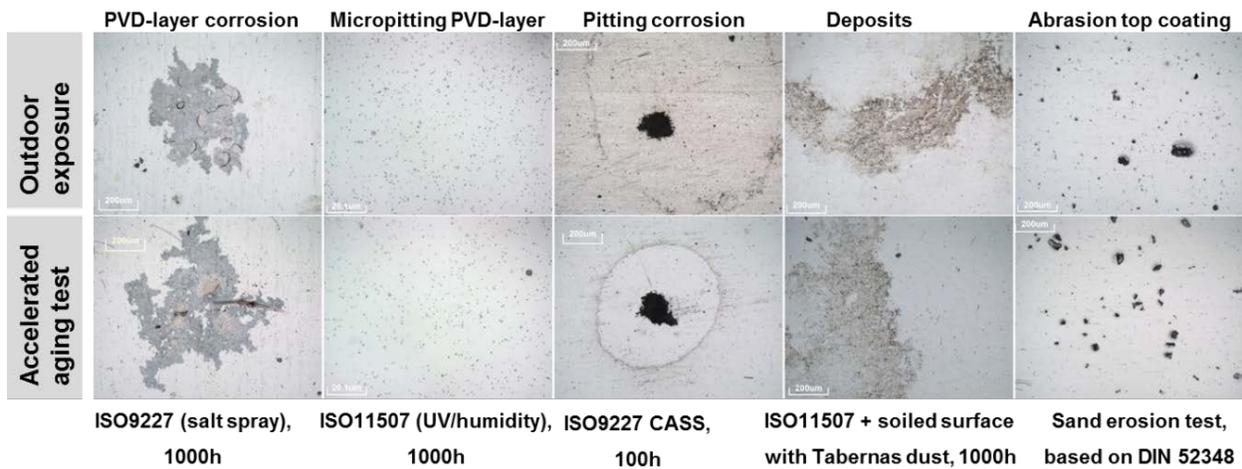


FIGURE 5. The five degradation mechanisms detected outdoors and reproduced in different accelerated tests

The degradation mechanism called *micropitting* consists of small perforations of the aluminum reflection layer. The size of these perforations ranges from below one to only a few micrometers, as can be seen in the optical microscope and SEM images of Fig. 6. This form of degradation only appears in samples from one manufacturer and it is likely that it originates from the production process. Outdoors this degradation mechanism already appears after weeks of exposure at all sites. The detailed mechanism of this kind of degradation is still unclear. In accelerated tests it was shown that a combination of UV radiation and humidity is necessary to provoke it. Therefore it was concluded that the best suited test is the UV/humidity test.

The micropitting is evaluated by using an automated code which counts the micropittings on microscopic pictures and in the end calculates the spot density. In Fig. 7 two graphs are displayed that show the development of two materials over time outdoors and in the UV/humidity test. The outdoor exposed samples were analyzed every day in the beginning. With ongoing time, the analysis frequency was lowered successively. The same was done with samples in the UV/humidity test. Here the first measurements were done after a few cycles already. Due to the faster evolution in the accelerated tests two horizontal axes were used in the graphs, the axis for the outdoor data at the bottom (blue) and the axis for the accelerated test on top (red).

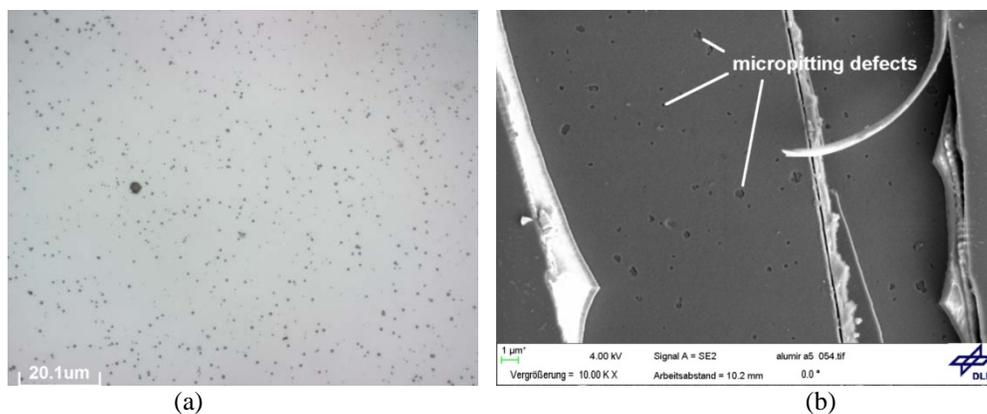


FIGURE 6. (a) microscopic image of the aluminum layer with micropitting after outdoor exposure, (b) SEM image

The micropitting density seems to reach stabilization in the outdoor tests as well as in the UV/humidity test. For the outdoor tests this degradation only grows in the beginning of exposure and no considerable evolution can be detected after the first six months. As for the lifetime prediction longer outdoor exposure times are of concern, it is enough to reach stabilization in the accelerated test as well to simulate this degradation mechanism. In the UV/humidity test, 480 h of exposure are enough for all the materials to comply with this. So this test duration is

chosen as representative for all outdoor exposure times over 6 months. A longer accelerated test would not increase the micropitting density but pose the risk of provoking unwanted side effects.

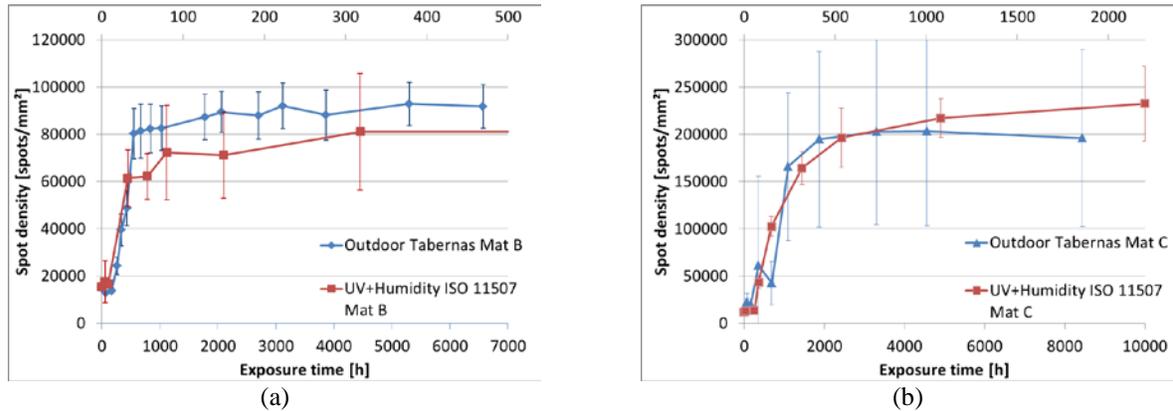


FIGURE 7. (a) Correlating micropitting in Tabernas, Spain with the UV-humidity test according to ISO 11507 for Material A. (b) for Material C. The data from the accelerated aging (red curves) correspond to the upper time-axis.

Pitting corrosion is a mechanism in which all the layers of the reflector material are affected down to the material substrate. The protective and reflective layers are attacked punctually and then the corrosion continues to grow and penetrates in to the aluminum. Typical pitting spots can reach hundreds of micrometers in diameter and depths of more than 50 μm were detected. Generated corrosion products can deposit on the surface and lower the reflectance around the primary degradation. Typical pitting spots can be seen in Fig. 8.

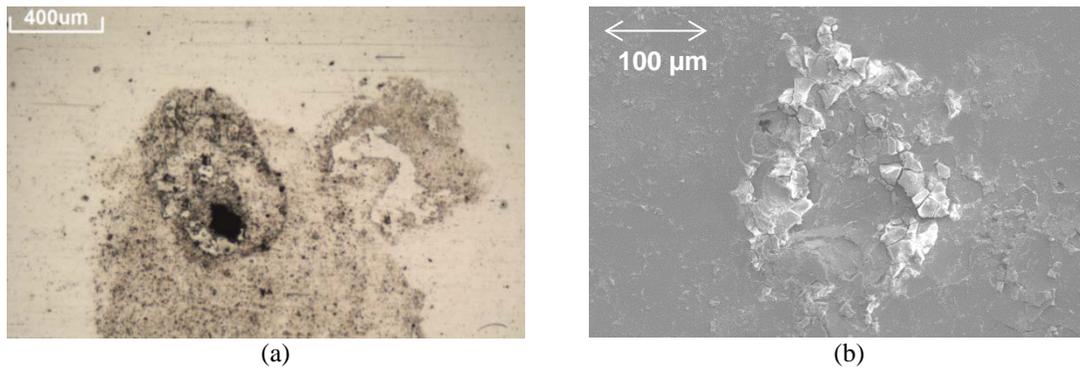


FIGURE 8. Pitting holes on outdoor samples with corrosion products on surface, (a) Light microscope image, (b) SEM image

Pitting corrosion is mainly an issue at sites close to the coast. On other sites it appears only sporadically. The sites in Almeria, Canarias and Tan Tan show a high number of these defects and were therefore chosen as representative for this kind of defect. The CASS test is the only accelerated test that reproduced the pitting corrosion in a considerable and reproducible extent. To establish a correlation between outdoor and accelerated degradation the number of pittings was counted. Factors like size, depth or severity of single pittings were not considered to keep the complexity low and because the defects in general showed a similar structure. Defects were counted directly on the samples or on photographic images of them if the number was very high. The identification as a defect was checked with microscopic images of the corresponding spot. This procedure was done for the outdoor samples and for samples from a CASS test. For outdoors samples the data available are the ones taken every six months. The test duration of the CASS was 120 h with measurements after 24, 48, 72, 96 and 120 h. Materials A, B and D were selected for the correlation determination because they represent kind of a worst case scenario as the number of pittings was higher outdoors than for other materials. The mean value of the number of pittings is calculated for the three materials. For the three sites the data is presented in the Fig. 9. As for the micropitting data, two horizontal axes are displayed, on top the one for the accelerated test (in blue) and on the bottom the one for the outdoor data.

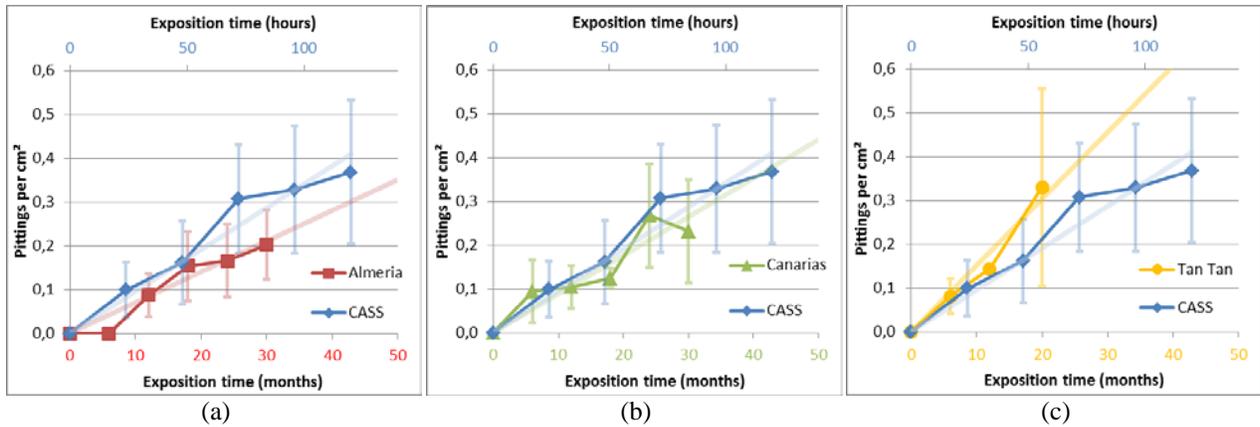


FIGURE 9. Evolution of number of pittings in (a) Almeria, (b) Canarias and (c) Tan Tan and in the CASS test

To calculate the correlation between the results a linear evolution of the number of spots was assumed and the slope of the corresponding lines was calculated. These data are summarized in Table 2 together with the coefficient of determination R^2 for the linear approximation. The acceleration factors for the different sites are calculated dividing the slope for the outdoor data by the slope of the CASS data. The acceleration factors for the different sites are included in the Table 2. A mean value for the three coastal sites is then calculated to represent this type of environment in general. The resulting average factor is 267.8 which means, that to reproduce the degradation of 5 years of outdoor exposure for example a duration of 164 h in the CASS test would be necessary.

TABLE 2. Data of the linear approximation for the different sites and the resulting acceleration factor

	Slope (pittings/m ² /month)	R ²	Factor
CASS	2.49612	0.95	
Almeria	0.00702	0.93	355.6
Canarias	0.00881	0.85	283.3
Tan Tan	0.0152	0.96	164.2

An easy setup was found to reproduce a part of the *abrasion* that was detected on the desert site of Zagora. This degradation consists in mechanical damage of the top coating by airborne particles (see Fig. 12). In the tests with the soil pipe a linear relation could be found between the used sand mass and the reflectance loss.

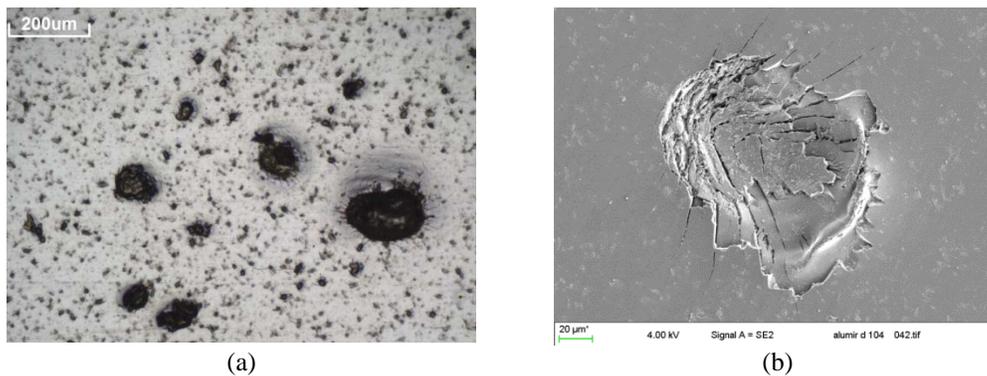


FIGURE 12. (a) light microscope image of abrasion defects on a sample exposed in Zagora, (b) SEM image of one defect

To correlate the results another automated procedure was used to determine number and size of the defects on the different materials. The main result of this analysis was that the soil pipe can only reproduce part of the damage found outdoors. On one hand the particles in the test are too big to properly reproduce the smaller defects (below

1500 μm^2). On the other hand the velocity (2.5-4 m/s) of the falling particles is determined by the height of pipe and cannot easily be augmented. That is why very high defect sizes are also not reproduced. A mass of 100 g of sand was found to reproduce well the medium range of defect size for Zagora after an exposure of 20 months. In the future it is planned use another device to reproduce the abrasion. A sand storm chamber is under development to reach higher flexibilities in the testing conditions concerning particles used and their velocity.

CONCLUSIONS

In this work accelerated aging tests are presented that can realistically provoke the degradation mechanisms found on aluminum reflector samples under outdoor exposure in representative sites. Correlations were derived to relate laboratory testing to outdoor exposure for each of the detected degradation mechanisms individually, making it possible to predict the specific degradation at different exposure sites and times based on accelerated aging.

In particular, micropitting of the aluminum reflection layer appearing during the first period of the outdoor exposure was reproduced with 480 h of the UV/humidity test. Pitting corrosion, which affects all the layers of the reflector including the substrate material, was detected at sites close to the coast. This mechanism was reproduced with the CASS test, being 164 h in the test chamber equivalent to 5 years of outdoor exposure. Finally, abrasion appeared on the top layer of samples exposed to the desert site of Zagora was reproduced with a simple abrasive setup, in which a mass of 100 g of trickled sand was used to properly reproduce the medium range of defect size after an exposure of 20 months.

First tests showed that a sequential combination of the different accelerated aging tests enables to excite several degradation mechanisms on the same sample. The herein derived correlations are the first step to develop a realistic accelerated aging methodology which allows making well-founded lifetime estimations for the analyzed material class. In the future the applicability of the method to other material classes will be studied to be able to make lifetime predictions for all solar reflectors materials and gain a higher standardization for their testing.

ACKNOWLEDGEMENTS

The present work was funded from the German Federal Ministry for Economic Affairs and Energy in the framework of the Alumir project (grant number 0325420). The authors want to thank IRESEN (Morocco), ITC (Gran Canaria) and Masdar Institute (Abu Dhabi) for hosting the samples and sending them periodically for analysis to PSA. The authors want to thank Lucía Martínez from CIEMAT and Tomás Jesus Reche Navarro and Florian Wiesinger from DLR for their contributions.

REFERENCES

1. C.E. Kennedy, K. Terwilliger, "Optical durability of candidate solar reflectors". J. Sol. Energy Eng. 127 (2005) 262-268.
2. T. Fend, B. Hoffschmidt, G. Jorgensen, H. Küster, D. Krüger, R. Pitz-Paal, P. Rietbrock, K. Riffelmann, "Comparative assessment of solar concentrator materials", Solar Energy 74 (2003) 149-155.
3. EN ISO 9227:2012 Corrosion tests in artificial atmospheres - Salt spray tests, International Organization for Standardization, ISO, 2012.
4. ISO 11507: 2007-02: Paints and varnishes - Exposure of coatings to artificial weathering - Exposure to fluorescent UV lamps and water, International Organization for Standardization, ISO, 2007.
5. DIN 52348: 1985: Testing of glass and plastics, abrasion test, sand trickling method, Deutsches Institut für Normung.
6. F. Wiesinger, F. Sutter, A. Fernández-García, J. Reinhold, R. Pitz-Paal, „Sand erosion on solar reflectors: accelerated simulation and comparison with field data”, Solar Energy Materials and Solar Cells, to be published.
7. F. Sutter, S. Ziegler, M. Schmücker, P. Heller, R. Pitz-Paal, Modelling of optical durability of enhanced aluminum solar reflectors, Solar Energy Materials & Solar Cells 107 (2012) 37-45.