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Cite as: AIP Conference Proceedings **2445**, 080010 (2022); https://doi.org/10.1063/5.0085744
Published Online: 12 May 2022

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A Guideline for Realistic Accelerated Aging Testing of Silvered-Glass Reflectors

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Abstract. Accelerated aging testing can be a useful tool to evaluate the durability of solar reflectors for CSP applications. The selection of suitable testing procedures and parameters is essential to be able to create viable results. Despite important research efforts in the past, there is still a lack of agreement on the selection of these tests for silvered-glass mirrors and only one standard was published so far. This standard presents a series of tests without acceptance criteria and still lacks a correlation to real outdoor results. In this paper a guideline is presented that helps to select tests and parameters for silvered-glass mirrors for different purposes. All parameters are determined based on the correlation of outdoor data and the respective accelerated test results for a variety of different materials. On one hand, it allows for quick and easy screening for degradation mechanisms and the direct comparison of the durability of different materials. On the other hand, more complex lifetime prediction procedures are presented that enable the estimation of the behavior of the reflector materials depending on the foreseen exposure site. Depending on defined maximum degradation by the user, acceptance criteria for the accelerated tests are proposed. The development of the guideline into an international standard within the IEC framework is ongoing.

INTRODUCTION

Reliability of components for concentrating solar power (CSP) plants has to be assured to be able to guarantee the performance and thus the commercial success of any CSP project. Primary mirrors are a crucial component, because their optical quality directly influences the amount of solar radiation that can be used for the later energy conversion process. Furthermore, large scale replacement of the reflectors that goes beyond the regular exchange of single broken facets is not foreseen during the lifetime of a power plant. Due to the large size of the installed solar field this would result in an unacceptable financial penalty, because of the direct costs of the mirrors and the necessary manpower as well as the indirect costs of a longer shutdown of plant operations. Hence, required lifetime for the material depends on the planned project duration. Typically, the mirrors are foreseen to reach lifetimes of 25 years and more [1]. During the lifetime their main goal is to maintain good optical quality, i.e. high solar specular reflectance. The long outdoor exposure during their service life poses a challenge to the material durability as different environmental stress factors act on the material. The main environmental stresses are temperature, humidity, ultra-violet (UV) radiation, chemical compounds and particles in the atmosphere. The presence of the stresses is extremely site dependent, and thus site conditions should be considered for material selection. With different environmental stresses the degradation mechanisms of the mirrors also vary. Two of the main identified degradation mechanisms for silvered-glass mirrors, the most commonly used type of mirrors, are the erosion of the glass front surface by airborne particles, and the corrosion of the silver layer due to humidity and chlorides in the atmosphere [2].

Accelerated aging testing is a useful and widely implemented tool to evaluate the durability of solar mirrors [3]. For this purpose, material samples are exposed to single stresses or combinations of several stress factors under controlled laboratory conditions. Usually, the stress levels are increased compared to outdoor conditions to provoke

SolarPACES 2020
AIP Conf. Proc. 2445, 080010-1–080010-8; https://doi.org/10.1063/5.0085744
Published by AIP Publishing. 978-0-7354-4195-8/$30.00

an acceleration of possible degradation effects and to limit test duration to an acceptable time frame. The selection of realistic tests and parameters is crucial to achieve meaningful results and to avoid degradation that is not detected during outdoor exposure (typically called side effects). Even though efforts have been made in the research of this topic in the past [4, 5], up to today, no general agreement has been reached in the CSP domain, on the exact procedures and parameters to be applied to achieve meaningful results. The first standard specifically addressing the accelerated aging testing of primary mirrors is the Spanish UNE 206016 published in 2018 [6]. This standard defines a set of tests with minimum durations without evaluation or acceptance criteria nor relation to outdoor performance.

In this work, a newly developed guideline for the testing of solar reflectors is presented, based on the results of long-term outdoor exposure and the correlation with accelerated aging results. The guideline is divided into two parts, one serving for quick direct comparison of reflector materials and the other one providing tools for lifetime prediction (LTP) of the reflectors, and thus enabling the estimation of the performance of materials, depending on the exposure site conditions over time. The here presented guideline is undergoing an adaptation process at the moment and the implementation into an international standard in the framework of the International Electrotechnical Commission (IEC) is being prepared.

METHOD

The guidelines presented here were developed based on data of an extensive outdoor exposure campaign and the performance of a series of different accelerated aging tests. The work was conducted within the Raiselife project funded by the EU Horizon 2020 Program. The goal of the project was to raise the lifetime of various components for CSP technologies. The first work package was dedicated to primary mirrors. Several commercial and novel mirror materials were evaluated by outdoor and accelerated laboratory experiments and testing procedures were optimized during the project execution.

The outdoor campaign included the exposure of different silvered-glass reflector types, with seven materials selected for the evaluation within this work, on 11 outdoor sites, covering a variety of possible CSP sites around the globe for over three years. The degradation during exposure of the materials was evaluated periodically in detail in the OPAC laboratory (a joint research group between DLR and CIEMAT). For all the exposure sites the main meteorological parameters and the corrosivity and erosivity were determined. Corrosivity was determined by the exposure of standard metal coupons according to ISO9223 [7] and erosivity, following a method specifically developed by OPAC based on the exposure of samples, the analysis of their degradation pattern and determination of the defect size density distribution (DSDD) [8]. Detailed results of the outdoor exposure campaign together with the site locations and conditions can be found in [2].

In parallel to the outdoor exposure, a wide accelerated aging testing campaign was performed. The performed accelerated aging procedures mainly included common tests already applied in the industry, and specified in the first standard addressing the testing of CSP reflectors UNE 206016, as well as more complex combinations of single tests [9, 10]. For the erosion testing, an open loop wind tunnel called Acetube, was specifically designed for the realistic simulation of the outdoor observed defect picture caused by the impact of windblown particles [8].

Different types of novel reflector materials were evaluated within the project. One group comprised anti-soiling front coatings on commercial silvered-glass mirrors and the other (ultra-)thin glass mirrors with a composite backing structure for the use in an innovative type of lightweight heliostat. The composite mirrors implemented reflectors of glass thicknesses from around 1 mm down to 0.1 mm. For the development of the guideline these two groups were not included. The focus for the guideline was on regular silvered-glass mirrors, including commercial products and novel systems in which the protective backside coating system had been slightly modified (e.g. by reducing coating thickness, number of layers or varying chemical composition of the lacquer).

The focus for the guideline is on the two major degradation mechanisms found during the outdoor campaign, namely the corrosion of the reflective silver layer and the erosion of the glass front surface by impacting windblown particles. Both mechanisms have the potential, depending on the magnitude of degradation, to severely affect the reflectance of the mirrors and by that compromising their optical quality.

Outdoor and accelerated aging results were compared in detail, to assure the realistic reproduction of all defects. Tests and parameters were selected specifically for the different parts of the guideline, to enable meaningful, realistic testing with minimal resources.

The most important parameter to determine the optical quality of the reflector material as well as its degradation is the solar-weighted specular reflectance. It is one of the factors that directly influence the ability of the reflector to redirect the sun’s incoming radiation onto the receiver. Several reasons exist why other degradation parameters should

be taken into consideration to evaluate the aging process of the reflector material. First of all, no commercial instrument exists that measures this parameter. Novel laboratory instruments exist that still have some shortcomings. For example, they are not able to measure a spatial distribution of the reflectance but only in single spots, and they cannot be used for measurements in the field. For some of the procedures the often measured parameters, solar-weighted hemispherical reflectance and the specular reflectance at a single wavelength are being considered. To assess corrosion effects, mainly the area fraction affected by corrosion as well as the number of appearing corrosion spots are taken into account. For the erosion it is the above mentioned DSDD. With these values it is possible to directly quantify the degradation and verify if the degradation mechanisms provoked in an accelerated aging test coincide with the ones found during outdoor exposure.

RESULTS

As a result of the evaluation described above a guideline was developed [11]. The guideline, presented in the following represents an adaptation of the version developed within the Raiselife project, to account for new findings and to be implemented in an international standard. Depending on several parameters the user of the guideline can select certain methods from the document to define the testing procedure for the specific material. In Figure 1, a schematic representation of the guideline is displayed, summarizing the purpose of the different parts, their selection process and the different parameters for the execution of the final procedures.

The right branch of the scheme presents the case that certain known degradation mechanisms are going to be investigated. With these methods it is possible to perform an LTP for the two mechanisms of erosion and corrosion and to predict their influence on the reflectance over the lifetime of the material. The test parameters depend on the conditions of the site where the material is intended to be exposed.

The left branch of the guideline provides quick and simple methods to directly compare different reflector materials. It is supposed to give qualitative results on the durability of the materials concerning corrosion and the ranking among them.

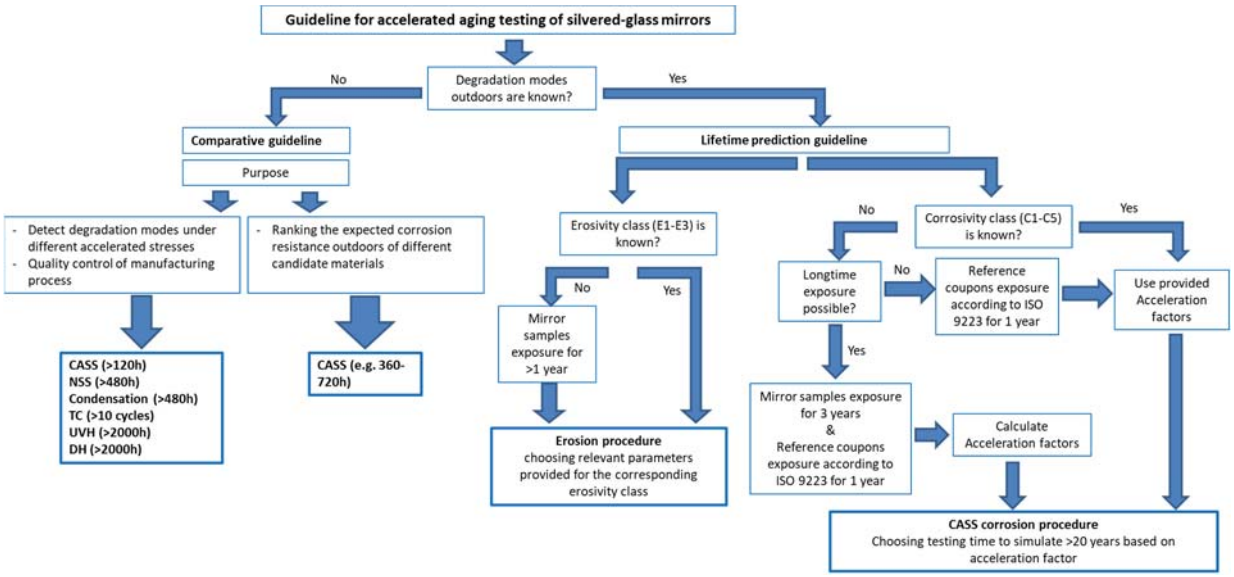

FIGURE 1. Scheme of the accelerated aging guideline; purposes, conditions leading to different procedures [11].

Comparative Guideline

The part of the comparative guideline (left branch in the scheme above) is divided into two sub parts: one focused on the corrosion resistance of the materials and one on the screening for all possible degradation processes.

Corrosion Resistance Ranking

The developed comparative guideline focuses on the resistance of reflector materials against the corrosive attack of the silver layer. Usually during outdoor exposure the silver layer gets attacked in two ways, the edges and penetrating the protective backside paint layers. As the edge corrosion is expected to only have a minimal effect on real size facets (because they will be properly sealed), the corrosion by penetration the backside was chosen as the main parameter. Because the corroded area fraction was still extremely small after 2-3 years of outdoor exposure, the corrosion spot density was evaluated as a more accessible parameter.

It was found, that the Copper Accelerated Salt Spray Test (CASS), included in the UNE standard, is the only test able to provoke that type of degradation in a reasonable time frame. Considerable degradation was detected, depending on the material, after ca. 360 h. When results from the CASS test were compared to data from two outdoor sites (PSA in Tabernas and Almería), which showed conceivable corrosion, it was verified that the test is able to reproduce the ranking, concerning the durability of the different materials found outdoors. As an example, in Fig. 2 the ranking of seven investigated materials is presented. For that, the corrosion spot density was compared on samples after 480 h in the CASS test with the values after two years of exposure on the two analyzed sites. Displayed are the ranks of the seven materials from 1 (lowest spot density, most resistant material) to 7 (highest spot density, weakest corrosion resistance) for the three cases (blue: CASS, yellow: PSA, red: Almería). It can be seen that certain differences between tests exist but the general tendency is the same (e.g. RLA1 and RLA3 perform very well, RLF4 and RLF4R show weak behavior). The ranking even differs between the two outdoor sites. Differences in the rankings possibly arise from the weak degradation after just 2 years of outdoor exposure resulting in a low number of spots per sample (around 0 to 5 spots on most materials) and a high statistical uncertainty. The outdoor campaign is still ongoing and results achieved up to now will be verified with longer available exposure durations.

For the procedure it is recommended to perform the CASS test for a duration after which considerable degradation and differences between materials are detected (usually 360 – 720 h). The ranking is then performed based on the corroded area fraction (without taking edge corrosion into account), if feasible, or otherwise on the corrosion spot density in the case of very weak degradation.

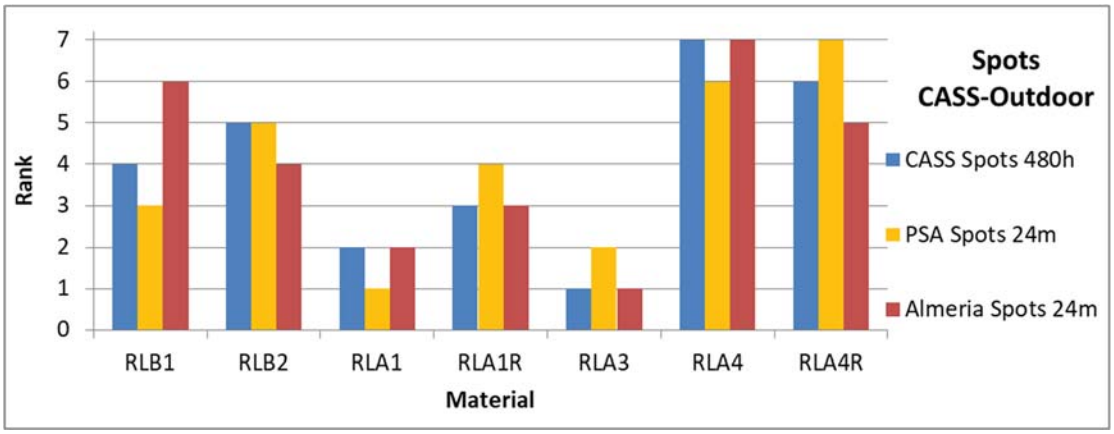

FIGURE 2. Ranking of seven investigated materials based on the corrosion spot density after CASS-Test (480 h) and outdoor exposure (2 years PSA and Almería, respectively) [11].

Degradation Screening and State-of-the-Art Evaluation

In the guideline it is recommended to perform the remaining tests already specified in the UNE 206016, to detect additional failure modes apart from corrosion or specific weaknesses of the materials to certain stresses (e.g. humidity, UV radiation). In Table 1, the tests and their corresponding parameters are presented. For most of the test, two durations are displayed. The short durations represent the minimum time to be tested for the respective tests. A set of acceptance criteria for these tests and durations is proposed which the materials have to meet to be considered state-of-the-art. These criteria are based on the evaluation of a large data set of test results of commercial mirror materials [5] and define maximum values for four degradation parameters: solar-weighted hemispherical reflectance loss ($\Delta\rho_{s,h}$), specular reflectance loss ($\Delta\rho_{\lambda,\varphi}$), corrosion spot density (d_{corr}) and original edge corrosion penetration ($l_{corr,o}$). It is

recommended to use the longer testing times in the table to screen for appearing additional degradation mechanisms, as it was shown in long term tests on the seven materials, that the minimum durations are not sufficient to provoke considerable degradation. This is especially important when new materials are tested, whose composition differs strongly from known materials, or if certain weaknesses are expected. Also, an additional mechanical test (Taber abrasion), which is was not part of the original guideline, is included for the standard together with its acceptance criteria.

TABLE 1. Set of proposed accelerated aging tests to perform with durations, parameters and acceptance criteria.

No.	Test	Duration	Summary of testing conditions	Acceptance criteria for short durations
A.1	Neutral Salt Spray (NSS) ISO 9227	480/1000 h	T=35±2°C, pH=[6.5, 7.2] at T=25±2°C Sprayed NaCl solution of 50 ± 5 g/l Condensation rate of 1.5 ± 0.5 ml/h on a surface of 80 cm²	$\Delta\rho_{s,h} \leq 0.004$ $\Delta\rho_{\lambda,\varphi} \leq 0.004$ $d_{corr} \leq 0.01\ cm^{-2}$ $l_{corr,o} \leq 0.1\ cm$
A.2	Copper accelerated acetic acid salt spray (CASS) ISO 9227	120/360 h	T=50±2°C, pH=[3.1, 3.3] at T=25±2°C Sprayed NaCl solution of 50 ± 5 g/l and 0.26 ± 0.02 g/l of $CuCl_2$ Condensation rate 1.5 ± 0.5 ml/h on surface 80 cm²	$\Delta\rho_{s,h} \leq 0.002$ $\Delta\rho_{\lambda,\varphi} \leq 0.002$ $d_{corr} \leq 0.01\ cm^{-2}$ $l_{corr,o} \leq 0.1\ cm$
A.3	Condensation ISO 6270-2 CH	480/2000 h	T=40±3°C RH=100%, with condensation on the samples	$\Delta\rho_{s,h} \leq 0.002$ $\Delta\rho_{\lambda,\varphi} \leq 0.002$ $d_{corr} \leq 0.01\ cm^{-2}$ $l_{corr,o} \leq 0.1\ cm$
A.4	Combined thermal cycling and humidity UNE206016	10/40 cycles	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%	$\Delta\rho_{s,h} \leq 0.002$ $\Delta\rho_{\lambda,\varphi} \leq 0.002$ $d_{corr} \leq 0.01\ cm^{-2}$ $l_{corr,o} \leq 0.1\ cm$
A.5	UV and humidity ISO 16474-3	1000 h (front side) + 1000 h (back side)	1 cycle: 4h at UV exposure at T=60±3°C followed by 4h at RH=100% at T=50±3°C	$\Delta\rho_{s,h} \leq 0.004$ $\Delta\rho_{\lambda,\varphi} \leq 0.004$ $d_{corr} \leq 0.01\ cm^{-2}$ $l_{corr,o} \leq 0.1\ cm$
A.6	Damp Heat IEC 62108 (test number 10.7, Procedure b)	2000 h	65°C and 85% RH	$\Delta\rho_{s,h} \leq 0.01$ $\Delta\rho_{\lambda,\varphi} \leq 0.01$ $d_{corr} \leq 0.2\ cm^{-2}$ $l_{corr,o} \leq 0.1\ cm$
A.7	Taber Abrasion UNE206016	1000 cycles	Abradant of diameter ¾" producing mild abrading action, pushed with a force of 3.4 N on the mirror (0.012 N/mm²), 25 cycles per minute and stroke length of 8 ± 2 cm. Intermediate inspections after 200, 400, 600, and 800 cycles.	$\Delta\rho_{\lambda,\varphi} \leq 0.017$

Lifetime Prediction Method

For the lifetime prediction part of the guideline (right branch of scheme) the different degradation mechanisms are treated separately. The main degradation mechanisms that may influence the reflectance of a mirror material during its lifetime are erosion and corrosion. Further effects were detected for mirror materials (e.g. silver tarnishing, surface incrustations, UV degradation), but their influence is negligible compared to the others and were therefore not included in the guideline. The reflectance loss over time, $\Delta\rho$, can be written as the sum of the effects of erosion, $\Delta\rho_e$, corrosion, $\Delta\rho_c$, and others, $\Delta\rho_o$:

$$\Delta\rho = \Delta\rho_e + \Delta\rho_c + \Delta\rho_o \quad (1)$$

In the following chapters it is described how the terms for corrosion and erosion can be determined. For the standard, it is proposed that the end user defines an acceptable reflectance loss for a material after a certain lifetime and the corresponding testing parameters are given in the document.

Corrosion Method

In some areas (e.g. coastal sites), corrosion has been identified as a main parameter that contributes to the reflector degradation. This corrosivity level of the locations might be classified between C1 to CX according to ISO 9223:2012.

The CASS test, also used for the corrosion resistance ranking, is the best method to reproduce the same corrosion defects appeared in the reflectors. In this case, one CASS-cycle consists of 120 h of testing and at least 48 h of drying phase. The evolution of the corroded area fraction in the CASS test follows the formula [12]:

$$A_c = 1 - e^{-b(t_{chamber})^c} \tag{2}$$

The parameters *b* and *c* can be determined based on the results of the performed test. The evolution of the corroded area fraction outdoors is assumed to follow the same tendency as in the CASS test but at a different time-scale. This difference in the time-scale is determined through the acceleration factor (a_f) which is defined as the ratio between the time necessary to obtain the same amount of corrosion in outdoors and under accelerating aging conditions. Then, the evolution of the corroded area in outdoor conditions can be calculated with the following expression:

$$a_f = \frac{t_{outdoor}}{t_{chamber}} \tag{3}$$

$$A_c = 1 - e^{-b\left(\frac{t_{outdoor}}{a_f}\right)^c} \tag{4}$$

If the exposure of material samples is feasible for the end user of the guideline (at least three years on site), it is recommended to determine the acceleration factor between the CASS and the site where the CSP plant will be built. If not, this work compiles the acceleration factor obtained for three types of reflectors exposed in a C2, C3 and C4 site (see Table 2) over three years of outdoor exposure and provides the user with the possibility to perform the LTP without previous outdoor exposure. As the degraded area directly decreases the reflective area of the material, the reflectance decreases in the same way. Based on the results of the project, the reflectance over the lifetime was calculated for the investigated materials. As an example, in Fig. 3 the reflectance of three materials over the lifetime is displayed for three different site classes (corrosivity classes C2, C3 and C4).

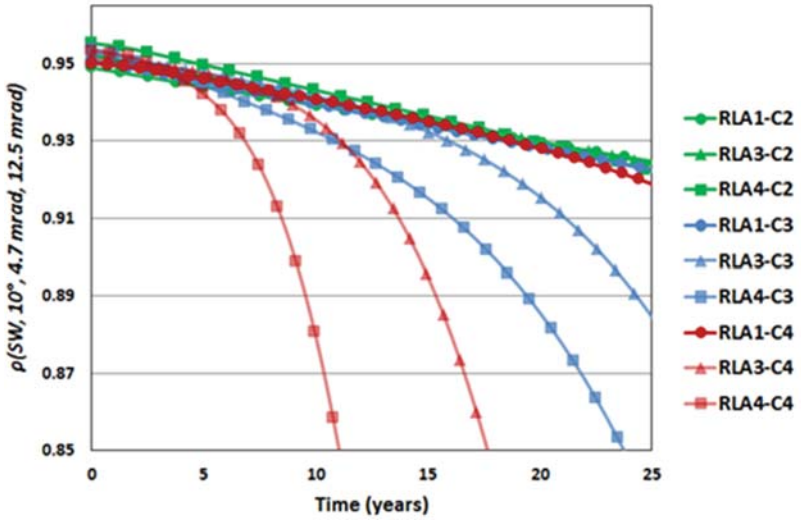

FIGURE 3. Reflectance drop over lifetime for three materials and three site classes [12].

Furthermore, an acceptance criterion based on the CASS test has been provided to determine the suitability of the reflectors in certain corrosive ambient. The end user can define an acceptable reflectance loss over a defined lifetime. Based on that, the material shall be accepted if the measured corroded area A_c is below the admissible corroded area $A_{c,ad}$ listed in Table 2 ($A_c < A_{c,ad}$). As a guidance case, the parameters $\Delta\rho_c$ =0.01 and $t_{outdoor}$=20 years are suggested.

The formula to compute the admissible corroded areas $A_{c,ad}$ in CASS for custom $\Delta\rho_c$ and $t_{outdoor}$ as well as CASS-testing time $t_{chamber}$ is also included in the table.

TABLE 2. Admissible corrosion (degraded area fraction) in CASS depending on selected admissible reflectance loss, lifetime and site corrosivity. Equation to calculate admissible loss for custom parameters.

		Corrosivity class (according to ISO 9223) in which reflector shall be employed		
CASE	$t_{chamber}$ [h]	C2	C3	C4
Guidance $\Delta\rho_c$=0.01 $t_{outdoor}$= 20 yrs	480 (4 cycles)	0.014		
	720 (6 cycles)	0.071	0.005	
	1080 (9 cycles)	0.310	0.023	0.001
Custom $\Delta\rho_c$ and $t_{outdoor}$	t	$< 1 - exp\left[\ln(1-\Delta\rho_c)\cdot\left(\frac{a_f \cdot t_{chamber}}{t_{outdoor}}\right)^4\right]$		
		a_f		
		400	200	100

Erosion Method

As devices for erosion testing are not as standardized as for example climate chambers for corrosion testing, the guideline gives a series of recommendations and minimum requirements these sand blasting devices have to fulfill. Analog to the corrosivity classes, a classification system is introduced to divide sites into classes of different erosivity and the way to determine these classes by the exposure of material samples. In the guideline, a method is proposed to estimate the classes based on several environmental parameters without the exposure of samples. Parameters for testing are proposed to simulate one year of exposure depending on the erosivity class. For the extrapolation to longer exposure durations, the employed sand mass is simply increased linearly. In the corresponding table, the parameters are given in the same format as for the corrosion LTP: the user choses an admissible reflectance loss after a certain lifetime, and the parameters to test for the erosivity classes E1 (mild) and E2 (intermediate) are presented (see Table 3). In the original guideline, testing parameters for the the class E3 (extreme) site are given as well. In the current version this class is omitted since the corresponding site conditions are very harsh and need to be addressed separately.

TABLE 3. Test parameters for erosion testing depending on admissible reflectance loss, lifetime and site conditions.

	Environment in which reflector shall be employed	
CASE	E1	E2
Guidance t_t= 20 yrs	m_d= 0.12 g/cm² m_s= 0 g/cm² $\Delta\rho_{\lambda,\varphi} < 0.025$	m_d= 0.32 g/cm² m_s= 1.46 g/cm² $\Delta\rho_{\lambda,\varphi} < 0.125$
Custom	$m_d = 0.006\ \frac{g}{cm^2 \cdot yrs} \cdot t_t$ m_s= 0 g/cm² $\Delta\rho_{\lambda,\varphi} < \Delta\rho_e$	$m_d = 0.016\ \frac{g}{cm^2 \cdot yrs} \cdot t_t$ $m_s = 0.073\ \frac{g}{cm^2 \cdot yrs} \cdot t_t$ $\Delta\rho_{\lambda,\varphi} < \Delta\rho_e$

CONCLUSION AND OUTLOOK

The herein presented guideline is a useful toolbox for the testing of silvered-glass reflectors for CSP applications. It enables the user of this guideline to select accelerated aging procedures and parameters for testing of materials depending on the needs and future application site of materials. Recommendations are given for quick material comparison purposes as well as more complex lifetime prediction studies. Most importantly, all parameters are based

on correlations of the laboratory tests with real outdoor data. This way the significance of the test procedures and parameters can be assured.

As the available outdoor data for the development of the guideline was limited to around three years of exposure durations, all parameters will be verified in the future with long term data from material samples that are still exposed at the moment. This will increase the confidence in the parameters and possible adaptation for further site classes will be possible.

At the moment, the guideline is being used as the basis for the development of an international standard within the IEC framework, which will further increase the impact of the developed procedures.

ACKNOWLEDGMENTS

This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 686008 (Raiselife). The authors want to thank Tomás Reche Navarro from DLR and Lucía Martinez Arcos from CIEMAT for their valuable contributions to the realization of the accelerated aging and exposure campaign and measurements.

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