Solar Energy 174 (2018) 149–163

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

Lifetime prediction of aluminum solar mirrors by correlating accelerated aging and outdoor exposure experiments

Florian Sutter[a,*], Johannes Wette[a], Florian Wiesinger[a], Aránzazu Fernández-García[b], Stefan Ziegler[c], Reinhard Dasbach[d]

[a] DLR German Aerospace Center, Institute of Solar Research, Plataforma Solar de Almería, Ctra. Senés Km. 4, P.O. Box 44, 04200 Tabernas, Almería, Spain
[b] CIEMAT, Plataforma Solar de Almería, Ctra. Senés Km. 4, P.O. Box 44, 04200 Tabernas, Almería, Spain
[c] Alanod GmbH & Co. KG, Egerstr. 12, 58256 Ennepetal, Germany
[d] Almeco GmbH, Claude Breda Straße 3, 06406 Bernburg, Germany

ARTICLE INFO

Keywords:
Concentrating solar thermal technology
Aluminum solar reflector
Degradation
Corrosion
Accelerated aging
Lifetime prediction

ABSTRACT

The reflectors used for Concentrated Solar Thermal (CST) technologies are expected to withstand harsh environmental conditions during their lifetime of more than 20 years without a significant specular reflectance loss. Accelerated aging testing is currently used by mirror manufacturers as a tool for quality assurance of their running production. So far, it was not possible to predict the lifetime under distinct environmental conditions based on accelerated aging. This paper presents a methodology to correlate accelerated aging testing with three reference exposure sites. The accelerated aging methodology consists of a multiple test sequence, in which the samples subsequently undergo three types of corrosion and one mechanical erosion test. This procedure has been already published as a SolarPACES guideline. The purpose of this paper is to present the underlying correlations that led to the selection of the testing parameters, which permit to derive service lifetime estimations of aluminum reflectors. In addition, this paper presents an updated mechanical erosion test to improve correlation to outdoors. Finally, the resulting reflectance losses caused by the accelerated aging testing sequence have been validated by comparing to outdoor exposure data after up to 36 months of exposure. According to the results obtained, the average errors of the accelerated aging tests with respect to real outdoor values are of around 2 ppt for the monochromatic specular and 1 ppt for the solar hemispherical reflectance losses to simulate 3 years of exposure in "desert" and "coastal" sites.

1. Introduction

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 (García-Segura et al., 2016). It is used for several purposes:

- Comparative testing: to compare different materials and to 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 a running production and to detect eventual issues in the coating lines.
- Material development: to achieve rapid responses regarding the durability of materials whose actual lifespan data is not available. Accelerated aging might be employed as an evaluation tool when the chemistry of coatings or manufacturing parameters is to be optimized.
- Lifetime prediction: to estimate the in-service lifetime under different environmental conditions.

This latter point is the most important and challenging one (Avenel et al., 2018), mainly due to the fact that the aggravated conditions used in accelerated aging tend to excite degradation mechanisms that are not realistic. At the current state of the art, the testing guideline developed in Sutter et al. (2016) the only method capable to estimate the performance loss of solar reflectors in-service. Special care was taken to reproduce the observed degradation from different outdoor exposure sites (as explained in Section 2.1) but the methodology is only applicable for aluminum reflectors. Lifetime prediction methods based on accelerated aging need to be specifically developed for the material

---

[*] Corresponding author.
E-mail addresses: Florian.Sutter@dlr.de (F. Sutter), Johannes.Wette@dlr.de (J. Wette), florian.wiesinger@dlr.de (F. Wiesinger), afernandez@psa.es (A. Fernández-García), Stefan.Ziegler@alanod.de (S. Ziegler), Reinhard.Dasbach@almecogroup.com (R. Dasbach).

https://doi.org/10.1016/j.solener.2018.09.006
Received 19 June 2018; Received in revised form 2 August 2018; Accepted 4 September 2018

Nomenclature

Acetube	accelerated erosion tube
CASS	copper accelerated salt spray
CPC	compound parabolic concentrator
CST	concentrated solar thermal
EDSD	erosion defect size distribution
GHI	global horizontal irradiance
PSA	Plataforma Solar de Almería
PTC	parabolic-trough collector
ppt	percentage-points
PVD	physical vapor deposition
a	acceleration factor [–]
k	formation velocity of newly emerging pits [pits/s]
$r.H.$	relative humidity (%)
T	ambient temperature (°C)
t	time [s]
v	wind velocity (m/s)
δ	density of the number of pits [pits/cm^2]
$\Delta\rho_{s,h}$	solar weighted hemispherical reflectance drop [%]
$\Delta\rho_{\lambda,\varphi}$	monochromatic specular reflectance drop [%]
θ_i	incidence angle [°]
λ	wavelength [nm]
$\rho_{s,h}([\lambda_1, \lambda_2], \theta_i, h)$	hemispherical reflectance at incidence angle θ_i, weighted with the ASTM G173 reference spectrum in the wavelength range λ_1 to λ_2 [%]
$\rho_{\lambda,h}(\lambda, \theta_i, h)$	spectral hemispherical reflectance at incidence angle θ_i
$\rho_{\lambda,\varphi}(\lambda, \theta_i, \varphi)$	specular reflectance at wavelength λ, incidence angle θ_i and acceptance angle φ [%]
φ	acceptance angle [mrad]

which is to be considered. It is not possible to apply the prediction procedure described in Sutter et al. (2016) to other material classes since the underlying degradation mechanisms may be completely different. For the commonly used silvered-glass mirrors in CST plants there are no useful lifetime prediction methods available.

Aluminum reflectors currently represent a promising solution to manufacture many different concentrating solar thermal collectors, such as small-size parabolic-trough collectors (PTC) (Fernández-García et al., 2015; Forman et al., 2015; Qiu et al., 2017), especially in highly corrosive acid atmospheres (García-Segura et al., 2018), compound parabolic concentrators (CPC) (Malato Rodríguez et al., 2004; Navntoft et al., 2008), solar cookers/driers (Mullick et al., 1991; Narasimha and Subramanyam, 2003; Harmim et al., 2013), end-reflectors in PTC for power generation (Fend et al., 2000), secondary concentrators in solar towers (Fernández-García et al., 2014), or even to construct cost-effective static concentrators, both for photovoltaic and solar thermal systems (Nostell et al., 1998; Hussein et al., 2000; Brogren et al., 2004a, 2004b; Nilsson et al., 2007). These collectors have in common a small-sized concentrator, made of considerably high curvatures that cannot be shaped by silvered-glass reflectors or are out of the standard size established in PTC for power generation. In these cases, aluminum reflectors are a suitable option because this material can be easily shaped to any possible curvature (Almanza et al., 1992; Sutter et al., 2012), but they have faced some difficulties regarding long-term durability (Mishra et al., 2016). Several applications have been identified for this kind of technology, such as industrial process heat, solar cooking, solar drying, domestic hot water, space heating, pumping irrigation water, desalination and water treatment.

This paper presents the methodology and the underlying data that led to the development of an accelerated aging testing protocol for aluminum reflectors. The method is able to simulate degradation processes of outdoor conditions of several representative sites. To accomplish this propose, an extensive research study was performed, consisting in analyzing the durability of nine differently coated aluminum mirror materials under real outdoor conditions through exposure at nine sites and at the same time in performing an intense accelerated aging test campaign.

2. Material and methods

This section describes the methodology followed to derive the testing guideline, by performing and analyzing both accelerated and outdoor experiments.

2.1. Methodology

The methodology followed throughout the paper to derive the accelerated aging testing procedure is illustrated in Fig. 1. An outdoor exposure campaign was conducted for up to three years under different environmental conditions. The samples were analyzed every six months employing the techniques described in Section 2.5. Four independent *natural* mechanisms were detected (see Section 3.1): pitting corrosion, top coating erosion, PVD layer corrosion and micropitting in the PVD layer.

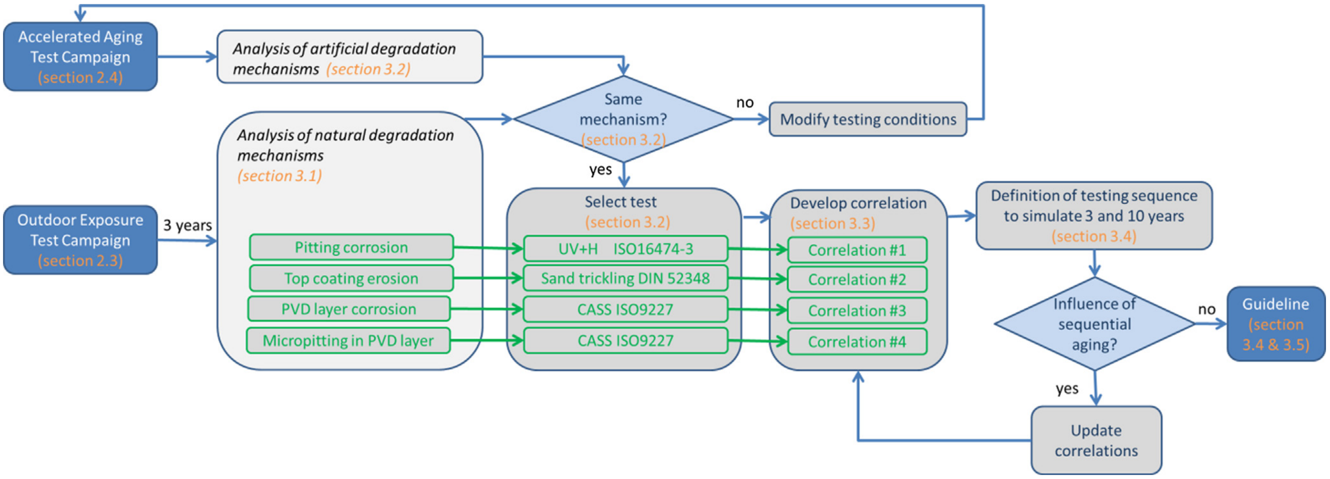

Fig. 1. Outline followed throughout this paper to derive an accelerated testing procedure for service lifetime estimations of aluminum reflectors. References to the different subchapters of the paper are highlighted in orange color. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)