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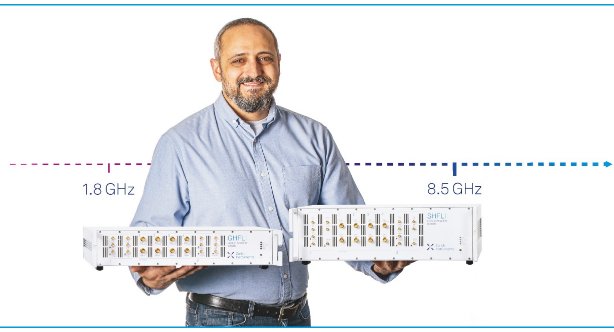

UV Degradation of Primary Mirrors in Outdoor Exposure and Accelerated Aging

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Abstract. Concentrating solar thermal (CST) energy plays a fundamental role in the energetic transition which is facing our society. The energy generation of these systems hugely depends on the optical behavior of the reflectors. CST plants are installed in zones where the solar irradiance is very high. As it is well known, UV radiation is a main degradation mechanism for some materials. The possible weathering of the solar reflectors provoked by this environmental agent could be fundamental to decide the feasibility of a CST plant in a certain location. In this work, the degradation provoked by UV radiation in a series of different silvered-glass solar reflectors was deeply studied. For that purpose, seven reflector types were exposed for three years in countries of high interest for CST plants such as Chile, Spain and Morocco. An UV aging test based on fluorescent lamps was carried out to reproduce the degradation mechanism observed outdoor. Finally, the acceleration factors between the outdoor sites and the UV test were obtained.

INTRODUCTION

Concentrated solar thermal (CST) technologies utilize reflectors to concentrate the solar radiation of a large area onto a receiver with a much smaller size. CST systems are located in sites with high solar irradiance where the amount of UV radiation is extreme. Degradation originated for this environmental agent could be remarkable in some places and it might originate undesired over cost in replacements and maintenance of the components. The service life-time of a CST plant must be at least 25 years. Then, materials whose replacement involves a high cost must resist for the whole duration of the system.

Solar reflector purchase represents an important share of the initial investment of the plant and its substitution is not contemplated [1]. An excessive weathering of this compound significantly affects to the entire energy conversion process of the CST plant [2]. Hence, solar reflectors must preserve their optical properties for the whole lifetime of the CST system. Commonly, silvered-glass reflectors are used instead of aluminum ones since its optical behavior and durability are exceptional. However, silvered-glass reflectors absorb more UV radiation than the aluminum ones. The absorption mainly occurs in the glass of the mirror and it might affect to its optical performance [3].

The analysis of the reflector degradation provoked by environmental agents can be performed by the exposure of several samples for a long time in the place where the solar plant will be build. Nevertheless, long exposure times are required and outdoor exposure for more than 5 years is not viable. Then, accelerated aging tests are needed to reproduce, in a short time, the possible degradation mechanisms which will take place in the samples over a long period of time under operation conditions. A Spanish standard for solar reflectors compiled the most representatives accelerated aging tests [4]. This standard contains a specific UV+Humidity test which consists of 2 individual stages of 4 hours each one. Firstly, a UV phase with the intensity set to 0.83 $W/m^2/nm$, between 290 y 400 nm and a temperature of 60 ºC, and secondly, a condensation phase at 100 % of relative humidity and 50 ºC, without radiation.

The objective of this work is to quantify the degradation originated by UV radiation in silvered-glass reflectors exposed in 3 different locations with high solar irradiance and to replicate the degradation mechanisms observed in

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outdoors through accelerated aging tests. To achieve this goal, several samples of seven different reflectors were exposed in all the places over 3 years and submitted to a high UV dose through an accelerated aging test.

MATERIALS AND METHODS

In this section, a brief description of the different materials employed in this work, the methodology to expose the samples outdoors, the climatology of the locations and the procedure to test the reflectors under accelerated aging conditions are presented. Finally, the analysis method used to assess the degradation of the solar reflectors is detailed.

Reflector Materials

7 different silvered-glass reflectors of the same manufacturer were selected for this work. Silvered-glass reflectors were chosen instead of aluminum ones because most of the CST plants employ this kind of material. The mirrors are composed by a silver layer protected on the upper face by low-iron glass and on the bottom side with a copper layer and 2 or 3 protective paint layers (FIGURE 1). All the silvered-glass reflector types possess the same glass and silver composition which are the components affected by the UV radiation. The overall thickness of all the samples was 2 mm and the size was 10x10 cm^2. Samples of the same batch were employed both for the outdoor exposure and the accelerated aging campaign.

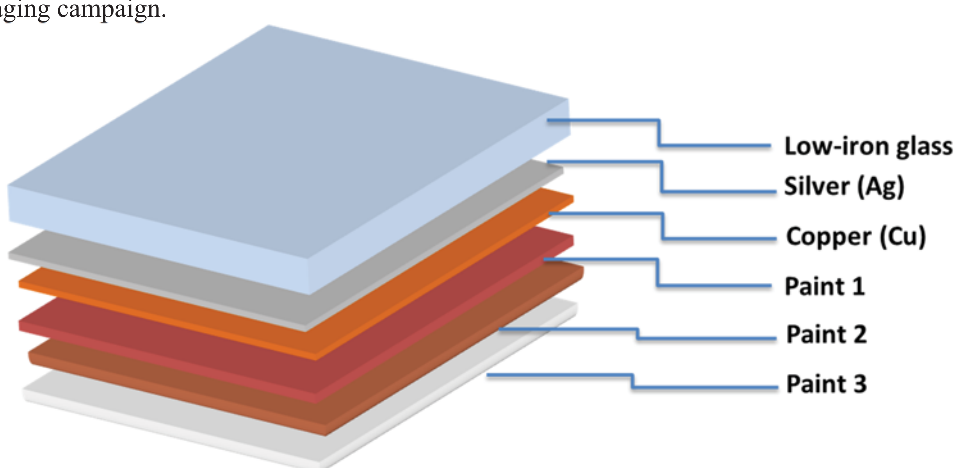

FIGURE 1. Scheme of a silvered-glass reflector

Outdoor Exposure and Accelerated Aging Campaign

5 samples of each reflector type were exposed in Chajnantor (Chile), Tabernas (Spain) and Missour (Morocco) with the purpose of identifying the main degradation mechanism observed in the reflectors when they are submitted to high UV doses. The radiation was monitored by a pyranometer Kipp Zonen cmp21 and chp1, and the temperature was controlled by a thermometer CS215L manufactured by Campbell Scientific. The samples were fixed in a metallic rack with a tilt angle of 45º (FIGURE 2). In Tabernas and Missour, the samples were exposed facing south and in Chajnantor facing north. During 3 years of outdoor exposure (first half of 2017 to 2020), the reflectors were periodically collected (once per year) and characterized in the OPAC laboratory (a joint group between CIEMAT and DLR).

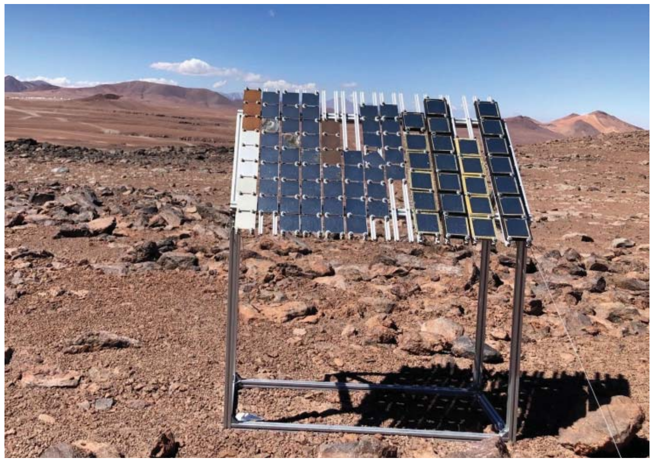

FIGURE 2. Clamping structure of the reflectors in Chajnantor (Chile)

TABLE 1 summarizes the characteristics of the locations where the reflectors were exposed. Chajnantor is located at an altitude of 5200 m and the climatology of this place is really extreme. The yearly Global Horizontal Irradiance (GHI) is 2609 kW·h/m^2, being one of the world sites with highest irradiance. However, the average temperature does not reach 0 ºC. Tabernas is situated in the south of Spain and the amount of GHI (1901 kW·h/m^2) is one of the highest of this country. Finally, Missour is one of the most interesting places of Morocco to build a CST plant due to its high GHI and the low probability of sand storms which can reduce to the durability of the solar components. The annual UV dose is calculated by multiplying the GHI accumulated over 1 year by the percentage of energy between 290-400 nm according to a standard solar spectrum (ASTM G173-03 standard [5]).

TABLE 1. Characteristics of the outdoor locations

Location	Coordinates	Altitude (m)	Yearly GHI (kW·h/m^2)	Annual UV dose (kWh/m^2)	Average temperature (ºC)
Chajnantor (Chile)	22.96°S 67.79°W	5200	2609	100	-2.7
Tabernas (Spain)	37.10°N 2.35°W	500	1901	73	18
Missour (Morocco)	32.86°N 4.11°W	900	2023	77	22

An accelerated UV test was carried out over 1000 hours to reproduce the same degradation observed outdoors and to analyze the resistance of the reflectors against the UV radiation. A chamber manufactured by Atlas with a set of fluorescent lamps that radiates in the wavelength range from 290 to 400 nm was used for this work. The intensity of the lamp was set to 0.9 W/m^2/nm at peak and the temperature was controlled at 37 ºC. The total radiation received by the reflector samples in this wavelength range [290-400 nm] was 48 W/m^2. Samples were placed in the chamber in such way that the radiation firstly impacted in the glass.

Analysis Method

Periodically, both the samples exposed outdoors and tested under accelerated aging conditions were collected and analyzed in the laboratory. Spectral hemispherical reflectance, $\rho_{\lambda,h}([\lambda_a,\lambda_b],\theta_i,h)$, at λ=[320, 2500] nm and θ_i=8º, was measured with a spectrophotometer model Lambda 1050 manufactured by Perkin Elmer (and an integrating sphere of 150 mm diameter) to observe the wavelength regions affected for the UV dose [6]. To properly appreciate the reflectance degradation in the same scale, the hemispherical reflectance drop in the whole spectrum was calculated. This value was obtained by subtracting the initial $\rho_{\lambda,h}$ value minus the value after a certain period of outdoor exposure or UV test for each wavelength, between 320 and 2500 nm. Thus, the hemispherical reflectance drop in the whole spectrum is achieved.

It was observed that UV radiation only provokes hemispherical reflectance drop between 320 and 750 nm (see RESULTS and DISCUSSION section). Then, $\rho_{\lambda,h}([320, 750]\ nm,\theta_i=8º,h)$ was weighed with the solar spectrum from ASTM G173-03 standard to calculate the solar-weighted hemispherical reflectance $\rho_{s,h}(SW,\theta_i,h)$ [5]. $\rho_{s,h}$ is the most representative reflectance value because the influence of the solar spectrum is taken into account.

RESULTS AND DISCUSSION

The results of the reflectors exposed outdoors and tested under accelerated aging conditions are addressed in this section. The reliability to reproduce the same degradation observed outdoors by means of accelerated aging test was studied. Also, it was evaluated the deterioration of the reflectors in all the outdoor sites in function of the UV dose received and the average temperature.

In FIGURE 3**,** the average spectral hemispherical reflectance drop between 320 and 2500 nm of the seven reflectors after 1 year (8760 hours) of outdoor exposure in Tabernas (blue line) and 1000 hours of UV test (red line) are presented. It is noticed that the reflectance slightly decreased between 320 and 750 nm. Also, an increment of the reflectance provoked for the solarization of the glass mirror is observed from 750 to 1500 nm [7]. Between 1500 to 2500 nm the reflectance is not substantially affected. The oscillations observed near to 2500 nm are noise coming from the spectrophotometer. Furthermore, it can be appreciated that the UV test carried out with the fluorescent lamp perfectly replicates the degradation observed in Tabernas. Then, this accelerating aging test is able to reproduce the same degradation observed in the reflectors exposed in Tabernas. The acceleration factor achieved between the UV test and the first year of outdoor exposure in Tabernas is approximately 9.

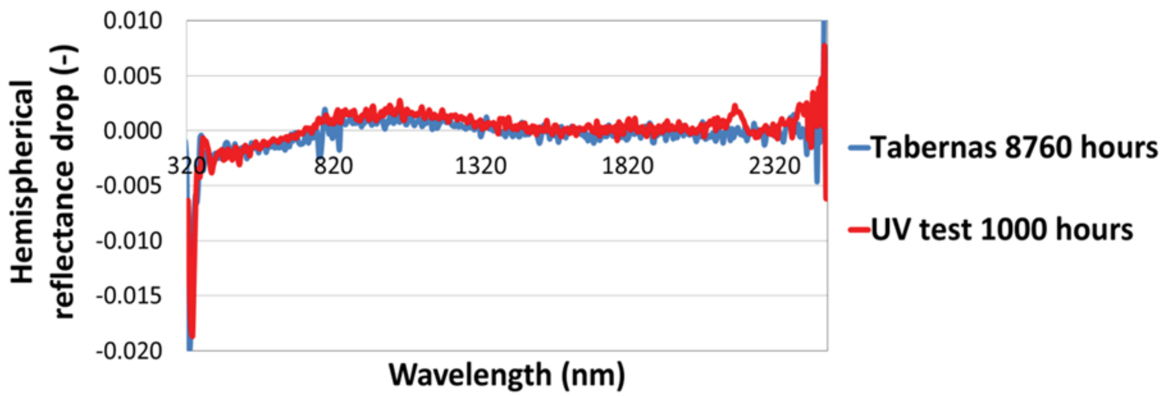

FIGURE 3. Hemispherical reflectance drop [320-2500 nm] after 8760 h of outdoor exposure in Tabernas (Spain) and 1000 h of UV test

FIGURE 4 depicts the sum of the average solar hemispherical reflectance drop between 320 and 750 nm in function of the UV dose received for the 7 types of solar reflectors tested in Chajnantor (green line), Tabernas (blue line), Missour (red line). As it is perceived, the reflectors exposed in Missour are the most damaged ones followed by Tabernas and Chajnantor. After 3 years of outdoor exposure, the solar hemispherical reflectance decreased 0.002 in Missour, 0.0014 in Tabernas and 0.0008 in Chajnantor. Up to now, this degradation mechanism does not significantly affect to the reflector durability. Furthermore, erosion degradation occasioned by sandstorms was detected at Chajnantor. This effect was not considered for this work because the hemispherical reflectance was measured, but the specular reflectance was significantly affected by this phenomenon, achieving a maximum specular reflectance drop equal to 0.007ppt.

The UV dose received in 3 years of outdoor exposure is significantly higher in the reflectors exposed in Chajnantor than in the rest of the sites, but the solar hemispherical reflectance of this site is the least affected (FIGURE 4**)**. Therefore, the reflectance is not only affected by UV radiation, but there are other parameters that jointly perform with the UV radiation. Seeing the data of the TABLE 1, it is probable that a synergism between temperature and UV radiation exists, being the temperature influence more critical than the UV dose. This would explain why the reflectors exposed in Chajnantor are the least deteriorated. Nevertheless, in-depth investigations are needed to assess the synergistic effects that could exist between temperature and UV radiation, and probably with others parameters such as the relative humidity of the ambient.

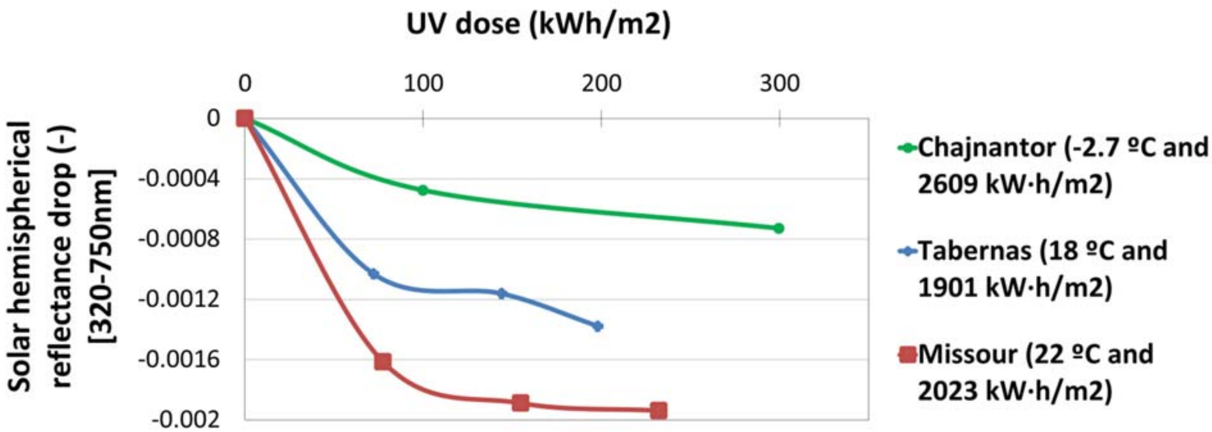

FIGURE 4. Solar hemispherical reflectance drop [320-750 nm] in function on the UV dose received for reflectors exposed in Chajnantor, Tabernas, Missour

FIGURE 5 illustrates the sum of the average solar hemispherical drop in the range [320-750 nm] depending on the exposure time in the selected sites and under accelerating aging conditions. As it is appreciated, the UV test is able to reproduce the same degradation observed outdoors in a much shorter period of time. To simulate the solar hemispherical drop occurred after 1 year (8760 hours) of outdoor exposure in Missour, it would be necessary 1600 hours of UV test, in Tabernas 1000 hours and in Chajnantor 500 hours, obtaining an acceleration factor for the first year of 5.5, 8.6 and 17.2, respectively. Then, the colder the site, the higher the acceleration factor is. These results also confirm that the influence of the temperature could be more critical than the UV radiation.

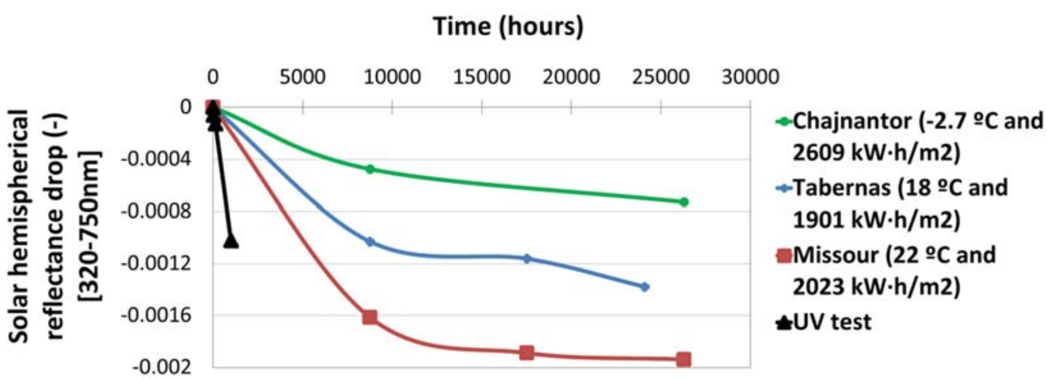

FIGURE 5. Solar hemispherical reflectance drop [320-750 nm] in function on the exposure time for reflectors located in Chajnantor, Tabernas, Missour and submitted to accelerating aging conditions in a UV test

CONCLUSIONS

This work presents the results of the study performed both in outdoor conditions (in 3 locations, during 3 years) and accelerated aging to analyze de degradation mechanism of silvered-glass reflectors due to UV radiation. According to the results obtained, the solar reflectors exposed in the Chajnantor site, which is the site with the highest UV dose, but the coldest one, are the least damaged. Conversely, the reflectors exposed in the hottest location (Missour) have shown the most significant reflectance drop during the outdoor exposure. Consequently, the results revealed that it probably exists a synergistic effect between UV radiation and temperature. In addition, the UV degradation mechanism observed outdoors was perfectly reproduced by means of an accelerating aging UV test carried out with fluorescent lamp. The acceleration factors calculated during the first year of outdoor exposure in Chajnantor, Tabernas and Missour were 17.2, 8.6 and 5.5, respectively. Also, it is remarkable that, up to now, this degradation mechanism does not significantly affect to the reflector durability.

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