Degradation of Primary Mirrors under Accelerating Aging Tests

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Abstract. Primary mirrors play an essential role in CST plants as their optical performance directly influences the overall efficiency of the plant as well as their durability will influence the complete lifetime of CST plants. Primary mirrors are exposed to a combination of environmental agents that provoke their degradation. The aim of this work is to study the degradation caused by UV radiation an. For this purpose, two commercial silvered-glass reflectors from two manufactures with different glass thickness have been subjected to accelerated aging tests. An additional 4-mm silvered-glass reflector with an abrasion resistant hard coating on non-solar glass was also tested. The measured degradation provoked by UV radiation showed to be temperature dependent causing enhanced degradation when both stresses acted simultaneously, just as the presence of an abrasion-resistant coating such as the one used in this work has shown to affect the behavior of reflectors.

INTRODUCTION

Primary mirrors are used in all concentrating solar thermal (CST) technology branches, i.e. dish, tower, trough and Fresnel systems, constituting an important part of the initial investment that cannot be replaced easily. The degradation of materials in CSP plants is one of the most important aspects to be taken into account for the feasibility of the CST technology [1] as this degradation can contribute to a decrease in the service lifetime of the plant. Thus, it is very important to study the degradation mechanisms of primary mirrors as they are the first component that solar radiation encounters in its pathway, which means that any solar radiation not reflected towards the receiver directly translates into efficiency losses [2]. The main environmental agents responsible of the degradation of primary mirrors include windborne particles, chemical agents, humidity, temperature and solar radiation. Changes produced by solar radiation on the optical properties of a glass are known as solarization, see [3] and [4].Among these environmental agents, UV radiation has been identified as an important stress factor contributing to the weathering of solar reflectors [5]. However, this degradation mechanism is not well characterized, not least because its temperature dependence has not been studied [5]. For this reason, this work focuses on the study of the dependence of the degradation by UV radiation on temperature.

METHOD

Interaction of UV radiation and temperature on samples of three commercial silvered-glass reflectors from two manufactures with different glass thickness, see Fig. 1, was studied by applying the accelerated ageing tests summarized in Table 1 for a total of 3000 h of testing. On the one hand, the three reflector materials were tested by applying UV radiation at a temperature slightly above room temperature, i.e. 37°C, and on the other hand, by increasing the test temperature to 60°C. Here the objective was to test whether the degradation caused by radiation is influenced by temperature. We also tested these same materials at the highest selected temperature without UV radiation, to see the effect of the temperature itself.

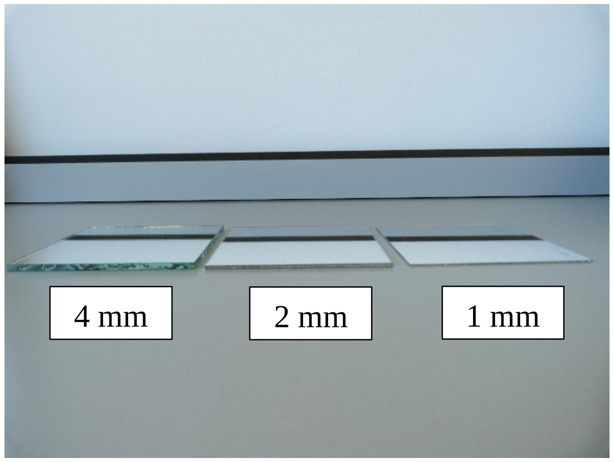


FIGURE 1. Reflector materials tested.

TABLE 1. Summary of accelerated ageing tests carried out in this study.

Test code	Tested materials	Radiation	Temperature (°C)	Weathering chamber
UV-37	4-,2-,1-mm silvered-glass reflectors	Fluorescent UVA-340 lamp, 0.9 W·m^{-2}·nm^{-1} at 340 nm, 290-400 nm	37	ATLAS UVTest
UV-60			60	
60		N/A	60	ATLAS SC 340 MH, VÖTSCH

The parameter used in this work to evaluate the dependence of the degradation by UV radiation on temperature has been spectral hemispherical reflectance, $\rho_{\lambda,h}\,(\lambda, \theta_i, h)$, at λ = [320, 2500] nm and θ_i = 8º. It was measured each 500 h with a spectrophotometer model Lambda 1050 manufactured by Perkin Elmer, with an integrating sphere of 150 mm diameter. The spectral hemispherical reflectance was measured at three different points on each sample and the mean value was used for Equations 1 and 2.

FIGURE 2. Perkin Elmer Lambda 1050 spectrophotometer.

To properly appreciate the reflectance degradation in the same scale, the hemispherical reflectance drop $\Delta\rho_{\lambda,h}$ was calculated by subtracting the initial value $\rho_{\lambda,h}(i)$ from the value after subjecting the sample to a certain test time $\rho_{\lambda,h}(f)$ for each wavelength, according to Equation 1.

$$\Delta\rho_{\lambda,h}\ ([\lambda_a,\lambda_b],\theta_i,h) = \frac{\sum_{j=1}^{n}\left(\rho_{\lambda,h,j}(f)-\rho_{\lambda,h,j}(i)\right)}{n} \qquad 1$$

where n is the number of samples of each reflector material tested ($n = 3$).

The solar-weighted hemispherical reflectance, $\rho_{s,h}\ ([\lambda_a,\lambda_b],\theta_i,h)$ was also calculated by weighting the hemispherical reflectance spectrum, $\rho_{\lambda,h}$, with the solar direct irradiance, G_b, on the earth surface for each wavelength, according to Equation 2 [7].

$$\rho_{s,h}\ ([\lambda_a,\lambda_b],\theta_i,h) = \frac{\int_{\lambda_a}^{\lambda_b}\rho_{\lambda,h}(\lambda,\theta_i,h)\cdot G_b(\lambda)\cdot d\lambda}{\int_{\lambda_a}^{\lambda_b}G_b(\lambda)\cdot d\lambda} \qquad 2$$

where $\rho_{\lambda,h}$ is the spectral hemispherical reflectance [2], measured with a spectrophotometer. For European and North American latitudes, typical solar direct irradiance spectra are given by the current standard ASTM G173-03 (air mass AM 1.5) [8].

Then, the solar-weighted hemispherical reflectance drop, $\Delta\rho_{s,h}\ ([\lambda_a,\lambda_b],\theta_i,h)$ was calculated by subtracting the initial value $\rho_{s,h}(i)$ from the value after subjecting the sample to a certain test time $\rho_{s,h}(f)$, according to Equation 3.

$$\Delta\rho_{s,h}\ ([\lambda_a,\lambda_b],\theta_i,h) = \frac{\sum_{j=1}^{n}\left(\rho_{s,h,j}(f)-\rho_{s,h,j}(i)\right)}{n} \qquad 3$$

where n is again the number of samples of each reflector material tested ($n = 3$).

RESULTS

It has been observed that samples subjected to accelerated ageing tests with UV radiation at a temperature of 60°C experience a drop in hemispherical reflectance in the wavelength range from 320 to 820 nm, with the most significant drop being around 345 nm, see Fig. 3 for the result of the 2-mm silvered-glass reflector. As can be seen in this figure, this drop in hemispherical reflectance becomes more significant as the number of hours the samples are tested increases. Also, in this Fig. 3, an increase in the hemispherical reflectance [6] is observed in the range of 820 to 1500 nm.

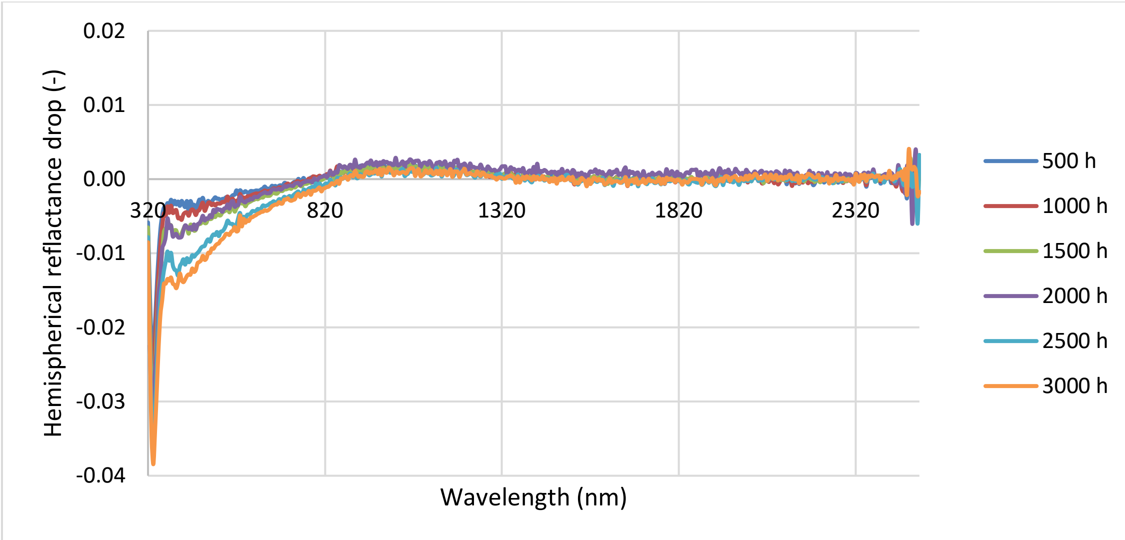


FIGURE 3. Hemispherical reflectance drop [320-2500 nm] of 2-mm silvered glass reflector samples after accelerated ageing with UV radiation at a temperature of 60°C.

In Fig. 4 the results of applying the same test, UV radiation and temperature of 60°C, to the 1mm silvered-glass reflector can be seen. In this case, again the drop in hemispherical reflectance in the 320 to 765 nm range can be observed and then, an increase in the hemispherical reflectance in the range from 770 to 1700 nm is now observed in a much more intense way. As was the case with the tests on the 2-mm silvered-glass reflector material in Fig. 3, the changes observed in the hemispherical reflectance becomes more significant as the number of hours the samples are tested increases.

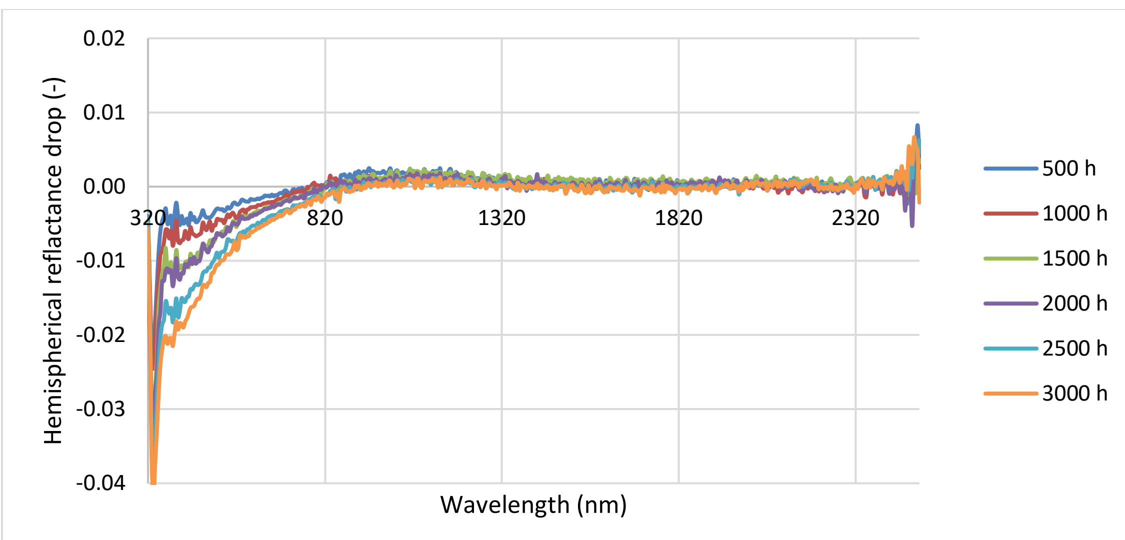


FIGURE 4. Hemispherical reflectance drop [320-2500 nm] of 1-mm silvered glass reflector samples after accelerated ageing with UV radiation at a temperature of 60°C.

Figure 5 shows the result of a commercially available 4-mm silvered-glass reflector that is coated with an abrasion resistant coating on top of the glass. In this case the performance of this reflector material is a bit different from the previous ones, due to the coating used on top of the glass. As can be seen, there is a less sharp drop in hemispherical reflectance in the range 320 to 735 nm, with the minimum values being around -0.03. Furthermore, it is observed that the behavior of the reflector is similar at 500 and 3000 h of testing, a different behavior to that observed in the two previous cases, where it could be seen that the hemispherical reflectance drop increases as the hours of testing increases. Between the wavelengths of 740 and 1815 nm, the increase in the hemispherical reflectance is now much more pronounced than in the two previous cases. This is due to the coating used, which is affected to a greater extent by the accelerated aging test combining UV radiation and temperature at 60°C, a fact that can only be verified by carrying out the same test with a bare solar mirror of this reflector material.

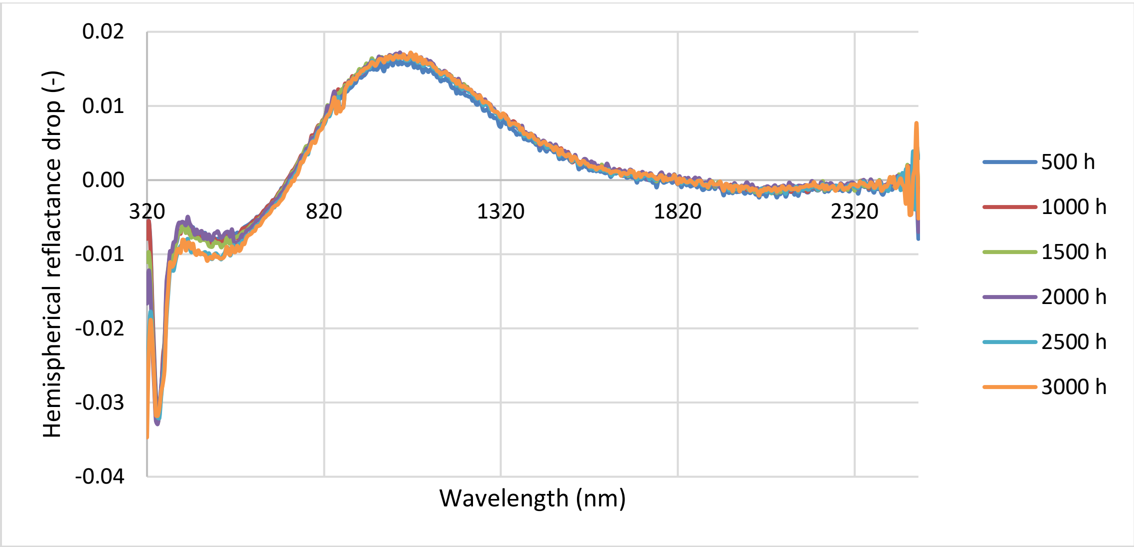


FIGURE 5. Hemispherical reflectance drop [320-2500 nm] of 4-mm silvered glass reflector samples, with abrasion resistant coating and non-solar glass, after accelerated ageing with UV radiation at a temperature of 60°C.

Once the drop in reflectance has been verified in this UV and temperature test, we have proceeded to discern which of the two factors (UV radiation or temperature) is the cause of this drop in reflectance, or whether it is the combination of both factors that produces such drop. For this, samples of the 2-mm silvered-glass reflector material have been also subjected to accelerated ageing tests at a temperature of 60°C and with UV radiation at a temperature of 37°C, see Fig. 6. This figure shows that both temperature alone and radiation alone affect the hemispherical reflectance of this material, although to a much lesser extent than the combination of both.

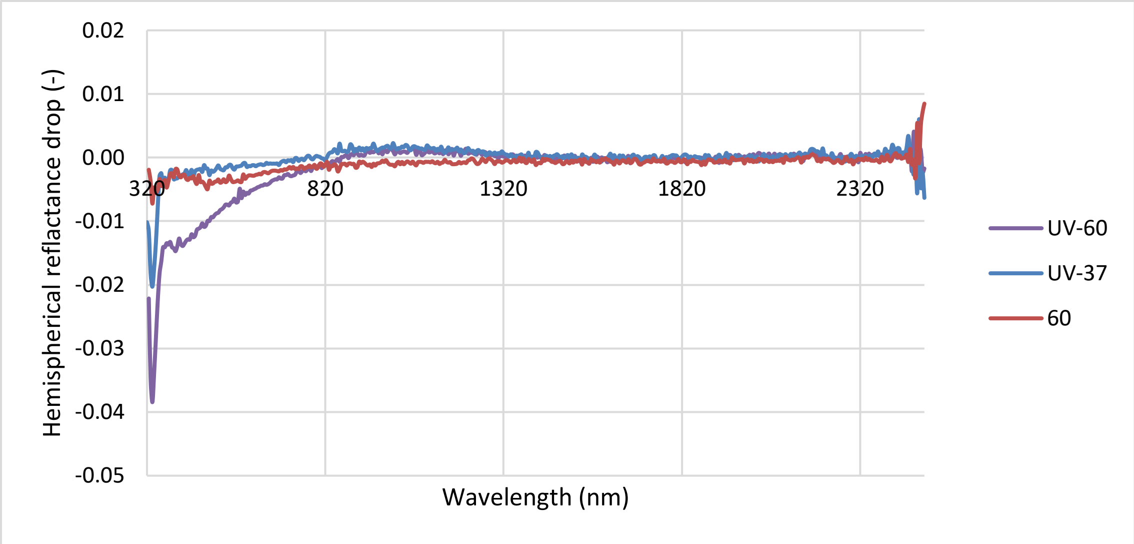


FIGURE 6. Hemispherical reflectance drop [320-2500 nm] after 2-mm silvered glass reflector samples were subjected to 3000 h of three different accelerated ageing test (see Table 1).

As can be seen in Fig. 7, samples of the 1-mm silvered-glass reflector material also subjected to the same accelerated ageing tests, i.e. temperatures of 60°C and UV radiation at a temperature of 37°C, behave in the same way.

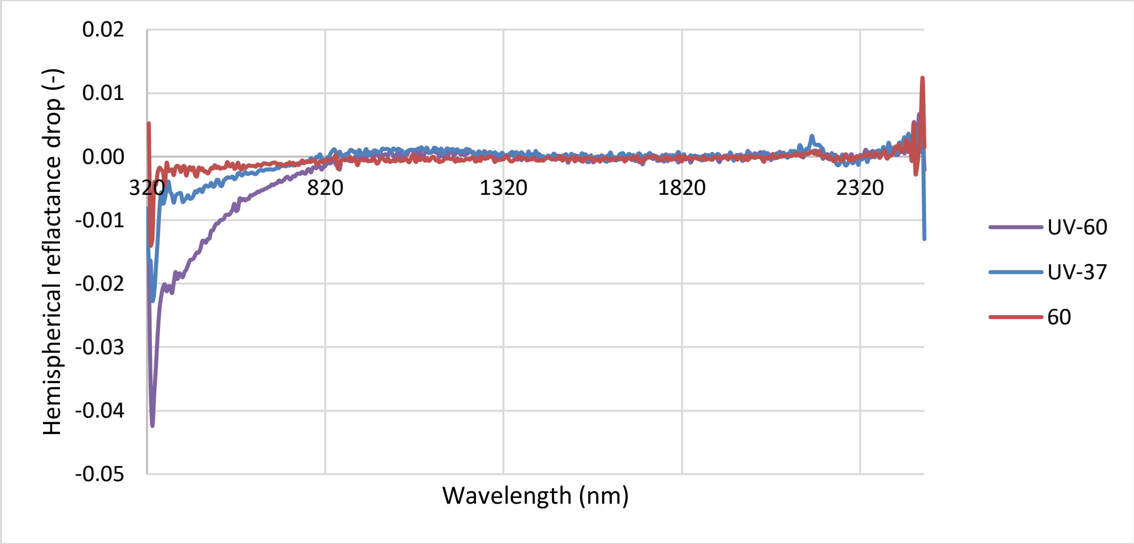


FIGURE 7. Hemispherical reflectance drop [320-2500 nm] after 1-mm silvered glass reflector samples were subjected to 3000 h of three different accelerated ageing test (see Table 1).

Figure 8 shows the behavior of the coated 4-mm silvered glass reflector in the same three tests described above. As can be seen, the behavior of this reflector material is similar in all three tests, which is probably due to the degradation of the coating rather than the degradation of the reflector mirror itself. If this is the case, it would indicate that the degradation of the coating occurs to the same extent as a consequence of applying only UV radiation (UV-37 test) or only temperature (60 test) or both (UV-60 test) on the coating. This again indicates a different behavior than the previous two uncoated reflector materials, which showed a dependence of UV degradation on temperature, something not observed in the degradation seen in this material.

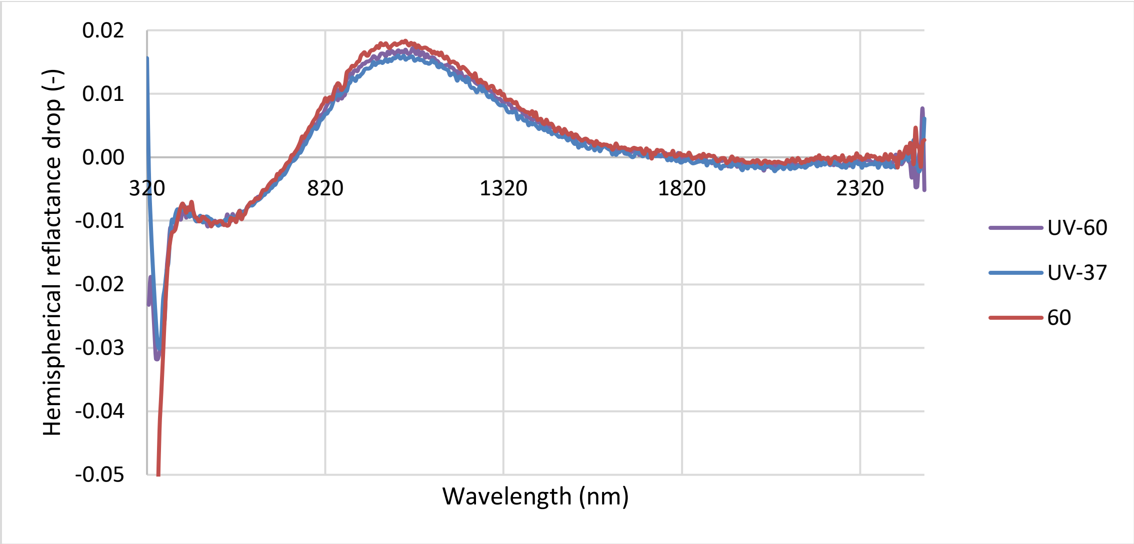


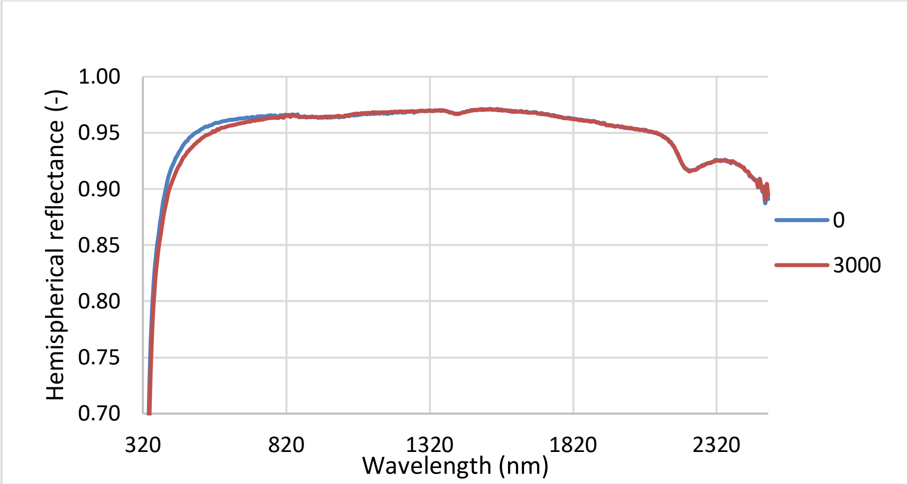
FIGURE 8. Hemispherical reflectance drop [320-2500 nm] after 4-mm silvered glass reflector samples, with abrasion resistant coating and non-solar glass, were subjected to 3000 h of three different accelerated ageing test (see Table 1).

Table 2 shows the solar-weighted hemispherical reflectance drop $\Delta\rho_{s,h}$ ([320,2500],8°,h) after 3000 h of testing for the three reflector materials subjected to the three different tests described in table 1. In the worst-case scenario, the overall efficiency of the 1-mm silvered glass reflector material is reduced by no more than 0.5%, which means that the reflector is hardly affected by this degradation.

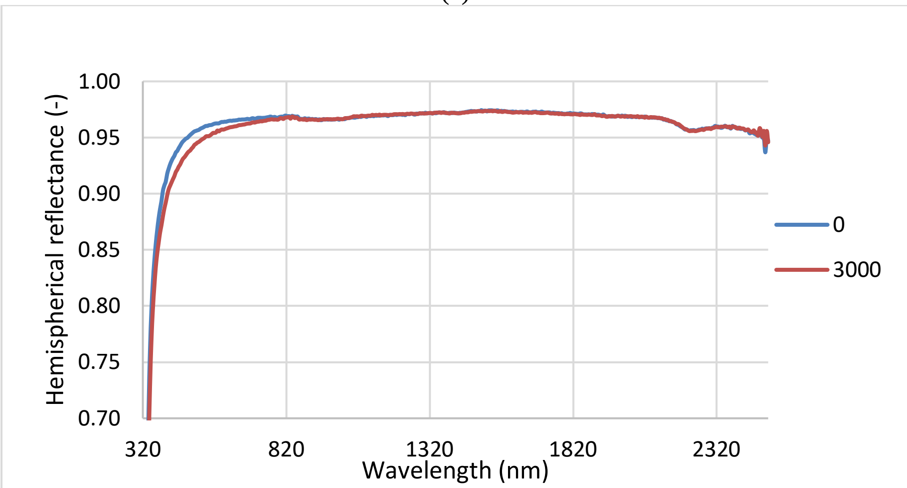
TABLE 2. Solar-weighted hemispherical reflectance drop $\Delta\rho_{s,h}$ ([320,2500],8°,h) after 3000 h of testing.

Test code	2-mm silvered glass reflector	1-mm silvered-glass reflector	4-mm silvered-glass reflector
UV-60	-0.00402	-0.00525	0.00019
UV-37	-0.00055	-0.00176	-0.00005
60	-0.00200	-0.00111	0.00001

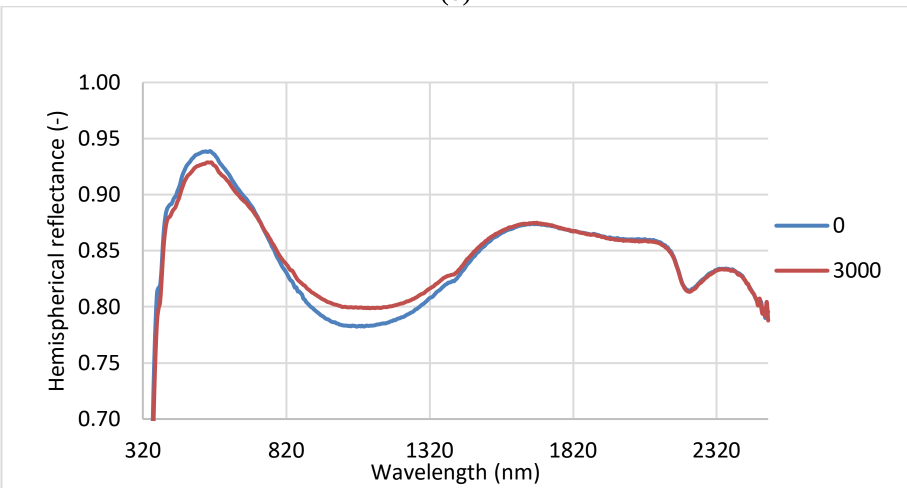
As an example, and with the aim of showing the effect of this degradation caused by the combination of UV radiation and temperature on the reflectance, Fig. 9 shows the hemispherical reflectance in the range from 320 to 2500 nm for the three reflector materials for the test combining UV radiation and temperature at 60ºC. As can be seen in Fig. 9.b where the hemispherical reflectance of the 1-mm silvered-glass reflector with the highest drop is shown, the variation in the spectral profile is minimal, also occurring at low wavelengths.



(a)



(b)



(c)

FIGURE 9. Hemispherical reflectance [320-2500 nm] before and after reflector samples were subjected to 3000 h of exposure to the accelerated ageing test with UV radiation at a temperature of 60°C. a) 2-mm silvered glass reflector samples, b) 1-mm silvered-glass reflector samples and c) 4-mm silvered glass reflector samples, with abrasion resistant coating and non-solar glass.

CONCLUSIONS

After 3000 h of accelerated aging test, it can be said that the degradation observed in the tested mirrors is mainly due to the combination of two factors, UV radiation and temperature. However small it may be, it cannot be neglected that just the presence of radiation or temperature alone can already lead to a slight degradation of the mirrors. Therefore, it would be necessary to perform an elemental analysis to see what changes are taking place in the composition of the mirror that are leading to the observed degradation. In addition, it would be useful in future studies to evaluate a third factor, i.e. humidity, to see how it influences this degradation process in combination with the other two stresses, and also to assess which layer is suffering the degradation (study of bare solar glasses).

The behavior of the coated reflector (4-mm silvered glass reflector) shows that further analysis of these materials is necessary, as the degradation observed in these materials is different from that of the other two uncoated reflector materials used in this study. In addition to the fact that the drop in solar hemispherical reflectance is smaller than in the other two materials, the solarization phenomenon is much more pronounced, with values for the $\Delta\rho_{\lambda,h}$ $([\lambda_a, \lambda_b], \theta_i, h)$ reaching 0.0184.

ACKNOWLEDGMENTS

This work is part of a project that has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 823802.

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