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Citation: AIP Conference Proceedings **2033**, 230003 (2018); doi: 10.1063/1.5067231

View online: https://doi.org/10.1063/1.5067231

View Table of Contents: http://aip.scitation.org/toc/apc/2033/1

Published by the American Institute of Physics

Accelerated Aging Test of Solar Reflectors according to the New AENOR Standard – Results of a Round Robin Test

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Abstract. Durability tests of reflector materials for concentrating solar applications are crucial to guarantee the profitability of the plants and to ensure a proper efficiency during their lifetime. A standard including a set of five accelerated aging tests is close to be published by the Spanish standardization entity AENOR, within the sub-committee AEN/CTN 206/SC117. Under the framework of the STAGE-STE project, a Round Robin Test was organized by six partners to evaluate the comparability of results obtained in their respective laboratories after performing these durability tests. According to the results, in general a good agreement among the partners was found, with negligible to slight reflectance losses. In addition, it was noticed that the reference standard used in the reflectance measurements is of high importance. The conclusions of this work will help to improve the standard in future versions.

INTRODUCTION

Durability testing of components for concentrating solar thermal technologies is a crucial aspect to guarantee the profitability of the plants and to ensure a proper efficiency during their lifetime. To save time, these tests must be performed under accelerated aging conditions that properly reproduce the real outdoor conditions in a realistic manner. A significant effort is being dedicated in the last years to the standardization of the testing protocols and evaluation methods in order to obtain reproducible and comparable results [1-4].

The goal of accelerated ageing testing is to estimate the durability of the solar reflectors under several extreme weather conditions, while simulating them in a reasonable time of a few days or weeks. In particular, the Spanish standardization entity, AENOR, created the sub-committee AEN/CTN 206/SC117 "thermoelectric solar energy systems" in 2010 to accomplish the valuable challenge of standardizing and regulating the activity related to power production with concentrating solar thermal systems. One of the standards that are close to be finished and published in 2017 is dedicated to the durability tests under accelerated aging conditions that are recommended to be performed on solar reflectors. This work presents the results of a Round Robin Test (RRT) carried out by six research institutes to check if the results obtained in their respective laboratories after performing durability tests by following this standard are comparable.

SolarPACES 2017
AIP Conf. Proc. 2033, 230003-1–230003-9; https://doi.org/10.1063/1.5067231
Published by AIP Publishing. 978-0-7354-1757-1/$30.00

METHODOLOGY

The RRT was coordinated by CIEMAT (Spain), with the participation of CEA (France), CENER (Spain), DLR (Germany), LNEG (Portugal) and TECNALIA (Spain). The test campaign corresponding to CIEMAT and DLR institutions were performed in their joint laboratory, OPAC, at the PSA. Consequently, the total number of evaluators was five. The name of the partners has been replaced by numbers to omit the origin of the results.

All the samples included in the tests were commercial 4-mm silvered-glass reflectors from the company of Flabeg FE. All the samples distributed to the partners were produced in the same manufacturing batch. Samples were not subjected to outdoor or indoor aging tests before the experiments. Samples tested by CEA, CENER and TECNALIA were 7 x 7 cm² size, while the ones by DLR/CIEMAT and LNEG were 10 x 10 cm² size. All samples contain original edge protection in one of the four edges. 3 samples were tested in each accelerated aging test and the mean values and standard deviations are presented in the results.

Optical reflectance analysis is performed according to the actual SolarPACES reflectance measurement guideline [5]. The measurement process consisted of measuring the spectral hemispherical and the monochromatic specular reflectance. The spectral hemispherical reflectance, $\rho_{\lambda,h}(\lambda,\theta_i,h)$, was evaluated in the solar wavelength range of 280-2500nm, and at a specific incidence angle, θ_i. Spectral hemispherical reflectance was obtained in 5 nm steps (except in the case of CENER, who measured every 10 nm). The data were evaluated with a reference reflectance standard (calibrated in the same specific λ). Three measurements were taken on each sample, by rotating the sample 90º each time.

Following ASTM Standard E903-82 (92) [6], the solar-weighted hemispherical reflectance, $\rho_{s,h}([\lambda_a,\lambda_b],\theta_i,h)$, can be calculated by weighting the spectral hemispherical reflectance, $\rho_{\lambda,h}(\lambda,\theta_i,h)$, with the solar direct irradiance on the earth surface, λ_i (G_b,λ_i), according to equation 1. For European and North American latitudes, typical solar irradiance spectra are given by the current standard norms ASTM G173-03 [7] (direct irradiance) for air mass AM 1.5. The λ range considered for the solar spectral irradiance is λ = [280,2500] nm. See [5] for more details.

$$\rho_{s,h}([\lambda_a,\lambda_b],\theta_i,h) = \frac{\int_{\lambda_a}^{\lambda_b} \rho_{\lambda,h}(\lambda,\theta_i,h)\cdot G_b(\lambda)d\lambda}{\int_{\lambda_a}^{\lambda_b} G_b(\lambda)d\lambda} \tag{1}$$

The monochromatic specular reflectance, $\rho_{\lambda,\varphi}(\lambda,\theta_i,\varphi)$, depends on λ, θ_i, and the (half) acceptance angle, φ, that is the angle associated to the detector aperture of the measurement instrument. Each sample was measured in five different positions. To characterize the specular quality of the mirror, the specular reflectance at a specific λ was compared with the hemispherical reflectance at the same λ, which should show approximately the same value for a mirror without surface scattering effects. Both solar hemispherical reflectance and monochromatic specular reflectance was measured before and after the tests to characterize the possible optical degradation.

The measurement equipment used by all the partners is presented in Table 1. Optical inspection of the samples was performed both visually and with a microscope to detect possible defects in the front and back side (corrosion spots or edge corrosion in the silver, bubbles in the back paint, etc.).

TABLE 1. Summary of the measurement equipment. IS: Integrating Sphere.

Partner	Instrument	Manufacturer	Model	Accessory	Reflectance
#1	Spectrophotometer	Perkin Elmer	Lambda 950	IS (Ø 15 cm)	$\rho_{s,h}([280,2500],8°,h)$
	Reflectometer	D&S	15R-USB	-	$\rho_{\lambda,\varphi}(660nm,15°,12.5mrad)$
#2	Spectrophotometer	Perkin Elmer	Lambda 1050	IS (Ø 15 cm)	$\rho_{s,h}([280,2500],8°,h)$
	Reflectometer	D&S	15R-USB	-	$\rho_{\lambda,\varphi}(660nm,15°, 12.5mrad)$
#3	Spectrophotometer	Perkin Elmer	Lambda 950	IS (Ø 15 cm)	$\rho_{s,h}([300,2500],8°,h)$
#4	Spectrophotometer	Optronics Lab	OL750	IS (Ø 15 cm)	$\rho_{s,h}([350,2500],10°,h)$
	Reflectometer	Abengoa	Condor	-	$\rho_{\lambda,\varphi}(650nm,12^o,204mrad)$
#5	Spectrophotometer	Jasco	V-670	IS (Ø 6 cm)	$\rho_{s,h}([280,2200],8°,h)$, $\rho_{\lambda,\varphi}(660nm,8°,\varphi)$

Table 2 summarizes the experiments performed, according to the draft AENOR standard [8].

TABLE 2. Main parameters of the accelerated aging tests performed.

Test	Duration	Summary of testing conditions	Institution
Neutral Salt Spray (NSS) ISO 9227 [9]	480 h	*T*= 35±2ºC, pH=[6.5,7.2] at 25ºC Sprayed NaCl solution of 50 ± 5 g/l with condensation rate 1.5 ± 0.5 ml/h on 80 cm²	#1, #2, #3, #4, #5
Copper-accelerated acetic acid salt spray (CASS) ISO 9227 [9]	120 h	*T*=50±2°C, pH=[3.1,3.3] at 25°C Sprayed NaCl solution of 50 ± 5 g/l and 0.26 ± 0.02 g/l $CuCl_2$ Condensation rate 1.5 ± 0.5 ml/h on 80 cm²	#2, #3
Condensation ISO 6270-2 [10]	480 h	*T*=40±3°C; *RH*: 100%	#1, #2, #3, #5
Combined thermal cycling and humidity	10 cycles (240 h)	4 h at *T*=85°C, 4 h at *T*=-40°C, Method A: 16 h at *T*= 40°C and 97±3% RH Method B1: 16 h at *T*=85°C and *RH*=85±3% Method B2: 40 h at *T*=65°C and *RH*=85±3%	#1, #2, #4, #5
UV + humidity ISO 16474-3 [11]	2000 h	1 cycle: 4h at UV exposure at 60±3°C followed by 4h at 100% RH at 50±3°C	#2, #3, #4, #5

RESULTS

The initial characterization of the samples was used to check the uniformity of the batch, and to compare the different commercial reflectance equipment used. As can be seen in Fig. 1 left, which shows the average hemispherical reflectance of the samples before the tests for the 5 evaluators, some differences among the evaluators were detected, particularly by #5, being 1.0 ppt the maximum difference of the solar-weighted hemispherical reflectance value among them and ±0.4 ppt the standard deviation. After a second step of measurements with a new reference standard, a good agreement was found (Fig. 1 right). The difference observed with evaluator #4 was also corrected after repeating the measurement with a new reference standard. As this correction was done after finishing the durability test, it was not included in Fig. 1. This means that the reference standard was the source of the previous differences.

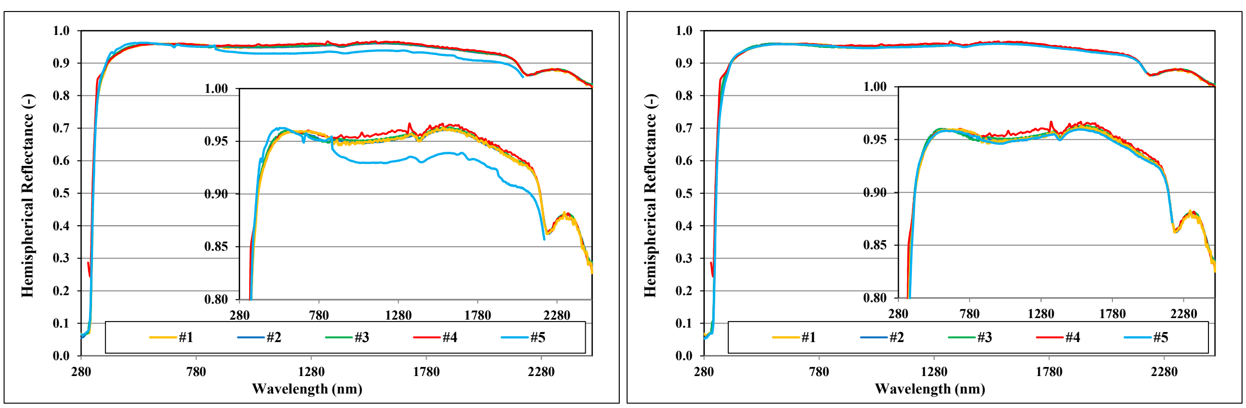

FIGURE 1. Average hemispherical spectra of the samples before testing for the five evaluators. First campaign (left), second campaign with a new reference standard used by #5 (right)

Neutral Salt Spray Test (NSS)

Table 3 and Fig. 2 show a summary of the reflectance differences after the NSS test for all the evaluators. As can be seen, similar results were presented by all of them. No significant spectral hemispherical reflectance loss was detected. The slight reflectance loss and increase can be considered negligible because they are in the range of the equipment uncertainty. Regarding the monochromatic specular reflectance, slight and medium reflectance losses were detected in the samples tested by the different partners, with an average of $\Delta\rho_{\lambda,\varphi}(660nm,15°,12.5mrad)$= -0.002 ± 0.001 by #1, $\Delta\rho_{\lambda,\varphi}(660nm,15°,12.5mrad)$= -0.006 ± 0.001 by #2 and $\Delta\rho_{\lambda,\varphi}(660nm,8°,\varphi)$= -0.004 ± 0.002 by #5. There is no clear explanation about the decrease detected by #2. However, no monochromatic specular reflectance loss was detected by #4. Regarding the visual inspection, as can be observed in Fig. 3, degradation at the non-protected edges of the samples was noticed by most of the evaluators. In the protected edges, none of the evaluators detected degradation. In addition, bubbles in the back paint layer of the samples were observed by #4 and corrosion spots in the silver layer were detected by #5 (see Table 3).

TABLE 3. Summary of the reflectance differences after the NSS test, [a]: per 245 cm^2.

Partner number	$\Delta\rho_{s,h}([\lambda_a,\lambda_b],\theta_i,h)$	$\Delta\rho_{\lambda,h}(\lambda,\theta_i,h)$	$\Delta\rho_{\lambda,\varphi}(\lambda,\theta_i,\varphi)$	Maximum non-protected edge corrosion (cm)	Number corrosion spots >200µm in the silver	Number bubbles in the paint
#1-NSS	+0.001 ± 0.002	+0.001 ± 0.004	-0.002 ± 0.001	0.01	-	-
#2-NSS	-0.002 ± 0.001	-0.002 ± 0.000	-0.006 ± 0.001	0.45	-	-
#3-NSS	0.000 ± 0.000	+0.001 ± 0.001		0.75	-	-
#4-NSS	-0.002 ± 0.001	-0.002 ± 0.001	-0.001 ±0.001	-	-	20[a]
#5-NSS	0.000 ± 0.001	+0.001 ± 0.001	-0.004 ± 0.002	0.60	2[a]	-
Av ± Std	**-0.001 ± 0.001**	**0.000 ± 0.002**	**-0.003 ± 0.002**	**0.36 ± 0.34**	**0 ± 1**	**4 ± 9**

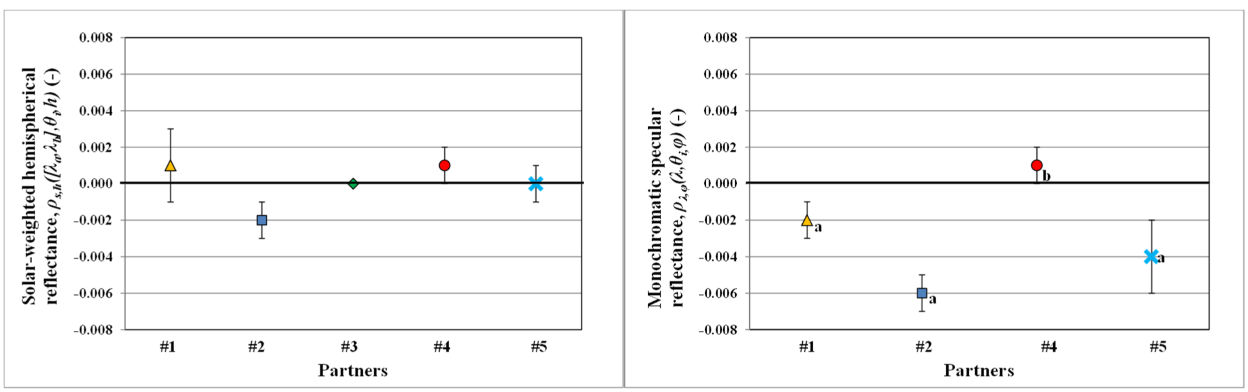

FIGURE 2. Average of the solar-weighted hemispherical reflectance differences (left) and monochromatic specular reflectance differences (right) after the NSS test.

FIGURE 3. Degradation at the non- protected edges of samples tested by #2 (left), #3 (center) and #5 (right) after the NSS test.

Copper-Accelerated Acetic Acid Salt Spray Test (CASS)

Table 4 and Fig. 4 show a summary of the reflectance differences after the CASS test for the partners performing it. As can be observed, similar results were presented. Neither spectral hemispherical nor specular reflectance losses were detected. Concerning the visual inspection, degradation at the non-protected edges and bubbles in the back paint layer were detected. Also, as can be seen in Fig. 5, corrosion spots in the silver layer were detected by #2.

TABLE 4. Summary of the reflectance differences after the CASS test, [a]:per 300 cm^2.

Partner number	$\Delta\rho_{s,h}([\lambda_a,\lambda_b],\theta_i,h)$	$\Delta\rho_{\lambda,h}(\lambda,\theta_i,h)$	$\Delta\rho_{\lambda,\varphi}(\lambda,\theta_i,\varphi)$	Maximum non-protected edge corrosion (cm)	Number corrosion spots >200µm in the silver	Number bubbles in the paint
#2-CASS	0.000 ± 0.001	0.000 ± 0.000	-0.001 ± 0.001	0.30	4[a]	56[a]
#3-CASS	0.000 ± 0.002	+0.001 ± 0.002	-	0.77	-	continuous from edges
Av ± Std	**0.000 ± 0.000**	**+0.001 ± 0.001**	**-0.001 ± 0.001**	**0.54 ± 0.33**	**2 ± 3**	-

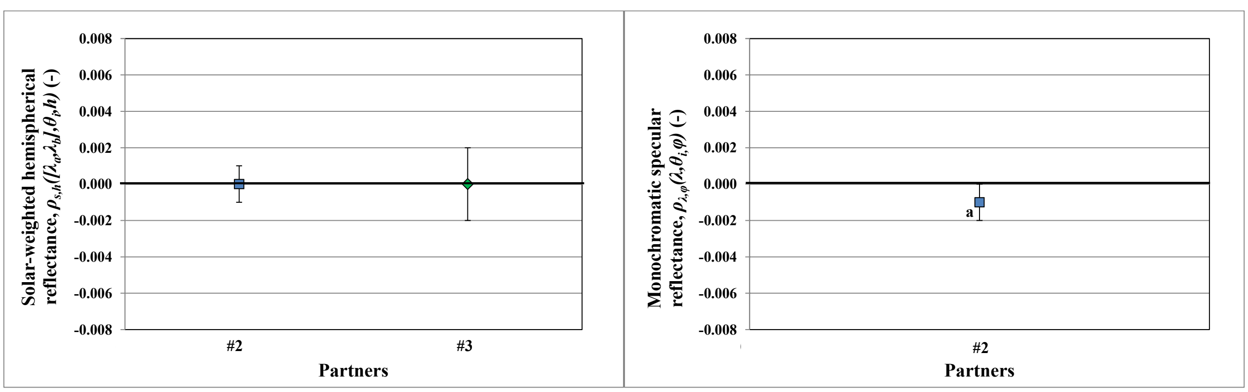

FIGURE 4. Average of the solar-weighted hemispherical reflectance differences (left) and monochromatic specular reflectance differences (right) after the CASS test.

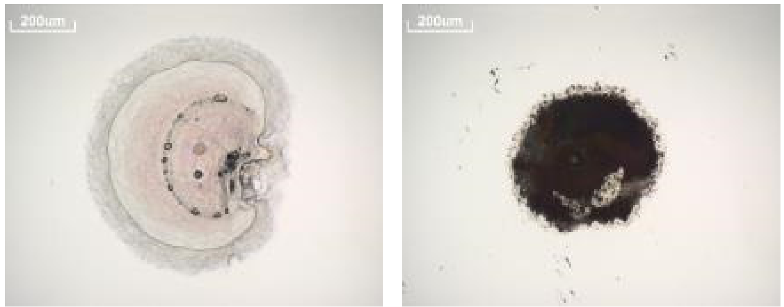

FIGURE 5. Corrosion spots in the silver layer of samples tested by #2 after the CASS test

Condensation Test

Table 5 and Fig. 6 show a summary of the reflectance differences after the condensation test for all the partners.

TABLE 5. Summary of the reflectance differences after the condensation test, [a]:per 300 cm^2, [b]:per 245 cm^2.

Partner number	$\Delta\rho_{s,h}([\lambda_a,\lambda_b],\theta_i,h)$	$\Delta\rho_{\lambda,h}(\lambda,\theta_i,h)$	$\Delta\rho_{\lambda,\varphi}(\lambda,\theta_i,\varphi)$	Maximum non-protected edge corrosion (cm)	Number corrosion spots >200µm in the silver	Number bubbles in the paint
#1-Con	-0.004 ± 0.001	-0.002 ± 0.001	0.000 ± 0.000	0.01	-	1[b]
#2-Con	0.000 ± 0.001	-0.001 ± 0.001	-0.001 ± 0.000	-	-	18[a]
#3-Con	-0.001 ± 0.001	0.000 ± 0.001	-	-	-	43[a]
#5-Con	+0.002 ± 0.001	+0.003 ± 0.002	+0.001 ±0.002	-	-	40[b]
Av ± Std	**-0.001 ± 0.003**	**0.000 ± 0.002**	**0.000 ± 0.001**	**-**	**-**	**34 ± 18**

As can be noticed, some inconsistent results were observed. A medium spectral hemispherical reflectance loss was detected by #1, which is not realistic because the samples do not present a monochromatic specular reflectance decrease. Also, a slight spectral hemispherical reflectance increase was detected by #5. These non-concordance results have to be considered negligible. Consequently, no spectral hemispherical reflectance loss was reported, as can be shown by #2 and #3. Regarding the monochromatic specular reflectance, the results of the three partners were in accordance because negligible losses were detected. In relation to the visual inspection, as can be seen in Table 5 and Fig. 7, bubbles in the back paint layer were observed by all the evaluators.

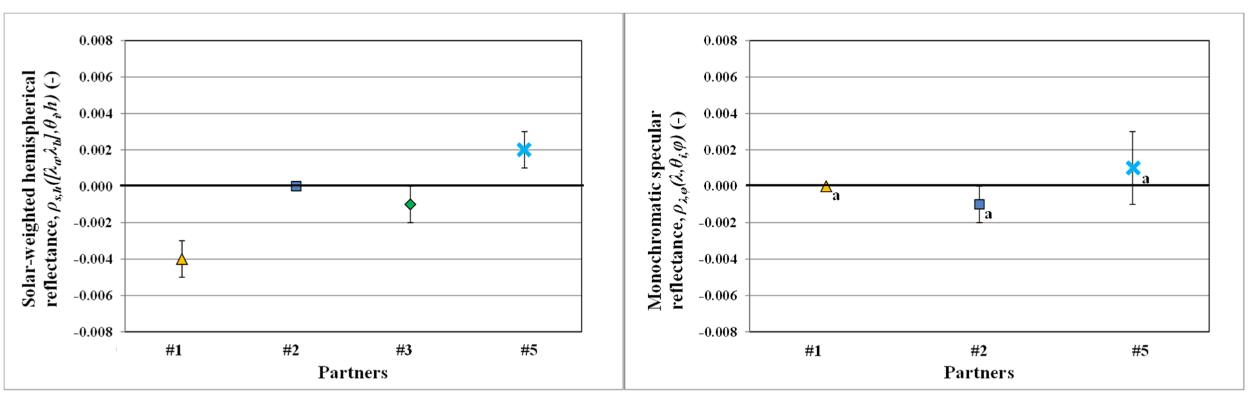

FIGURE 6. Average of the solar-weighted hemispherical reflectance differences (left) and monochromatic specular reflectance differences (right) after the condensation test.

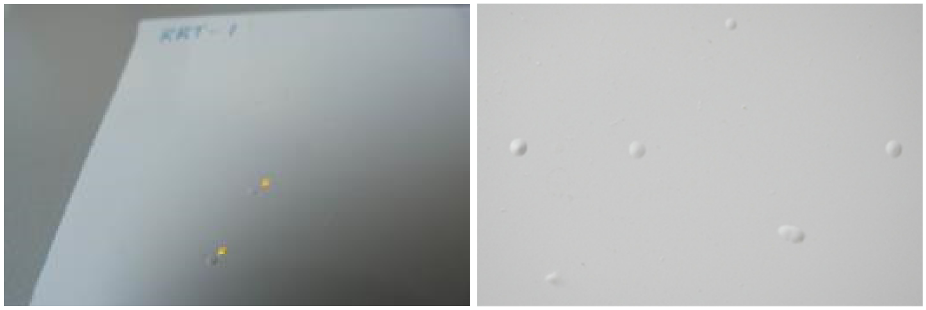

FIGURE 7. Bubbles in the back paint layer of samples tested by #2 (left) and #3 (right) after the condensation test

Cyclical Temperature and Humidity Test

Table 6 and Fig. 8 show a summary of the reflectance differences after the cyclical temperature and humidity test for all the partners.

TABLE 6. Summary of the reflectance differences after the cyclical temperature and humidity test. [a]: method A; [b]: method B 1. [c]:per 245 cm^2.

Partner number	$\Delta\rho_{s,h}([\lambda_a,\lambda_b],\theta_i,h)$	$\Delta\rho_{\lambda,h}(\lambda,\theta_i,h)$	$\Delta\rho_{\lambda,\varphi}(\lambda,\theta_i,\varphi)$	Maximum non-protected edge corrosion (cm)	Number corrosion spots >200µm in the silver	Number bubbles in the paint
#1-Cycles[a]	-0.006 ± 0.002	-0.006 ± 0.003	0.000 ± 0.000	0.05	-	-
#2-Cycles[a]	-0.001 ± 0.000	0.000 ± 0.001	0.000 ± 0.001	0.70	-	-
#4-Cycles[b]	0.000 ± 0.002	0.000 ±0.002	-0.001±0.001	0.14	5[c]	-
#5-Cycles[a]	-0.002 ± 0.001	-0.001 ± 0.001	-0.010 ± 0.003	0.80	22[c]	-
Av ± Std	**0.002 ± 0.003**	**0.002 ± 0.003**	**0.003 ± 0.005**	**0.42 ± 0.38**	**7 ± 10**	-

As can be seen, some inconsistent results were observed. A high spectral and monochromatic hemispherical reflectance loss was detected by #1. As it was explained before, it is not possible if the samples do not present a monochromatic specular reflectance decrease. These non-concordance results have to be considered negligible. Consequently, no hemispherical reflectance loss was detected after testing, as shown by #2, #4 and #5. Concerning the monochromatic specular reflectance, a very high loss was detected in the samples by #5. However, the method used by this evaluator cannot be compared with the others because hemispherical and diffused reflectance is measured to obtain the specular reflectance (with a bigger φ). Therefore, it can be considered that no monochromatic specular reflectance losses were detected, as shown by #1, #2 and #4. To conclude, the results according to both methods A and B (option 1) were similar. Regarding the visual inspection, degradation at the non-protected edges was detected by all evaluators. Also, corrosion spots in the silver layer were detected by #4 and #5.

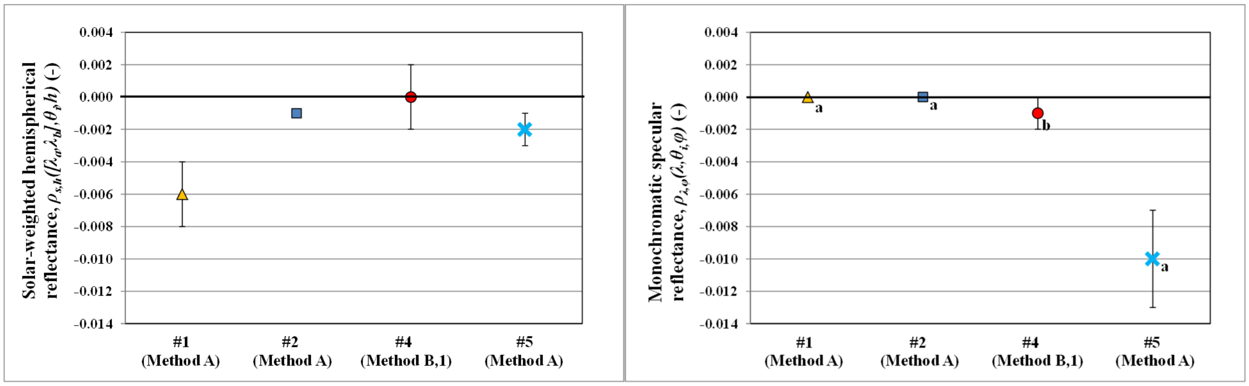

FIGURE 8. Average of the solar-weighted hemispherical reflectance differences (left) and monochromatic specular reflectance differences (right) after the cyclical temperature and humidity test.

UV Light and Humidity Test

Table 7 and Fig. 9 show a summary of the reflectance differences after the UV light and humidity test.

TABLE 7. Summary of the reflectance differences after the UV and humidity test. [a]: ISO 11507, [b]: ISO 16474-3. [c]:per 245 cm^2

Partner number	$\Delta\rho_{s,h}([\lambda_a,\lambda_b],\theta_i,h)$	$\Delta\rho_{\lambda,h}(\lambda,\theta_i,h)$	$\Delta\rho_{\lambda,\varphi}(\lambda,\theta_i,\varphi)$	Maximum non-protected edge corrosion (cm)	Number corrosion spots >200µm in the silver	Number bubbles in the paint
#2-UV+H[a]	-0.001 ± 0.000	-0.002 ± 0.001	-0.001 ± 0.001	-	-	-
#2-UV+H[b]	-0.001 ± 0.001	-0.003 ± 0.001	-0.002 ± 0.001	-	-	-
#3-UV+H[b]	-0.002 ± 0.000	-0.002±0.000		-	-	-
#4 UV+H[a]	-0.003 ± 0.004	-0.002 ± 0.001	-0.004 ± 0.001	-	-	4[c]
#5-UV+H[a]	-0.001 ± 0.003	-0.002 ± 0.003	-0.004 ± 0.003	-	-	-
Av ± Std	**-0.002 ± 0.001**	**-0.002 ± 0.000**	**-0.003 ± 0.002**	-	-	**1 ± 2**

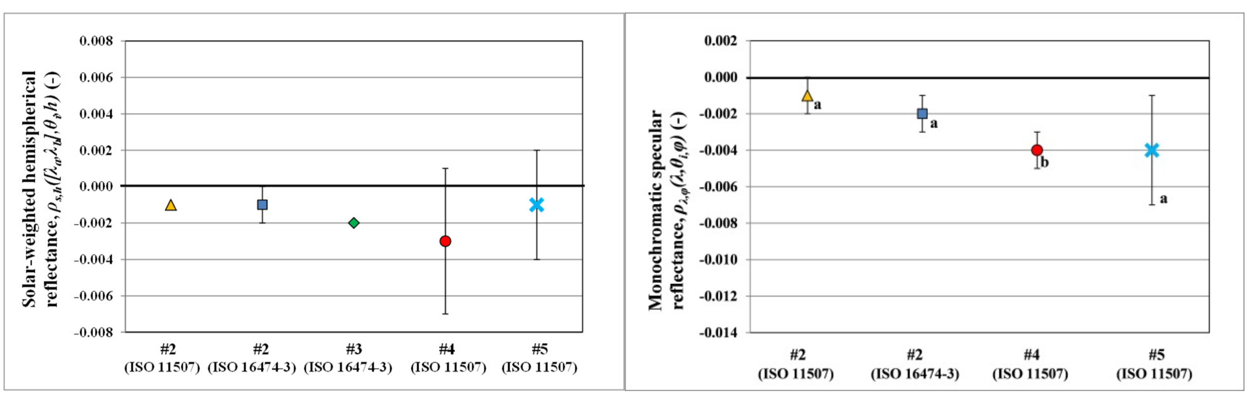

FIGURE 9. Average of the solar-weighted hemispherical reflectance differences (left) and monochromatic specular reflectance differences (right) after UV light and humidity test.

Results in agreement by all the partners were observed. A slight spectral and monochromatic hemispherical reflectance loss was detected by all the partners. Concerning the monochromatic specular reflectance, also results in accordance by all the partners were observed. Slight and medium losses were detected in the samples tested. The samples tested by #4 and #5 presented the highest loss, with an average of -0.004. Finally, the results according to both standards ISO 11507 and ISO 16474-3 were similar.

CONCLUSIONS

A RRT was performed to compare the results obtained by five research laboratories after applying the durability test campaign proposed in the new AENOR standard. Although an acceptable agreement was achieved, several differences were detected in the testing and optical characterization protocols. Conclusions obtained are reported to improve further versions of the standard.

- The reference reflectance standard is highly important and should be properly chosen and maintained. Regarding the initial characterization, the average of solar-weighted hemispherical reflectance values presented by all the partners was slight different, being 1.0 ppt the maximum difference among them and 0.4 ppt the standard deviation. However, the average of monochromatic hemispherical reflectance at 660 nm was similar, being 0.2 ppt the maximum difference and 0.1 ppt the standard deviation. It indicates that the hemispherical differences appeared in the rest of the spectrum. For the monochromatic specular reflectance at 660 nm, 0.7 ppt was the maximum difference and 0.3 ppt the standard deviation among the laboratories.
- After the durability tests, the highest standard deviations among the laboratories were observed in the thermal cycling test. In general, it can be concluded that the average standard deviation among five laboratories regarding the hemispherical and specular reflectance losses is in the order of 0.1 ppt and 0.2 ppt, respectively, after accelerated aging of typical silvered-glass reflectors according to the AENOR protocol. The average standard deviation of the maximum non-protected edge corrosion penetration, the number of corrosion spots per dm^2 (>200µm) and the number of bubbles per dm^2 in the paint layer is 0.19 cm, 4 corrosion spots and 8 bubbles, respectively. The visual inspection to detect the maximum non protected edge corrosion, number corrosion spots and number bubbles in the paint is being improved in order to obtain more reproducible results.
- The above presented results represent the uncertainty of the results to be expected when plant constructors or mirror manufacturers test silvered-glass mirrors in different European research centers.

ACKNOWLEDGMENTS

The research leading to this work has received funding from the European Union Seventh Framework Programme (FP7/2007-2013) under grant agreement n° 609837 (STAGE-STE). The authors would like to thank the participants of the working group for solar reflectors of WG 2 of the Spanish sub-committee AEN/CTN 206/SC 117.

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