SFERA (Solar Facilities for the European Research Area)

Final results of secondary concentrators solar mirror testing

(Work Package 13, Task 2, Subtask “Hardware”)

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1. Introduction

This paper summarizes the final results of secondary concentrators' solar mirrors testing according to the Work Package 13, Task 2, Subtask "Hardware" integrated in SFERA project (Joint Research Activities).

Mirrors samples selected were exposed to accelerated conditions to simulate and analyze the effect caused by the ambient conditions. The detailed description of the methodology followed can be found in Annex 1 of [1].

1.1 Scope

Secondary concentrators' solar mirrors are always exposed to ambient conditions for long periods of time. This research focused on the study of the solar mirror degradation caused by several ambient parameters (salty atmosphere, temperature and humidity), under accelerated exposure. The tests have been carried out by CIEMAT at the Plataforma Solar de Almería (Almería, Spain).

2. Methodology

2.1 Samples Description

A total number of 9 manufacturers provided 5 samples each to conduct the tests. Therefore, the total amount of samples included is 45. Due to the laboratory instruments requirements, the mirror samples size was 8x8 cm. It was asked to the manufacturers that, if possible, the mirror samples were glued to a structure similar to its real use in the solar system (e.g. a back aluminium sheet) to analyze the behaviour of the mirror integrated in the whole system. It was also emphasized that the 5 samples of every mirror type had to be exactly equal to avoid heterogeneity between samples.

Two types of mirrors are included in the study. The first type is mirrors suitable for secondary concentrators of central tower systems applications, also called 3d-CPC's. In these systems the secondary concentrator will be cooled with water, reaching maximum temperatures around 85ºC. The second type is mirrors suitable for secondary concentrator of Fresnel collectors, also called 2d-CPC's. In this case, the concentrator will not be artificially cooled, reaching higher temperatures, around 350ºC. The categories and description of the samples tested are shown in table 1.

It is relevant to mention that the study of the aluminium material (code 1) is particularly very interesting in this application because the support structure of the secondary concentrators is typically made of this material. The main reason is that aluminium mirrors will not suffer mechanical stress due to different dilatation coefficient. In addition, the fact that aluminium mirrors do not present glass cover is an asset against breakages. Finally, an aluminium mirror can be easily be stuck to a support aluminium structure, which is an advantage.

The rest of the mirror types included in this study are low-iron glass covered, which is the most common and effective protective layer for the metal reflectors against aging.

	MANUFACTURER CODE	THICKNESS (mm)	REFLECTOR MATERIAL	DESCRIPTION
COOLED SYSTEM MIRRORS	1	0.5	Aluminium	First surface mirror with special lacquer on front surface
	2	1	Silver	Second surface mirror with 0.95mm thin low-iron glass cover. Back surface white painted (type 1). No protected edges
	3	1	Silver	Second surface mirror with 1mm low-iron glass cover. Back surface white painted (type 2). No protected edges
	4	1	Silver	Second surface mirror with 1mm low-iron glass cover. Back surface white painted (type 3). No protected edges
	5	5.3	Silver	Second surface mirror with 1mm thin low-iron glass cover. Back side glued to an aluminium structure for cooling system. No protected edges
	6	5.3	Silver	Second surface mirror with 1mm thin low-iron glass cover. Back side glued to an aluminium structure for cooling system. Edges protected with protection type 1
	7	5.3	Silver	Second surface mirror with 1mm thin low-iron glass cover. Back side glued to an aluminium structure for cooling system. Edges protected with protection type 2
NO COOLED SYSTEM MIRRORS	8	3.4	Silver	Second surface mirror with 3mm thick low-iron glass cover. No protected edges. Black painted back surface
	9	2	Silver	Second surface mirror with 1.5mm thick low-iron back glass cover and 0.5mm low-iron front glass cover. Glass protected edges.

Table 1 Samples description

2.2 Experimental Set Up

The whole accelerated aging test campaign was carried out by CIEMAT at the PSA (Almería, Spain). The instrumental and devices used can be grouped in two blocks:

- Weathering chambers, to simulate the accelerated ageing conditions applied under specific settings (see figures 1 and 2):

    - Salt spray test chamber, CSF-500 by *Control Técnica*. This chamber has been manufactured to make tests according to DIN-50021 and ISO-9227 standards. Combined cycles can be programmed (salt spray, condensation and ambient conditions). Different temperatures can also be applied during tests, from 10 to 50ºC.

- Weathering chamber, SC340 by ATLAS. Several combinations of humidity and temperature can be applied, both in steady conditions and in cycling combinations. If only temperature testing is done, the temperature range is from -40 to 120ºC. If temperature and humidity testing is done, the temperature range is from +10 to +90ºC and the humidity range is from 10 to 90%.

- Muffle furnace, LT 40/12 by Nabertherm. Constant temperature tests can be done at temperatures up to 1200ºC. Additionally, a special device has been developed by CIEMAT to carry out automatic temperature cycles tests. This device uses a conventional muffle furnace for the heat up cycle and a fan for the cold down cycle. In addition, water can be sprayed in the cold down cycle. The useful area is 30 x 45 cm.

- Measurement and visual inspection instruments. Here the two first instruments mentioned below were used to make the reflectance measurements. The last two listed, were employed for visual inspection of the samples.

    - Spectrophotometer. Lambda 1050 by Perkin Elmer with integrating sphere (λ =250-2500 nm). The Spectral hemispherical reflectance, $\rho_h(\lambda,8º,h)$, is measured with a Perkin Elmer Lambda 1050 (see Figure 3).

    - Reflectometer. 15R-USB by Devices and Services. The measuring of monochromatic specular reflectance, $\rho_s(660nm,15º,\varphi)$, has been done with this instrument which allows taking the measurements at 1 wavelength (λ=660nm) and 3 aperture angles (φ =15, 25 and 46 mrad) (see Figure 3).

    - Microscope. DMI5000 M 2D by Leica. A first fully motorized microscope with colour intensity, remote control of all motorized functions and 7 variable function keys.

    - Digital photo camera. IXUS 105 by Canon with 12.1 Megapixel and 4X zoom.

Figure 1 Salt spray test chamber

Figure 2 Muffle furnace (left side) and weathering chamber (right side)

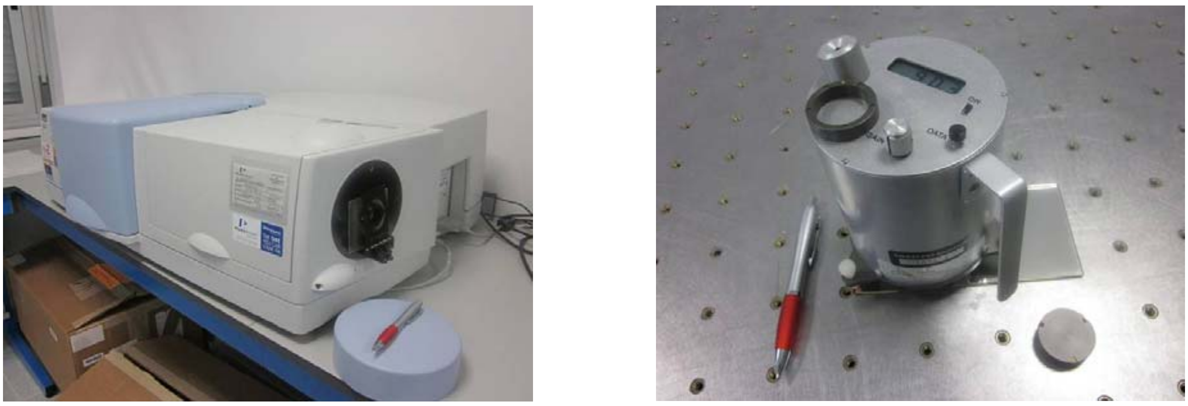

Figure 3 Spectrofotometer (left side) and portable reflectometer (right side)

2.3 Experimental Procedure

One sample of each material type was treated as reference sample and was not aged. The other 4 samples of each material type were tested under the following 2 methods (2 samples per every single method):

- Salt Spray Test. The aim of this test is to analyze the influence of a salty atmosphere on the degradation of the mirrors, in order to estimate sensitivity to locations near the coast for a CSP plant. All the mirror types underwent this test. The testing conditions are shown in table 2.

Chamber	Standard	Type of test	Temperature (ºC)	pH	Time (h)
Salt Spray	ISO 9227:2006	Neutral Salt Spray (NSS)	35±2	6.5-7.2	480

Table 2 Testing conditions for the Salt Spray Test (all mirror types)

- Combined Weathering Test. The aim of this test was to analyze the influence of temperature and humidity in the mirrors' degradation. In this case the samples were exposed to several consecutive tests. Both weather parameters were applied separately and combined during the tests in order to determine the most aggressive condition. In this case, the mirrors designed for working with and without a cooling system were tested separately. The testing conditions for cooled mirrors (mostly secondary concentrators of central tower systems applications) are summarized in table 3.

Chamber	Standard	Type of test	Temperature (ºC)	Humidity (%)	Time (h)
Muffle Furnace	-----	Constant Temperature	+85	ambient	480
Weathering chamber	ISO 61215: 2005	Thermal Cycling	From -40 ± 2 to +85 ± 2	ambient	300 (50 cycles x 6h)
Weathering chamber	6270-2:2005	Humidity (CH)	+40 ± 3	100	480
Weathering chamber	ISO 61215: 2005	Damp Heat	+85 ± 2	85 ± 5	1000

Table 3 Testing conditions for the Combined Weathering Test (cooled mirrors)

Results obtained in this test supply high valuable information for the design and operation of the secondary reflectors. For example, if a mirror is damaged after the constant temperature test, the maximum temperature must be reduced by improving the cooling system, but if a mirror is damaged after the thermal cycling testing, the cooling system should be kept on during night.

The testing conditions for no cooled mirrors (e.g. secondary concentrator of Fresnel collectors) are in table 4.

Chamber	Standard	Type of test	Temperature (ºC)	Humidity (%)	Time (h)
Muffle Furnace	----	Constant Temperature	+350	ambient	480
Muffle Furnace	----	Thermal Cycling	From ambient to +350	ambient	50 cycles
Weathering chamber	6270-2:2005	Humidity (CH)	+40 ± 3	100	480

Table 4 Testing conditions for the Combined Weathering Test (no cooled mirrors)

2.4 Degradation Indicators

The mirror samples degradation has been established by measuring the reflectance, as it is the key indicator in solar reflectors. Also, as mentioned previously, visual inspection methods were used: 2D microscope images and digital camera pictures.

Both, reference samples and tested samples, were measured in terms of monochromatic specular reflectance at 25 mrad aperture angle, $\rho_s(660nm,15º,25mrad)$, as well as spectral hemispherical reflectance, $\rho_h(250\text{-}2500nm,8º,h)$. In addition, monochromatic specular reflectance at 15 mrad aperture angle, $\rho_s(660nm,15º,15mrad)$, was measured for the reference samples. It is also important to highlight that the mentioned measurements for the tested samples were taken after the experiments to track the reflectance evolution. Finally, pictures of the reference samples and the most relevant tested samples were taken.

The final useful reflectance values, refer to solar-weighted specular reflectance, $\rho_s(SW,15º,25mrad)$. This parameter is calculated from the $\rho_h(250\text{-}2500nm,8º,h)$ measured with the spectrophotometer and $\rho_s(660nm,15º,25mrad)$ measured with the reflectometer as follows:

- In order to find out the $\rho_h(SW,8º,h)$, the $\rho_h(250\text{-}2500nm,8º,h)$ was measured within the 250-2500 nm wavelength interval. For this purpose, 3 measurements were realized in every single sample type rotating 90º the mirror (hence, 0º, 90º and 180º values were recorded). Therefore, the $\rho_h(250\text{-}2500nm,8º,h)$ is the average of these three measurements taken. From here, the $\rho_h(SW,8º,h)$ is obtained by applying the following equation [2]:

$$\rho_h(SW,8^o,h)=\frac{\sum_{i=1}^{n}\rho_h(\lambda_i,8^o,h)\cdot E_{dir,\lambda i}\cdot\Delta\lambda_i}{\sum_{i=1}^{n}E_{dir,\lambda i}\cdot\Delta\lambda_i} \quad (1)$$

Equation 1 Solar weighted hemispherical reflectance calculation

Where the solar irradiance spectrum, $E_{dir,\lambda i}$, was taken from ASTM G173-3 AM 1,5 spectrum [3].

- Afterwards, the second step was to measure the $\rho_s(660nm,15º,25mrad)$. Five points were measured in every single sample and the average was calculated.
- Finally, the $\rho_s(SW,15º,25mrad)$ was calculated by using this equation [4]:

$$\rho_s(SW,15^o,25mrad)=\frac{\rho_s(660nm,15^o,25mrad)}{\rho_h(660nm,8^o,h)}\cdot\rho_h(SW,8^o,h) \quad (2)$$

Equation 2 Solar weighted specular reflectance calculation

3. Results and Discussion

To get a better understanding of how the tests degraded the mirrors, Table 5 shows the initial average solar-weighted specular reflectance, ρ_s*(SW,15º,25mrad),* used as the base to compare with all the tests results. The reason why just hemispherical reflectance has been shown for the sample 1, is that, after finalizing the experiments, no reliable values of specular reflectance were obtained due to the heterogeneous behaviour of this material (i.e. illogical specular reflectance swings were found). Therefore, just this material will be analyzed from the hemispherical reflectance perspective throughout this report.

MANUFACTURER CODE	1	2	3	4	5	6	7	8	9
ρ_s (SW,15º,25mrad) [%]		94.9	94.9	94.8	93.1	93.2	93.2	94.5	92.1
ρ_h(SW,8º,h) [%]	90.9								

Table 5 Initial average reflectance ρ_s*(SW,15º,25mrad)* of reference samples from 2 to 9 and initial hemispherical reflectance ρ_h*(SW,8º,h)* of sample 1

As it can be seen in table 5, all manufacturers presented reflectance values between 92.0 and 95.0%, except the aluminium (code 1), with a hemispherical reflectance of 90.9%. Reflectance value of laminated mirror (code 9) is slightly lower than rest of the glass based mirrors (codes 2 to 8).

Further down, figure 4, offers the reference samples hemispherical spectral reflectance, ρ_h*(250-2500nm,8º,h)*, plotted by the spectrophotometer in a graph. This figure shows the typical spectrum of silvered-glass mirrors (samples 2 to 9) and aluminium with special protection mirrors (sample 1). Reflectance spectrum of samples 2 to 8 are quite similar, having reflectance spectrum of sample 9 a deeper elbow in the visible range. Reflectance spectrum of sample 1 has a valley around 800 nm, as usual for this aluminium material.

Then, from figures 5 to 10, the results for salty spray, constant temperature, temperature cycling, humidity, damp heat and muffle furnace high temperature tests, are respectively shown.

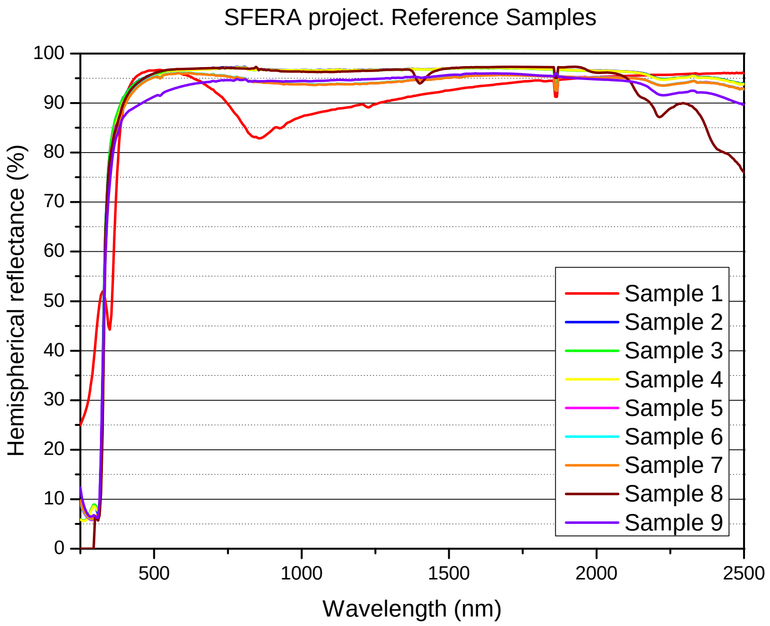

Figure 4 Hemispherical spectral reflectance of reference samples

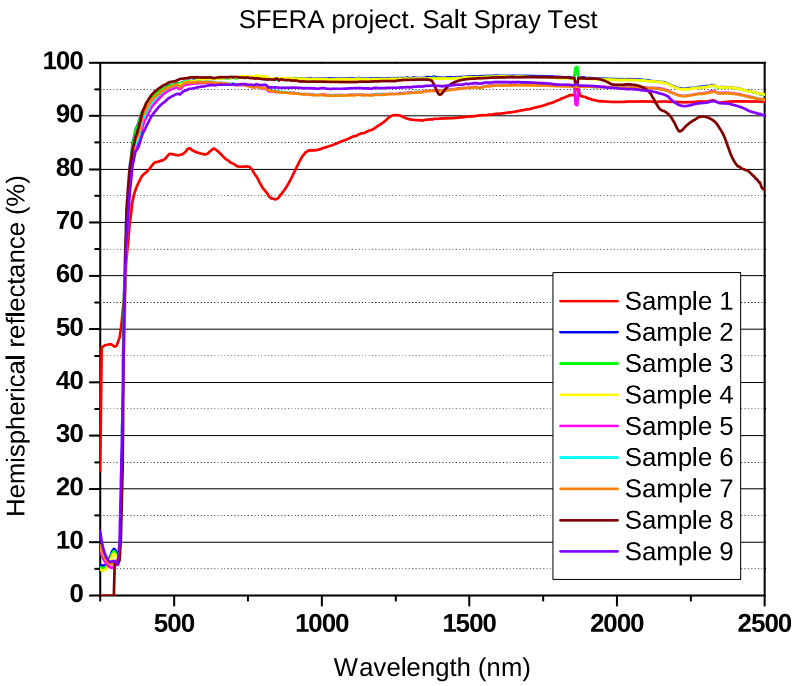

Figure 5 Hemispherical spectral reflectance after salty spray test

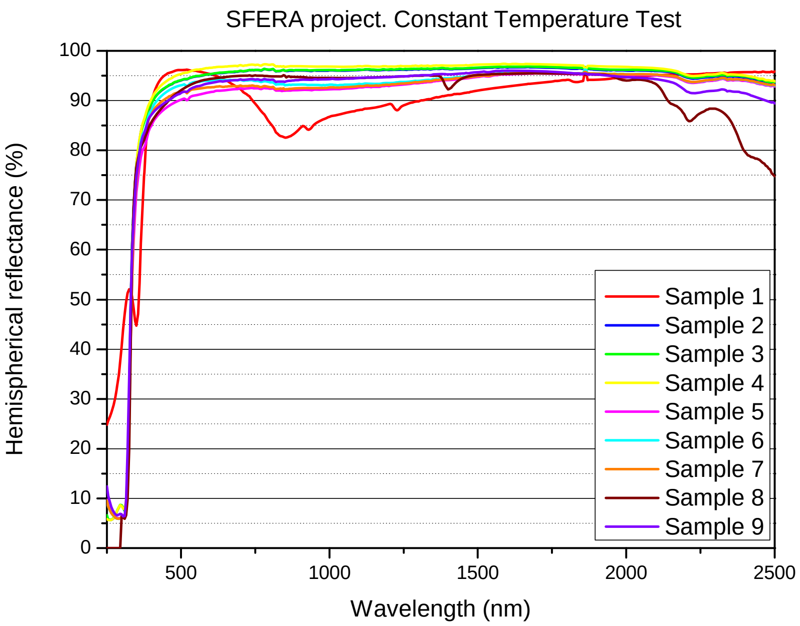

Figure 6 Hemispherical spectral reflectance after constant temperature test

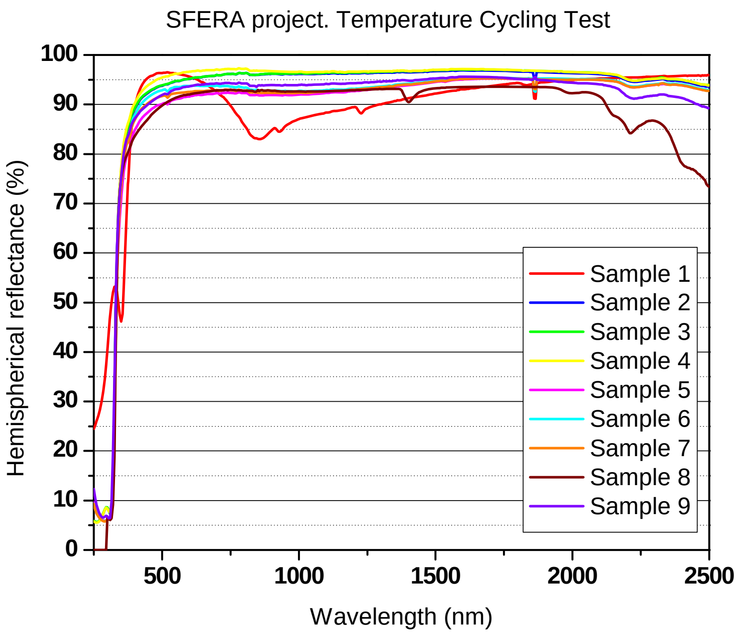

Figure 7 Hemispherical spectral reflectance after temperature cycling test

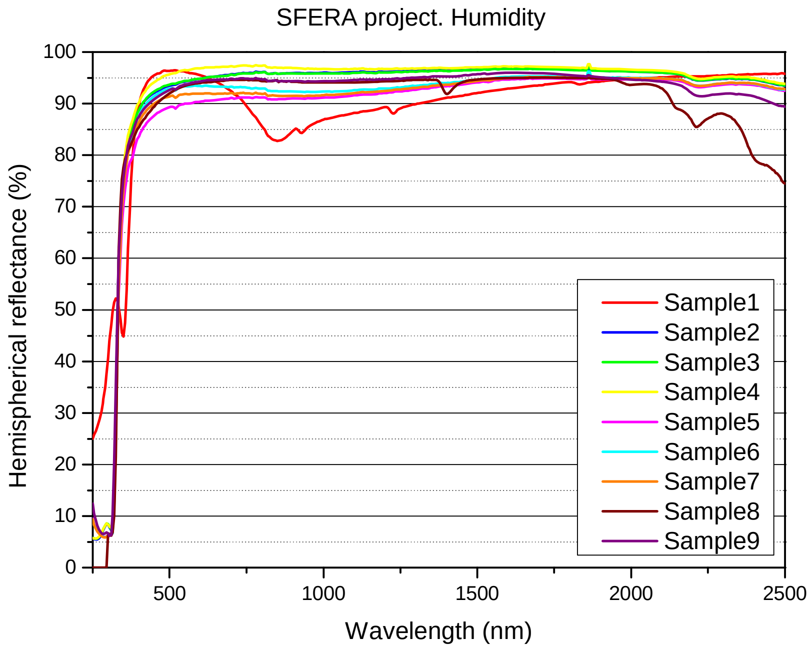

Figure 8 Hemispherical spectral reflectance after humidity test

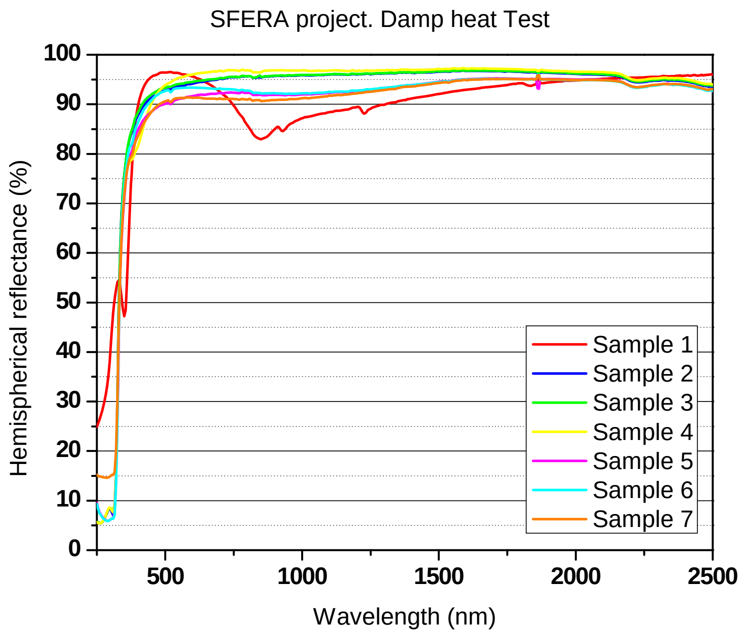

Figure 9 Hemispherical spectral reflectance after damp heat tests (performed only to no cooled samples, that is 1 to 7)

After a first observation of the previous graphs, Table 6 shows finally what difference of reflectance occurred after the experiments compared to the initial reference samples reflectance:

		MANUFACTURER CODE	SALT SPRAY TEST	CONSTANT TEMPERATURE TEST	HUMIDITY TESTS	THERMAL CYCLING TESTS	DAMP HEAT TESTS
	$\Delta\rho_h$ *(SW,8°,h)* [%]	1	-8.0	-0.5	-0.3	-0.2	-0.2
REFLECTANCE DIFFERENCE FOR EACH TEST CONDUCTED $\Delta\rho_s$ *(SW,15°,25mrad)* [%]	COOLED SYSTEM MIRRORS	2	0.5	-1.1	-1.3	-1.7	-1.4
		3	0.3	-0.9	-1.7	-1.4	-1.1
		4	0.2	-0.1	0.0	0.1	-11.0
		5	0.0	-2.1	-3.5	-3.9	-6.8
		6	0.2	-1.9	-2.7	-1.6	-2.9
		7	0.2	-3.2	-4.0	-2.9	-5.5
	NO COOLED SYSTEM MIRRORS	8	0.6	-5.7	-8.9	-4.6	N/A
		9	0.8	-0.7	-0.4	-0.5	N/A

Table 6 Reflectance difference (between reference samples and tested samples) results

Several interesting ideas can be drawn from the previous figures and table results:

- **In terms of salt spray tests,** the samples from manufacturer type 1 (aluminium) presented the highest decrease in reflectance (note that this is referring to hemispherical reflectance in this particular case). Figure 10 shows a picture of sample 1 after the salt spray test, where a visible degradation can be clearly observed. As a consequence of this degradation, reflectance decreased by 8% (see table 5) and reflectance spectrum differs deeply from the initial one (see figure 5). This indicates that it is not recommendable to employ them in salty atmosphere locations (see Figure 10). However, there is no reflectance loss in the rest of the mirrors, made on silver. It was necessary to clean all mirrors with acetone to eliminate salty residues and it has been assumed that, this is the reason why a slight increase in reflectance was detected in some cases. In addition, this test demonstrates the need of special cleaning of the reflectors with acetone or similar, once in a while for these salty environments.

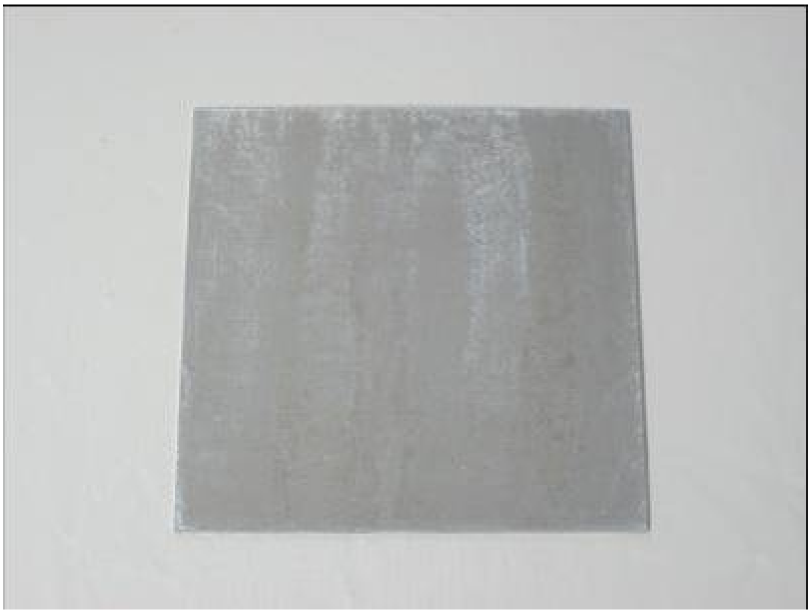

Figure 10 Sample 1 picture after salt spray test

- **Concerning combined weathering tests** of constant temperature, humidity and temperature cycling (see figures 6, 7 and 8), it seems that the manufacturer 4 and 1 have the best behaviour, with reflectance losses between 0.0 and 0.5%, followed by number 9, with a 0.7% maximum reflectance losses.

  The other two types of thin-glass mirrors (manufacturer number 2 and 3) have suffered minor reflectance losses (between 0.9 and 1.7%). This is probably related to the fact that the mirrors presented the back coating degraded after the tests, as it is shown in Figure 11.

Figure 11 Sample 3 with back coating degraded, after humidity test

Medium to high reflectance losses (between 1.6 and 4.0%) have been detected in thin-glass mirrors glued to an aluminium support structure (manufacturer types 5, 6 and 7). The increasing degradation throughout the combined weathering tests could be due to a chemical reaction caused by the glue employed at the back to joint the reflector surface to the aluminium structure (as can be seen in Figure 12). This degradation was less aggressive in sample type 6, where protection type 1 was applied on the edges. Therefore, this type of protection has demonstrated to be more effective than the other two options tested, that is, no protection and protection type 2.

Figure 12 Degradation stains due to a glue chemical reaction (sample 5), after humidity test

Finally, the highest reflectance loss (8.9%) was observed in the thick glass mirror (samples number 8) due to corrosion of the silver layer (see Figure 13). This degradation started to appear after the constant temperature test and significantly increased after the humidity test. The reason why manufacturer 8 appears more degraded might be due to the lack of protected edges and an insufficient back protective layer.

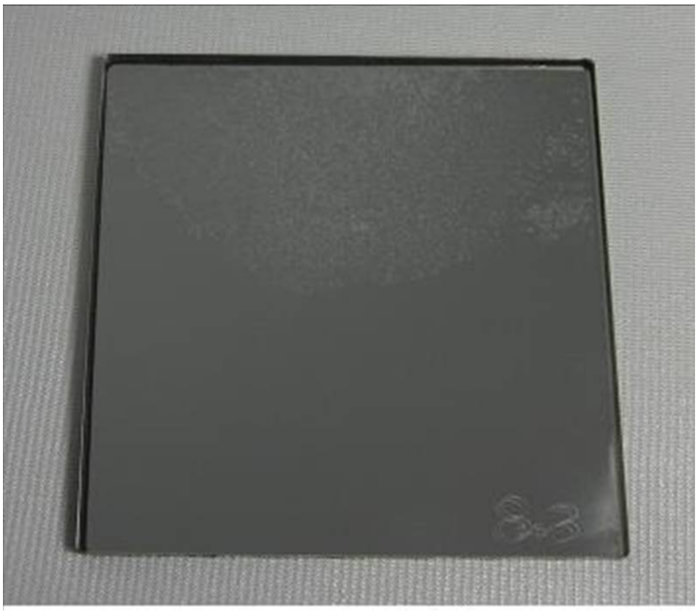

Figure 13 High corrosion on sample 8, after humidity test

- **Damp heat tests.** This test involved very extreme conditions and it has been applied to the manufacturers 1 to 7, providing interesting results. It seems that it has been one of the most aggressive tests due to the high reflectance losses recorded in the manufacturers 4, 5 and 7). The mirror from the manufacturer number 4 has lost reflectance up to 11.0%, followed by the manufacturer number 5, with a 6.8% loss and the manufacturer number 7 with a 5.5% loss. Manufacturers 1, 2, 3 and 6 have suffered from low to medium losses (between 0.2 and 2.9%). A few representative images show the evidences of degradation after damp heat tests.

  Here, figure 14 shows a typical degradation occurred at the edges. Figure 15 is a microscopic observation about the geometry of the degradation patterns.

Figure 14 Sample 3 edges degradation example, after damp heat test

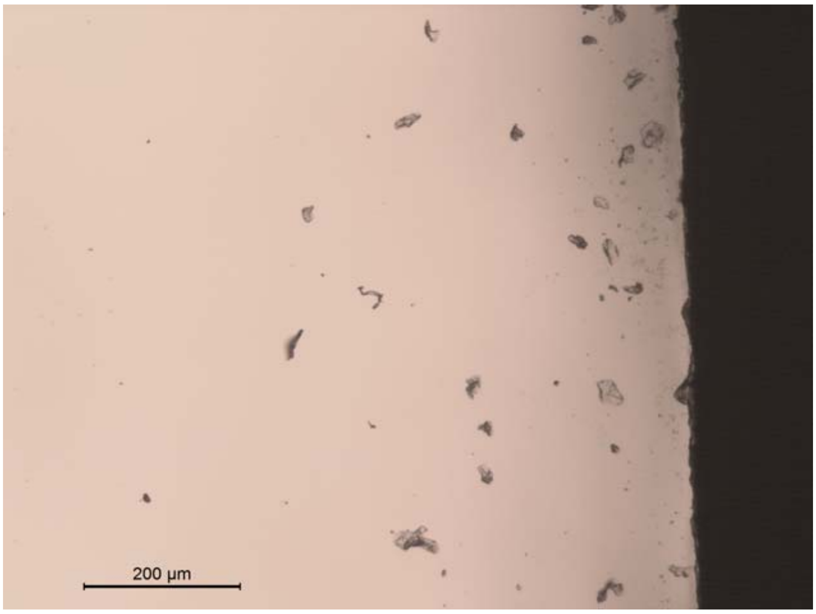

Figure 15 Sample 3 microscope edges observation, after damp heat test

The following two images show how the previously mentioned reaction against the back side glue, has evolved after the damp heat tests in sample 5, which appears certainly more degraded (compare figures 12 and 16).

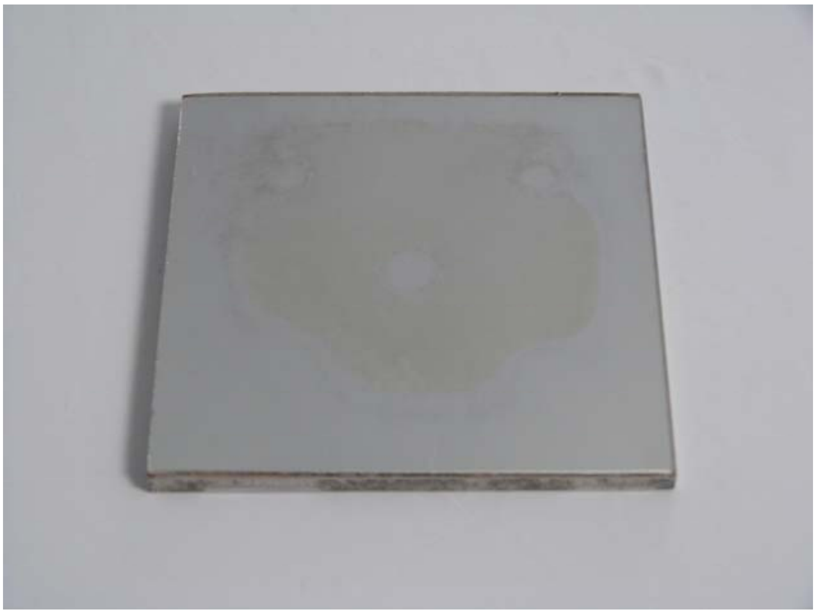

Figure 16. Sample 5 degradation, after damp heat test

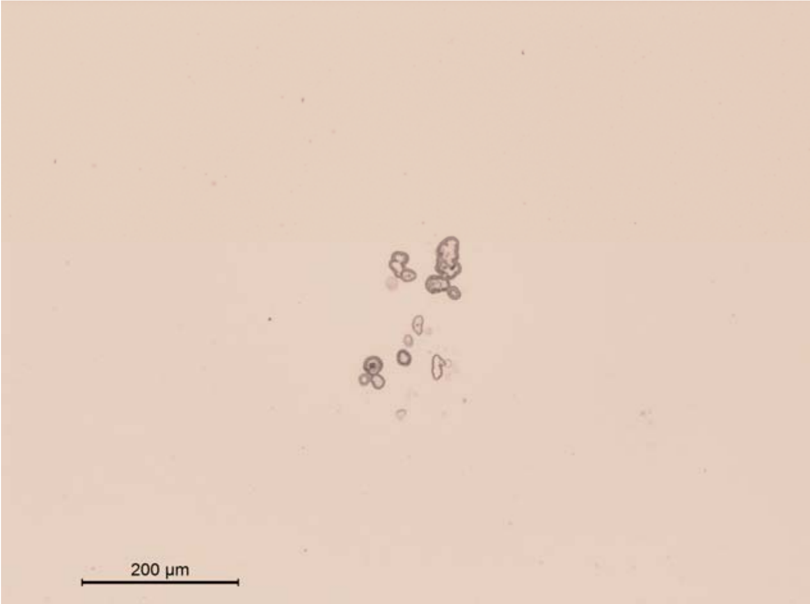

Figure 17 Microscopic detail of sample 5 degradation stain, after damp heat test

Finally, the next two figures show the reflector layer coming off the glass. This justifies the most serious reflectance loss within all the samples:

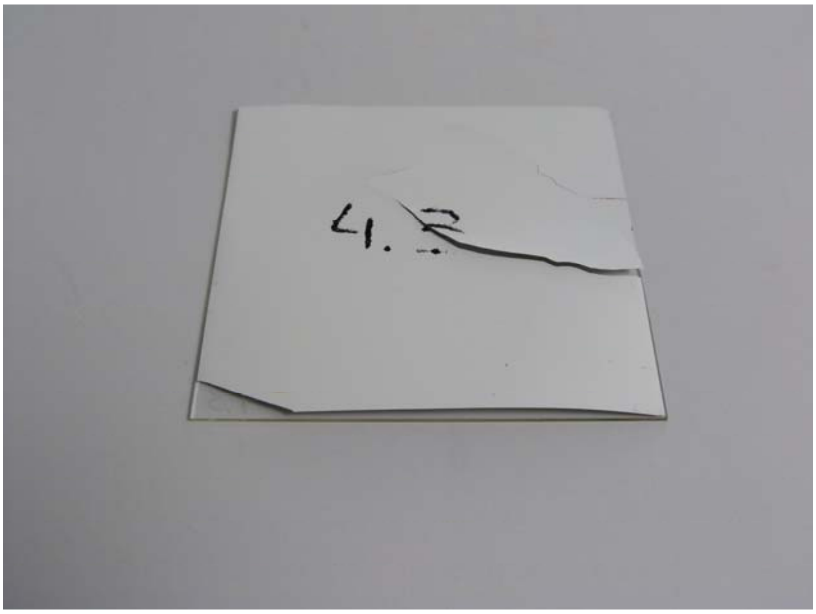

Figure 18 Back side degradation in sample, after damp heat test

Figure 19 Front edges appearance when reflector surface loses have occurred (sample 4), after damp heat test

4. Conclusions

After the results examinations, main conclusions were made according to the experiments course:

- **Initial reflectance.** As can be seen in Table 5, the thin and thick glass mirrors have the highest reflectance values (samples type from 2 to 8), laminated mirrors have intermediate reflectance values (samples type 9) and aluminium mirrors (sample 1) have the lowest reflectance value (note this refers to hemispherical reflectance for this material, used as indicator instead of specular reflectance, due to the heterogeneity values recorded for the specular reflectance).

- **After salt spray tests** it can be drawn that just aluminum mirrors are not suitable for salty atmospheres due to a severe reflectance loss after this test. In general, both groups, mirror for cooled and no cooled systems have experienced a reflectance increase. This is due to they were cleaned with acetone to remove salty residues before measuring reflectance, and it caused a very effective cleanliness as a result. Hence, this test demonstrates the need of special cleaning with acetone or similar once in a while for these salty environments.

- **After the first three combined weathering tests (constant temperature, temperature cycling and humidity)**, and from a cooled mirror systems perspective, minimum reflectance losses were detected in thin-glass mirrors from the manufacturer type 4. This is followed by low reflectance losses in the aluminum mirror from manufacturer 1 (in terms of hemispherical reflectance for this one). In thin-glass mirrors number 2 and 3, the reflectance losses are a bit higher and they presented degradation at the back coating.

An increasing degradation throughout the tests was detected in thin-glass mirrors glued to an aluminium support structure (samples 5, 6 and 7). This could be due to a chemical reaction caused by the glue employed at the back to joint the mirror with the aluminum structure. This degradation was less aggressive in sample type 6, where protection type 1 was applied on the edges.

In terms of no cooled systems, the conclusion emerges immediately: very small reflectance losses were detected in laminated mirrors from manufacturer type 9. Nevertheless, the second surface mirror with 3mm thick low-iron glass cover and non protected edges (manufacturer type 8) experimented high reflectance losses. Perhaps this kind of reflector is not a suitable option against sharp weather swings.

- **Regarding the damp heat tests results**, the highest and surprising loss corresponded to the thin glass mirror from manufacturer number 4. The sample 5 (thin-glass mirrors glued to an aluminium support structure) has also suffered a considerable loss. It is probably due to the lack of protected edges.

References

[1] Testing of solar mirrors for secondary concentrators (Work Package 13, Task 2, Subtask Hardware). A. Fernández and C. Wieckert 2nd draft Jan. 17, 2011.

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