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Johannes Wette, Florian Sutter, Mai Tu, Aránzazu Fernández-García, Francisco Buendia, M. João Carvalho, and Teresa Diamantino

Advanced Cyclic Accelerated Aging Testing of Solar Reflector Materials

Johannes Wette[1, a)], Florian Sutter[1, b)], Mai Tu[1, c)], Aránzazu Fernández-García[2, d)], Francisco Buendia[2, e)], M. João Carvalho[3, f)] and Teresa Diamantino[3, g)]

[1]*DLR, German Aerospace Center, Institute of Solar Research, Plataforma Solar de Almería, Ctra. Senés Km. 4, P.O. Box 39, E04200, Tabernas, Almería (Spain)*
[2]*CIEMAT Plataforma Solar de Almería, Ctra. Senés Km. 4, P.O. Box 22, E04200, Tabernas, Almería (Spain)*
[3]*LNEG. - Laboratório Nacional de Energia e Geologia, Estrada do Paço do Lumiar, 22, 1649-038 Lisboa, Portugal*

[a)]Corresponding author: Johannes.Wette@dlr.de
[b)]Florian.Sutter@dlr.de
[c)]Mai.Tu@dlr.de
[d)]afernandez@psa.es
[e)]fbuendia@psa.es
[f)]mjoao.carvalho@lneg.pt
[g)]teresa.diamantino@lneg.pt

Abstract. Realistic lifetime prediction and testing procedures for solar mirrors have been demanded by investors, plant developers and material manufacturers during the last years. It has been proven that most of the commonly used accelerated aging tests, which were adopted from other industries, cannot be correlated to outdoor exposure. This work studies different accelerated aging test sequences and analyzes the produced degradation. The results made it possible to discover the most demanding environmental conditions for the three tested mirror types. The degradation of the mirrors was strongly affected by the share of the Copper Accelerated Salt Spray (CASS, ISO9227) testing time in the cycle. The CASS test was combined with several other aging tests and it was concluded that especially the combination with the UV/humidity test according to ISO16474-3 was harmful for the protective coatings of the tested silvered-glass mirrors. The conclusions from the testing campaign presented in this paper are helpful to design suited comparative accelerated aging testing procedures.

INTRODUCTION

The EU Horizon 2020 project Raiselife is focused on raising the lifetime of different functional materials used in the concentrated solar power (CSP) industry. One work package of this project is dedicated to the primary mirrors of the solar field. Investigation is conducted on the methods of accelerated aging and lifetime prediction of the mirrors and especially of different protective back side coating systems. In addition, anti-soiling coatings are being analyzed and a novel light weight heliostat using composite reflector panels with thin glass mirrors is being developed.

Lifetime prediction methods for the components of CSP plants have been in the focus of interest of manufacturers and plant developers for the past years. Recently, an accelerated aging standard for solar mirrors was published by the Spanish UNE committee [1]. This standard allows performing comparative testing but it is not suited to derive meaningful lifetime estimations. Firstly, the tests defined in the standard are not aggressive enough to produce significant degradation on most of the materials and secondly, it has been shown that the passing of these tests does not guarantee a high durability during outdoor exposure [2]. These findings have proven the need for the investigation of more realistic procedures. To provoke the mechanisms that are detected during outdoor exposure, a more realistic application of environmental stresses is being investigated. In this work, a series of tests is conducted

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in which several weathering stresses are combined and applied in a cyclic manner or in a sequence. Some of these cycles have shown to correlate better with real outdoor behavior for certain tested materials.

METHODOLOGY

The focus of this work is to analyze the influence of different parameters of the accelerated aging tests on the degradation of the samples. This is the first step to be able to choose a realistic test procedure. The main parameters to be studied here are:

- Influence of the single tests
- Effect of the combination of the single tests
- Duration, cycles and sequences

To find a suitable test procedure and include a high quantity of combinations of parameters, a high number of different cycles were conducted. Three different materials were tested of which only one sample was used per test. The results will allow for a first screening of the aggressiveness of the different accelerated aging cycles. Further studies with higher sample numbers are planned in future test campaigns in order to check repeatability and standard deviations of the results.

The three differently coated silvered-glass mirror materials (A, B, C) were tested at the OPAC laboratory (a joint research group between DLR and CIEMAT at the PSA) and LNEG. At the same time, the samples were also exposed on different outdoor sites. Material A and B are commercial products of two different mirror manufacturer companies, each material consisting of 3 (material A) and 2 (B and C) protective paint layers respectively, a copper and a silver layer and a 4 mm low-iron glass. Material C was specifically manufactured for the project with a protection layer system of reduced thickness. The purpose of this weak material is to be able to gain exploitable results, especially from outdoor exposure, in a relatively short period of time.

14 different test cycles and sequences were conducted, combining the following standard tests: UV/humidity (UVH), copper accelerated salt spray (CASS), neutral salt spray (NSS), damp heat (DH) and combinations of corrosive gases, with H_2S and NO_2 (GAS) and with SO_2 and NO_2 (GAS 2). The detailed parameters of the tests and the corresponding standards are presented in Table 1.

TABLE 1. Details of single tests, corresponding standards and test parameters.

Test	Name	Standard	Conditions
NSS	Neutral Salt Spray	ISO9227 [4]	[NaCl]=50±5 g/l; T=35±2°C; r.H.=100%; pH=6.5-7.2
CASS	Copper accelerated salt spray	ISO9227 [4]	[NaCl]=50±5 g/l; [CuCl2]=0.26±0.02 g/l; T=50±2°C; r.H.=100%; pH=3.1-3.3
UVH	UV light/ Humidity	ISO16474-3 [5]	4h: UV (with 1.55W/m^2/nm at340 nm); T=60±3°C; 4h: T=50±3°C; r.H.=100%
DH	Damp Heat	IEC 62108 [6]	T=65±2°C; r.H.=85±5%
GAS	H_2S/H_2S corrosive gases	Based on EN 60068-2-60 [7]	[H_2S]=0.025 g/l;[H_2S]=0.025 g/l;T=40 ºC; r.H.=80%
GAS 2	NO_2/SO_2 corrosive gases	ISO21207 [8]	[NO_2]=1.5x10-6; [SO_2]=0.5x10-6; T=25ºC; r.H.=95%
Dry	Laboratory ambient conditions	-	T=25°C±3°C
Acc.Out	Accelerated Outdoor	Based on ASTM G90 [9]	8x concentrated natural radiation at PSA

The cycles and sequences differ in the combination of the standard tests and the frequency and duration of the single tests, which include drying phases with storage at normal laboratory conditions (Dry). Test 11 and 13 were conducted with samples, only from Material B, that had been exposed in an outdoor exposure setup with concentrated natural radiation (Acc Out) for half a year before conducting the cycles, the cycles were the same as in test 2 and 14 correspondingly. In Fig. 1 the different cycles are represented and grouped to similar cycles. All tests were conducted for 2000 h, except test 15.

Prior to the testing campaign, other preliminary tests were conducted with a different mirror material, which had proven to be very weak during outdoor exposure. A part of the results of these experiments were already published [2]. Further tests included mainly the combination of the CASS and UVH tests and led to the conclusion that this combination can be more aggressive than conducting the single tests (see results section).

Taking these results as a base, the main experimental campaign was designed. The first group of tests comprises cycles in which every single test duration is one week (T1, T3, T5 and T7). T4 is a simple combination of UVH and CASS. The others are focused on the addition of further single tests (T1, T5 with the DH) or the replacement of the CASS (T3 with NSS and T7 with GAS).

The second group (T9, T11, T14, T14Z and T15) are higher frequency cycles. The whole cycles last one week with the single test durations being considerably shorter, down to one day or less and similar test composition as for the first group. T15 is a combination of two standard tests (ISO 16474-3 and ISO 21207), combining UVH, NSS and two corrosive gases.

Finally, T2, T6, T8 and T12 are focused on the effect of the single tests (or a sequence of 2 tests in the case of T6) but for a longer duration.

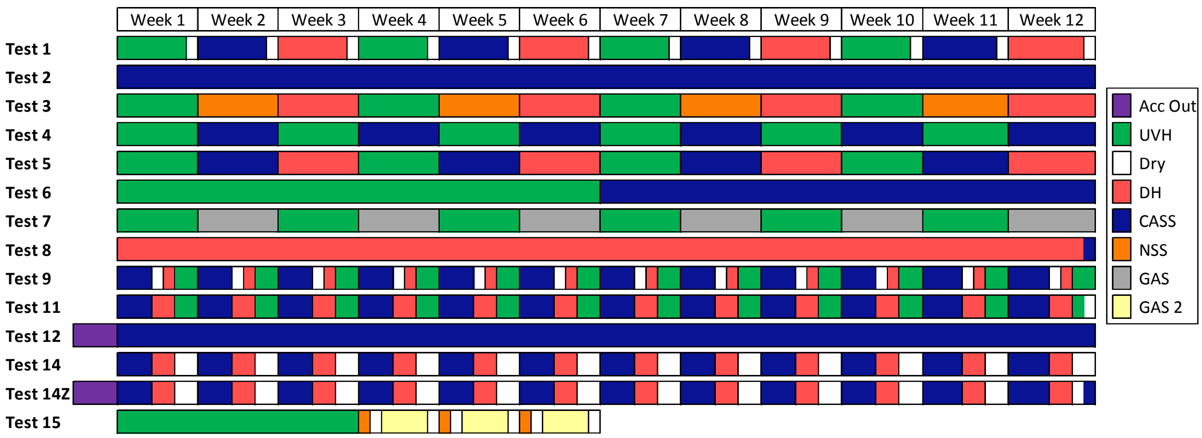


FIGURE 1. Composition and frequency of cycles conducted during the durability test campaign.

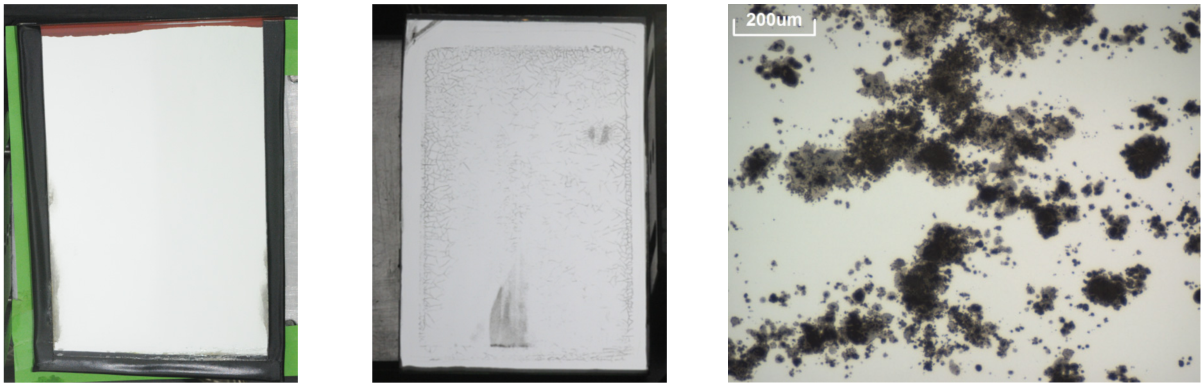
After completion of each cycle the samples were optically analyzed. Photographs of the front and back surface were taken and the degradation parameters were determined.

The main analyzed parameters are:

- Reflectance loss: Monochromatic specular reflectance $\rho_{\lambda,\varphi}$(660 nm; 15°; 12.5 mrad). The portable specular reflectometer model 15R-USB, manufactured by Devices and Services, called D&S, was used to measure the reflectance with an incidence angle of 15° and in a wavelength range between 635 and 685 nm, with a peak at 660 nm. The measurements were taken with an acceptance angle of 12.5 mrad. To calculate the reflectance loss, reflectance measurements were taken before and after the tests, in the same spots of the samples.
- Number of corrosion spots: Number of appearing corrosion spots, visible with the naked eye (around 200 µm and bigger in diameter).
- Degraded area: Affected area by corrosion spots, fraction of the whole surface, determined with an image processing software
- Edge corrosion area: Affected area by edge corrosion, fraction of the whole surface, determined with an image processing software

RESULTS

The principal result of the tests prior to the main campaign presented in this paper was, that for the tested material the UVH test worked to damage the backside coatings of the samples, which created points of attack for stresses applied in the CASS test. In Fig. 2 images of samples are displayed that were exposed only to the CASS test for 1500 h and others that were exposed to 1000 h UVH and 480 h CASS. It can be appreciated that the samples that underwent the pure CASS test, even for a much longer duration, didn't show any corrosion of the reflective silver layer, while the UVH-CASS combination provokes considerable corrosion. The linear appearance of the corrosion corresponds to the forming crack pattern on the back side of the sample.



a) b) c)

FIGURE 2. Images of sample surface after 1500h CASS (a), 1000h UVH + 480h CASS surface image (b) and microscopic image of corroded area after UVH/CASS (c).

For the conducted main campaign of this work, the evolution over time of the four degradation parameters can be appreciated in Fig. 4 (degraded area on the left and reflectance loss on the right) and Fig. 5 (left: number of corrosion spots and right: edge corrosion area fraction) for the three materials. The most important parameter is the degraded area fraction, which correlates well with the reflectance loss for stronger degradation. When the degradation is only weak, the correlation can be worse due to the fact that not the whole degraded area is covered by the punctual reflectance measurements. The number of corrosion spots does not include the size of the spots and thus, correlations to the other parameters depend on the homogeneity of the spot size. The edge corrosion area is not taken into account for the evaluation of the tests. As the samples were cut from whole facets and present cut edges, the corrosion on these edges is not realistic because commercial facets don't present these cut edges. Anyhow, in the future the parameter can be interesting for the correlation to the results from the outdoor exposed samples because there it is an important degradation mechanism, which allows the comparison of different materials and sites.

In Fig. 6 the images of the sample surface for all materials are presented after completion of the test sequences. The degradation of the samples differs strongly among materials and cycles. Only the tests are displayed, in which considerable degradation was provoked for at least one of the materials.

The results show that the CASS test has a major influence. All tests which do not include CASS, show only minor degradation (T3, T7, T8, T15) and are thus not displayed with their final images in Fig. 6. One exception is T15 which provoked very strong edge corrosion, but only small degradation in the surface (Fig. 3)

The so called high frequency cycles have proven to be less aggressive. These tests comprise weekly cycles, with a duration of the single tests of only 1 to 3 days (T9, T11, T14, T14Z). The images of these tests are displayed in Fig. 6 and corrosion spots can be appreciated, but the size of the spots remains very small. This fact can also be seen in the Fig. 5 and Fig. 6. Compared to the most aggressive tests, the affected area and reflectance difference remain negligible. For some of the tests and materials a slightly higher number of corrosion spots can be perceived (e.g. material A in T5 and material C in T9)

Three tests stick out when comparing the surface images after 2000 h: T2, T4 and T6 are the most aggressive tests and provoke the strongest degradation. All of them include a high duration of CASS time (1000-2000 h) and their aggressiveness can also be appreciated in Fig. 4 and Fig. 5. T2 is the most aggressive one leading basically to the total loss of the samples from material A (after 1000 h) and C (after 1500 h).

One interesting fact is that for the CASS test, there is not always a gradual development of the degradation but there seems to be a kind of break down point when the degradation goes from very little to considerable or even extreme. One explanation for this fact is that the intervals between measurements are quite high in some cases (up to 500 h). This breakdown can well be seen in the development of the affected area (material A between 500 and 1000 h, B between 1500 and 2000 h, C between 1000 and 1500 h).

Considering the degraded area after finishing the tests, a ranking of the materials can be done from the weakest to the strongest material. This ranking is not the same for all tests, which can again be grouped: for the first tests in Fig. 6 (T2, 4, 5, 6) material A is the weakest followed by C, for the other tests (T9, 11, 14) material C is the weakest followed by A. For all the tests, material B is the most resistant one.

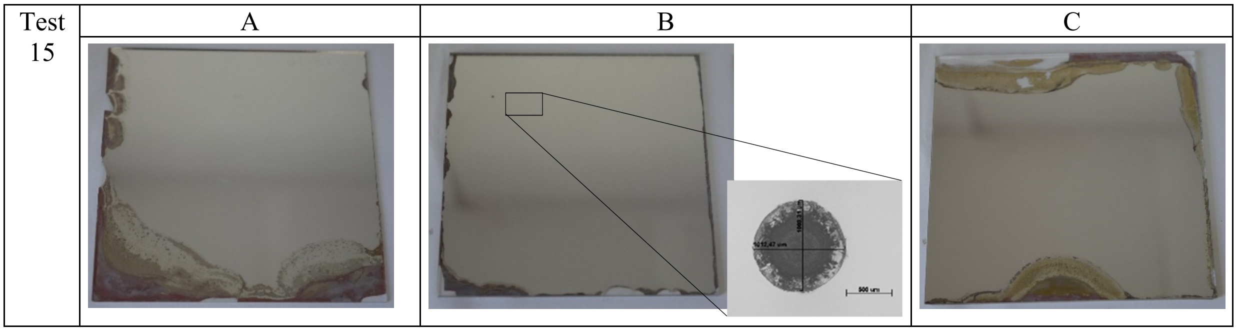


FIGURE 3. Images of sample surfaces after T15 (UVH + NSS + NO_2/SO_2) and detailed view of corrosion spot (sample B).

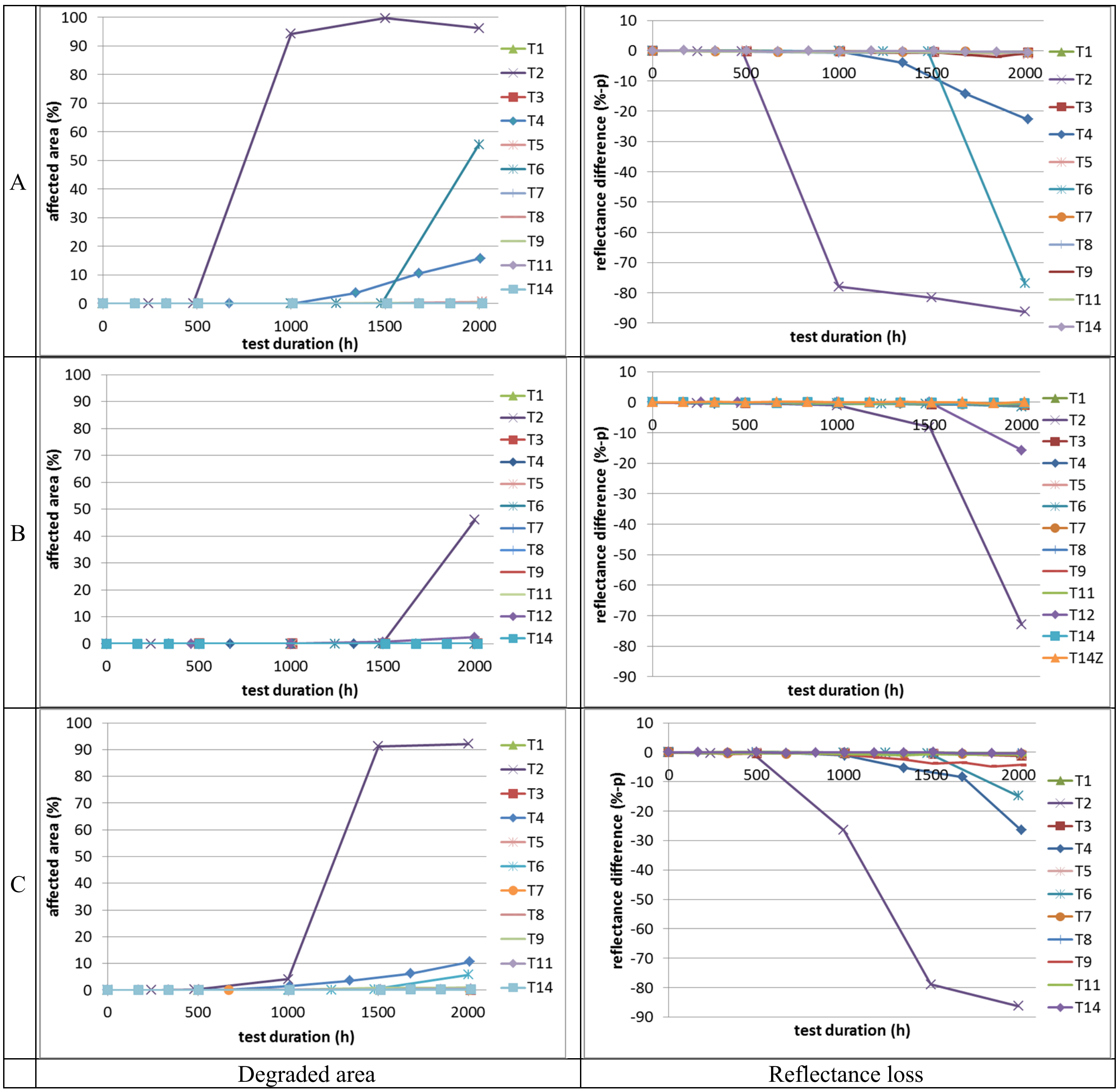


FIGURE 4. Time series for degraded area and reflectance loss for the three materials.

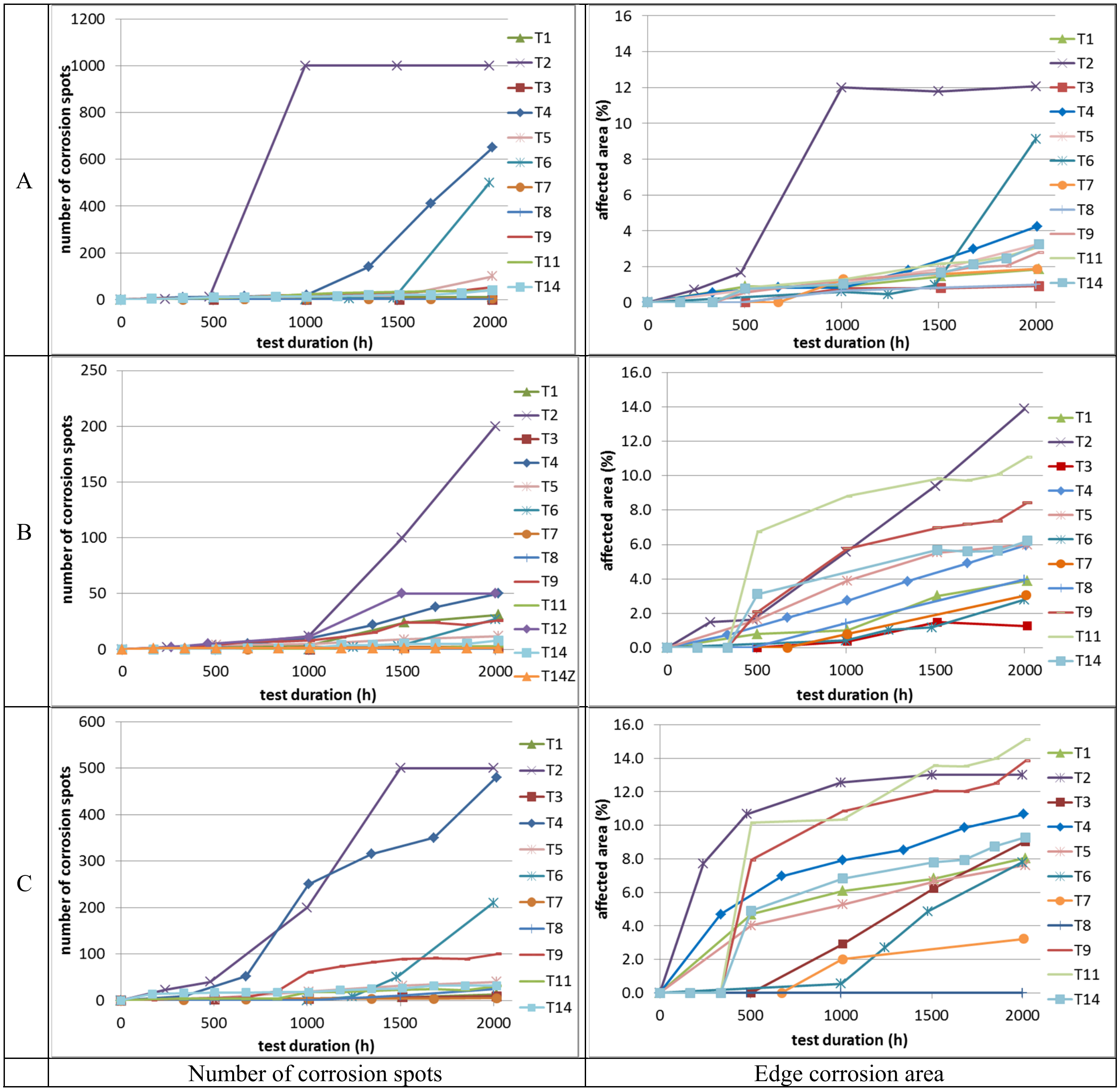


FIGURE 5. Time series for number of corrosion spots and edge corrosion area for the three materials.

The findings that the UVH test has an important role as pre-damaging factor before the CASS test, as found for the former testing campaign, could only be confirmed in special cases. When the complete testing time of 2000 h is taken into consideration the UVH test doesn't show to be decisive, but the duration the sample spends in the CASS test. An example where the pre-damaging effect can be appreciated, is material C after shorter test times.

For this material, photographic images of the reflective surface are displayed in Fig. 7 for three different cycles. The duration the different samples were subjected to the CASS conditions, was roughly 500 h in all of the three cases. The degradation on the surface is considerably stronger for the case of T4, which consists of the weekly cycling between UVH and CASS. This can also be appreciated when the affected area is displayed over the CASS time instead of the total testing time (see Fig. 7 d). Also here T4 shows the strongest degradation until 1000 h, followed by T6 (sequence of UVH and CASS). After that only T2 continues, which leads to the total loss of the sample and the extreme growth of the degraded area in this tests.

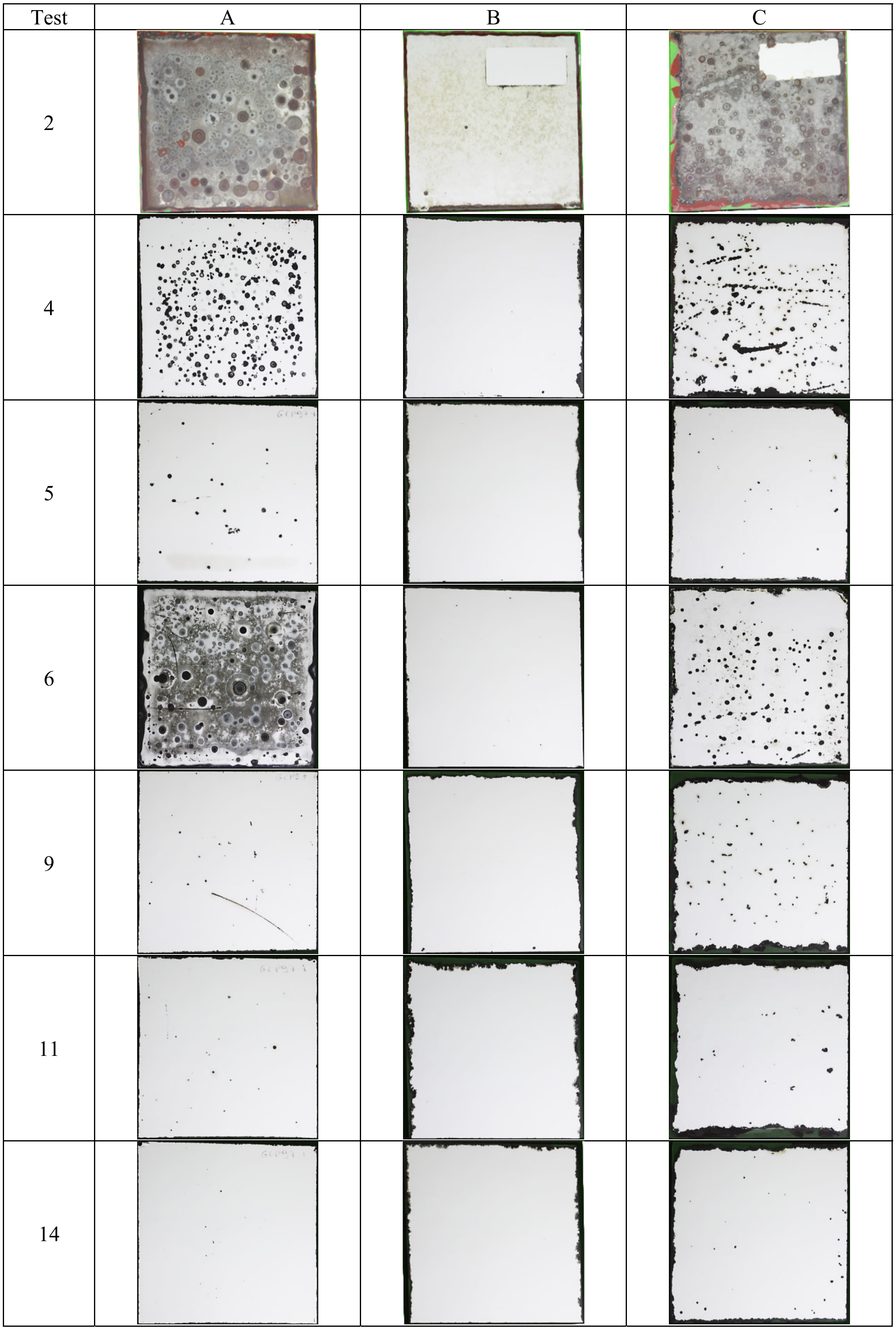
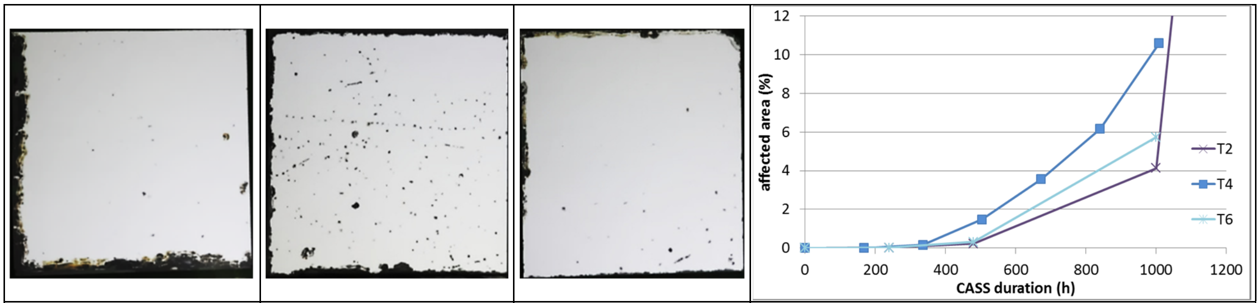


FIGURE 6. Images of sample surface after completion of tests (2000 h) for the three materials.



a) b) c) d)

FIGURE 7. Surface of material C after a) T2: 480 h, b) T4: 1008 h, c) T6: 1480 h, d) degraded area over time in the CASS test.

CONCLUSIONS

The main conclusions that can be drawn from the testing campaign are the following:

- The CASS test, as already known, is very aggressive. It can be useful to provoke degradation in solar mirrors in a reasonable time and to compare different mirror materials. Care has to be taken in choosing an appropriate testing duration to avoid unrealistic strong degradation.
- The higher frequency cycles conducted have shown to be less aggressive and are discarded for the moment, because in addition they require more handling which leads to higher effort and the risk of damages to samples by the handling.
- Indications for the pre-damaging effect of the UVH tests were only detected in a very limited number of situations and may be restricted to certain materials.

A further testing campaign has already started to investigate in more detail the break down effect in the CASS test and the influence of the UVH test and other contaminants, mainly by using a higher number of samples per material and increase the measurement frequency.

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