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CLEANING RESISTANCE OF GLASS COATINGS

Test Report V403/2018

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Project Number: 431168
Project Name: CSP_fglasBau1
Test Date: 20.09.2017 – 30.04.2018
Customer: f | solar GmbH, Mr. Ihno Baumann, Appendorfer Weg 5, 39171 Sülzetal (OT Osterweddingen)

Report Date: 30.05.2018

Please note that this is a preliminary version of the final test report and further changes are possible.

Content

1
Introduction

1.1 Task Breakdown

Regular cleaning of PV modules can damage glass surfaces and glass coatings. It becomes especially relevant in desert areas with high cleaning frequency due to increased soiling of the glass surfaces.

Within this report the damage potential of cleaning shall be examined for different glass coatings. For this purpose, the test methods to be applied shall be as realistic as possible and based on existing standards. Glass and coating abrasion shall be compared with regard to possible changes in optical transmission and reflection behavior as well as microstructural damage patterns.

Figure 1: Soiled PV modules, image was taken at the STF of QEERI after a dust storm in Doha, Qatar.

1.2 Objectives

The abrasion resistance of coatings and glass surfaces are evaluated on the basis of their optical performance before and after stress tests.

1.3 Fundamentals/Literature Overview

With regard to possible damage characteristics for glass coatings, it is particularly important to distinguish between differences in abrasion caused by natural factors such as wind-borne dust/sandstorms and abrasion caused by cleaning.

There are many different laboratory tests for the durability testing of coatings, some of which are described in standards. These include, among others, sand trickle tests (DIN 52348, ASTM D968), wind blow tests (MIL-STD-810G, IEC 60068-2-68, DIN ISO 9022-6, ASTM G76) or mechanical abrasion and scratch tests (DIN EN 1096-2, DIN 52347, ISO 20566, ASTM D6279, ASTM D7027). Up to now, all types of these tests have been used in the PV industry by glass manufacturers, AR coating suppliers and PV module manufacturers. However, the associated standards come from distinctly different application areas such as architectural glazing, military applications or the automotive industry and are therefore often designed for different environmental conditions, application specifications and product lifetimes. Scientific studies have shown that none of the standards in their existing form is well suited to accurately test the abrasion behavior caused by intensive cleaning.[1]

Within the scope of this study, abrasion tests are suggested, which are based on the damage mechanisms of frequent cleaning. For this, extensive preliminary work[2] was carried out by Fraunhofer CSP including the design of a test method which is as close as possible to reality but also follows existing standards.

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[1] Miller et al.: "Review of Artificial Abrasion Test Methods for PV Module Technology", NREL/TP-5J00-66334 (2016).

[2] This work was supported by the Federal Ministry for Economic Affairs and Energy (BMWi) within the project "Fidelitas" (funding no. 0325735C) and supported by the state of Saxony-Anhalt within the project „MetroLarge" (FuE 065/17)

2
Materials and Methods

2.1 Glass Samples Description

The following glass samples have been provided for testing from f | solar GmbH and commercial sources:

- *f | solarfloat T*:
  - short name F-T
  - float glass supplied by f | solar GmbH
  - 3.2 mm ESG
  - no ARC
- *f | solarfloat HT*:
  - short name F-HT
  - float glass supplied by f | solar GmbH
  - 3.2 mm ESG
  - ARC (single-side)
- *Ref-ARC*:
  - reference solar glass with state-of-the-art ARC (single-side, commercially available)
  - textured surface
  - 3.2 mm ESG

2.2 Brush Cleaning Test

Fraunhofer CSP developed a new test method and test setup for abrasion testing which realistically simulates damages caused by dry cleaning processes on soiled surfaces.
For this, the glass surface is homogenously covered with a test dust, a brush with defined properties (i.e. weight, material) is set upon the dusted surface and moved back and forth linearly for a certain number of brush cycles. This test was designed as a possible worst case cleaning scenario in order to obtain reliable results on abrasion resistance of various coatings as quickly as possible. The dry cleaning with a high dust load and linear brushing at comparably high contact pressure reflects damages which could arise for example from manual dry cleaning processes with typical nylon brushes applied by a field worker on soiled PV modules. It is known that potential cleaning damage could be reduced by the use of wet cleaning techniques or rotating brushes (i.e. automatic cleaning robots) with low contact pressure.

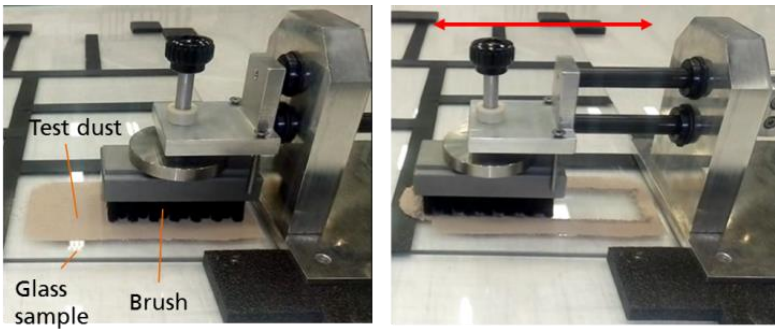

Figure 2: Images of brush testing procedure

The used test specifications were as follows:

- Testing Procedure by analogy to ISO 11998 and ASTM D2486 standards
- Brush specifications according to ASTM D2486 (Nylon, 454 g)
- Effective scrubbing length: 70 mm
- Test frequency 2 Hz / speed approx. 24 cm/s (based on DIN EN 1096-2 Appendix E)
- Uniform distribution of initial 1 g dry Arizona Test Dust A2 fine (defined in ISO 12103) on the glass surface, re-deposition of 0.5 g dust every 100 cycles
- Typical set of test cycles: 100, 200, 300, 400 and 500

The following table provides an approximation for expected damage scenarios for outdoor cleaning assuming that 1 brush stroke (1/2 cycle) reflects 1 manual cleaning operation:

Table 1: Approximation for expected damage scenarios

	Cleaning frequency		
Test cycles	**Daily**	**Weekly**	**monthly**
100	½ year	3,5-4 years	16-17 years
200	1 year	7-8 years	33 years
300	1,5 years	11-12 years	n.a.
400	2 years	15 years	n.a.
500	2.5 -3 years	19 years	n.a.

2.3 Characterization Methods

2.3.1 Optical Spectroscopy

In order to evaluate the influence of frequent cleaning by brush on the optical performance of solar glass and ARC also with respect to wavelength of the incident light, spectroscopic transmittance and reflectance measurements were performed. For this, a dual-beam spectrophotometer *Perkin Elmer Lambda 1050* with integrating sphere (Ø 150mm) was used. Due to the large sample sizes (tempered glass which cannot be cut) and configuration of the brush abrasion test setup, transmission measurements could only be performed in edge positions of the samples (undamaged areas). These results are used as a reference for calculations of light transmittance, see chapter 3.2.3. For the characterization of areas after brush testing, reflectance measurements were used.
The measurement of the hemispherical reflectance has been performed according to IEC CD 62805-2 © IEC:2015 (wavelength 300 to 1800 nm), whereby all measurements were carried out with incident light from the coating side. The measurement of the reflectance of substrates with extended dimensions was performed as shown in the pictures below. The substrate was placed on a frame adjustable in X and Y direction directly at the output of the reflectance measurement device. To avoid scattered radiation from the ambient, the system was covered by a black curtain during the measurement.

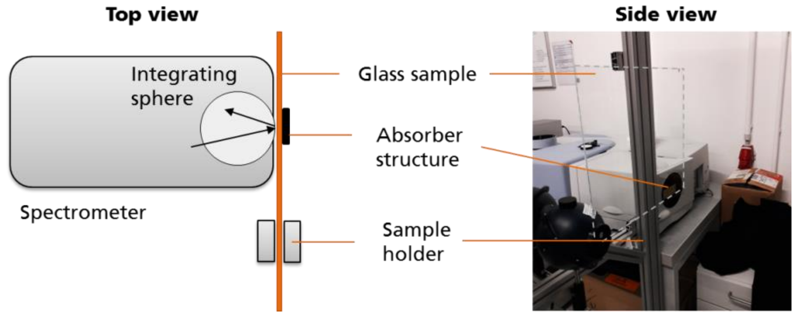

Figure 3: Reflectance measurement setup on large substrates

Reflectance measurements can be strongly influenced by surface structures introducing scattering of light, for example by changing internal reflections from the backside of the glass. Therefore, the second (backside) surface reflection has been reduced by a special absorber structure to reduce measurement uncertainty arising from the different surface structures of the glass samples. Both the results from measurements with and without absorber structure will be displayed in sections 3.1 and 3.2.

The measurement error of device can be estimated to be below 0.2 %, additional uncertainty of 0.5-1.0 % is introduced by large sample configuration, coating and abrasion inhomogeneity, positioning errors and relative humidity (water ingress) during the measurements and sample storage.

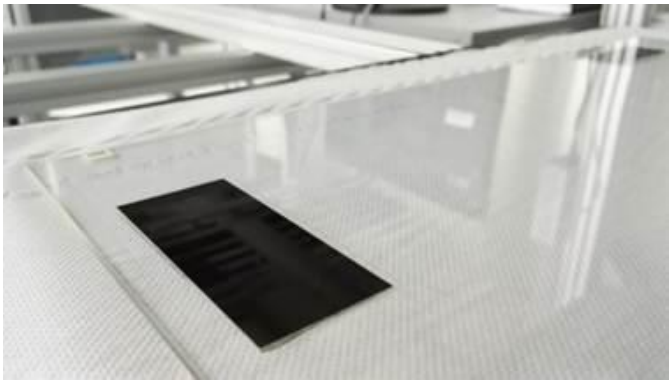

Figure 4: Absorber structure to reduce backside reflection

2.3.2 Light Microscopy

Optical microscopy inspection has been performed using a portal setup for inspection of large sample formats up to module size.
For this, a *Keyence Digital Microscope VHX-2000* (colour camera) with an *100-1000x objective* and the diffusor *OP 87299* was used.
The microscope has been operated in dark field imaging at diffuse light conditions which gives optimum results for scratch evaluation.

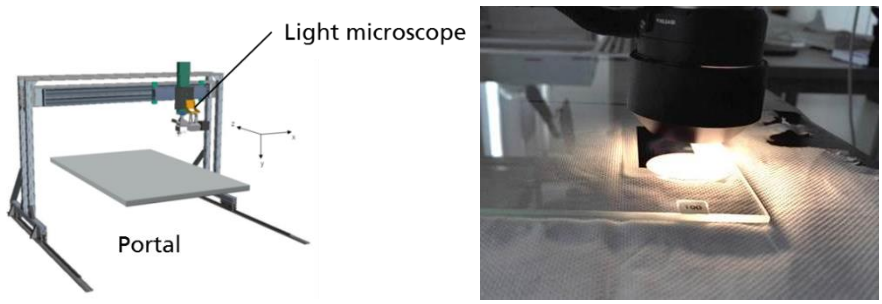

Figure 5: Portal for inspection of large sample formats up to module size

2.3.3 Scanning Electron Microscopy

High-resolution diagnostics of coating defects after abrasion testing were performed in scanning electron microscopy.
For target preparation of the tested coatings after abrasion by brush testing, small samples of 1.5 x 1.5 cm² were prepared from the middle of tested regions. The samples were conductively coated. For the microstructural investigations, a scanning electron microscope (SEM) *Hitachi SU70* was used, which is capable of high resolution SE-imaging. With acceleration voltage of 3kV, several regions were imaged in different magnifications up to 40k. The results were compared with results from undamaged or uncoated reference samples.

Figure 6: Scanning electron microscope (SEM) Hitachi SU70 for microstructural investigations of the glass surfaces.

3
Results

3.1 Initial Sample Characterization

Samples have been initially characterized before abrasion testing directly after unpacking and after several days of exposure to laboratory environmental conditions. In Fig. 7 (left), the reflectance measurement is shown for the samples F-T (*f* | *solarfloat T*), F-HT (*f* | *solarfloat HT*) and the commercial ARC-Ref sample.
The sample F-T (*f* | *solarfloat T*) shows the typical reflectance behavior of glass without ARC layer. The samples F-HT (*f* | *solarfloat HT*) and ARC-Ref present a decrease of reflectance at around 600 nm, that suggest the presence of ARC coating. The spectra exhibit an elevated reflection of more than 4% reflectance that is due to reflectance on both (front and back) surfaces of the glass.
Measurements of the samples F-T and F-HT after unpacking show a slight increase in reflection due to environmental and process conditions and sample aging. Adsorption of thin water films (change of refractive index) is presumably the main cause of these increases. The absorbed water film plays only a minor role in realistic application due to heating of surfaces during day (for PV, temperatures rise up to 70°C).

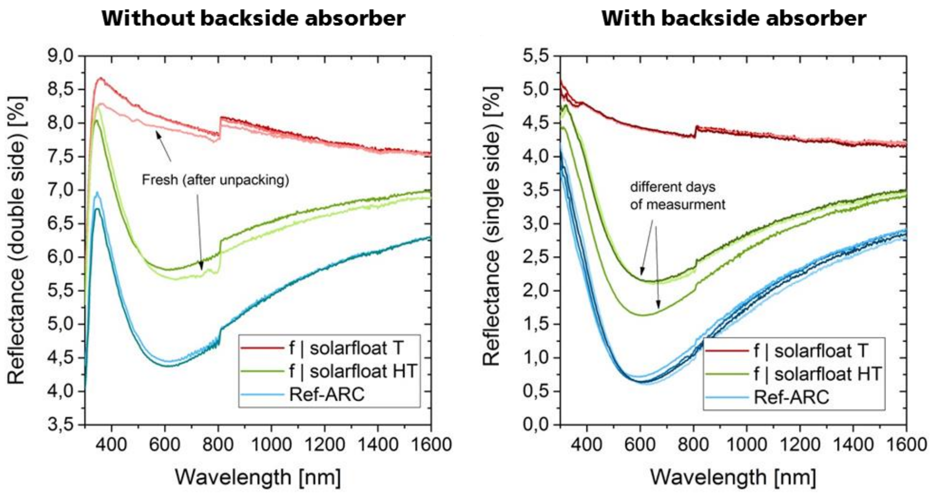

Figure 7: Spectral Reflectance of the fresh samples before abrasion testing including the backside sample reflection (without backside absorber coating) and suppressing the backside sample reflection (with backside absorber coating)

In order to obtain a better characterization of the reflectance related to the front side coating, it is necessary to suppress the internal reflection from the back side. For this purpose an absorber coating is attached at the back side of the glass.
The spectral reflectance of the front side of the samples F-T, F-HT and *Ref-ARC* is presented in Fig. 7 (right). As expected, the overall light reflection was significantly reduced compared to Fig. 7 (left) by inhibiting internal backside reflection.
The *Ref-ARC* sample shows about 1% less reflection than *f* | *solarfloat HT* at 600 nm. Here, we have to note that the *Ref-ARC* sample has – in addition to the ARC coating – also a micro pattern/structured glass surface. This pattern reduces the direct reflection of light but presumably increases the backward scattering.

The comparison of AR behavior/effect for F-HT in relation to F-T over several days/experiments shows very good agreement of reflection data. We conclude that the measurement method is stable for large glasses, which is also supported by the following considerations.

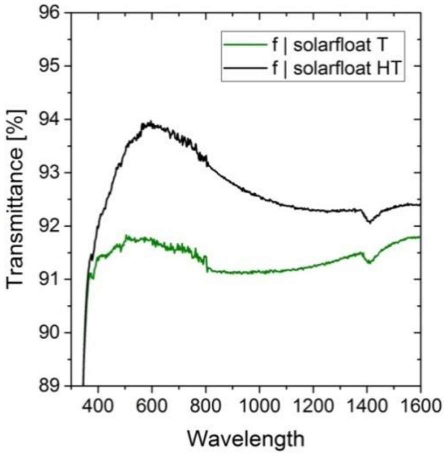

Figure 8: Measured hemispherical transmittance for coated F-HT (*f* | *solarfloat HT*) and uncoated F-T (*f* | *solarfloat T*) samples

The hemispherical transmission measurements (Fig. 8) show the expected course for F-T (f | solarfloat H) and F-HT (*f* | *solarfloat HT*) samples, in the range around 600 nm is obtained a maximum AR effect of 2.25%.

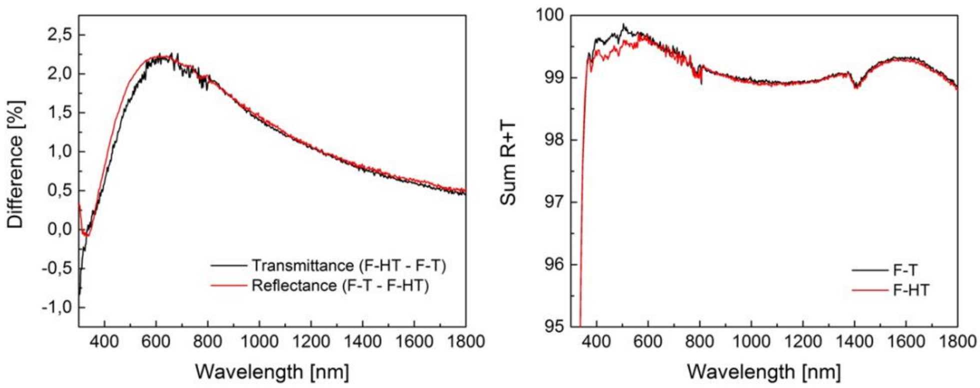

Figure 9: (left) Differences between coated F-HT and uncoated F-T samples for relfectance and transmittance measurements; (right) Sum of reflectance and transmittance for coated F-HT and uncoated F-T samples

Fig. 9 (left) shows the difference between the coated (F-HT) and uncoated (F-T) f|solarfloat samples as derived from of reflection and transmission measurements. Fig. 9 (right) shows the sum of reflectance and transmittance for both F-T and F-HT samples. Both results are almost identical for both samples (slight deviations in the UV-near range). This also indicates a good comparability of reflectance and transmittance measurements, which is needed for data interpretation and calculation of the equivalent light transmittance from reflectance measurements as can be seen in chapter 3.2.3.

3.2 Optical Performance after Brush Testing

3.2.1 Reflectance including front and back surface (without absorber structure)

The optical reflectance of the samples was investigated after various abrasion/cleaning cycles (0 – 500 by steps of 100). The results are presented subsequently, for *f | solarfloat T* (no ARC), *f | solarfloat HT* (with ARC) and *Ref-ARC*. Since the spectra are acquired without application of a back side absorber structure, it includes reflectance contribution from front and back of the glass.

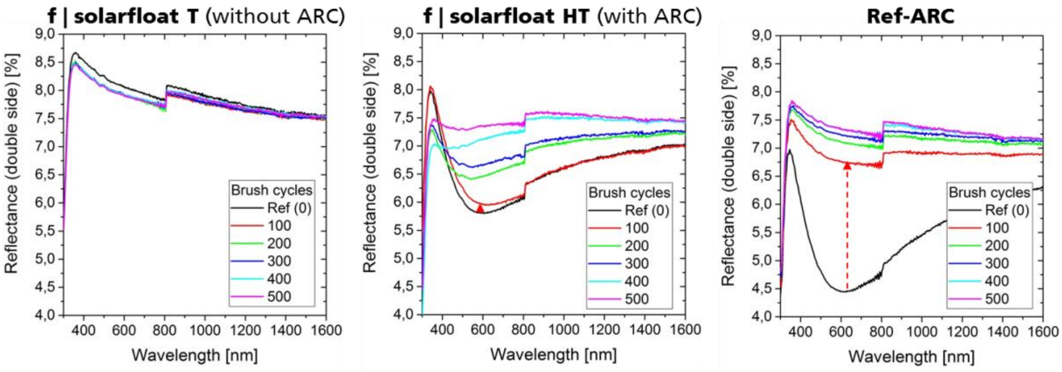

Figure 10: Reflectance including front and back surface (without absorber structure) for *f | solarfloat T* (without ARC), *f | solarfloat HT* (with ARC) and *Ref-ARC*

From the obtained data in Fig. 9 it is obvious that significant abrasion changes are not detected for *f | solarfloat T* without ARC. The spectral reflectance is ranging between 8 – 8,25 % at 600 nm.
The ARC coated sample *f | solarfloat HT* in Fig. 9 shows anti-reflective properties with reflectance continuously decreasing with the number of abrasion cycles from 5 % to 7,5 % at 600 nm. After 500 brush cycles a significant ARC behavior is still present compared to *f | solarfloat T* without ARC.
The initial AR-advantage of *Ref-ARC* (reflectance 4,5 % at 600 nm) vanishes after 100 cycles due to coating abrasion (see chapters 3.3 and 3.4) and approaches a rather stable behavior after 200 cycles which could correspond to a sample without ARC/complete coating abrasion. Here, the reflectance is ranging between 6,5 - 7,5 % at 600 nm.

3.2.2 Reflectance of front surface (with absorber structure)

As described in part 3.1 the back side reflection contribution leads to a systematic error in evaluation the front side reflection (ARC performance) only. In order to more precisely quantify the impact of the front side ARC abrasion due to cleaning processes, the optical characterization has been repeated with an absorber structure at the back of the glass sample.

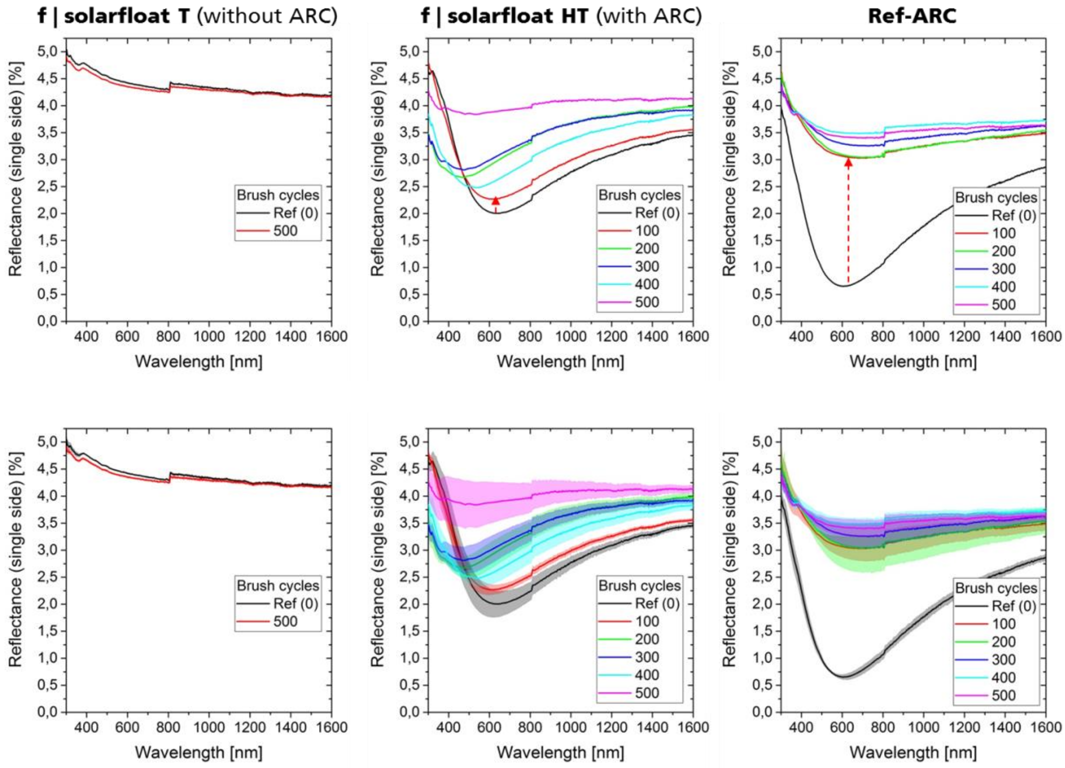

Figure 11: Mean values and standard deviation of reflectance from front surface (with absorber structure) for *f | solarfloat T* (without ARC), *f | solarfloat HT* (with ARC) and *Ref-ARC*. The standard deviation was plotted in an exra row for better visibility

The abrasion behavior as observed by the reflectance measurements without absorber structure is reproduced qualitatively for all samples, see Fig. 10. The displayed results represent the mean values of 4 measurements at different sample positions, the standard deviation is provided in the bottom graphs.
As before, the reflectance is not changing for *f | solarfloat T* without ARC with about 4,5 % reflectance at 600 nm before and after 500 abrasion cycles. A continuous reflectance increase is observed for *f | solarfloat HT* from 2 – 4 % at 600 nm over 500 abrasion cycles. A rapid increase within the first 100 cycles is observed for *Ref-ARC* from 0,75 % to 3 % at 600 nm.
As stated before, the measurement error of the measurement device can be estimated to be below 0.2 %, but an additional uncertainty of 0.5-1.0 % is introduced through the large sample configuration, coating and abrasion inhomogeneity, positioning errors as well as relative humidity. This is also clearly indicated by the standard deviation as plotted in Fig. 10. Within this approximation of uncertainty, there is still a clear difference in coating behavior with huge changes for the *Ref-ARC* within the first 100 brush cycles and only minor changes for *f | solarfloat HT* samples.

3.2.3 Calculation of transmittance from measured reflectance spectra

For the large, tempered glass samples, it was not possible to measure directly the transmission losses after brush testing due to experimental limitations in spectroscopy and abrasion test configuration. This was only possible locally close to undamaged/unstressed edges of the samples. Anyhow, another possibility is to calculate the transmission from the measured reflectance data on the basis of the glass transmittance of undamaged areas as was determined and presented in Fig. 8.

For the calculation of the transmission coefficient we start from energy conservation:

$$1 = R + T + A$$

where, R=reflectance, T=transmittance, and A=absorbance. The absorbance can be calculated from transmittance and reflectance measurements of the undamaged samples. The sum of (R + T) is displayed in Fig. 9 (right) for *f | solarfloat T* and *f | solarfloat HT*, indicating a comparable glass absorbance for both glass samples. Accordingly, in the following the absorbance was assumed to be constant as

$$A_{const} = 1 - (R + T)$$

with similar values for the *Ref-ARC* as well (not measured here due to absence of uncoated glass samples).
On that basis, the individual transmittance T_{calc} of the front surface was calculated from reflectance data R_{meas} for exemplary data sets as

$$T_{calc} = 1 - R_{meas} - A_{const}$$

For R_{meas}, the reflectance data from measurements with absorber structure were used because of their reduced measurement uncertainty. The calculated transmittance of the *f | solarfloat HT* and for the *Ref-ARC* are represented in Fig 12 and represent the light transmittance at the first/front surface.

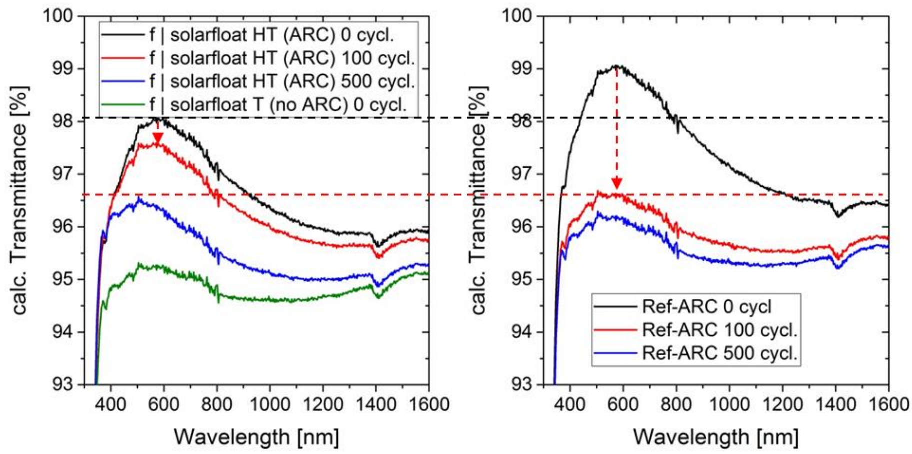

Figure 12: Calculated transmittance from reflectance measurements

Again, the results demonstrate that the initial AR-benefit from *Ref-ARC* compared to *f | solarfloat HT* vanishes already after 100 brush cycles. Furthermore, the graph clearly indicates that *f | solarfloat HT* shows also higher light transmittance for higher numbers of brush cylcles.

3.3 Scratch Evaluation by Light Microscopy

Finally, the microstructural appearance of the abrades regions has been investigated using optical microscopy for all 3 samples. Images have been acquired before abrasion test, after 100 and after 500 cycles, respectively. All sample positions were investigated at three different magnifications.

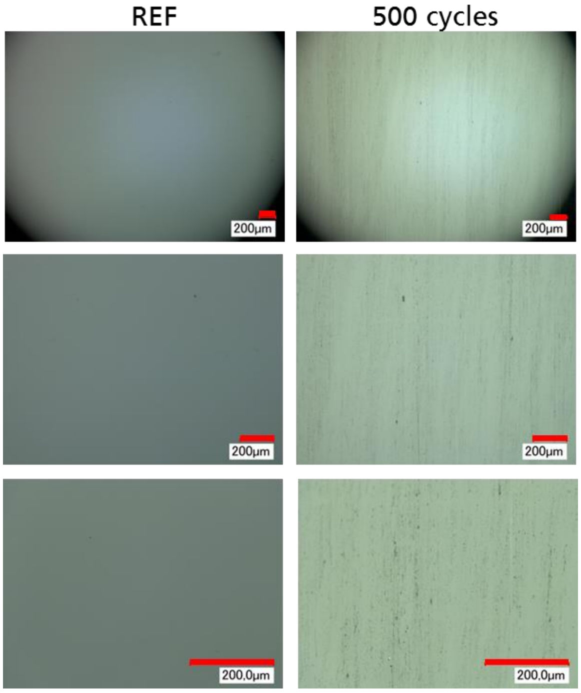

Figure 13: Light microscopy images at different magnification for *f | solarfloat T* undamaged reference (REF) and after 500 brush cycles

Fig. 13 shows the light microscopy images for *f | solarfloat T* substrates. There are only small changes visible in surface appearance of this uncoated reference glass before and after 500 brush cycles.

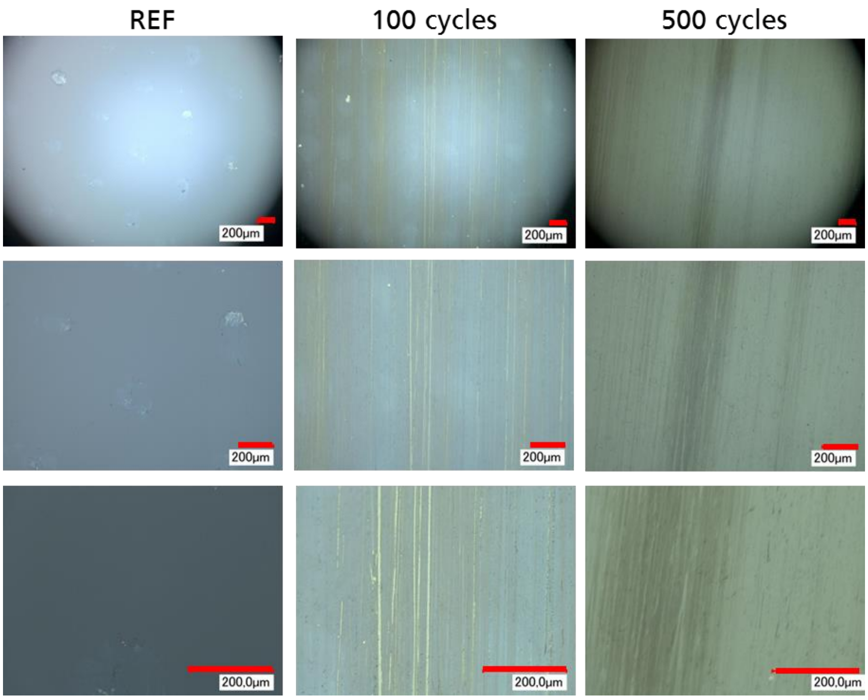

Figure 14: Light microscopy images at different magnification for *f | solarfloat HT* undamaged reference (REF) and after 100 and 500 brush cycles

The light microscopy images of the *f | solarfloat HT* in Fig. 14 show small visible patterns for the undamaged/non-stressed reference position (REF), which we attribute to coating contamination/damaging during the lamination process of the backside absorber. For the sample position after 100 brush cycles, the light microscopy indicates isolated, parallel scratches. Similar structures can be observed after 500 brush cycles.

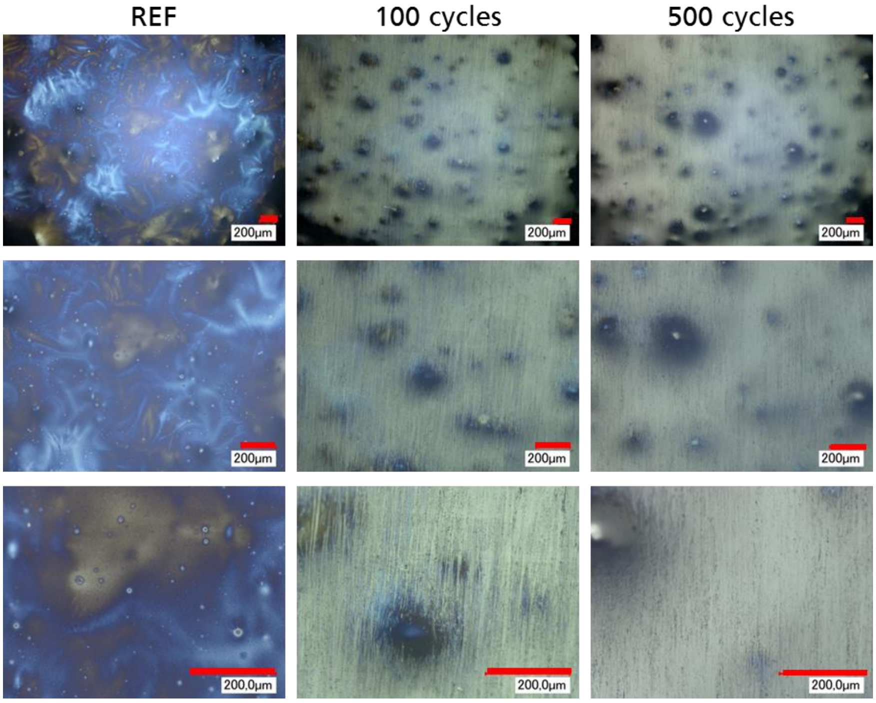

Figure 15: Light microscopy images at different magnification for *Ref-ARC* undamaged reference (REF) and after 100 and 500 brush cycles

For the *Ref-ARC*, the AR coating appears as „grey-bluish veil" in light microscopy, see Fig. 15. After 100 cycles of brush testing, the „veil" completely disappeared and scratch patterns are observed. Single, localized dark/bluish areas indicate an influence of the glass structure resulting in inhomogeneous coating abrasion. This could be attributed "valley-structures" in the surface which are more or less protected from mechanical load. After 500 cycles, the scratch patterns and bluish areas are less visible compared to 100 cycles, which indicates a nearly complete removal of coating.

3.4 Scratch Evaluation by Electron Microscopy

For high-resolution defect diagnostics, the abrasion/cleaning induced surface/coating damages have been investigated by scanning electron microscopy (SEM).

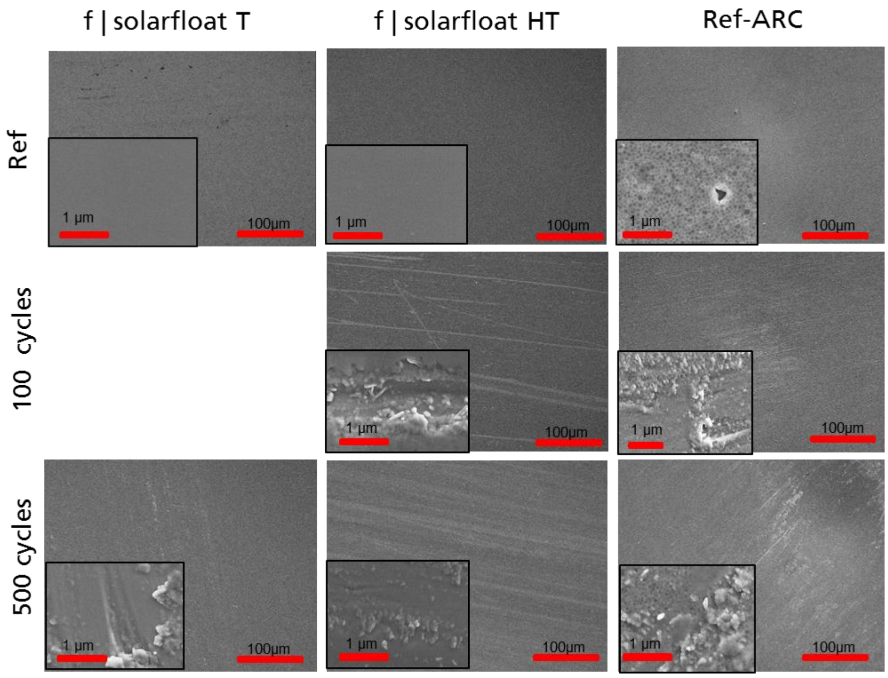

Figure 16: SEM overview images for differently stresses surfaces (undamaged reference Ref, after 100 and 500 brush cycles) at 300 fold magnification, inlets show the surface at 40k magnification

Fig. 16 shows SEM overview images and comparison of the samples investigated at 300 fold magnification, whereby the inlets show the surface at a magnification of 40,000 at the same sample position.

The SEM results confirm the results from light microscopy with no damages for the reference images. Even at higher magnification, no clear differences can be seen for *f | solarfloat T* and *f | solarfloat HT*. This can be attributed to the properties of the ARC coating which can be estimated to be rather dense and glass-like and therefore comparable to the uncoated glass surface. In contrast, the *Ref-ARC* shows a "bubble-like" morphology indicating a porous coating structure in the sub-micron range.

There are just a few superficial scratches detectable for the solar glass *f | solarfloat T* after 500 brush cycles.
In contrast, for the AR-coated *f | solarfloat HT*, already after 100 cycles localized, parallel scratches can be detected as bright stripes which are up to 100 µm apart. The investigation at high magnification indicates that for some detected scratches, both the ARC and the glass substrate got damaged. With an increase of the number of brush cycles to 500, the number and density of the scratches increased.
For the *Ref-ARC*, rather fine/thin scratch structures can be seen in the overview images. The high resolution images indicate a complete distortion of the "bubble-like" coating morphology already after 100 cycles, indicating a substantial distortion of the ARC. It should be noted that after 100 and after 500 cycles, localized areas were detected on the *Ref-ARC* where the coating morphology seems to be undamaged. This could be attributed to the surface structure which may "shades" some parts which are recessed in the glass surface from mechanical abrasion. However, these areas are very confined and make up only a small portion of the surface, see also the dark/bluish areas in Fig. 15.

4
Summary and Conclusion

Within this study, the damage potential of cleaning on solar glass (*f | solarfloat T*) and two different anti-reflective (AR) glass coatings (*f | solarfloat HT* and a commercial reference *Ref-ARC*) was examined.
For this, a new cleaning test method was developed based on the estimated damage mechanisms for frequent dry cleaning processes in desert environments and also based on existing cleaning/abrasion standards. For this, a standardized nylon brush was set upon soiled surfaces and moved back and forth linearly for a certain number of brush cycles. For the soiled surfaces, Arizona Test Dust A2 fine was used as abrasive media.

The glass and coating abrasion was compared for the different samples with regard to possible changes in optical transmission and reflection behavior as well as microstructural damage patterns.

For the reference solar glass *f | solarfloat T*, it was found that dry brushing causes only little damage to the glass surface which does not change hemispherical reflectance or transmittance even at high numbers of brush cycles.

The comparison of the initial anti-reflection performance of the two investigated coatings showed a better AR performance fot the *Ref-ARC* with about 1 % lower light reflectance/higher light transmittance at a wavelength of about 600 nm. However, already after 100 brush cycles, the *f | solarfloat HT* outperformed the *Ref-ARC* with up to 1 % lower reflection because of different abrasion resistance against dry brush cleaning. This behavior was also seen for higher numbers of brush cycles. While *f | solarfloat HT* indicated a rather continuously increase in reflection with number of brush cycles and AR properties present still after 500 brush cycles, the *Ref-ARC* showed a strong increase in reflection at the beginning with 100 cycles and only small changes for proceeding cleaning cycles.

These results are supported by microstructural investigations with light microscopy and electron scanning microscopy, indicating localized scratches for *f | solarfloat HT* and extensive coating distortion for the *Ref-ARC* already after 100 brush cycles.

By assuming a direct correlation between the developed dry brush test and realistic cleaning processes of glass surfaces in desert environments, 100 brush cycles of the test could be estimated to correspond to about 4 years of operation with weekly cleaning of soiled glass surfaces. The test itself is assumed to reflect a worst case cleaning scenario. Overall cleaning damages of the linear dry cleaning could be reduced by the use of wet cleaning techniques as well as rotating brushes.

Test Report: Cleaning Resistance of Glass Coatings (Summary)

Fraunhofer CSP

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Customer: f | solar GmbH, Mr. Ihno Baumann, Appendorfer Weg 5, 39171 Sülzetal (OT Osterweddingen)	
Offer Number: C 321138/17-ils	**Test date:** 20.09.2017 – ongoing
CSP Project Name.: CSP_fglasBau1	**CSP Project No.:** 431168
Report created by: Klemens Ilse	**Date:** 30.05.2018
Report revised by: Dr. Christian Hagendorf	**Date:** 30.05.2018

Objectives

Wearing resistance evaluation of anti-reflective coatings (ARC) against dry brush cleaning

Testing items

- *f | solarfloat T*: float glass supplied by f | solar GmbH, no ARC
- *f | solarfloat HT*: float glass supplied by f | solar GmbH, single-sided ARC
- *Ref-ARC:* reference solar glass with state-of-the-art ARC (textured surface, commercially available)

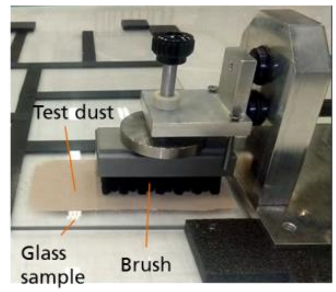
Cleaning test

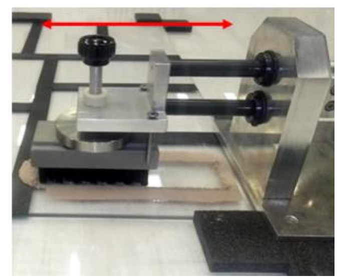
Fraunhofer CSP developed a test method and test setup for abrasion testing of large glass samples for realistic simulation of damages caused by dry cleaning processes on soiled surfaces. This test was designed in analogy to **ISO 11998, ASTM D2486** and **DIN EN 1096-2 Appendix E** standards with following testing parameter:

- Brush specifications according to ASTM D2486 (Nylon, 454 g)
- Effective scrubbing length: 70 mm
- Test frequency 2 Hz / speed approx. 24 cm/s (based on DIN EN 1096-2 Appendix E)
- Uniform distribution of initial 1 g dry Arizona Test Dust A2 fine (defined in ISO 12103) on the glass surface, re-deposition of 0.5 g dust every 100 cycles
- Testing of 100, 200, 300, 400, and 500 brush cycles

The testing procedure reflects a possible worst case cleaning scenario (dry cleaning with dust load and brushing). The following table provides an approximation for expectable damage scenarios for outdoor cleaning assuming that 1 brush stroke (1/2 cycle) reflects 1 manual cleaning operation.

	Cleaning frequency		
Test cycles	**Daily**	**Weekly**	**monthly**
100	0.5 years	3.5-4 years	16-17 years
500	2.5 -3 years	19 years	

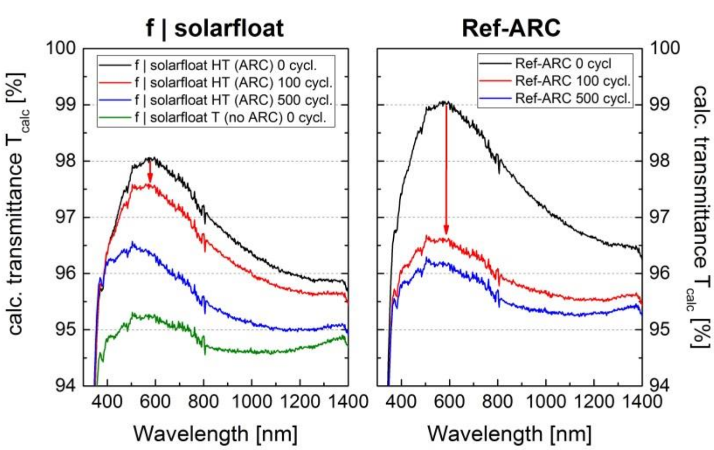




Sample characterization

- Measurement of hemispherical reflectance according to IEC CD 62805-2 © IEC:2015 (wavelength 300 to 1800 nm)[1]
- *Measurement device*: dual-beam spectrophotometer Perkin Elmer Lambda 1050 with integrating sphere Ø 150mm
- *Sample orientation*: all measurements were carried out with incident light from the coating side, second (backside) surface reflection has been reduced by a special absorber structure[2]

Test results



- Graph shows selected results for calculated light transmittance at the front interface (sunny-side) of tested glass before/after brush tests

  $T_{calc} = 100\% - R[\%] - A_{ref}[\%]$

  R… reflectance measured with backside absorber

  A_{ref}… absorbance of solar glass
- Optical performance before cleaning: at 600 nm *Ref-ARC* shows approx. 1% less reflection than *f | solarfloat HT*[3]
- *f | solarfloat HT* shows continuously increasing reflection with brush cycles
- *Ref-ARC* shows strong increase in reflection after 100 cleaning cycles and only minor variations for higher numbers of brush cycles
- Initial AR-advantage of *Ref-ARC* vanishes after 100 brush cycles due to coating abrasion (see red arrow)
- Scratch analysis using light and scanning electron microscopy indicated localized scratches for *f | solarfloat HT* and extensive coating distortion for the Ref-ARC already after 100 brush cycles
- After 500 brush cycles *f | solarfloat HT* still shows anti-reflective properties compared to *f | solarfloat T* (no ARC)
- In the context of measurement uncertainty, no changes in reflectance have been detected for *f | solarfloat T* (no ARC) after brush testing

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[1] Measurement error of device can be estimated to be below 0.2 %, additional uncertainty of 0.5-1.0 % is introduced by large sample configuration, coating and abrasion inhomogeneity, positioning errors, relative humidity

[2] Synowicki, Phys. stat. sol. (c) 5, No. 5, 1085–1088 (2008) / DOI 10.1002/pssc.200777873

[3] Note: glass surface of *Ref-ARC* is textured with a micro pattern, while *f | solarfloat HT* sample surface is smooth. Textures reduce direct reflectance.