AIP Conference Proceedings

Durability of anti-reflective coatings for parabolic trough receivers

Cite as: AIP Conference Proceedings **2303**, 150015 (2020); https://doi.org/10.1063/5.0028751
Published Online: 11 December 2020

Florian Sutter, Tomás Jesús Reche-Navarro, Gema San Vicente, and Aránzazu Fernández-García

Durability of Anti-Reflective Coatings for Parabolic Trough Receivers

Florian Sutter[1, a)], Tomás Jesús Reche-Navarro[1, b)], Gema San Vicente [2, c)], Aránzazu Fernández-García[3, d)]

[1] *German Aerospace Center (DLR), Plataforma Solar de Almería, Senes Road, Km. 4.5, P.O. Box 44, E04200 Tabernas, Spain.*
[2] *CIEMAT, Avd. Complutense 40, 28040 Madrid, Spain*
[3] *CIEMAT-Plataforma Solar de Almería, Senes Road, Km. 4.5, P.O. Box 22, E04200 Tabernas, Spain*

[a)] Corresponding author: Florian.Sutter@dlr.de
[b)] TomasJesus.RecheNavarro@dlr.de
[c)] gema.sanvicente@ciemat.es
[d)] afernandez@psa.es

Abstract. Anti-reflective coatings are employed on both sides of the glass envelope tube of evacuated parabolic trough receiver tubes to minimize reflectance losses. This paper reports the measured initial transmittance values of seven different receiver tube manufacturers as well as the degradation rates after accelerated aging, outdoor exposure and in-service testing. The presented data represents a summary of measurements carried out in the *OPAC* laboratory at Plataforma Solar de Almería in the period between 2013 and 2019.

INTRODUCTION

Anti-reflective coatings (ARC) are employed to reduce reflectance in a variety of products: eyeglass lenses, windows, photographic camera lenses, coupling components for optical fibers, telescope or microscope lenses… In CSP, anti-reflective coatings are used on the glass envelope tube, which covers the absorber coating of parabolic trough receivers (see **FIGURE 1**a). This glass cover is used to reduce thermal convection losses and to preserve the absorber coating form oxidation and environmental degradation. The glass tube is made of borosilicate glass, which has a low thermal expansion coefficient and therefore a good thermal shock resistance. A metallic bellow is employed to compensate the mismatch of expansion coefficients between the glass and the metallic absorber tube.

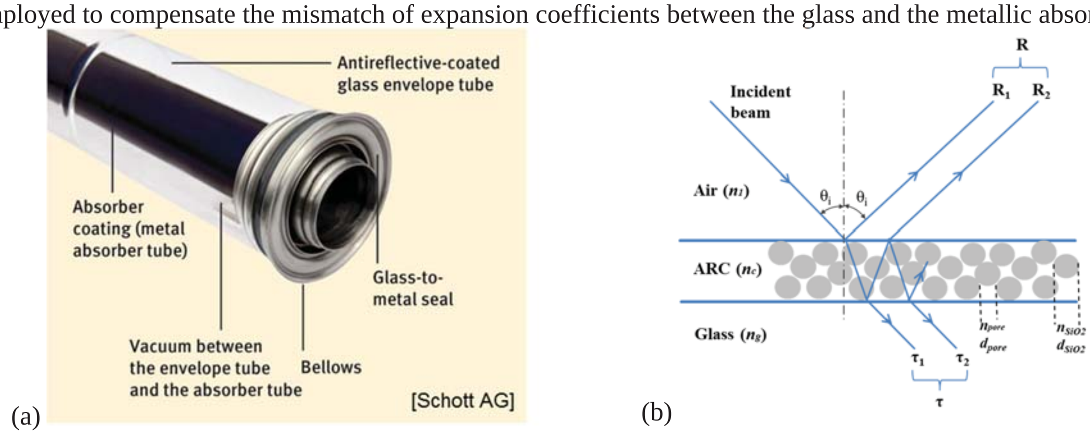


FIGURE 1. a) Typical receiver tube for parabolic trough technology. b) Optical path at surface of glass envelope tube with ARC.

SolarPACES 2019
AIP Conf. Proc. 2303, 150015-1–150015-10; https://doi.org/10.1063/5.0028751
Published by AIP Publishing. 978-0-7354-4037-1/$30.00

The 3 mm thick borosilicate glass tube has a solar-weighted hemispherical transmittance $\tau_{s,h}$ of 0.91-0.93, which is significantly higher compared to standard soda-lime glass ($\tau_{s,h}$ = 0.82-0.86). In order to minimize optical reflectance losses further, the inner and outer surface of the borosilicate glass are coated with an ARC, which typically increases $\tau_{s,h}$ to 0.96-0.97.

The anti-reflective effect relies on destructive interference, for which two conditions need to be fulfilled [1]:

1. The reflected rays at the air-coating and coating-glass interfaces R_1 and R_2 need to have the same amplitude (see **FIGURE 1**b), therefore

$$n_C = \sqrt{n_1 \cdot n_g} = \sqrt{1 \cdot 1.52} = 1.23 \tag{1}$$

   where n_1 is the refractive index of air and n_g the refractive index of the borosilicate glass tube.

2. The optical path difference between R_1 and R_2 needs to be an odd-numbered multiple of $\lambda_0/2$. Typically ARC coatings are designed for normal incidence ($\theta_i = 0°$) and for $\lambda_0 = 550$nm, since at solar spectrum peaks at this wavelength. From this it follows that the minimum ARC coating thickness d needs to be:

$$\mathrm{d} = \frac{\lambda_0}{4n_C} = \frac{550\mathrm{nm}}{4 \cdot 1.23} = 112nm \tag{2}$$

The required low refractive indices cannot readily be obtained in a bulk material. Instead, the low refractive index value is achieved by introducing porosity in the coating, consisting of high-index particles and low-index pores. The most widely used material as ARC on glass is silicon dioxide (SiO_2), forming a nano-porous layer where the pores are filled with a low-index medium (air). The sol-gel dip-coating technology is the most commonly used method for producing AR layers on large glass areas. The porosity can be achieved by using a colloidal solution or by adding a "porogen" material to the polymeric sol-gel solution. This compound is removed during a heat treatment, generating pores inside the polymeric silica films [2].

The pores in SiO_2-based materials tend to adsorb water from the relative humidity of the surrounding atmosphere, and also organic compounds or carbonates. Such contaminants increase the refractive index of the ARC and lower the transmittance. However, this process is mostly reversible [3].

The ARC's porosity is also its weak point in terms of durability. The low binding force between the SiO_2 particles among each other and to the substrate leads to weak mechanical performance [4]. In fact, special care needs to be taken during cleaning of AR coated receiver tubes in the solar field. Receiver tubes are typically cleaned by a pressurized water jet and several parameters like water pressure, nozzle diameter and distance can have an influence on the coating abrasion during the cleaning process. The study in [5] concluded that in order to avoid the risk of ARC delamination, the distance between a typical nozzle (25° and diameter of 0.55mm) the receiver should be larger than 30 cm. For 15°-nozzles the distance should be ≥ 40cm, while as for nozzles with confined water jet (0°) the coating was damaged under all conditions. The study conducted in [6], presents transmittance data of 80 receiver tubes after four years of operation in the 50 MW commercial parabolic trough plant in Seville (Spain). The measured average transmittance was 96.6 ± 0.2% and minimum of 95.0%. Thus, minor degradation was recorded after four years of receiver operation although it was not specified if or how the receiver tubes were cleaned during operation. A different study [7] reported stable transmittance after 14 months of outdoor exposure and 2200 h under condensation exposure inside a climate chamber of the ARC coating. The study in [2] showed that AR coated glasses degrade faster under artificial sand erosion conditions than the bare borosilicate glass. Coatings with reduced porosity (in [2] a hydrophobic coating with filled pores was tested) showed slightly lower initial transmittance, but the erosion rate was reduced considerably.

The recommended accelerated testing protocol of AR coated glass samples for CSP application has been elaborated in a draft of standard / technical specifications, codified as IEC 62862-3-3, which is under development within an expert group in the international committee IEC TC 117 for solar thermal electric plants [8]. According to the draft standard, the recommended tests to qualify ARC are: the stationary abrasion resistance test (also called Taber test [9]) and the humidity test according to ISO 6270-2:2005 [9]. Both tests are described more in detail in "materials and methods"-section of this paper.

Current research activities comprise the development of ARC with increased resistance to mechanical wear and combined anti-soiling or self-cleaning coatings on top of the ARC (see activities in the H2020 projects WASCOP and RAISELIFE). The aim of this paper is to summarize the measurements of outdoor exposed and accelerated aged samples that were conducted in the past 7 years on commercial ARC coatings. The presented results can then be used to benchmark new coating developments.

MATERIALS AND METHODS

Small AR coated glass envelope tube samples have been cut out of commercial full-size receiver tubes to an approximate size of 10 x 10 cm². The receiver tubes were sampled by independent third parties directly from the manufacturing lines. The glass thickness is 3 mm. The transmittance of the small samples was measured before and after testing in outdoor exposure, in-service and accelerated aging experiments as described below.

Sample Characterization

Prior and after testing, the samples were characterized with the double beam spectrophotometer *Perkin Elmer Lambda 1050* and the light microscope *Axio CSM 700* by *ZEISS*. Hemispherical transmittance is the easiest and the most reliable parameter to be measured. On the other hand part of the transmitted radiation could be scattered by ARC roughness out of the acceptance angle of the receiver, and be lost to the energy conversion process. That loss is not evidenced by hemispherical measurements.

Before each measurement, the samples were immersed for 2 minutes in ethanol. The samples were blown dry and eventual dust was removed by filtered pressurized air. Immediately afterwards the sample's transmittance was measured. This had the purpose to minimize adsorption of ambient humidity by the porous anti-reflective coating, since adsorbed humidity would influence the optical transmittance.

Spectral hemispherical transmittance, $\tau_{\lambda,h}$, was measured with a setup consisting of a *Perkin Elmer Lambda1050* spectrophotometer with an integrating sphere of 150 mm diameter in the solar wavelength range of λ = 280 – 2500 nm and at an incidence angle of θ_i=8°. The wavelength resolution of the measurement was dλ= 5 nm. The measurement light beam was incident on the convex side of each sample at the measurements and had the size of approx. 9 x 17 mm². The long side of the illuminated area was aligned with the longitudinal axis of curvature of the sample. Baseline measurements of air were used as a reference for 100% transmittance and the sample transmittance was calculated using the following equation:

$$\tau_{\lambda,h} = \frac{I_{sample}(\lambda) - Zeroline(\lambda)}{I_{air}(\lambda) - Zeroline(\lambda)} \quad (3)$$

where I_{sample} denotes the measured detector intensity recorded during the sample measurement and I_{air} is the measured baseline intensity in air. Prior to the measurements a Zeroline has been recorded in order to correct the measurements from noise. The Zeroline is recorded by performing a wavelength scan in the dark.

Following ASTM Standard E903-82 (92) [12], the solar-weighted hemispherical transmittance, $\tau_{s,h}$, can be calculated by weighting the spectral transmittance, $\tau_{\lambda,h}$, with the solar direct irradiance G_b on the earth surface for each wavelength according to equation 4. For European and North American latitudes typical solar irradiance spectra are given by the current standard norms ASTM G173-03 [13] (direct irradiance) for air mass AM 1.5.

$$\tau_{s,h} = \frac{\int_{280nm}^{2500nm} \tau_{\lambda,h} \cdot G_b(\lambda) d\lambda}{\int_{280nm}^{2500nm} G_b(\lambda) d\lambda} \quad (4)$$

The spectral transmittance, $\tau_{\lambda,h}$, was measured on three slightly different spots per sample. From the 3 measurements, an average spectrum was computed. The solar-weighting to compute $\tau_{s,h}$ according to equation (4) is performed with the average spectrum.

Outdoor Exposure Testing (OET)

ARC samples were exposed to the ambient conditions of two different environments:

- **Outdoor exposure at Plataforma Solar de Almería in Tabernas, Spain:** four samples were weathered for a total exposure time of 12 months. An intermediate optical characterization was performed after 6 months of exposure. The samples were exposed on an exposure rack at 1.5 m above the ground.
  Two of the four exposed samples were cleaned every two weeks with pressurized water using the spray gun Kärcher HDS 10/20-4M (see FIGURE 2a). The pressure was 100 bar, the distance between nozzle and sample

was 50 cm, the nozzle angle was 25° and the diameter was 0.54mm. Cleaning was always performed the same way with five strokes per sample (about 3 seconds in total).
The other two samples were cleaned with the same device but using a contact cleaning method with a brush under a low pressure water flow. Also 5 strokes were conducted for each cleaning operation (about 7 seconds in total).
Demineralized water was used for both cleaning methods.

- **Outdoor exposure at Zagora, Morocco**: one sample was exposed for 1.8 years. No intermediate measurements were conducted. The sample was exposed at a height of about 1m from the ground (see FIGURE 2b). Zagora is known to be an aggressive site in terms of sand erosion and has caused erosion damage on several exposed glass mirror samples [11].

(a) (b)

FIGURE 2. Outdoor exposure testing a) Cleaning devices used for the exposure experiments in Tabernas, Spain. b) Exposure of sample from manufacturer B in Zagora, Morocco.

In-Service Testing (IST)

Cut glass envelope tube samples from receiver tubes have been received by plant operators. For confidentiality reasons the exact exposure location and cleaning procedure is not published in this paper.

- **In-service testing in demo plant:** The samples have been in operation for 1.6 years in a demo plant located in Southern Europe. The receiver tubes have been cleaned approximately 3 times per month using pressurized deionized water.

- **In-service testing in commercial plant:** the samples have been in operation during 5 years in a commercial power plant in Southern Spain. No information on the cleaning method is disclosed.

Accelerated Aging Testing (AAT)

The following two accelerated aging tests recommended in [9] were conducted on the ARC samples:

- **Condensation test** according to ISO 6270-2 [11] consisting in exposure of the samples to the constant climate of 40°C at 100% relative humidity during 480 hours. The purpose of this test is to determine the possible degradation of the AR coated glass envelope to a condensation-water atmosphere. Note that in this test both sides of the glass envelope tube are exposed to condensation water. In real operation only the outer surface would be in contact with the condensing humid atmosphere, since the inner part of the receiver tube is evacuated.
- **Abrasion resistance test** (Taber test) according to [9]: This test is meant to simulate the mechanical wear of the glass coating in the solar field due to cleaning, sandstorms or other mechanical forces on the glass surface. Even though the test does not reproduce the abrasion mechanism experienced by the ARC during operation in a realistic way, it is still a useful method to compare the mechanical stability of different ARC under controlled conditions. The test parameters described in [9] are based on ISO 9211-4.

The Taber Linear Abraser – Model 5750 was used to carry out the test (see **FIGURE 3**a). The test consists of an abrasion head, which is moving with low pressure on the glass surface in a straight line back and forth. The abrasion head material consists of abrasive inside a rubber matrix. One cycle is defined as the movement of the grinding head once forth and back. The movement of the abrasion head produces grinded stripes on the glass surface, where the light transmittance is affected by the scratches. The normal force acting on the sample is constant throughout the test, the mass of arm and abradant pushing on the surface of the sample is 350g. The velocity of the moving arm is 7 cycles per minute at a stroke length of 38.1mm. Samples have been rotated several times to increase the abraded area necessary to perform transmittance measurements. The abradant used is the MIL-E-12397 which is very mild abrading action. Its diameter is 6 mm (see **FIGURE 3**b).
Before each test the surface of the abradant is shaped by performing 5 cycles using an abrasive paper glued to a glass envelope tube sample. The abradant is cleaned carefully with a brush after being reshaped. That way homogeneous contact between sample and abradant across the entire diameter is assured. Transmittance was measured after 20, 50 and 100 cycles of testing.

(a) (b)

FIGURE 3. a) Taber Linear Abraser used to conduct the abrasion resistance test. b) Abradant according to MIL-E-12397

RESULTS

Transmittance in Pristine Condition

FIGURE 4 shows the solar-weighted hemispherical transmittance of glass envelope tubes of seven tube manufacturers as deposited in pristine condition. It can be seen that all manufacturers achieve transmittance values $\tau_{s,h}$ >0.955. The highest transmittance measured is $\tau_{s,h}$ = 0.978. The average transmittance of the different manufacturers is $\tau_{s,h}$ =0.968 (indicated by the dashed line). This value can be considered as the state of the art.

Note that samples from manufacturer E have been deposited on different glass substrates, which can explain the high standard deviations.

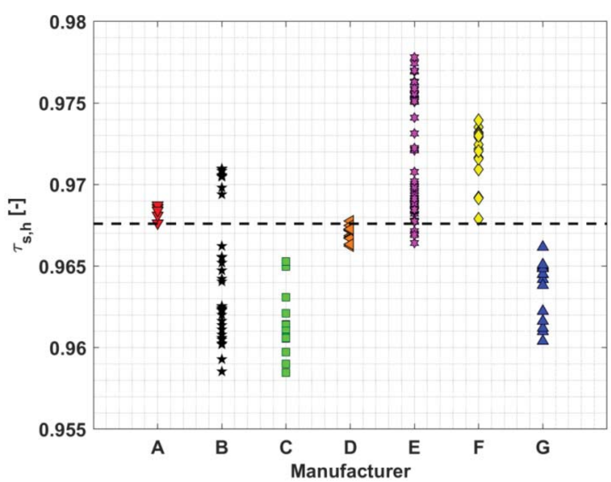


FIGURE 4. Solar-weighted hemispherical transmittance $\tau_{s,h}$ of the ARC samples of seven manufacturers in pristine state before aging. The dashed line indicates the average $\tau_{s,h}$ from the different manufacturers.

Aging Testing

FIGURE 5 shows a summary of the measured degradation of solar-weighted hemispherical transmittance $\Delta\tau_{s,h}$ after the conducted aging tests. As described in the introduction, the 3 mm thick borosilicate glass tube achieves a solar-weighted hemispherical transmittance $\tau_{s,h}$ of typically 0.92 and the ARC boosts the $\tau_{s,h}$ to 0.968 as seen in the previous section. Hence, the ARC is responsible for a transmittance gain of approximately 0.05. Since both sides (inner and outer surfaces) of the glass tube are coated with ARC, one can estimate that each ARC is responsible for a transmittance gain of 0.025. This needs to be taken into account for interpretation of the results. The red line in **FIGURE 5** represents the transmittance gain caused by the ARC of 0.05 (for samples tested from both faces) and 0.025 (for samples tested from only one face). Degradation beyond those limits means that either the glass substrate is being damaged throughout the test or that a non-coated borosilicate sample would perform better. This is the case for the OET in Morocco and partly for the IST in Southern Europe, while abrasion testing up to 100 Taber cycles also approaches the 0.025 degradation limit. For all the other tests, the measured degradation is below the red line, meaning that the ARC is still contributing to a transmittance gain after the conducted aging tests.

The red line is dashed for the OET experiments since those samples were exposed from both sides to the climatic conditions of Tabernas and Zagora but only the front side is subjected to the predominant degradation mechanism. In Tabernas, the samples are only cleaned from the front side in 2 week intervals and in Zagora the predominant wind direction is southwest, meaning that the sand particles will only degrade the front side of the coating. However, a minor degradation of the AR back coating cannot be excluded and this is why the line is dashed.

The results shown in **FIGURE 5** will be discussed more in depth in the following subsections.

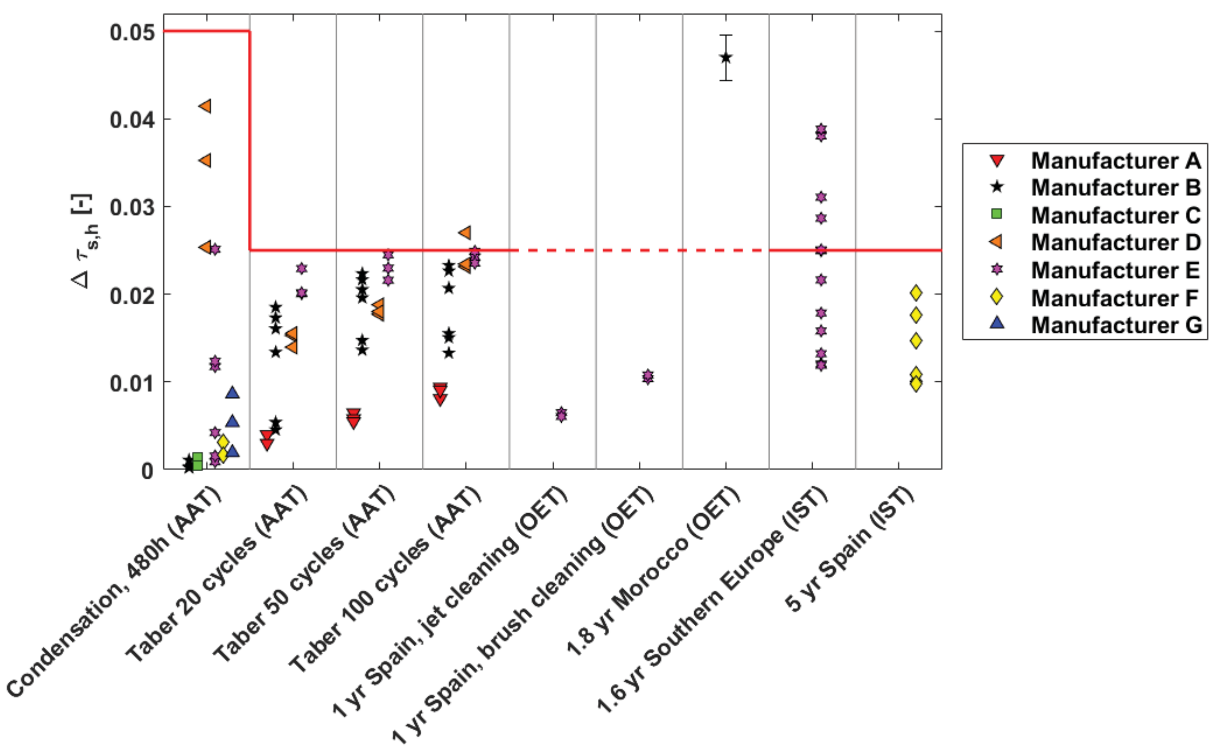


FIGURE 5. Summary of measured transmittance losses $\Delta\tau_{s,h}$ during AAT, OET and IST from seven manufacturers A-G. Each dot corresponds to the average value of one measured sample at 3 different spots.

Outdoor Exposure Testing (OET)

The conducted outdoor exposure tests in Tabernas, Spain demonstrate the influence of the applied cleaning method on the ARC degradation rate. **FIGURE 6** shows the measured transmittance spectra in initial state and after

6 and 12 months of exposure of ARC samples from manufacturer E. The samples, which were cleaned by pressurized water in two week intervals, degraded by $\Delta\tau_{s,h}$ = -0.006 ± 0.001, while the samples, which were cleaned by brush, showed a higher degradation rate of $\Delta\tau_{s,h}$ = -0.010 ± 0.002. The microscopic analysis revealed several scratches in the ARC, showing that the applied contact cleaning method is not applicable. The glass substrate was not affected by the brush cleaning.

The sample tested in Zagora, Morocco shows a degradation close to $\Delta\tau_{s,h}$ = -0.05. The strong reduction in transmittance is not only related to ARC degradation. The exposed sample also shows signs of erosion of the borosilicate glass substrate due to the aggressive sand impacts in Zagora (see **FIGURE 7**b).

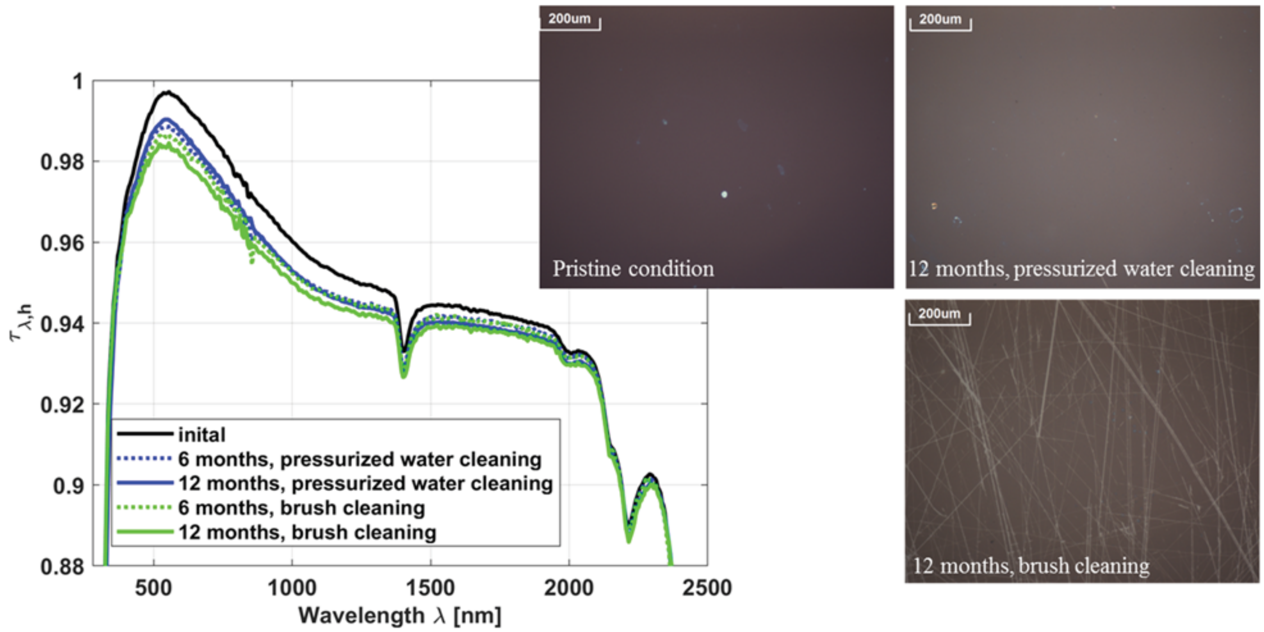
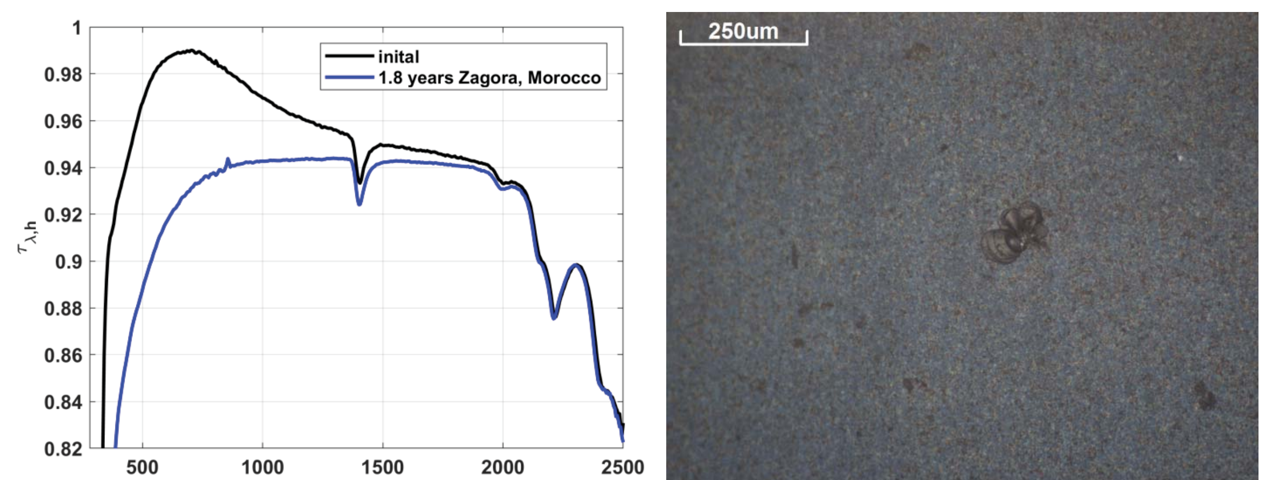


FIGURE 6. Spectral hemispherical transmittance of ARC samples from manufacturer E in initial state and after 6 and 12 months of outdoor exposure in Tabernas, Spain, as well as corresponding microscope images.



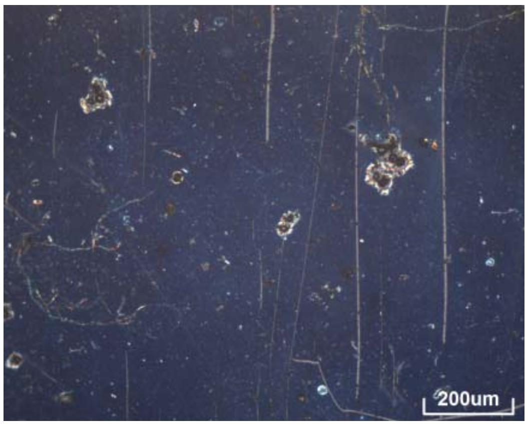
(a) (b)

FIGURE 7. ARC sample from manufacturer B after 1.8 years of OET in Zagora, Morocco. a) Spectral degradation of hemispherical transmittance. b) Microscopic image of ARC coating degradation and glass erosion.

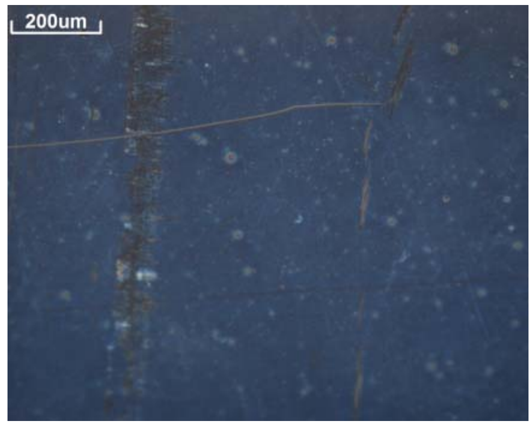
In-Service Testing (IST)

The in-service tested samples also show abrasion as main degradation mechanism, although the risk of sand erosion is considerably low in European exposure sites. Scratching of the anti-reflective layer of these samples is probably caused during the cleaning process. Samples from manufacturer E have been cleaned 2.7 times per month with pressurized deionized water. The average transmittance loss of the samples exposed in the demo plant for 1.6 years was $\Delta\tau_{s,h}$ = -0.023±0.008, meaning that some samples exceeded the 0.025 degradation limit (compare **FIGURE 5**). This can also be explained by degradation of the glass substrate. **FIGURE 8**a shows signs of erosion craters in the glass substrate which might have been caused during the cleaning process or due to small rocks hurled during passing of the cleaning vehicle.

After 5 years of in-service testing in a Spanish CSP plant, the measured degradation on the tubes from manufacturer F was below 0.025 ($\Delta\tau_{s,h}$ = -0.014 ± 0.002), meaning that after 5 years of operation the ARC is still contributing to a transmittance gain of the receiver (**FIGURE 8**b). No information regarding the cleaning procedure is available.



(a)



(b)

FIGURE 8. a) Abrasion and scratching on sample from manufacturer E after 1.6 years of IST in Southern Europe. b) minor defects on samples from manufacturer F after 5 years of IST in Spain.

Accelerated Aging Testing (AAT)

FIGURE 5 shows that four out of six manufacturers pass the condensation test with transmittance losses below $\Delta\tau_{s,h}$ = -0.01. The highest degradation measured is $\Delta\tau_{s,h}$ = -0.041 for manufacturer D. During condensation testing, both coated sides of the glass tube are exposed to the conditions of the accelerated aging chamber. After 480 hours of testing, all tested samples show a higher transmittance than a bare glass tube. The measured degradation is smaller than $\Delta\tau_{s,h}$ = -0.05 in any case.

The Taber abrasion test shows the expected increment of transmittance losses with growing cycle number (see **FIGURE 5**). Complete removal of the ARC on one side of the sample would result in a transmittance loss of $\Delta\tau_{s,h}$ = - 0.025. After 100 cycles of testing, most of the coating from manufacturers D and E is removed, while coatings from manufacturers B and especially A show higher abrasion resistance. **FIGURE 9** shows a comparison of samples from manufacturers A and D up to 100 cycles of Taber testing. While samples from manufacturer A lost $\Delta\tau_{s,h}$ = -0.009 ± 0.001, the ARC samples from manufacturer D lost $\Delta\tau_{s,h}$ = -0.025 ± 0.002. The microscopic images confirm that the ARC has almost been completely removed in the case of manufacturer D.

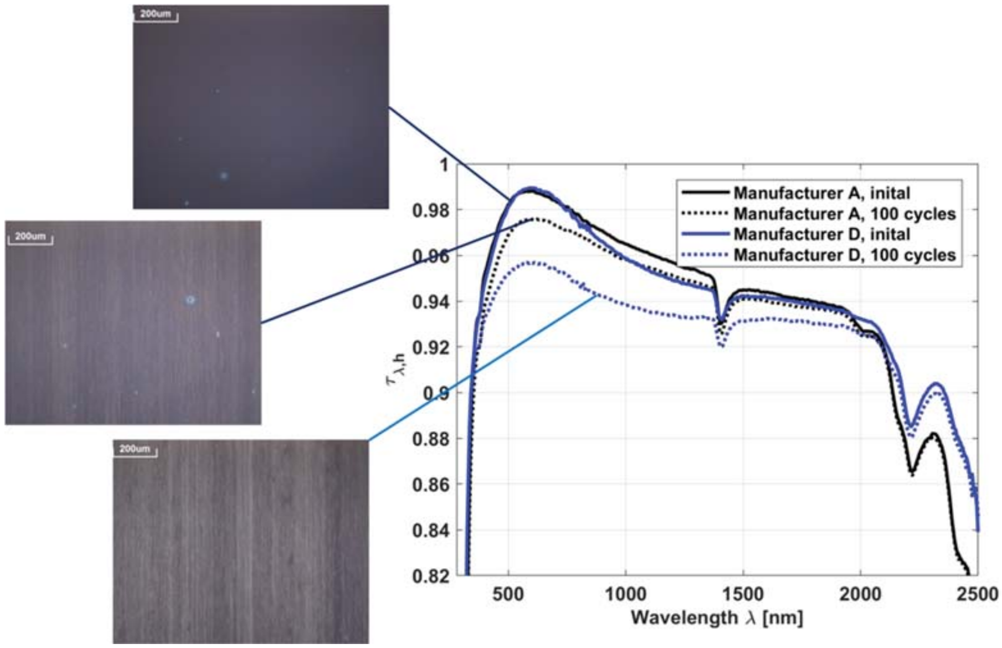


FIGURE 9. Spectral hemispherical transmittance of ARC samples from manufacturer A and D in initial state and after 100 cycles of Taber abrasion testing, as well as microscope images.

CONCLUSION

This paper presented initial transmittance and degradation data of AR coated glass envelope tubes from different manufacturers. The data can be used to benchmark different commercial receiver tube manufacturers. The average initial solar-weighted hemispherical transmittance of $\tau_{s,h}$ = 0.968 can be considered as the state of the art. Degradation rates of $\Delta\tau_{s,h}$ = 0.009 and 0.019 can be considered the state of the art for the accelerated Condensation and Taber abrasion test after 480 hours and 100 cycles respectively.

The samples tested during outdoor exposure, revealed that pressurized water cleaning at 100 bar with a 25°/0.54 mm nozzle, keeping a distance of 50 cm between the nozzle and the samples, caused less abrasion than contact cleaning with a soft brush and demineralized water. Abrasion was the main degradation mechanism detected during the microscopic analysis of samples tested outdoors. Thus, it is of importance to carefully select the cleaning procedure to ensure the life-time of the receiver tube. After 5 years of in-service testing in a Spanish CSP plant, only a low degradation rate of $\Delta\tau_{s,h}$ = -0.014 ± 0.002 was measured, showing that the ARC can be a long-lasting and profitable enhancement to raise the optical efficiency of parabolic trough receiver tubes.

NOMENCLATURE

AAT	Accelerated aging testing
AR	anti-reflective
ARC	anti-reflective coating
CSP	Concentrated Solar Power
d	thickness of the ARC
$G_b(\lambda)$	spectral direct normal irradiance of the ASTM G173-03 reference spectrum, in $W \cdot m^{-2} \cdot nm^{-1}$.
h	hemispherical
I_{air}	measured baseline intensity of the spectrophotometer in air
I_{sample}	measured detector intensity of the spectrophotometer during the sample measurement
IST	In-service testing
n_1	refractive index of air
n_c	refractive index of the ARC
n_g	refractive index of borosilicate glass envelope tube

OET	Outdoor exposure testing
$\Delta\tau_{s,h}$	Solar-weighted hemispherical transmittance loss
θ_i	incidence angle, in °
λ	wavelength, in nm
λ_0	design wavelength of the ARC, in nm
$\tau_{s,h}$	Solar-weighted hemispherical transmittance
$\tau_{\lambda,h}$	Spectral hemispherical transmittance

ACKNOWLEDGEMENTS

The research conducting to the results of this paper has partly been funded by the EU H2020 project WASCOP under Grant Agreement 654479. The authors thank the staff of the OPAC laboratory, where the accelerated aging tests have been carried out.

REFERENCES

1. F. Pedrotti, L. Pedrotti, W. Bausch, H. Schmidt, Introduction to Optics (originally in German: Optik für Ingenieure) (ISBN 3-540-22813-6), Springer, 2005
2. F. Wiesinger, G. San Vicente, A. Fernández-García, F. Sutter, A. Morales, R. Pitz-Paal: Sandstorm erosion testing of anti-reflective glass coatings for solar energy applications. Solar Energy Materials and Solar Cells 179 (2018) 10-16
3. K. Nielsen, T. Kittel, K. Wondraczek, L. Wondraczek: Optical Breathing of Nano-porous Antireflective Coatings through Adsorption and Desorption of Water. Scientific Reports 4:6595 (2014) DOI: 10.1038/srep06595.
4. A. Morales, G. San Vicente: Catalogue of Best Practices of RAISELIFE project. To be published in 2020.
5. M. Arntzen, S. Dreyer, J. Specht, T. Kuckelkorn, M. Schmidt, A. Sauerborn. Accelerated Ageing Tests on Schott PTR 70 HCE, SolarPACES 2011, Granada, Spain, (2011)
6. G. Espinosa-Rueda, J. Navarro Hermoso, N. Martínez-Sanz: Degradation of receiver tube optical performance after four years of operation. Solar Energy 135 (2016) 122-129
7. G. San Vicente, R. Bayón, N. Germán, A. Morales: Long-term durability of sol–gel porous coatings for solar glass covers. Thin Solid Films 517 (2009) 3157–3160.
8. F. Sallaberry, A. García de Jalón, J. García Barberena, I. David Bernad: Standardized Testing of Receiver Tubes and Solar Mirrors of Parabolic Trough Solar Thermal Power Plants. AIP Conference Proceedings 2126, 120019 (2019); https://doi.org/10.1063/1.5117637
9. IEC 117/104/DTS: Solar thermal electric plants – Part 3-3: Systems and components – General requirements and test methods for solar receivers
10. ISO 6270-2:2017: Paints and varnishes – Determination of resistance to humidity – Part 2: Condensation (in-cabinet exposure with heated water reservoir)
11. F. Wiesinger, F. Sutter, F. Wolfertstetter, N. Hanrieder, A. Fernandez-Garcia, R. Pitz-Paal, M. Schmücker: Assessment of the erosion risk of sandstorms on solar energy technology at two sites in Morocco. Solar Energy 162 (2018) 217-228.
12. ASTM E903-82. Standard Test Method for Solar Absorptance, Reflectance, and Transmittance of Materials Using Integrating Spheres, ASTM International, 2012.
13. ASTM G173-03 Standard Tables for Reference Solar Spectral Irradiances: Direct Normal and Hemispherical on 37° Tilted Surface, ASTM International, 2003.