SFERA
(Solar Facilities for the European Research Area)

Thermal testing of solar mirrors for secondary concentrators

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

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1 INTRODUCTION

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

The selected mirror samples were exposed to different levels of concentrated radiation [1] to investigate their suitability for operation under these flux conditions.

2 SCOPE

Solar mirrors of secondary concentrators are exposed to high radiation flux for a long period of time. In this task potential reflecting surfaces shall be exposed to flux concentrations similar to the ones that will occur in secondary concentrators. Major issue is the potential degradation of the mirrors due to high material temperature.
Hence the purpose of the test is to investigate, whether a mirror construction is capable to withstand a certain flux density. Therefore the samples for these tests should be cooled in the same way as anticipated for a CPC using these mirrors. For 3D-CPC's (e.g., tower systems) this normally requires water cooling, for 2D-CPC's (e.g., Fresnel systems) air cooled mirrors will be considered as well.

3 SAMPLES

Two water cooled and one air cooled (maximal temperature allowance 350 °C) system were tested. The water cooled mirror samples were glued onto a structure similar to its later use in a solar system, i.e., a water cooled aluminium plate, to analyse the behaviour of the complete system. The air cooled samples will only be cooled by natural convection. The assembly and dimensions of the three different samples are presented in Figs. 1, 3 and 5, while Figs. 2, 4 and 6 provide photos of respective samples.
Sample *PSI* consists of an aluminium plate (122 x 122 x 20 mm^3) with three bore holes. The cooling water flows in serial through all three holes. On the top surface an aluminium mirror foil (80 x 80 x 0.5 mm^3) with special top layers provided by company A is glued with twin-sided high temperature and high thermal conductivity adhesive tape in the geometrical centre, Figs. 1+2. This material without the cooling plate has manufacturing code "1" in the weathering tests Ref. [4].
Sample *DLR* consists of an aluminium plate (80 x 80 x 15 mm^3) with two bore holes. The cooling water is led in serial through the two bore holes. A glass-silvered mirror (80 x 80 x 1 mm^3) is glued onto the plate with high temperature adhesive, Figs. 3+4. Sample *DLR* is divided into three types of edge protection of the water cooled plate. One is untreated and the other two are "type 1" and "type 2", respectively. The untreated one has manufacturing code "5", protected type 1

code “6” and protected type 2 code “7” in Ref. [4] (same mirror sample, but different plate thickness underneath).
Sample *SOL* consists of a both front and back glass covered mirror (80 x 80 x 2 mm^3) with silver reflective layer of 70 x 70 mm^2, provided by company B This sample is not actively cooled but only cooled by natural convection, Figs. 5+6.

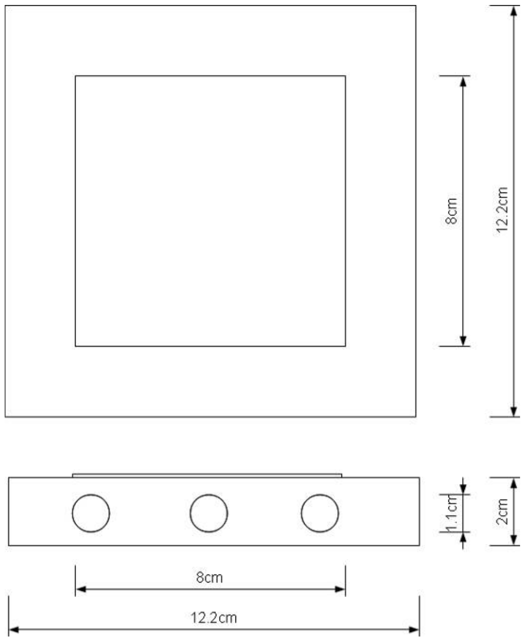

Figure 1: Schematic of the water cooled sample *PSI* with the mirror sample glued onto a water cooled aluminium plate (the water is flowing in serial through three bore holes).

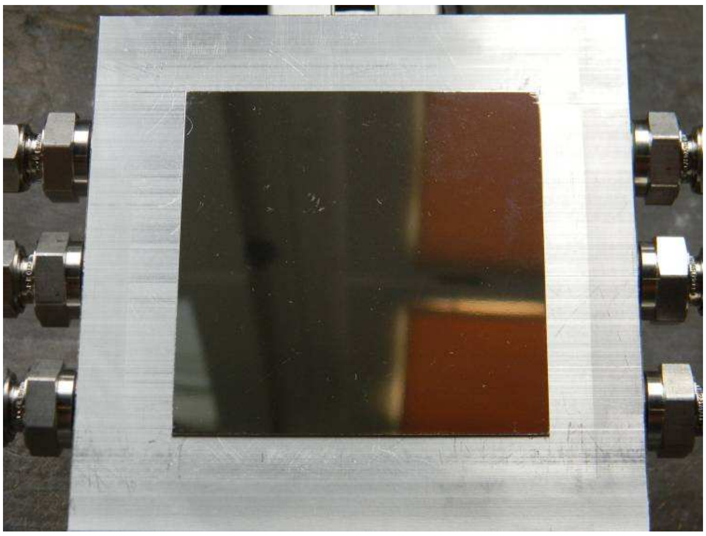

Figure 2: Photo of a sample *PSI* (manufacturer code “1” [4]) prior the test

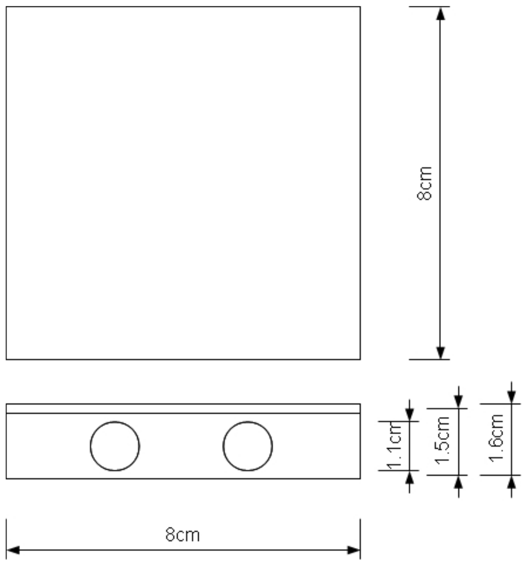

Figure 3: Schematic of the water cooled sample *DLR*, with the mirror surface glued onto an aluminium plate. The cooling water flow in serial through two bore holes.

Figure 4: Photo of a sample *DLR* (manufacturer code “5” [4]) prior to test

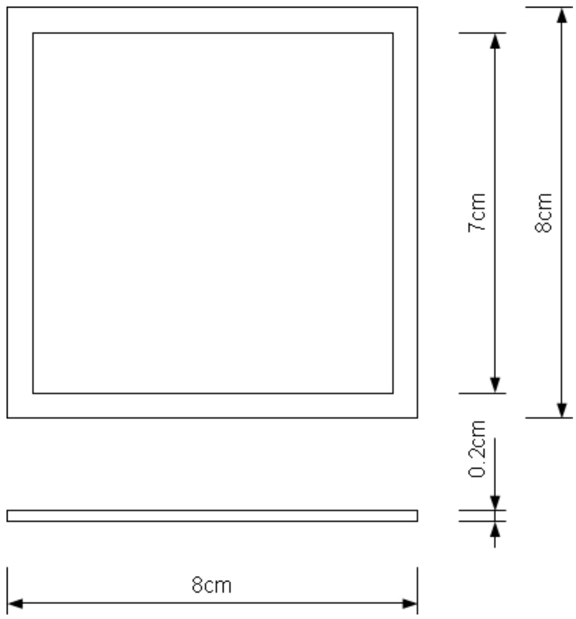

Figure 5: Schematic of the only air cooled sample *SOL*.

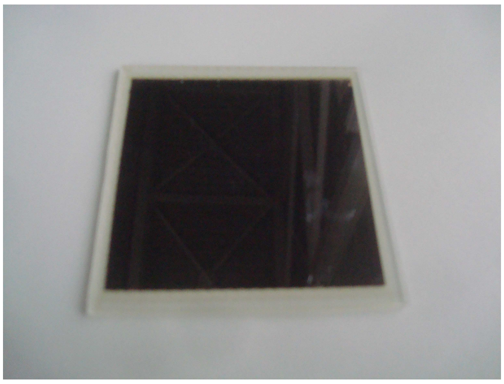

Figure 6: Photo of a sample *SOL* prior to test

4 EXPERIMENTAL SETUP AND PROCEDURE

4.1 Solar simulator

The samples were exposed to concentrated radiation using the High Flux Solar Simulator (HFSS) at the Solar Technology Laboratory (STL) of the Paul Scherrer Institute (PSI). The HFSS consists of 10 water cooled Xenon (Xe) arc lamps (15 kW_e each) [2]. Its flux distribution is very inhomogeneous. For these tests, however, an approximately homogeneous flux distribution over an area of 80 x 80 mm^2, the area of the mirror surface, is required. To realise this, a new "optical mixer" (OMX) adapted to the 80 x 80 mm^2 size of the mirror surface of the samples was built and characterised. The OMX is a rectangular tube consisting of mirrored inner walls, leading to an approximate homogenisation of the flux at its exit where the samples were placed. This new OMX was built according to the design of an existing 150 x 150 mm^2 OMX already in use at PSI.

4.2 Experimental setup

The setup consists of a compound parabolic concentrator (CPC) in front of the OMX (80 x 80 x 325 mm^3 inner dimensions) with the probe mounted at the outlet of the OMX. Both the CPC and the OMX are water cooled and cooling water temperatures and flows are monitored throughout the experiment. The experimental setup was slightly adjusted for different tested samples.
Samples *PSI* and *DLR* (water cooled mirror samples) were mounted vertically on mobile aluminium modular profile system (Bosch Rexroth AG) at the exit of the OMX, Fig. 7.
Sample *SOL* (air cooled mirror sample) was also mounted vertically at the exit of the OMX. It was held in place with alumina insulation and bricks to absorb spillage radiation, Fig. 8.
In a second test, sample *DLR* (water cooled mirror samples) was - following the wish from DLR - mounted 45° inclined from the verti cal axis on a Bosch profile at the exit of the OMX, Fig. 9. For this test, *DLR* samples with two different and without edge protection were used.

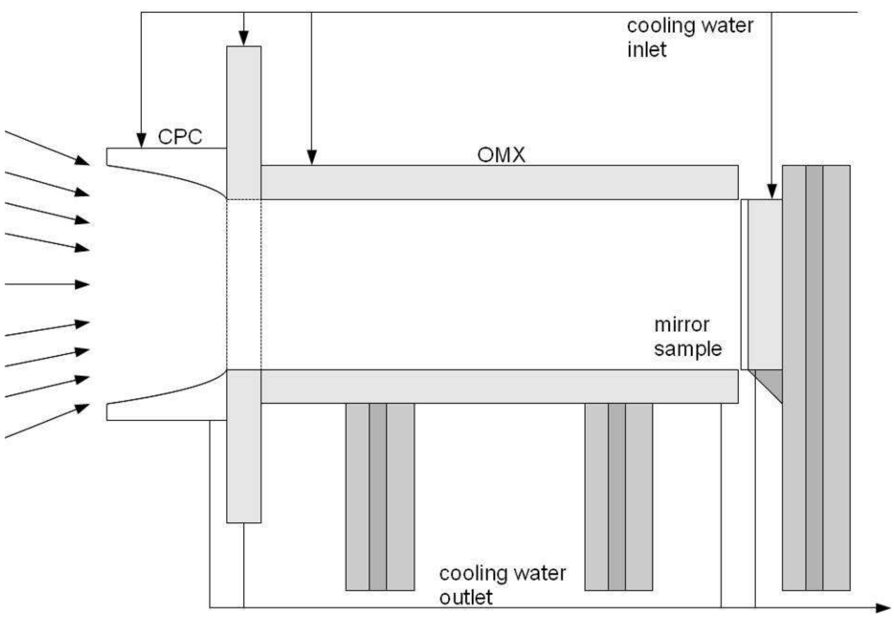

Figure 7: Experimental setup to conduct the test with water cooled mirror samples. The samples were mounted at the exit of the OMX (Sample *PSI* and Sample *DLR*).

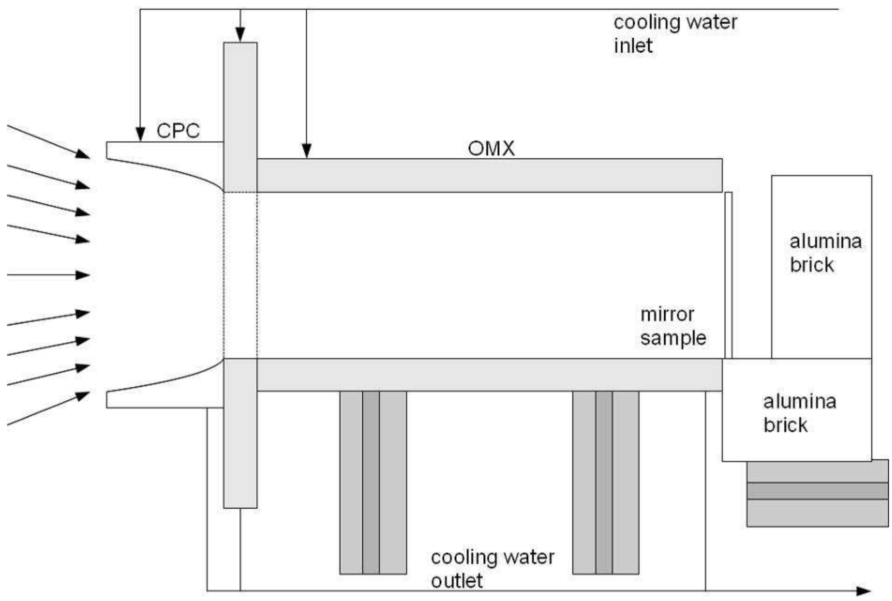

Figure 8: Experimental setup to conduct test with air cooled mirror samples (Sample *SOL*).

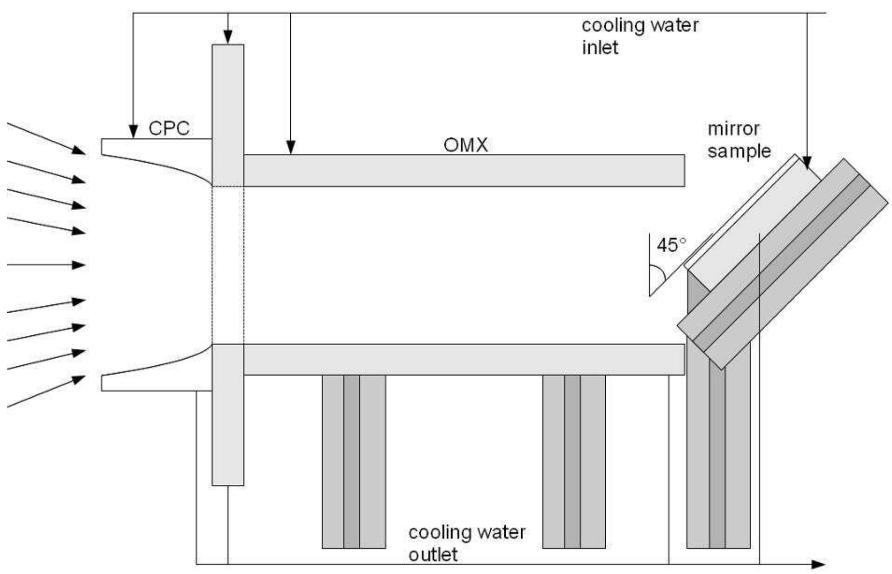

Figure 9: Experimental setup to conduct test with 45° inclined water cooled mirror samples (Sample *DLR*).

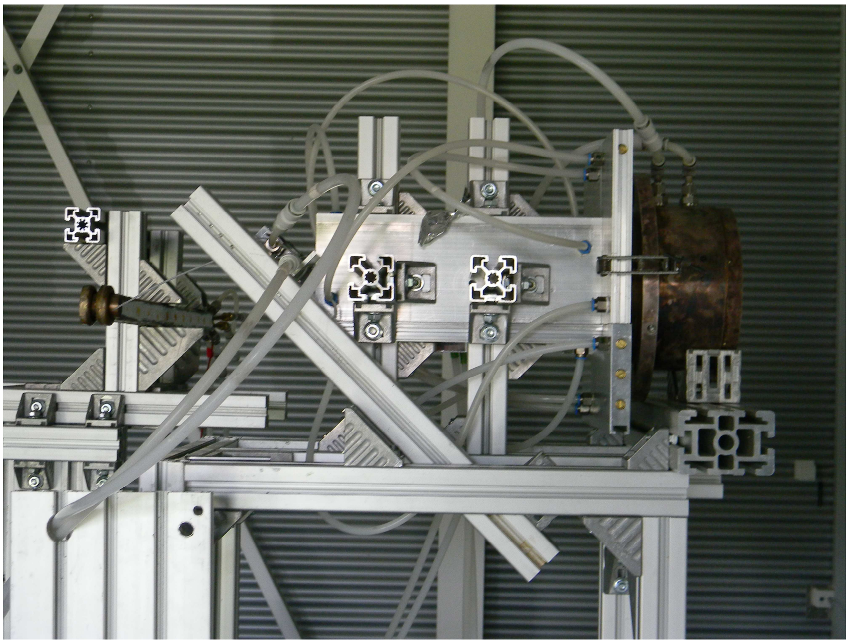

Figure 10: Photo of the experimental setup

4.3 Determination of the average flux

The average flux was determined from local flux measurements with a commercial thermo gauge (Vattel 1000-58F water cooled, accuracy ± 3 *%*). The flux was measured at 9 locations on an area of 80 x 80 mm^2, Fig. 11. The standard deviation was for all determined average fluxes below 6 % for low fluxes (< 300 kW/m^2) and below 4 *%* for higher fluxes (> 300 kW/m^2).

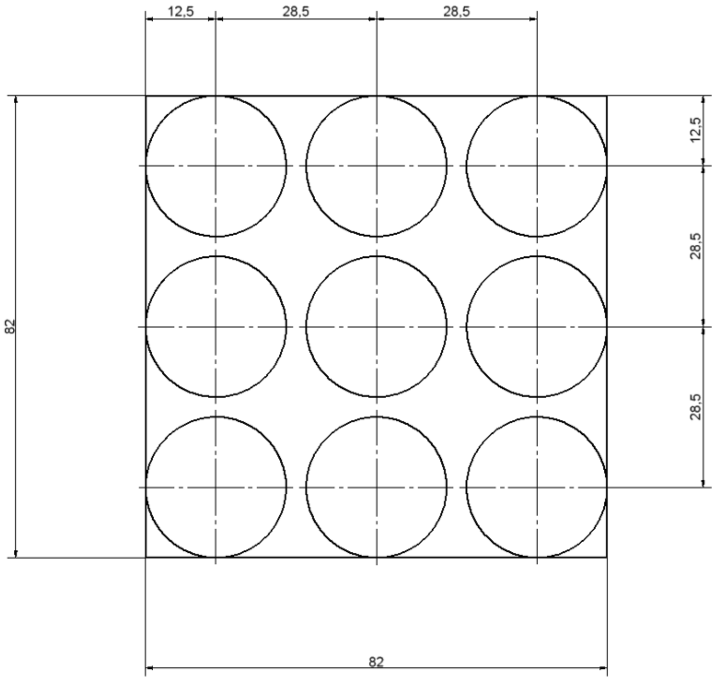

Figure 11: Locations of the 9 flux measurement points, indicating the spatial resolution of the flux measurement. The circle diameter represents the size of the flux measurement surface of the thermo gauge.

4.4 Experimental procedure

One sample of each material type was defined as reference sample and not irradiated. The other samples were used for irradiation tests at different heat flux levels. For each flux level and sample, the flux distribution was measured as described earlier to guarantee an approximately homogenous distribution.
For all tests with vertical positioned mirror samples (i.e., *PSI*, *DLR* and *SOL*) the radiative flux was gradually increased from 0 kW/m^2 to the nominal flux level of the test within 10 minutes. The samples were then irradiated at the nominal flux for 50 minutes. After shut off and a waiting time of 15 minutes a 2nd and a 3rd identical test with the same sample under the same conditions were performed. This resulted in total test duration of 3 *h* 30 *min* per material and flux level.
In case a physical destruction of a candidate material is observed during the irradiation, the test was aborted.
Aimed flux levels for the water cooled samples (3D-CPC) are 600, 1000 and 1400 kW/m^2 and for the air cooled samples (2D-CPC) are 80, 160 and 300 kW/m^2. The last high flux level of 300 kW/m^2 is well above the typical conditions in a 2D-CPC and was chosen in agreement with the provider to evaluate the limits (160 kW/m^2 is already slightly above typical 2D-CPC radiative fluxes).

For the 45° inclined water cooled samples, fluxes of 600 and 1000 *kW/m²* were planned. However, for the inclined samples a slightly altered testing procedure was adopted. Initially the flux is steadily increased to the nominal flux within 10 minutes and held constant for 20 minutes.
After shut off and a waiting time of 15 minutes the flux was steadily increased again within 10 minutes until the nominal flux was reached and this time held constant for 50 minutes.
After a visual check, the specular reflectance of all reference and irradiated test samples was measured at CIEMAT. Specular reflectance is the ratio between the radiation collected inside an acceptance angle around a specular direction and the incident radiation. The monochromatic specular reflectance (ρ_s (660 *nm*; 15°; 15, 25, 46 *mrad*)) was measured with a portable specular reflectometer (Devices and Services, model 15R, Fig. 12). This reflectometer has a LED source of wavelength range between 635-685 *nm*, with a peak at 660 *nm*. The selected aperture angle for measuring was 25 *mrad*. The specular reflectance was measured at three different points on each sample.

Figure 12: Portable specular reflectometer 15R by Devices and Services [3].

5 EXPERIMENTAL RESULTS

An overview of all conducted experiments is given in Tables 1.1 and 1.2. Most irradiated samples had no visual surface damage. Exception is *SOL_4*, which was destroyed during the 2nd irradiation test at the highest planned flux of 300 *kW/m²*, a flux level far above the typical level in a 2D-CPC (see Figure 13). Furthermore the sample DLR-16 showed multiple cracks after the irradiation, which were apparently originating from stress induced by the holes in the Al-plates rather than being caused by the radiative flux (Figure 14).

The results of the specular reflectance measurement are presented in Table 2. The specular reflectivity was measured at three different locations on each sample. Differences between reference and irradiated sample are generally small for all three sample types, indicating no damage due to the irradiation.

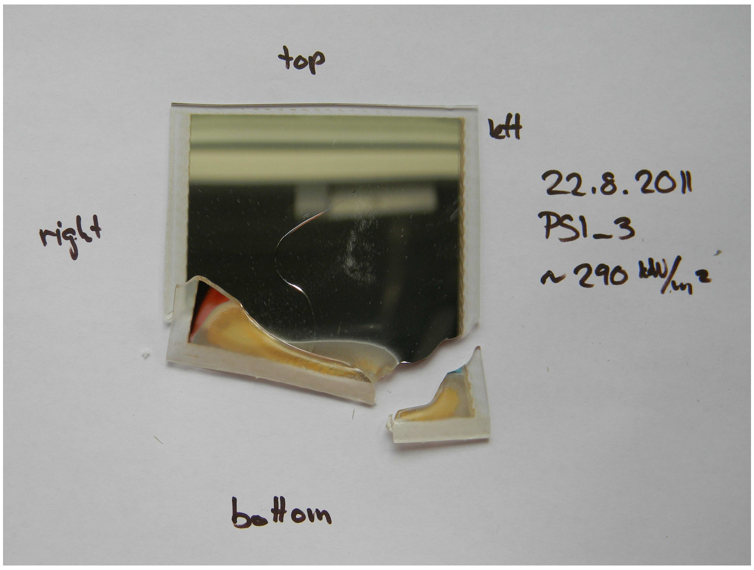

Figure 13: Sample SOL_4 after 2nd test with close to 300 kW/m²

Figure 14: Sample DLR_16 after irradiation with 1400 kW/m^2 showing mechanical cracks (part of which were already visible before the thermal tests, see Fig. 4), but no traces of mirror melting.

The tests with the tilted samples DLR targeted the behaviour of the edge coatings rather than the reflectance that was investigated in the tests with samples perpendicular to the radiation (samples DLR_10, DLR_12, DLR_16). Both coatings type 1 and type 2 performed well under the experimental conditions.

6 CONCLUSIONS

During an experimental campaign at the Solar Technology Laboratory at PSI three very different types of solar reflectors were tested for radiation flux densities in the range or slightly higher as to be expected in secondary concentrator applications. Nearly all samples had no visual damage after the well defined experimental procedure. Furthermore, specular reflectance measurements showed no significant difference between treated and untreated samples. Hence, the respective system can principally be expected to be suitable for use in secondary concentrators. It should be noted, however, that system failure due to long term operation influences, e.g., aging effects, can not be excluded based on these comparatively short thermal tests. Weathering effects of mirrors for CPC's have been investigated in a complementary activity within SFERA [4] including the same types of samples.

Table 1.1: Overview of conducted tests (1).

Sample name	Manufacturer code as in [4]	Test number [#]	Average Flux [kW/m^2]	Heat up time [*min*]	Test time [*min*]	Orientation	Remarks
PSI_1	*1*	1	581	10	50	vertical	
		2	581	10	50	vertical	
		3	581	10	50	vertical	
PSI_2	*1*	1	966	10	50	vertical	
		2	966	10	50	vertical	
		3	966	10	50	vertical	
PSI_3	*1*	1	1469	10	50	vertical	
		2	1469	10	50	vertical	
		3	1469	10	50	vertical	
PSI_ref	*1*						untreated
DLR_10	*5*	1	587	10	50	vertical	no edge protection
		2	587	10	50	vertical	
		3	587	10	50	vertical	
DLR_12	*6*	1	990	10	50	vertical	edge protection type 1
		2	990	10	50	vertical	
		3	990	10	50	vertical	
DLR_16	*7*	1	1469	10	50	vertical	edge protection type 2
		2	1469	10	50	vertical	mechanical cracks, increased
		3	1469	10	50	vertical	after tests
DLR_8 (ref)	*5*						untreated

Table 1.2: Overview of conducted tests (2).

Sample name	Manufacturer code as in [4]	Test number [#]	Average Flux [kW/m^2]	Heat up time [*min*]	Test time [*min*]	Orientation	Remarks
SOL_1	*n.a.*	1	93	10	50	vertical	
		2	93	10	50	vertical	
		3	93	10	50	vertical	
SOL_2	*n.a.*	1	151	10	50	vertical	
		2	151	10	50	vertical	
		3	151	10	50	vertical	
SOL_3	*n.a.*	1	253	10	50	vertical	
		2	253	10	50	vertical	
		3	253	10	50	vertical	
SOL_4	*n.a.*	1	291	10	50	vertical	
		2	291	10	50	vertical	sample broken after test
SOL_ref	*n.a.*						untreated
DLR_9	*5*	1	610	10	20	45°	no edge protection
		2	610	10	50	45°	
DLR_14	*6*	1	610	10	20	45°	edge protection type 1
		2	610	10	50	45°	
DLR_13	*7*	1	610	10	10	45°	edge protection type 2
		2	610	10	50	45°	
DLR_15	*5*	1	979	10	10	45°	no edge protection
		2	979	10	50	45°	
DLR_2	*6*	1	979	10	15	45°	edge protection type 1
		2	979	10	50	45°	
DLR_4	*7*	1	979	10	10	45°	edge protection type 2
		2	979	10	50	45°	

Table 2: Results of specular reflectance measurements of reference and irradiated samples.

Sample	Manufacturer code as in [4]	Point 1	Point 2	Point 3	Average
PSI_Ref	*1*	88.5	88.5	88.5	88.5
PSI_1	*1*	88.8	88.9	88.9	88.9
PSI_2	*1*	89.2	89.1	89.2	89.2
PSI_3	*1*	88	88	87.9	88.0
DLR_Ref	*5*	96.7	96.7	96.8	96.7
DLR_10	*5*	95.9	96.1	96	96.0
DLR_12	*5*	96.7	96.7	96.7	96.7
DLR_16	*5*	96.5	96.4	96.5	96.5
SOL_Ref	*n.a.*	91.7	92	92	91.9
SOL_1	*n.a.*	89.4	89.4	89.7	89.5
SOL_2	*n.a.*	90.8	90.9	90.8	90.8
SOL_3	*n.a.*	91	91	91	91.0

7 References

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

[2] Petrasch J., Coray P., Meier A., Brack M., Haeberling P., Wuillemin D., Steinfeld A., *A 50-kW 11,000-suns novel high-flux solar simulator based on an array of Xenon arc lamps*, ASME - Journal of Solar Energy Engineering, Vol. 129, No. 4, pp. 405-411, 2007.

[3] Specification sheet “Portable Specular Reflectometer 15R-USB”, Device & Service Co.

[4] *Primary results of secondary concentrators solar mirror testing* (SFERA Work Package 13, Task 2, Subtask “Hardware”), A. Fernández-Garcia and M.E. Cantos-Santos, 10th Oct., 2011.