IEA SHC Task 27: Adoption of the general methodology to the assessment of solar facade absorber durability

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1. Introduction

During the past decades the thermal performance of buildings has improved enormously due to better awareness and new regulations in most EU countries. The energy need for both heating and cooling of low-energy buildings has achieved a level close to self-sufficiency. A major share of the existing building stock in Europe will be used for more than 20 years and renovation of these buildings towards a low energy level is a major challenge for the coming decades. Here exists a particularly ideal application for unglazed solar facades allowing direct solar energy conversion and well-controlled energy management. The thermal energy from these solar facades can be used for either air- and water-heating systems, solar combi-systems and desiccant cooling devices, or be stored in heat storage units.

One of the drawbacks of unglazed solar collectors lies in their black appearance and their relatively low durability and performance. New coatings which have recently been developed combine high performance due to improved spectral selectivity with high durability. Variations in colour can be achieved with only a minor reduction in performance.

Another issue is the use of the facade as an unglazed solar collector in order to reduce the costs. Therefore different environmental stresses will be relevant for the durability of the absorber coatings compared to glazed, ventilated solar collectors. Following the general methodology for durability assessment presented in the paper by Bo Carlsson and adopting it to this special component in ist application is the major task of this case study.

2. Monitoring of the outdoor climate

Objective of the monitoring of the outdoor climate and the microclimate of the samples is the need to have a database with the stress levels for unglazed solar facade collectors and a comparison between the stress levels at different test sites. Test sites were ISE in Freiburg and SPF in Rapperswil. A database was built up and evaluated with climatic data for one year. The following table shows the equipment used for the monitoring at ISE.

measure	**with**
Rh_{amb}/T_{amb}	Rotronic I155C
p_{amb}	FSM APS pressure sensor
H_{sol}	pyranometer Kipp&Zonen CM11
H_{ir}	pyrgeometer Kipp&Zonen CG1
UVA	EKO MS210A
UVB	EKO MS210W
rain qualitatively	inductivity rain sensor
rain quantitatively	Thies Clima sensor
Sample Temperature	Pt100

Temperature

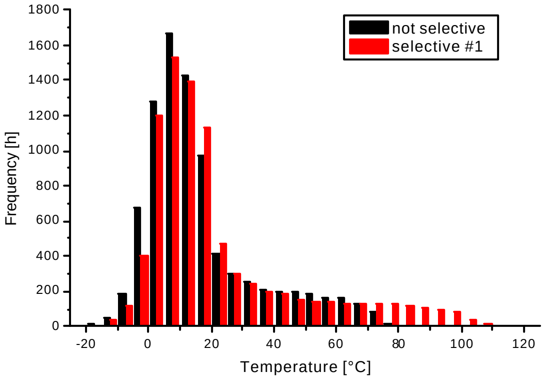

Figure 1: Temperature histogram of the south45 samples at ISE

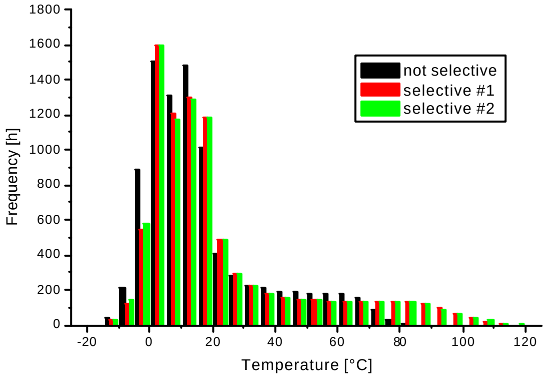

Figure 2: Temperature histogram of the south45 samples at SPF

The temperature histograms shows the difference between the non-selective and the selective samples. The selective sample temperatures at ISE and SPF reaches values up to 115°C. The maximum temperatures for the not selective samples is at both labs about 80°C. It can be clearly seen that in the lower temperature range the frequency for the non-selective coatings is higher than for the selective coatings in both figures. This increases the risk for formation of condensation.

Wetness

To define the time of wetness due to formation of condensation on the samples it is necessary to calculate the dew point temperature. We used the formula from the german weather service DWD for the saturated water vapour pressure:

$p_s(t)=c1*\exp(c2*t/(c3+t))$

with c1=6.10780mbar, c2=17.08085, c3=234.175°C, t is in °C and $p_s(t)$ in mbar.

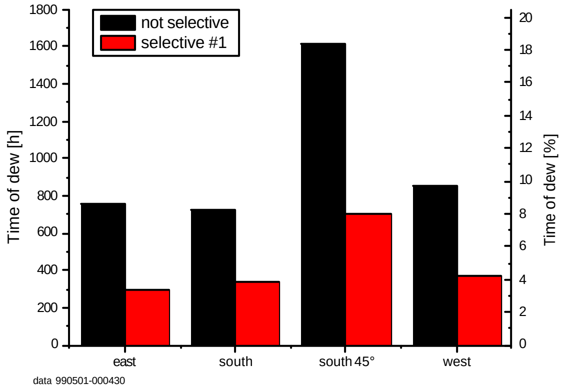

Figure 3: Time of dew (TOD) at ISE

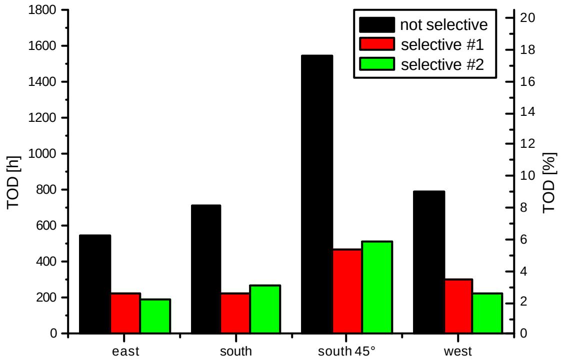

Figure 4: Time of dew (TOD) at SPF

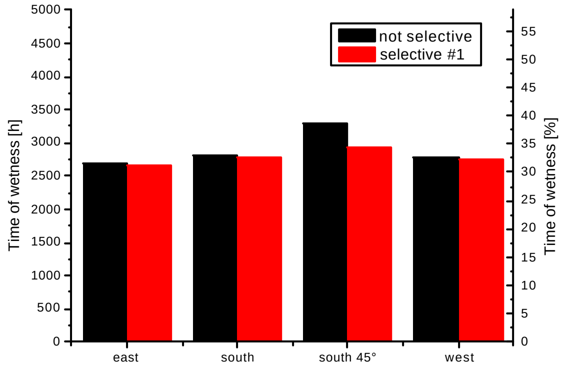

Figure 5: Time of wetness (TOW) at ISE

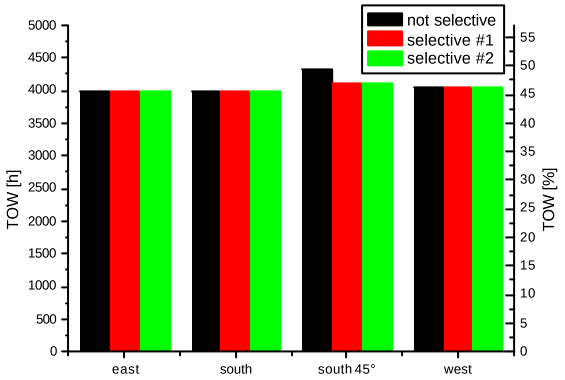

Figure 6: Time of wetness (TOW) at SPF

The overall time of wetness includes the time of dew, times, when the samples are wet due to rain and times of a relative humidity of the ambient air above 80%.

UV-Radiation

UV-A and UV-B radiation was monitored besides the global solar radiation. Usually the UV-Dose is the main degradation factor

Corrosivity of outdoor test

The corrosivity of typical outdoor conditions for solar façade elements was determined at ISE in Freiburg, Germany and at SP Swedish National Testing and Research Institute at Borås, Sweden. Corrosivity was determined through one-year exposures of reference metal specimens of copper, zinc, and carbon steel as recommended in ISO 9226. The reference metal specimens were placed on racks at different orientations and inclinations.

The results in terms of metallic mass losses after one year of exposure are presented in table 2.

Table 2 Corrosivity of outdoor conditions for solar façade elements at three different locations and at varying orientations and inclinations as determined by exposure of reference metal specimens

Position of metal reference specimens	**First year metallic mass loss of copper (g/m^2)**	**First year metallic mass loss of zinc (g/m^2)**	**First year metallic mass loss of carbon steel (g/m^2)**
ISE, Freiburg, Germany			
specimens faced south at 5° inclination to horizontal plane	12.1	6.7	116
specimens faced south at 45° inclination to horizontal plane	9.5	4.7	83
specimens faced south at 90° inclination to horizontal plane	7.2	2.8	73
specimens faced east at 90° inclination to horizontal plane	7.2	2.6	80
specimens faced west at 90° inclination to horizontal plane	8.3	3.2	81
SP, Borås, Sweden			
specimens faced south at 90° inclination to horizontal plane	4.0	2.6	43
specimens faced north at 90° inclination to horizontal plane	5.4	7.9	30
SPF, Rapperswil; Switzerland			
specimens faced south at 90° inclination to horizontal plane	4.0	3.8	71
specimens faced north at 90° inclination to horizontal plane	5.2	5.8	81

3 Results of outdoor-tests

Four different absorbers were exposed to outdoor climate at SPF in Rapperswil (CH) and ISE in Freiburg (D). Two of them were exposed in both labs and both labs had one additional sample exposed. The samples exposed at both test sites were:

- Non-selective black paint
- Spectrally selective black-chrome coating

Additionally, two highly selective samples with weak corrosion resistance were exposed as reference samples for monitoring coating degradation.

All samples were exposed to different orientations: vertical to the south, east and west and with a tilt angle of 45° to the south. The results are shown for the comparable samples exposed at SPF and ISE, the black paint and the black-chrome. After 1 year and after 2 years of exposure a 10 cm wide strip was taken from the lower end of all absorber samples for analysis. Optical measurements have been performed. As a results of the optical integral values solar absorption $\alpha_{AM1.5}$ and thermal emission ε_{373K} the performance criterion pc is calculated, defined by $pc = -\Delta\alpha_{AM1.5} + 0.5\ \Delta\varepsilon_{373K}$.

Black paint

No significant changes could be observed at the black paint samples after 2 years exposure time neither in Switzerland nor in Germany (table 3)

Table 3: PC of the Black Paint solar absorber sample after 1 and 2 years of exposure in Rapperswil, Switzerland and Freiburg, Germany.

SPF		**south (45°)**	**east**	**south**	**west**
1 year	pc	-0.0015	-0.001	-0.0035	0.003
2 years	pc	-0.011	-0.005	-0.0105	-0.006
ISE					
1 year	pc	-0.008	-0.0035	-0.003	-0.0055
2 years	pc	-0.0045	0.004	0.004	0.0015

Blackchrome

The absorption edge of the Black Chrome absorber showed a clear shift towards shorter wavelength (see figure 22). In case of the south (45°) and west orientation most of the change occured after the first year already. The second year lead to a slight change only. Possibly, a saturation of this effect was met already. The same phenomenon can be seen for the remaining two orientations. The shift after 2 years for the east orientation approximately corresponds to the south orientation after 1 year.

Table 4: PC of the Blackchrome solar absorber sample after 1 and 2 years of exposure in Rapperswil, Switzerland and Freiburg, Germany.

SPF		**south (45°)**	**east**	**south**	**west**
1 year	pc	-0.004	0	-0.0025	-0.0005
2 years	pc	-0.0035	-0.004	-0.005	-0.0035
ISE					
1 year	pc	0.0035	-0.0015	-0.018	-0.002
2 years	pc	0.0015	0.003	0.0025	-0.001

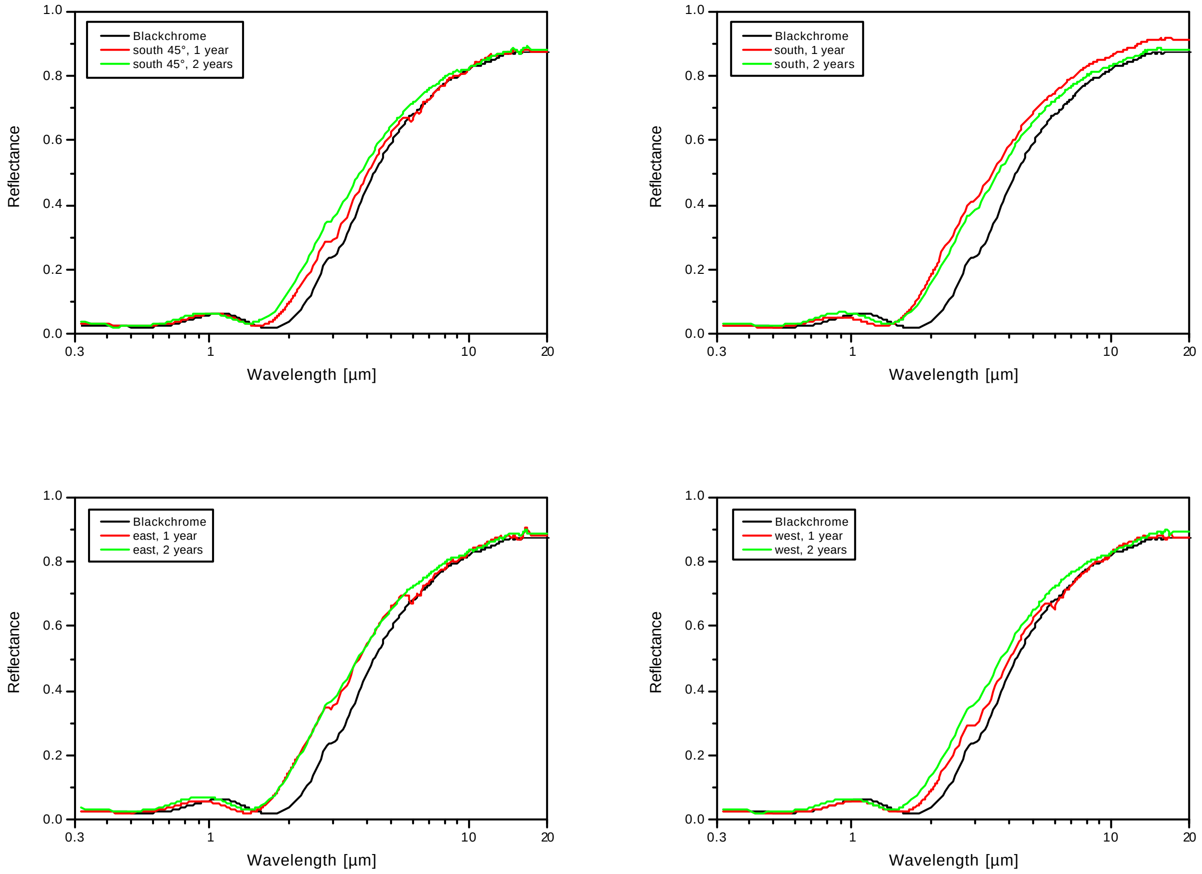

Figure 22: Spectral reflectance of the Black Chrome absorber sample, exposed in Freiburg, Germany

Due to the shift both, the solar absorption and the thermal emission are decreasing. Therefore, the performance criterion was not changed significantly.

Reference sample 1

Regarding the change in spectral reflectance of RS1 (figure 23), all 4 orientations show almost the same degradation after 2 years of outdoor exposure. In case of the south (45°) and west orientation most of the degradation occured after one year already while the sample facing east showed the slowest degradation.

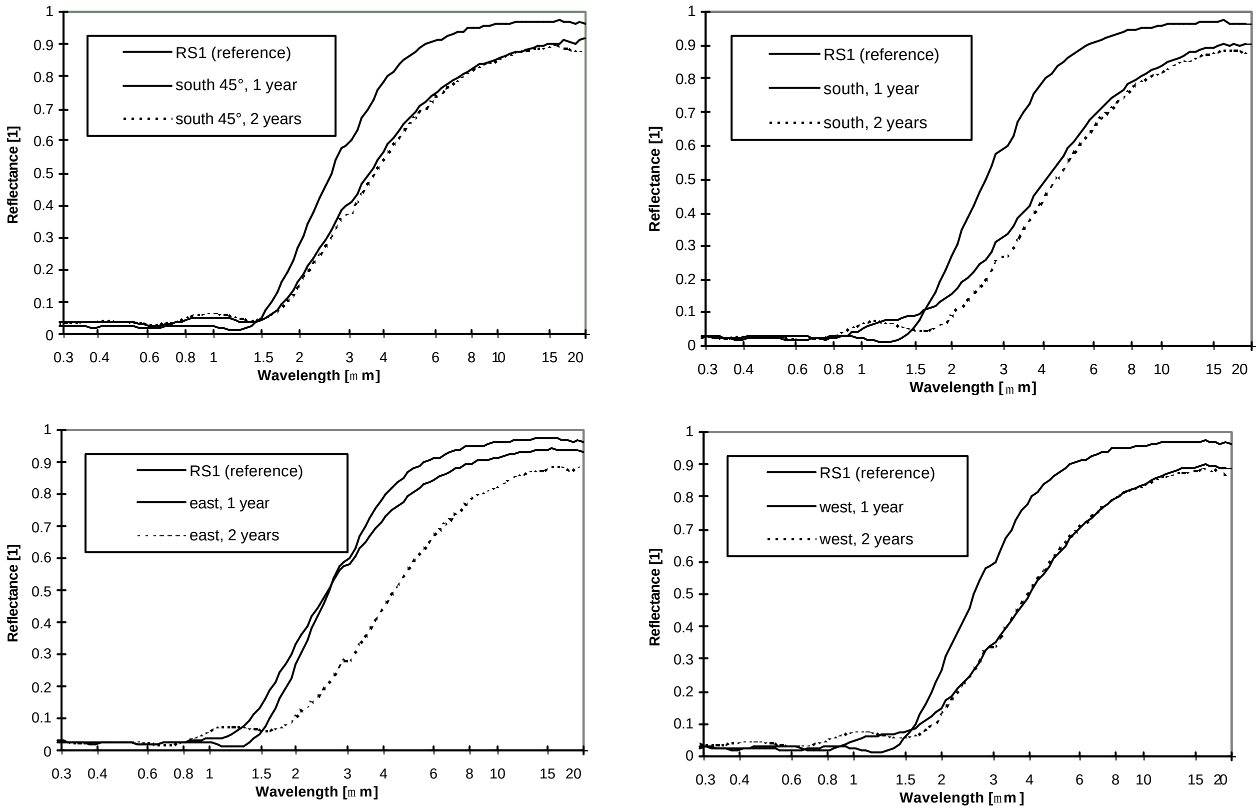

Figure23: Spectral reflectance of reference sample 1 (RS1)

A dramatic loss in adhesion of the coating was observed for the south (45°) orientation after 1 year. In the same time adhesion was reduced for the east orientation but was still sufficient for the west and the south orientation. After the second year the coating could be easily wiped off with a soft tissue from all samples.

Table 5 PC of the Reference sample 1 sample after 1 and 2 years of exposure in Rapperswil, Switzerland

SPF		**south (45°)**	**east**	**south**	**west**
1 year	pc	0.0565	0.0355	0.066	0.062
2 years	pc	0.068	0.072	0.0715	0.076

Reference sample 2

The reference sample 2 showed a different degradation behaviour. The south-oriented samples had a lower degradation as the east/west samples.

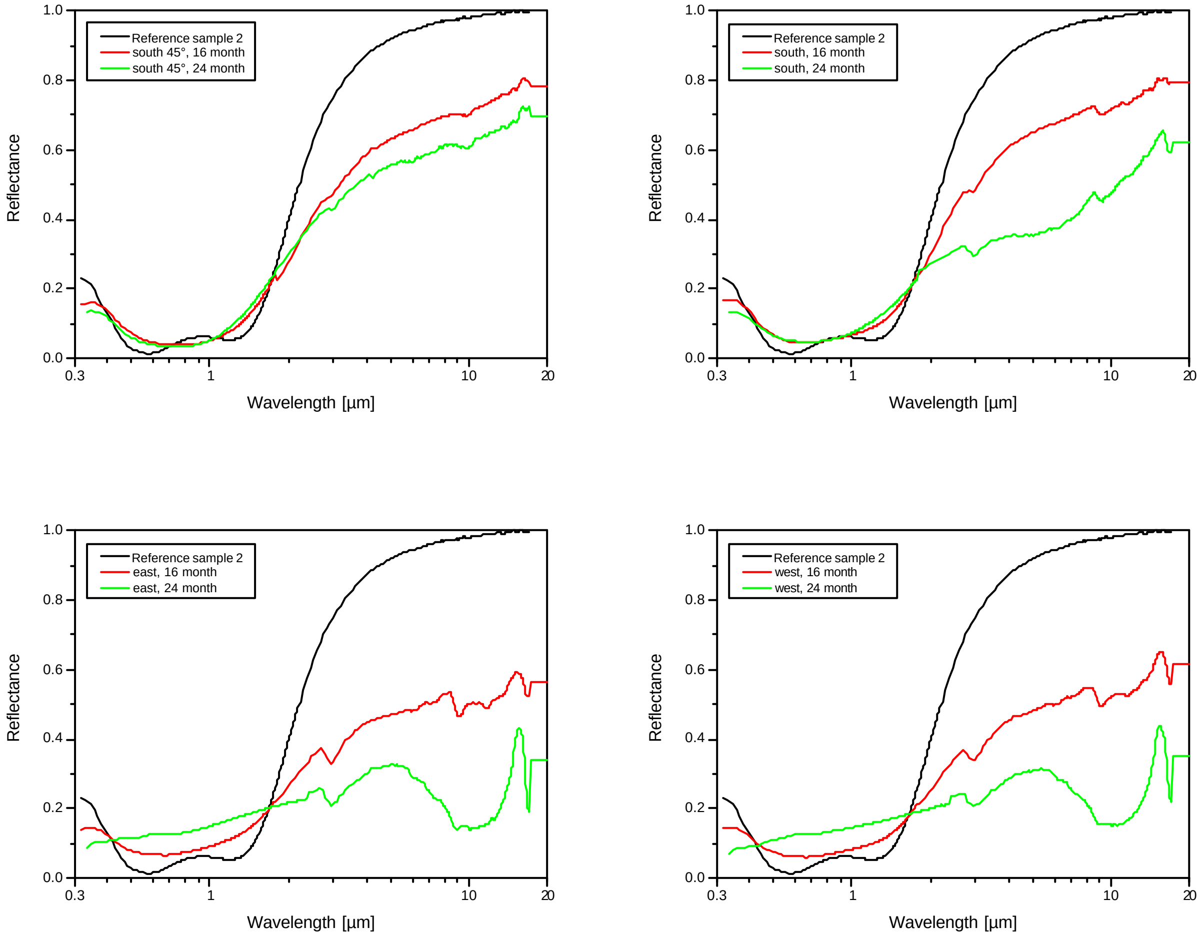

Figure24: Spectral reflectance of the Reference sample 2, exposed in Freiburg, Germany

Table 6: PC of the Reference sample 2 sample after 16 and 24 months of exposure in Freiburg, Germany

ISE		**south (45°)**	**east**	**south**	**west**
16 months	pc	0.131	0.251	0.1305	0.228
24 months	pc	0.17	0.423	0.2425	0.412

4 Accelerated indoor tests

Testing times for temperature test

Test conditions for temperature testing were derived from transformation of one-year data from outdoor monitoring results from the south 45° installed samples – they were assumed to be the worst case for temperature load. Testing times are calculated using the Arrhenius-transformation as follows:

$$t_{ref} = \sum_i t_i \cdot e^{\frac{\Phi}{R}\cdot\left(\frac{1}{T_{ref}}-\frac{1}{T_i}\right)}$$

with:

t_{ref}	Testing time	R	ideal gas law constant
T_{ref}	Test temperature	T_i	Real temperature
Φ	Activation energy	t_i	Time at real temperature

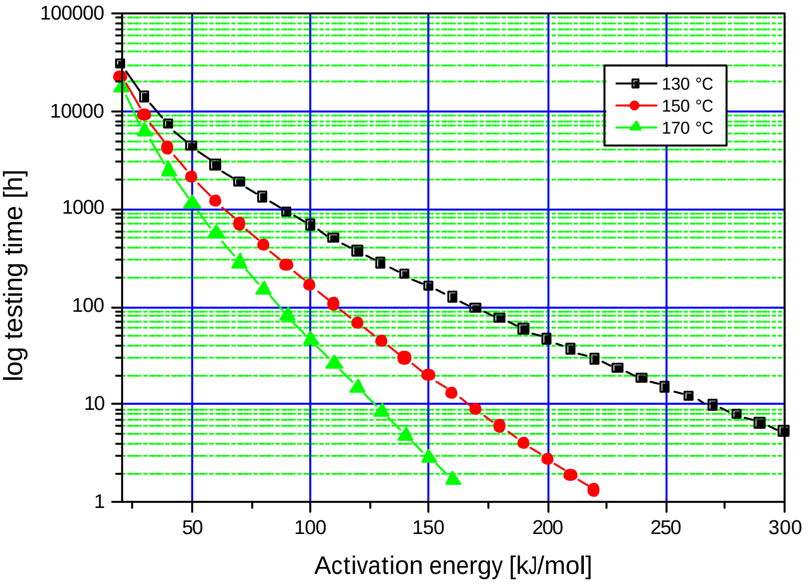

Figure 25: Testing times for temperature test

The activation energy is an unknown parameter of the degradation process. The diagramme says:

If the degradation of the sample would be the same after 3h testing at 170°C and after 20h at 150°C and after 190h at 130°C, the activation energy of the degradation process is about 150kJ/mol and the degradation would be similar to 25 years outdoor exposure under similar climatic conditions as during the monitoring.

Temperature and condensation tests

This report contains the results of the indoor temperature and condensation tests performed on numerous samples out of different coating development phases. Temperature tests were performed at 150 and 170°C. These temperature levels were derived from arrhenius based transformation of temperature loads from the monitoring of the outdoor exposed samples. Levels of 170° and 150°C were identified to be suitable values, also considering the upper limit of temperatures applicable for samples with coatings containing organic components. Condensation tests were performed at 65 and 40°C. Detailed test results are not presented here, since they are not of public interest. The duration of the project was too short for finishing the development successfully with a final durability assessment useful for a service life estimation.

Changes in integral values $?_s$, ?373K) and PC

In order to have a comparable measure for the degradation of the samples during accelerated ageing a performance criterion (PC) is calculated. Following the recommendations from the 'IEA Working group Materials in solar thermal collectors' and the IEA-Task 10 'Accelerated life testing of solar energy materials' this criterion is calculated as $PC= - ? ?_s + 0.5 ? ?_{373K}$, where $?_s$ is the spectral reflectance, weighted with the solar spectrum AM1.5 from ISO 9845 and $?_{373K}$ is the spectral reflectance, weighted with the spectrum of a black body radiator at a temperature of 373K. This PC is well suited for the jugdement of coatings for flat plate solar collectors and despite the fact it has to be modified for the use with unglazed facade materials it is a reasonable measure.

Condensation Test

The condensation tests are performed in a climatic cabinet equipped with liquid cooled sample holders. The temperature of the samples is 5K below the cabinet temperature and relative humidity is 95% to get condensation on the samples. Cabinet temperature is 70°C. in case of the 70/95/65/UV test additional UV-load is performed by a light source above the samples (about factor of 7 compared with natural sunlight).

Most of the coatings did not show serious degradation up to a testing time of 384 hours, i.e. the pc function is less than 1% over the whole testing time. However, some of the samples obviously changed their optical properties appreciable.

High Temperature Test (170 & 170/Sol)

Test conditions for temperature testing were derived from transformation of one-year data from outdoor monitoring results from the south 45° installed Black Chrome samples which were assumed to be the worst case for temperature load.

As a starting point the tests were performed at 170°C sample temperature. For the tests without artificial irradiation a circulating air furnace was used. For the high temperature tests combined with irradiation the samples were fixed with a thermal heat sink compound onto a precision hotplate. The temperature of the hotplate was controlled by a selective coated Pt100 foil sensor pasted onto the surface of the plate. In this way, both, the sensor and the absorber samples are irradiated by the light source in order to measure a temperature as close as possible to the real sample temperature.

“Dr. Hönle Sol 1200” solar simulator was used as light source. The source was installed 70 cm above the samples (measured from the exit window of the simulator). The spectral distribution of the lamp is in the order of the solar terrestrial irradiation.

Most of the samples did not show serious degradation up to a testing time of 384 hours, i.e. the pc function is less than 1% over the whole testing time, as in the condensation tests. The coatings that changed their optical properties during testing are discussed in the following:

Reference sample 1 (RS1) shows increasing degradation with testing time. Both, solar absorption and thermal emission are getting worse. Of the coloured SunSelect coatings only the red one shows degradation. After a violent change during the first 48 hours of testing the velocity of the degradation is reduced.

Selective paints from NIC showed some degradation as well. In the beginning of the test the reflection was reduced in the UV and VIS part, but increased in the infrared. This is leading to an improved performance. After this initial change the reflectance is increasing with testing time over the whole spectra.

Corrosion tests

For corrosion testing two different cyclic tests were used.

Corrosion test 1

The first was SP method 2499 A, also corresponding to ISO/CD 21207 method A, which defines the following one week test cycle:

a) traditional salt spray testing (ISO 9227) for 2 h in a mist of a salt solution containing a mass fraction of 5 % of sodium chloride at 35 °C, followed by drying for 22 h in standard laboratory climate, and

b)exposure for 120 h in a test atmosphere containing a mixture of corrosion promoting gases, volume fraction of NO_2 equal to $1,5{\cdot}10^{-6}$ and of SO_2 equal to $0,5{\cdot}10^{-6}$, at a relative humidity of 95% and at a temperature of 25 °C, followed by drying for 24 h in standard laboratory climate.

Corrosion test 2

The second was a less corrosive method. It can be described as a slightly modified SP method 2499 A cycle differing from the former in that no salt spray exposure is performed in step a) only drying for 24 h in standard laboratory climate.

Reference metal specimens

In both tests reference metal specimens of copper and zinc were used to determine the corrosivity of the tests. The reference metal specimens were also utilised in converting the corrosion resistance obtained in test to expected service performance as regards corrosion resistance.

Test results

In Table 7, the failure times, *i.e.* time to PC=0.05, of the absorber materials in corrosion test cycle I are shown together with the corresponding mass loss of copper at that testing time. It should be pointed out that the corrosivity of corrosion test cycle 1 compared to corrosion test cycle 2 is nearly twice as high in terms of corrosion of copper, see Table 8

Table 7 Failure times of the absorber materials in corrosion test cycle

Absorber material	**Failure time (PC =0.05) in corrosion test 1 (Test cycles)**	**Corresponding metallic mass loss of copper[*] (g/m^2)**
Sol-gel covered absorbers from CIEMAT	0.74	4.1
Sol-gel covered absorbers from Interpane with SnO_2	**0.82**	4.5
Sol-gel covered absorbers from Interpane with SnO_2	**0.74**	4.1
Sol-gel covered absorbers from Interpane without SnO_2	**0.71**	3.9
Sunselect red	**0.90**	4.8
Sunselect green	**0.83**	4.5
Sunselect yellow	**1.24**	6.4
Selective paint NIC-blue	-	-
Selective paint NIC-red	-	-
Highly selective Energy Solaire	0.57	3.2
Sunselect (old,blue)	0.47	2.7
Energie Solaire (IEA Task 10)	-	-

* When calculating the metal mass loss rate of copper it is assumed that the following relation is valid: $M = M_1 \cdot t^x$, where M = mass loss, M_1 = constant at a given corrosivity, t = time, and x = constant at a given corrosivity, equal to 0.88 for the present test

(Design of accelerated corrosion tests for electronic components in automotive applications; P. Eriksson, B. Carlsson, I. Odnevall- Wallinder, *IEEE Transaction Components and Packaging Technologies,* **Vol. 24**, No 1, March 2001)

Table 8 Corrosivity of corrosion test cycles

After four cycles of testing according to	**Metallic mass loss of copper (g/m^2)**	**Metallic mass loss of zinc (g/m^2)**
Corrosion test cycle 1	18,0	39.0
Corrosion test cycle 2	10,6	10,7

By use of results from corrosivity measurements in outdoor environments, the failure times in the corrosion test may be used in roughly estimating the expected service life for solar façade elements with the absorber materials tested.