



TASK 27

Performance of Solar Facade Components

Performance, durability and sustainability

of advanced windows and solar components for building envelopes

Final Report

Subtask B: Durability

PROJECT B3: Durability and reliability assessment of static solar materials

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PROJECT B3: “Durability and reliability assessment of static solar materials”

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1. General introduction

The methodology of durability assessment is based on the work of Project B1 and is described in the respective final report. A brief description is given below.

1. General methodology for durability assessment

The methodology adopted by Task 27 includes three steps:

- initial risk analysis of potential failure modes,
- screening testing/analysis for service life prediction and microclimate characterisation, and
- service life prediction involving mathematical modelling and life testing.

2. Initial risk analysis

The initial risk analysis is performed with the aim of obtaining

- a checklist of potential failure modes of the component and associated with those risks and critical component and material properties, degradation processes and stress factors,
- a framework for the selection of test methods to verify performance and service life requirements,
- a framework for describing previous test results for a specific component and its materials or a similar component and materials used in the component and classifying their relevance to the actual application, and
- a framework for compiling and integrating all data on available component and material properties.

The programme of work in the initial step of service life assessment is structured into the following activities:

- Specify from an end-user point of view the expected function of the component and its materials, its performance and its service life requirement, and the intended in-use environments;
- Identify important functional properties defining the performance of the component and its materials, relevant test methods and requirements for qualification of the component with respect to performance;
- Identify potential failure modes and degradation mechanisms, relevant durability or life tests and requirements for qualification of the component and its materials as regards durability.

Table 1 Specification of end-user and product requirements for the booster reflectors

Function and general requirements	General requirements for long-term performance during design service time	In-use conditions and severity of environmental stress
Efficiently reflect solar radiation to increase the solar gain of a flat plate solar collector	Loss in material performance should not result in reduction of the solar system performance with more than 5%, in relative sense, during the material service life. Material service life should exceed 25 years	The reflector is exposed to open air conditions involving climatic stress of UV irradiation, high temperature, high humidity and moisture, and the effect of icing. It may be exposed to corrosion promoting air pollutants and acid rain. It may also be subjected to mechanical loads from hail and wind, stress from mechanical fixing and due to its own weight Soiling agents, e.g. from birds, may effect performance as well as cleaning agents as required to maintain performance

Table 2 Specification of critical functional properties of booster reflectors and requirements

Critical functional properties	Test method for determining functional properties	Requirement for functional capability and long-term performance
Reflectance (specular, $\Delta \rho_{\text{spec}}$, and diffuse, ρ_{dif})	ASTM E903-96 „Standard test method for solar Absorptance, Reflectance, and Transmittance of Materials Using Integrating Spheres“	$PC = 0.35 \cdot \Delta \rho_{\text{spec}} + (0.1/C) \cdot \Delta \rho_{\text{dif}}$ < 0.05 with concentration ratio C=1.5
Adhesion between coating and substrate	Visual assessment ISO 4624:2002 „Pull-off test for adhesion“ ISO 2409:1992 „Paints and varnishes - Cross cut test“	No blistering Adhesion > 1 MPa Degree 0 or 1

The first activity specifies in general terms the function of the component and service life requirement from an end-user and product point of view, and from that identifies the most important functional properties of the component and its materials.

In Table 1 and Table 2 results are shown from the analysis made on booster reflectors. How important the function of the component is from an end-user and product point of view needs to be taken into consideration when formulating the performance requirements in terms of those functional properties. If the performance requirements are not fulfilled, the particular component is regarded as having failed. Performance requirements can be formulated on the basis of optical properties, mechanical strength, aesthetic values or other criteria related to the performance of the component and its materials.

Potential failure modes and important degradation processes should be identified after failures have been defined in terms of minimum performance levels. In general, there exist many kind of failure modes for a particular component and even the different parts of the component and the different damage mechanisms, which may lead to the same kind of failure, may sometimes be quite numerous. In Table 3 an example on booster reflectors is presented.

Table 3 Potential failure modes and associated degradation mechanisms, degradation indicators and critical factors of environmental stress for booster reflectors identified

Failure/Damage mode / Degradation mechanism	Degradation indicator	Critical factors of environmental stress
<i>Unacceptable loss in reflector performance</i> Degradation of the protective layer	$PC = 0.35 \cdot \Delta\rho_s + (0.1/1.5) \cdot \Delta\rho_d$ < 0.05 Reflectance spectroscopy, visual inspection, TIS, FTIR, Film thickness measurement	High humidity, high temperature, air pollutants (acid rain), UV irradiation, hail, wind
Corrosion of the reflecting layer	Reflectance spectroscopy, visual inspection, TIS	High humidity, high temperature, air pollutants (acid rain), and impacts from other materials in contact with reflecting layer
Surface abrasion	Visual inspection, TIS	Sand, dust, cleaning, icing, hail, touching, scratching
Surface soiling	Reflectance spectroscopy, visual inspection, TIS	Microorganisms, wind, dust, pollutants, birds, etc
Degradation of the substrate	Visual inspection, FTIR, mechanical testing	High humidity, high temperature, air pollutants (acid rain), UV irradiation, and impacts from other materials in contact with reflecting layer
Loss of adhesion of protective coating	Visual inspection, Cross-cut testing	High humidity, high temperature, air pollutants (acid rain), and UV irradiation
Loss of adhesion of reflector from substrate	Visual inspection, Cross-cut testing	High humidity, high temperature, air pollutants (acid rain), and UV irradiation

Fault tree analysis is a tool, which provides a logical structure relating failure to various damage modes and underlying chemical or physical changes. It has been used for the static solar materials studied in Task 27 to better understand observed loss in performance and associated degradations mechanisms of the different materials studied.

In Figure 1 and Figure 2 examples on how the different failure modes and associated degradation mechanisms can be represented for booster reflectors and antireflective glazing materials, are shown.

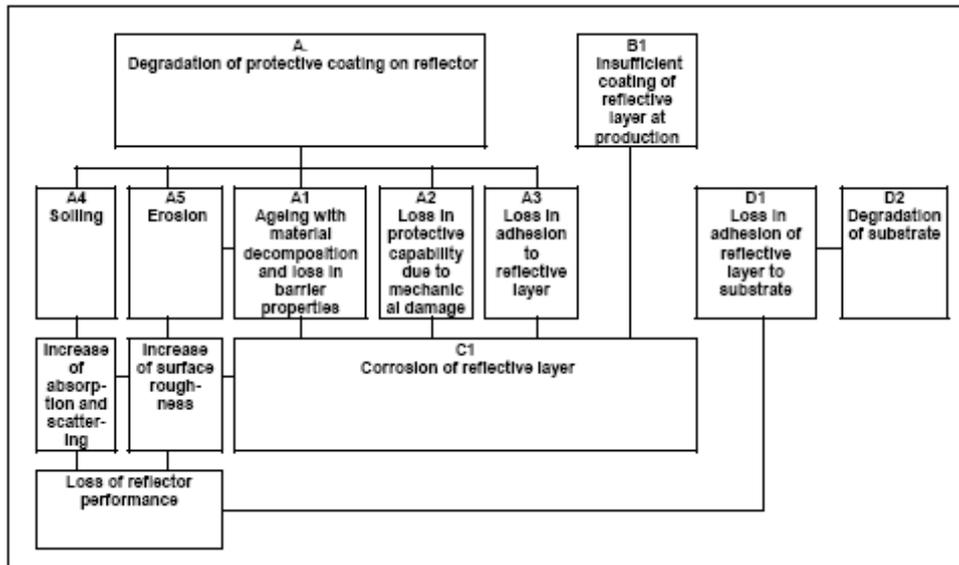


Figure 1: Representation of failure modes and associated degradation mechanisms for booster reflectors

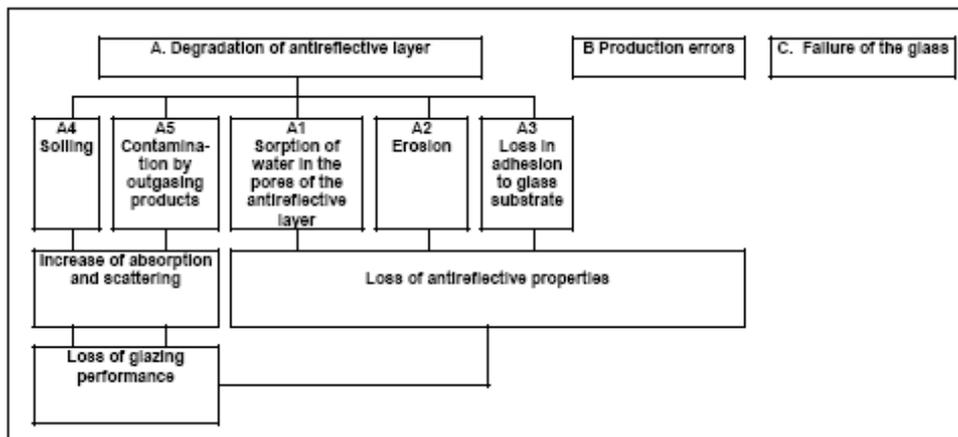


Figure 2: Representation of failure modes and associated degradation mechanisms for antireflective glazing

Table 4: Risk assessment on different damage modes of booster reflectors made by using the methodology of FMEA

Failure/Damage mode / Degradation process	Estimated risk number associated with damage mode (based on FMEA)
A1 Degradation of the protective layer - Ageing with material decomposition	80
A2 Degradation of the protective layer- Loss in protective capability due to mechanical damage	40
A3 Degradation of the protective layer - Loss in adhesion to reflective layer	64
A4 Surface soiling	56
A5 Surface erosion	50
B1 Insufficient coating of reflective layer at production	70
C1 Corrosion of the reflecting layer (Result of mechanisms A1-A3, B1)	112
D1 Loss of adhesion of reflector from substrate	70
D2 Degradation of the substrate	32

The risk associated with each potential failure/damage is taken as the point of departure to judge whether a particular failure mode needs to be further evaluated or not. Risks may be

estimated jointly by an expert group adopting the methodology of FMEA (Failure Modes and Effect Analysis). In Table 4 the result of a risk analysis made on booster reflectors is presented.

3. Screening testing/analysis for service life prediction

Screening testing is thereafter conducted with the purpose of qualitatively assessing the importance of the different degradation mechanisms and degradation factors identified in the initial risk analysis of potential life-limiting processes.

3.1 Test methods

When selecting the most suitable test methods for screening testing, it is important to select those with test conditions representing the most critical combination of degradation factors.

Using artificially aged samples from the screening testing, changes in the key functional properties or the selected degradation indicators are analysed with respect to associated material changes. This is made in order to identify the predominant degradation mechanisms of the materials in the component.

When the predominant degradation mechanisms have been identified also the predominant degradation factors and the critical service conditions determining the service life will be known.

Screening testing and analysis of material change associated with deterioration in performance during ageing should therefore be performed in parallel. Suitable techniques for analysis of material changes due to ageing may vary considerably.

On the static solar materials of Task 27, a number of accelerated screening have been performed including simulation of possible degradation in performance under the influence of high temperature, high humidity/condensation, UV, and corrosion loads; either single or combined loads; see Table 5.

3.2 Results

In Figure 3 the results from a series of screening tests on pure aluminium, used as reference reflector material, are shown as an example of result. Degradation in optical performance is observed mainly, as expected, in the corrosion tests. In Figure 4 the result from the testing of a number of antireflective glazing materials at 80 °C and 95 %RH is given. The cause of degradation in optical performance is in this case not understood and the degradation therefore needs to further analysed. To identify degradation mechanisms for the tested materials various analytical techniques are presently employed.

Table 5: Examples of screening tests performed on the reflector materials, antireflective glazing materials, and solar façade absorbers studied by the IEA SHCP Task 27 group

Damage/degradation mechanisms	Test methods
Reflector materials	
Degradation of the protective layer	Constant load condensation tests at 40°C and 60°C with UV irradiation Constant load temperature test at 80°C with UV irradiation exposure Artificial weathering test with acid rain (SP-method 2710)
Corrosion of the reflecting layer	Corrosion test according ISO/FDIS 21207 method A with and without salt spray exposure
Adhesion losses	Cyclic condensation and cyclic high humidity tests
Antireflective glazing	
Sorption of water and adhesion loss	Cyclic temperature test (-18°C to +80°C) at high humidity 95% RH
Erosion (etching ?)	Constant load condensation tests at 58°C Corrosion test according ISO/FDIS 21207 method A with salt spray exposure
Loss in performance by outgasing products	Outgasing tests with various thermal insulation materials
Solar façade absorbers	
High temperature oxidation	Constant load high temperature tests at 150°C and 170°C
Photooxidation	Constant load high temperature tests at 150°C and 170°C with UV irradiation exposure
Hydrolysis	Constant load condensation tests at 40°C and 65°C
Hydrolysis and photooxidation.	Constant load condensation tests at 40°C and 65°C with UV irradiation Artificial weathering test with acid rain (SP-method 2710)
Corrosion of substrate	Corrosion test according ISO/FDIS 21207 method A with and without salt spray exposure

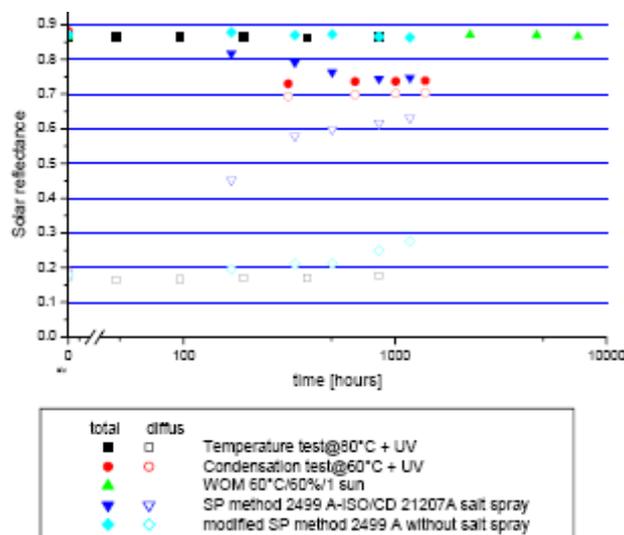


Figure 3: Results from screening tests on pure Aluminium

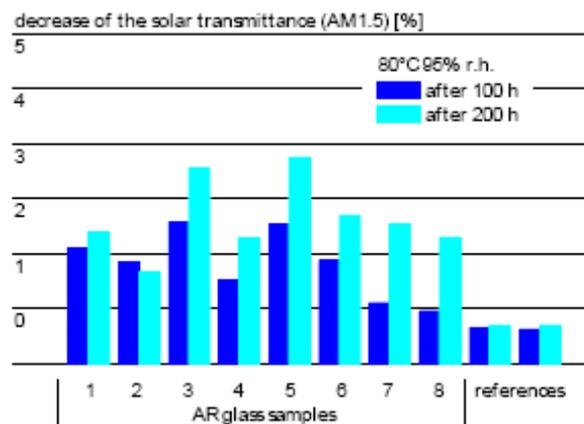


Figure 4: Result of the most significant screening test on antireflective glazing materials involving exposure at 80°C and 95 %RH

3.3 Microclimate characterization

In order to be able to predict expected service life of the component and its materials from the results of accelerated ageing tests, the degradation factors under service conditions need to be assessed by measurements. If only the dose of a particular environmental stress is important then the distribution or frequency function of a degradation factor is of interest.

For measurement of microclimatic variables relevant in the assessment of durability of the static solar materials studied in Task 27, various kinds of climatic data during outdoor exposure at different test sites are monitored such as global solar irradiation, UV-radiation, surface temperatures, air humidity, precipitation, time of wetness, wind conditions, and atmospheric corrosivity. Such data will be used to predict expected deterioration in performance over time by making use of degradation models developed from results of accelerated tests. Some results from the measurement of microclimatic data are shown in Table 6 and Figure 5.

Table 6: Atmospheric corrosivity measured at three test sites for outdoor exposure of solar façade absorbers in the IEA Task 27 study

Exposure Site of the metal reference specimens Orientation South/90° - South/45°	First year metallic mass loss [g/m ²]		
	Copper	Zinc	Carbon steel
ISE, Freiburg, Germany	7.2 – 9.5	2.8 – 4.7	73 – 83
SP, Boras, Sweden	4.0	2.6	43
SPF, Rapperswil, Switzerland	4.0 – 5.2	2.6 – 7.9	71 – 81

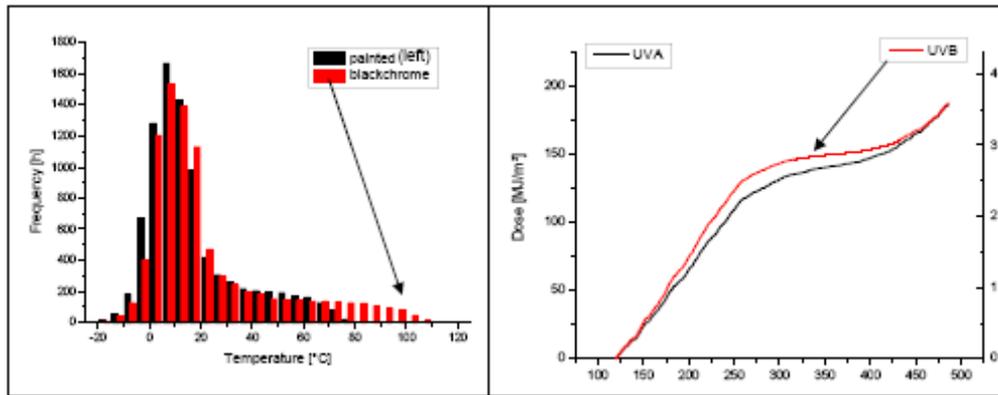


Figure 5: Microclimatic data measured during outdoor exposure of solar façade absorbers at ISE. Left diagram: Surface temperature frequency histograms for a black painted and a black chrome absorber; Right diagram: UVA and UVB light doses versus exposure time.

4. Service life prediction from results of accelerated testing

Accelerated life testing means to quantitatively assess the sensitivity to the various degradation factors on the overall deterioration of the performance of the component and its materials.

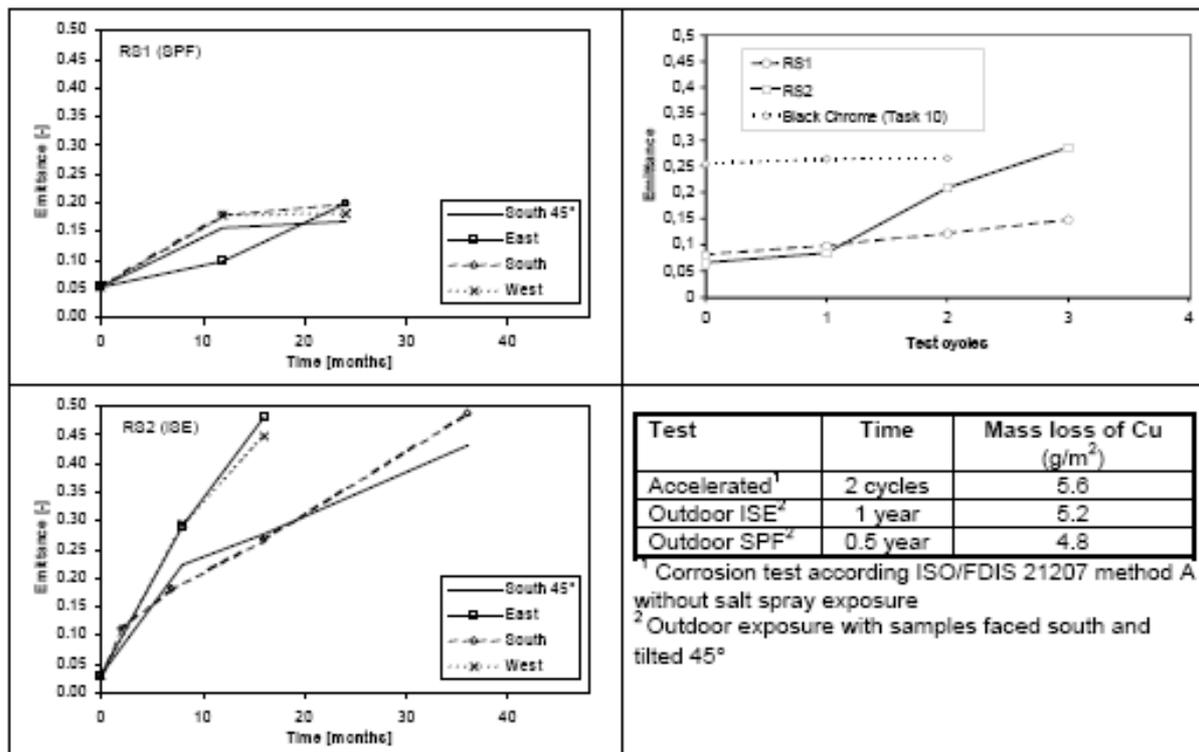


Figure 6: Change in thermal emittance observed for some reference solar façade absorber materials during outdoor testing and during accelerated corrosion testing. The corrosivity dose in terms of metallic mass loss of copper at an exposure time is also given for the different tests to illustrate that outdoor performance of those absorbers can be predicted by making use of the equivalent corrosivity dose approach.

Mathematical models are then set up to characterize the different degradation mechanisms identified and from the accelerated life test results the parameters of the assumed model for degradation are determined and the service life then estimated.

In Figure 6 is illustrated how the principle of equivalent corrosivity dose in accelerated corrosion testing can nicely be adopted in the prediction of the long-term outdoor performance of some solar façade absorbers. A prerequisite for this is that the accelerated corrosion test correctly simulates the predominating corrosion mechanism occurring under normal outdoor conditions.

5. Validation

The best approach in validating an estimated service life from accelerated testing is to make use of the results from the accelerated life tests to predict expected change in material properties or component performance versus service time and then by long-term service tests check whether the predicted change in performance with time is actually observed or not.

The results of validation tests therefore can be used to revise a predicted service life and form the starting point also for improving the component tested with respect to environmental resistance, if so required. It should be remembered that the main objective of accelerated life testing is to try to identify those failures which may lead to an unacceptable short service life of a component. In terms of service life, the main question is most often, whether it is likely or not, that the service life is above a certain critical value.

In the case studies of Task 27 outdoor tests at different test sites are performed for measurement of microclimatic variables and for validating predicted loss in outdoor performance from accelerated test results. Tests are performed by CSTB in Grenoble (France), ENEA in Rome (Italy), INETI in Lisbon (Portugal), ISE in Freiburg (Germany), NREL in Colorado/ Florida/Arizona (USA), SP in Boras (Sweden), SPF-HSR in Rapperswil (Switzerland) and Vattenfall in Älvkarleby (Sweden). In Figure 7 a view of the test site at INETI in Lisbon is shown.



Figure 7: View of the outdoor exposure site with facilities for monitoring of climatic data at INETI in Lisbon

6. Conclusions

The work in IEA Task 27 on durability assessment of static solar energy materials has shown that it is possible to employ a systematic approach in the evaluation of the expected service life of the materials studied. Based on the work performed recommended test procedures will be worked out for qualification of new materials with respect to durability.

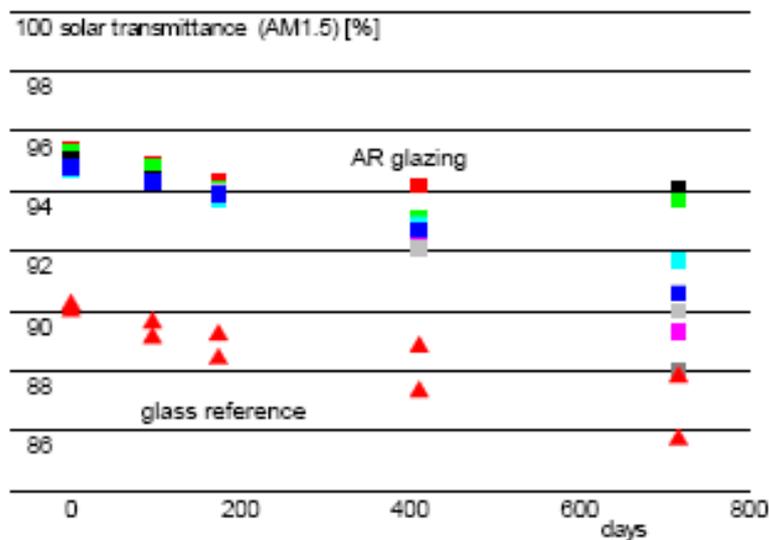


Figure 7: Results from outdoor exposure of antireflective glazing materials performed at SPF-HSR Rapperswil, Switzerland. The decrease in the solar transmittance with time is due to soiling effects, which vary very much with exposure site.

For recommended durability test procedures to be accepted as international standards, it is of utmost importance to demonstrate their relevance for predicting real in-service long-term performance.

7. References

- [1] M. Köhl ; New IEA-SHC Task: Performance of Solar Façade Components – Performance, durability and sustainability of advanced windows and solar components for building envelopes, Proceedings Eurosun 2000 Conference, Copenhagen 19-22 June 2000
- [2] B. Carlsson, K. Möller, M. Köhl, M. Heck, S. Brunold, U. Frei , J.- C. Marechal, G. Jorgensen; The applicability of accelerated life testing for assessment of service life of solar thermal components, Solar Energy Materials and Solar Cells (in press)
- [3] R.E. Mc Dermott, R.J. Mikulak, M.R. Beauregard, R. Mikylak, The basics of FMEA, Productivity Inc. 1996, ISBN: 0527763209

Case study 1: Glazing

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1.1 Anti-reflective coatings for glazing

1.1.1 Introduction

Over the past decades, different attempts have been made to enhance the solar transmittance of glazing. The potential for improving solar facade components is rather high. Many of them are covered with a glazing on which the losses per surface due to reflection are typically between 4% for normal incidence and 9% for an angle of incidence of 60°. For a double glazing these losses can sum up to 15% for normal incidence and 31% for 60°.

The main difficulty in developing efficient broadband antireflection (AR) layers is the need for layers with a refractive index lower than 1.3. Conventional multilayers with alternating high and low refractive indices are very effective in the visible region but cannot be used for the solar spectrum because their effect is to increase reflection at double the design wavelength. In publications concerning solar anti-reflective surfaces [1 - 4], the principle to achieve the necessary low refractive indices is always the same: substrate material is mixed with air on a subwavelength scale. This results in layers with sufficiently low effective refractive indices.

On the market available are now two different technological approaches to make inorganic glasses antireflective:

- Porous surfaces produced by etching the substrate material
- Porous SiO₂ sol-gel coatings
- Further developments which use similar processes are ongoing.

Porous sol-gel coatings are produced by dipping a glass pane into a sol containing very small SiO₂ particles. After withdrawal of the glass pane and drying of the wet film the coating has to be heated at high temperature: a process which is normally done by using the glass strengthening process. Thus, no extra energy is required. The etching technology using HF und H₂SiF₆•SiF₄ as described for example in [3] includes in reality not only etching but also re-deposition of SiO₂. Thus, the morphologies of the etched glazing and sol-gel coated glazing which are available on the market are similar. In both cases, a single layer with a porosity of around 50% is formed.

Slight differences concern the homogeneity of the porosity over the depth of the layer. A cross section of a porous sol-gel coating on glass is shown in Fig. 1. Such layers are

applied in thicknesses from 120 – 140nm and contain almost only SiO₂ and air. The solar transmittance (AM1.5) of a glass pane AR treated on both surfaces is typically increased by around 5% under near-normal incidence.

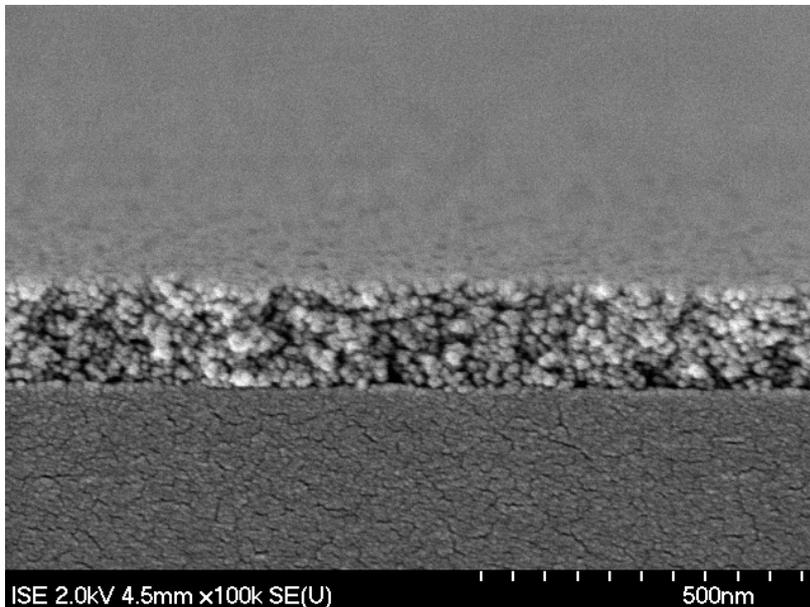


Fig. 1: SEM picture of a cross section of a porous sol-gel coating on glass.

The goal of this work was to analyse potential failure modes and to develop suitable qualification testing in order to enable us to predict service life based on the test results. We did not reach this goal because we were not able to find a really suitable accelerated test method which degrades the material in a sufficiently short time and is relevant for the practical use of such glazing.

What we found is that the AR glazing performance is significantly determined by processes which cannot be allocated to material degradation but more to a reversible modification of the pores. Additionally, natural soiling of glass panes cannot be neglected.

1.1.2 Performance degradation due to filling of the pores

The low effective refractive index requires that the pores of the porous AR layer are filled with air. If the pores are filled with a material which has a refractive index close to that of the SiO₂ network surrounding the pores the AR effect vanishes. We found that water vapour and vapours of organic compounds can condense in the pores. This happens for water only at very high humidity. Therefore the condensation of water in the pores is almost negligible in practise according to our experience so far. Organic compounds can originate from materials used at elevated temperatures in the neighbourhood of such glazing. Such organic compounds can be removed from the pores just by rinsing with water.

Therefore the AR layers facing outwards are always cleaned by rain if there is some filling of the pores but AR layers on inward glass surfaces can be affected. A solar thermal collector may serve as an example. A sketch of such a collector is shown in Fig. 2. Inside the collector the thermal insulation material and the seals may contain organic materials. Our tests showed that the AR effect of the inner layer can be totally removed when mineral

wool with high content of a phenolic resin as binder are used as soon as the absorber reaches typical stagnation temperatures (Fig. 3).

A variety of thermal insulation materials do not show the outgasing effect. For example, a mineral wool with a gradient of the phenolic resin (low concentration close to the absorber, higher concentration with larger distance to the absorber) performed very well in combination with AR glazing.

This is possible due to the high temperature gradient within the thermal insulation. This temperature gradient can be made visible by the brownish colour of degraded phenolic resin which is shown in Fig. 4. So-called binder-free mineral wool is not in general better than mineral wool containing binders. Some of the binder-free mineral wool which we tested did not contain phenolic resin but contained large amounts of other organic materials. As a result, the materials used in combination with porous AR layers should be selected carefully.

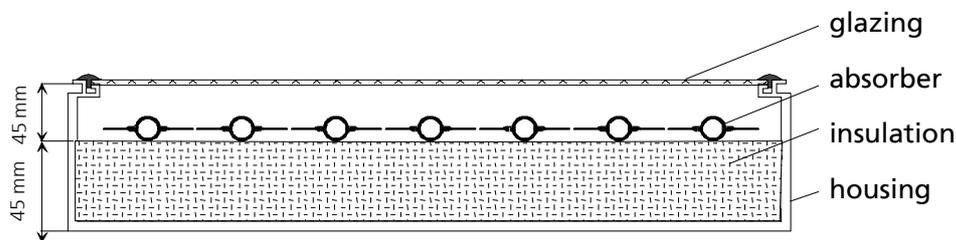


Fig. 2: Sketch of a solar thermal collector

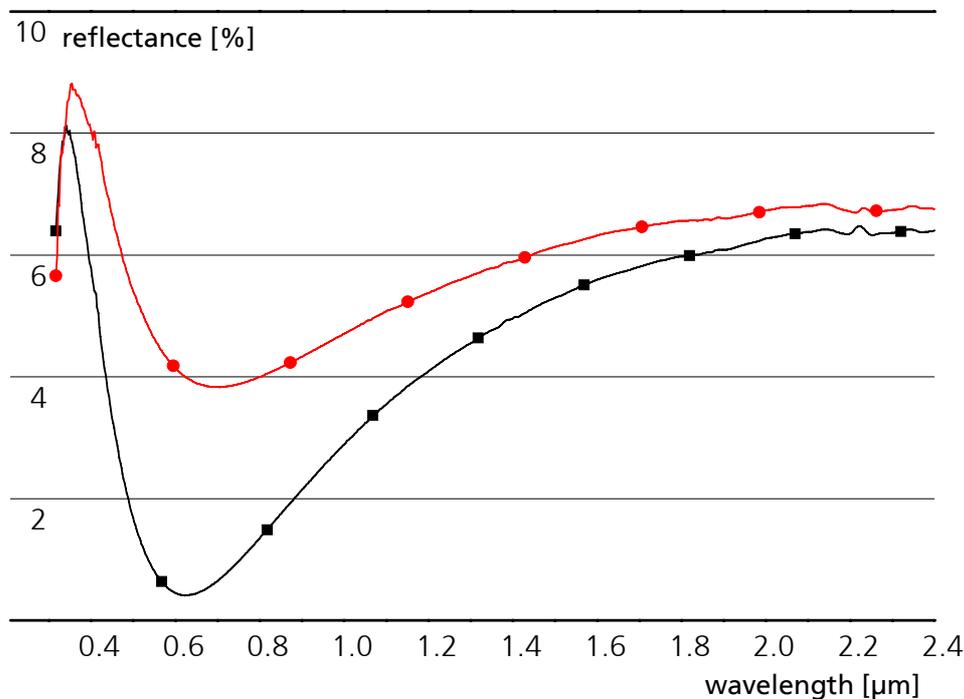


Fig. 3: Reflectance spectrum of an AR glazing before (squares) and after (dots) 170°C absorber temperature for 24 h on a small test solar collector equipped with a thermal insulation containing a high amount of phenolic resin as binder.



Fig. 4: Photo of different insulation materials based on mineral wool after treatment in a small test solar collector at stagnation temperatures for 24 hours (left and middle: top view and cross section of a mineral wool containing phenolic resin; right: binder-free wool)

1.1.3 Accelerated testing

As potential failure modes of the porous AR layers we identified: loss of adhesion, degradation of the SiO₂ network and irreversible filling of the pores. All these potential failure modes are based on chemical reactions which can be accelerated by using elevated temperatures, high humidity and condensation. Neither the porous network nor the substrate will significantly be affected by solar radiation. Therefore, the search for suitable screening tests concentrated on the following tests which were performed in laboratories in France, Switzerland, Sweden and Germany:

Test name	Test conditions
High temperature, high humidity	58°C, 95% r.h.
High temperature, high humidity	80°C, 95% r.h.
Condensation	58°C (sample at 53°C), 95% r.h.
Cyclic temperature, high humidity	-18°C - +80°C, 95% r.h. when possible
Pollutants	SO _x

The good news is that no significant loss of adhesion or destruction of the AR layers was observed in any of the tests. Only traces of water droplets running down the glass panes have been seen partly as slight colour changes. The bad news is that in none of the tests the AR layers degraded with a sufficient speed in order to use that test as suitable accelerated test.

For example in Fig. 5, results from the high humidity / high temperature test are shown. This was the only test which resulted in significant changes of the AR treated glasses. One can see that even after 200 hours of testing the maximum decrease of the solar transmittance of the samples is below 3%. The variation of the results between the two samples of each of the different types of AR layers is in the range of the variation between

different types. Additionally, it is questionable whether with such a test real outdoor conditions are accelerated. As a result, one can say that a careful decision for the most suitable testing method still cannot be made.

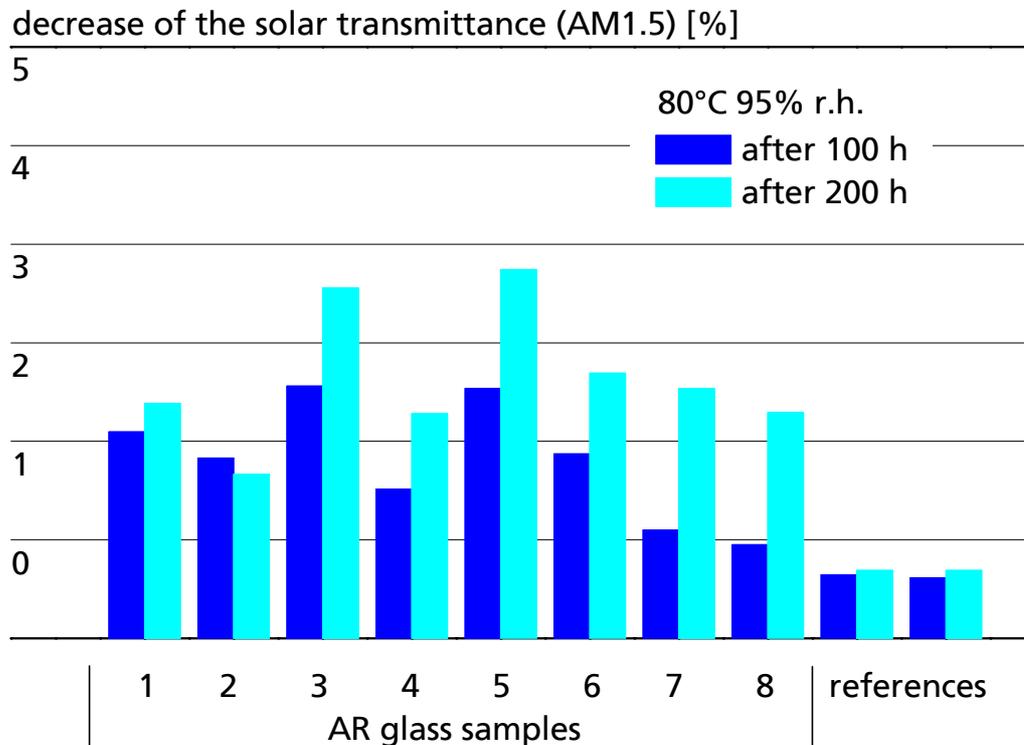


Fig. 5: Decrease of the solar transmittance of the samples from the initial values after testing 100h and 200 h at 80°C/ 95% r.h. The variation of the reference values is probably due to measurement errors

1.1.4 Outdoor testing

At six different places around Europe 15 x 15 cm² large samples were exposed outdoors and their transmittance and reflectance was measured in defined intervals and some of the samples were never cleaned others before the measurement. Unfortunately, due to difficulties in funding or personal resources not all data are completely available. The important results are: in the first 3-4 months of outdoor exposure the solar transmittance of inorganic glass with and without AR layers is reduced by typically 1% in one case even by 3%. This natural soiling can not fully be removed by washing the glass and there is no significant difference between AR treated and untreated glass.

This means that the initial improvement of the solar transmittance by using the AR layers remains for the period of investigation almost unchanged at those places at which also a glass reference is measured. An example is shown in Fig. 6. For reference, also an organic glazing which is known for quick degradation was tested. For the locations at which no reference was measured it is impossible to decide whether a measured slight degradation is due to natural soiling or not. In all locations, a slight degradation of the transmittance of all inorganic glass samples (with and without AR layers) could be

observed. No significant difference was found for the different types of AR layers. The testing period is definitely too short to give final recommendations now.

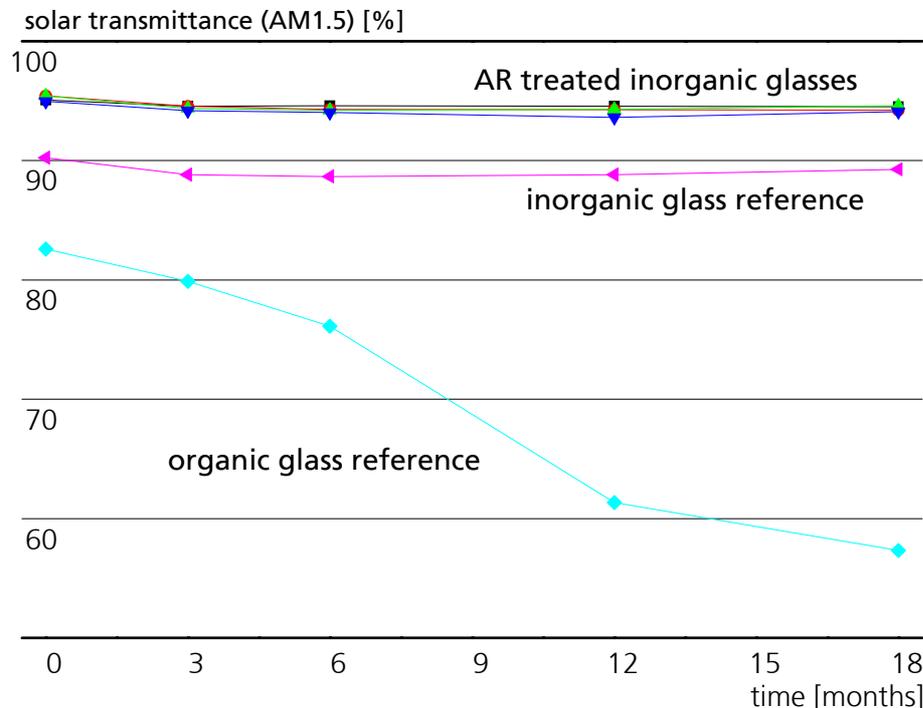


Fig. 7: Measured values of the solar transmittance (AM1.5) for the samples exposed at Freiburg, Germany, during the first 18 months.

1.1.5 Conclusions

So far, the goal to determine real failure modes and to develop a method for service life prediction could not be reached. Performance degradation due to processes which are not directly related to the used materials such as filling the pores with organics or natural soiling was identified. The samples under investigation are very stable in all the accelerated tests which were applied. For the outdoor testing a longer observation period is required in order to identify real use degradation modes.

1.1.6 References

- [1] Cathro, K. J., Constable, D. C. and Solaga, T. (1981). "Durability of porous silica antireflection coatings for solar collector cover plates", *Solar Energy*, Vol. 27, No. 6, 491 - 496.
- [2] Cathro, K. J., Constable, D. C. and Solaga, T. (1984). "Silica low-reflection coatings for collector covers, by a dip-coating process", *Solar Energy*, Vol. 32, No. 5, 573 - 579.
- [3] Chinyama, G. K., Roos, A. and Karlsson, B. (1993). "Stability of antireflection coatings for large area glazings", *Solar Energy*, Vol. 50, No. 2, 105 - 111.
- [4] Gombert, A. et al. (1998). "Glazing with high solar transmittance ", *Solar Energy* Vol. 62, No. 3, 177 – 188.

1. 2. Durability of polymeric glazing materials

Main contributions from Gary Jorgensen, NREL, USA

The economic viability of solar collector systems for domestic hot water (DHW) generation is strongly linked to the cost of such systems. Installation and hardware costs must be reduced by 50% to allow significant market penetration. An attractive approach to cost reduction is to replace glass and metal parts with less expensive, lighter weight polymeric components. Weight reduction decreases the cost of shipping, handling, and installation. The use of polymeric materials also allows the benefits and cost savings associated with well established manufacturing processes, along with savings associated with improved fastening, reduced part count, and overall assembly refinements.

A key challenge is to maintain adequate system performance and assure requisite durability for extended lifetimes. Results of preliminary and ongoing screening tests for a large number of candidate polymeric glazing materials are presented. Based on these results, two specific glazings are selected to demonstrate how a service lifetime methodology can be applied to accurately predict the optical performance of these materials during in-service use. A summary is given for data obtained by outdoor exposure and indoor testing of polyvinyl chloride (PVC) and polycarbonate (PC) materials, and an initial risk analysis is given for the two materials. Screening tests and analyses for service lifetime prediction are discussed. A methodology that provides a way to derive correlations between degradation experienced by materials exposed to controlled accelerated laboratory exposure conditions and materials exposed to in-service conditions is given, and a validation is presented for the methodology based upon durability test results for PVC and PC.

1.2.1 Introduction

Polymeric glazings offer significant potential for cost savings both as direct substitutes for glass cover plates in traditional solar collector systems and as an integral part of all-polymeric systems. A review of polymeric solar collector systems development efforts is provided in [1]. Cost savings result from lower base material costs and lower costs associated with shipping, handling and installation. Glazings must have high transmittance across the solar spectrum and must be able to survive 10 to 20 y exposure to service conditions including operating at temperatures of 55 to 90 °C and in solar ultraviolet (UV) light. They must also retain mechanical integrity e.g., impact resistance and flexural rigidity, under these harsh environmental stresses. The emphasis of current efforts is to identify new or improved candidate glazings and to evaluate their optical and mechanical durability during exposure to actual and simulated in-service conditions.

Recently, several reviews of candidate polymeric glazing materials have been undertaken [2-4]. These were guided by the expectation that advances in the polymer manufacturing and materials industry would allow identification of potential new and improved collector glazing candidates. An international collaborative effort surveyed commercial producers of advanced polymer materials in the U. S., Europe, and Japan [2].

The most promising class of polymers were fluoropolymers. These have excellent thermal and optical durability but are expensive and are limited to use with thin film collector designs. Film products such as Tefzel® (ethylene-tetrafluoroethylene copolymer; ETFE), Duralar® (also an ETFE), Halar®, Teflon®, and Kynar® exhibit very high spectral transmittance and many have sufficient tear resistance to be considered as collector glazings [3]. Suitably UV-stabilized polyetherimide (PEI), polyimide (PI), and polycarbonate (PC) were also suggested for consideration, although PI is quite expensive. Preliminary exposure test data for several dozen polymeric glazing materials being screened was reported in [3]; most materials identified by [2] were included. These exposures have continued and further results are discussed herein. Another complementary review also surveyed potential polymeric glazing materials [4]. In addition to twin walled PC, fluoropolymer films, and multilayered polyethylene (PE) films under test, consideration of polyurethane films, silicones, enhanced acrylics, clay-filled thermoplastics, and polycyclohexylethylene (PeCHE) were also recommended.

Screening tests have revealed the more promising candidates, along with glazing materials that have failed. The most common mode of failure has been yellowing of the glazing material. These have generally included non-fluoropolymer thin film materials (PET and PE, including UV-stabilized versions), and non-UV stabilized PC constructions. Additional (less common) modes of failure include materials developing a cloudy white opaque appearance, temperature-related deformation and/or discoloration, and physical damage caused by hail and other natural weathering events. Materials that have maintained high solar-weighted hemispherical transmittance values (>90%) after more than 2 years outdoor and accelerated exposure include: Kynar®, Duralar®, Tefzel®, and Halar® and PC with UV-screening layers.

Polycarbonate has high optical clarity and excellent impact strength. However, it will yellow during UV exposure and become brittle. Recently, stabilized versions of PC have been developed. For example, Bayer has two products designated APEC 5391 and APEC 5393. The first is a thermally stabilized formulation, which is offered for a maximum continuous use temperature of up to 180°C, and the second is stabilized for UV exposure and elevated temperatures. General Electric has incorporated an integral UV-screening coating into a number of their Lexan products. Because PC has excellent initial properties and is available in a variety of forms, e.g., sheet or channeled, suitable for use with solar collectors, it has been extensively studied as a promising glazing candidate. Parallel test results for PVC serve as a control, because it is known to weather poorly.

1.2.2 Durability exposure testing

From 1993-2002, numerous samples of PVC and PC materials were exposed to accelerated life testing in laboratories and to the outdoor environment at test sites located in Europe and in the USA by colleagues participating in the Working Group "Materials in Solar Thermal Collectors" (MSTC) of the IEA Solar Heating and Cooling Programme. The details of these test results are provided in [5]. Samples of PC and PVC, along with other candidate polymeric glazing materials, were subjected to in-service outdoor and accelerated laboratory exposure conditions. Outdoor testing was carried out in Switzerland at the Institut für Solartechnik (SPF), Germany at the ISE in Freiburg, and at three sites in the United States, namely, Golden, CO; Phoenix, AZ; and Miami, FL. A precise and

detailed knowledge of the specific environmental stress conditions experienced by weathered samples is needed to allow understanding of site-specific performance losses and to permit service lifetime prediction of candidate glazings.

Consequently, each operational exposure site is fully equipped with the appropriate meteorological and radiometric instrumentation and data-logging capability.

1.2.3 Outdoor Exposure Testing

The materials tested are for the intended use in solar thermal flat plate collectors. Thus, the samples for outdoor exposure were attached to mini-collector boxes, as illustrated in Figure 1. To simulate the elevated temperature collector covers are exposed to, the "mini-collectors" are made of solar selective coated stainless steel. A thermocouple is affixed to the glazing material to monitor sample temperature, and a reflective light shield hood is used to prevent direct heating of the thermocouple.

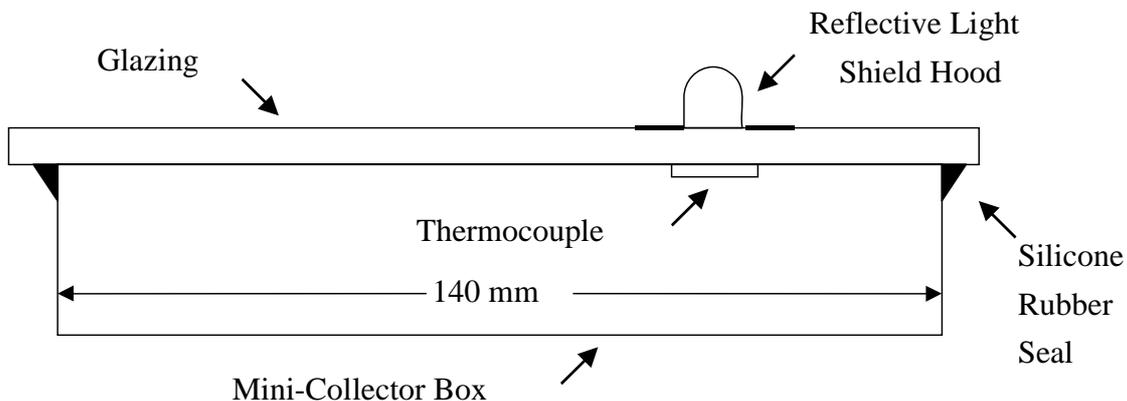


Figure 1: "Mini-collectors" used for outdoor exposure of transparent cover materials

The samples prepared in this way were exposed to the ambient climate at locations in Europe and in the USA, facing south at an inclination angle equal to the latitude of the site. The spectral transmittance of all samples was measured prior to exposure. After some time, some of the samples were remeasured and exposed again without any cleaning. Other samples were measured before and after cleaning and then exposed again.

Solar-weighted transmittance values integrated over the solar spectrum (τ_{sol}) and between 400-600 nm ($\tau_{400-600}$) are computed as degradation indicators. The bandwidth 400-600 nm is useful because degradation of optical transmittance of many polymeric glazing materials is most pronounced in that spectral range.

Representative τ (400-600) data are plotted in Figures 2 and 3 for APEC 9353 PC and Duraglas PVC, respectively. Figure 2 shows a loss in τ (400-600) of about 5% per year for samples of APEC 9353 exposed outdoors in Europe and the US. Duroglas, a PVC glazing material, degrades very rapidly when exposed to UV light. Figure 3 presents outdoor test results for Duroglas exposed in the United States and Europe. Samples of Duroglas exhibited between 25-40% loss in τ (400-600) after only one year exposure, depending upon the outdoor site.

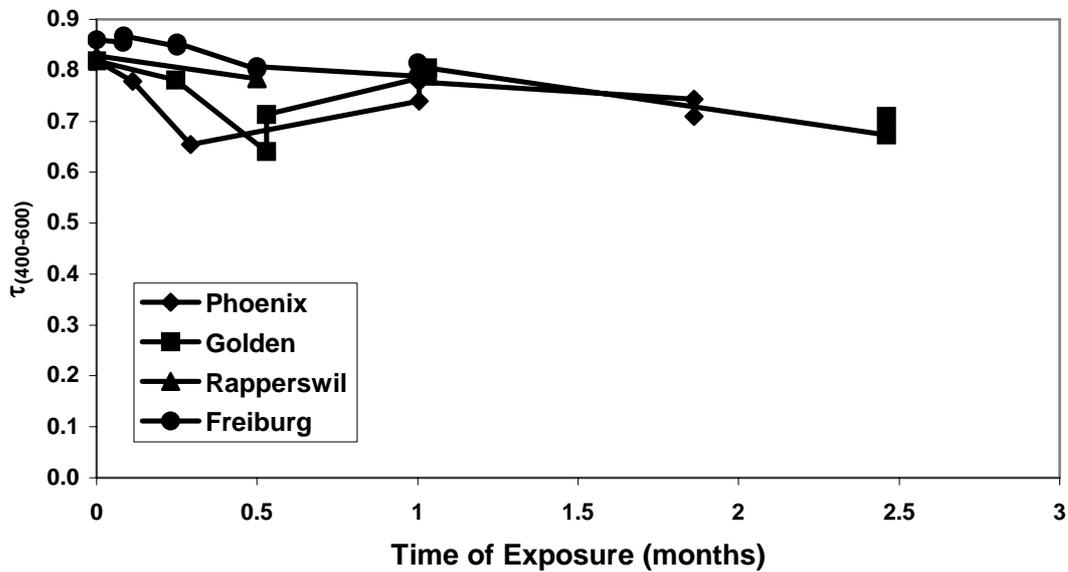


Figure 2: Outdoor exposure test results for APEC 9353 PV

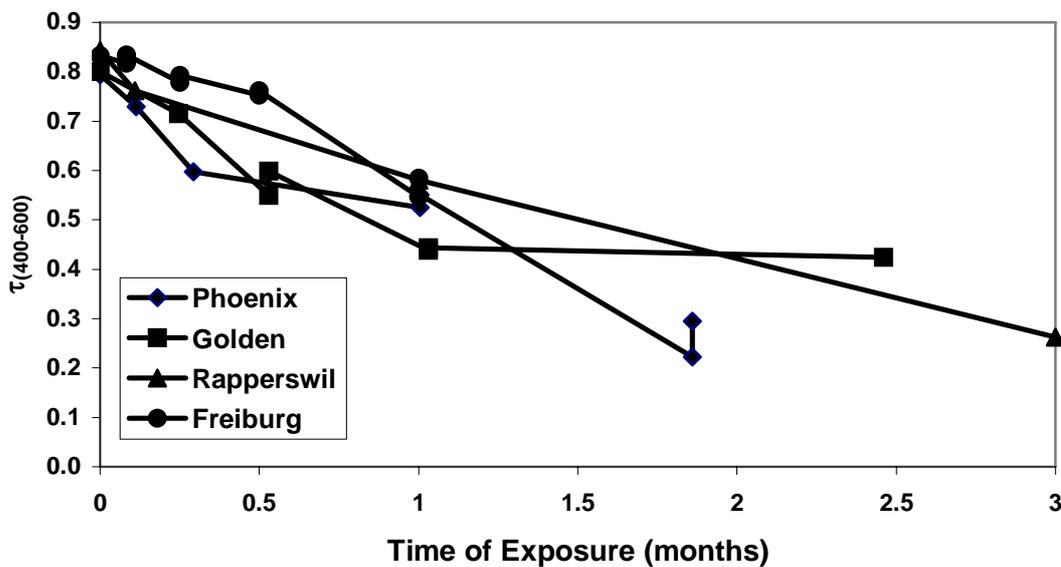


Figure 3: Outdoor exposure test results for Duroglas PVC

1.2.4 Accelerated Laboratory Exposure Testing

Accelerated indoor testing was carried out with different types of test equipment available at the participating laboratories. Several test protocols were performed using corresponding types of exposure chambers. In the first type, UV exposure was combined with various combinations of elevated temperature and a defined level of relative humidity (RH), i.e., 60°C / 80% RH, 80°C / 40% RH, and 50°C / 95% RH. These tests were performed in climatic cabinets at SPF and ISE with an unfiltered metal halide (HMI) lamp as a light source. The intensity of the irradiation compared to an air-mass (AM) 1.5 solar spectrum is about 3 times as much UVA and 7 times as much UVB.

In the second type of exposure test, an Atlas Ci5000 Weather-Ometer® (WOM) was operated at 60°C and 60% RH, and an irradiation level of about twice an AM 1.5 solar spectrum throughout the UV and visible portion of the spectrum. In the final test protocol, an Atlas XR35 WOM – SPART 14 test was used. The SPART 14 test procedure was originally developed for clear coats in automotive paint systems. The test is a weatherability test that includes acidic rain spraying.

In test method SPART 14, which is a modification of SAE J1960 [6], the Xenon arc light source is filtered through borosilicate filters and has an irradiance level of 0.5 W/m² at 340 nm; this corresponds to an intensity of roughly 1.4 times an AM 1.5 spectrum. The test cycle is comprised of a) 40 min of light only; b) 20 min of light with water sprayed on the front surface of the sample; c) 60 min of light only; and d) 60 min of no light with water sprayed on the back surface of the sample. Every fourteenth cycle, the water used to spray the front of the samples is acidic, with a pH of 3.2. The black standard temperature and relative humidity during light periods are 70°C and 75%, respectively. The chamber temperature and relative humidity during the dark periods are 38°C and 95%.

An exposure time of 1000 h (~6 weeks) in the SPART 14 test is estimated to correspond to about 1.3 years of outdoor testing in Miami, Florida for automotive paints. Thus, 4000 h of SPART 14 testing corresponds to about 5 years outdoors in Florida. However, one can assume that the temperature of an automotive coating will be at least 10 K higher than for transparent low light absorbing glazing materials. Consequently, the acceleration factor for the glazing can be estimated to be a factor of 2 higher. Accordingly, 1000 h of artificial weathering corresponds to 2.5 y outdoors.

Highly accelerated exposure testing of selected samples using natural sunlight was also performed at NREL [7]. Parallel testing with the relevant stress factors of UV, temperature, RH, and acid spray at different levels was intended to allow the sensitivity of materials degradation to these factors to be quantified, and allow damage function models to be evaluated. These in turn can be used to compare the time-dependent performance of these materials with measured results from in-service outdoor exposure.

The values obtained for τ (400-600) are plotted in Figures 4 and 5 for APEC 9353, and Duroglas after the different types of exposure. Figure 4 shows that results for APEC 9353 exposed in the SPART 14 chamber are in good agreement with Ci5000 data. However, exposure of APEC 9353 in the unfiltered metal halide chambers is much more severe than in the Ci5000 and SPART 14. With the unfiltered metal halide light source, a ~15% loss in τ (400-600) occurs after only 25 days, whereas it took roughly 100 days for an equivalent loss to occur in the Ci5000 and SPART 14.

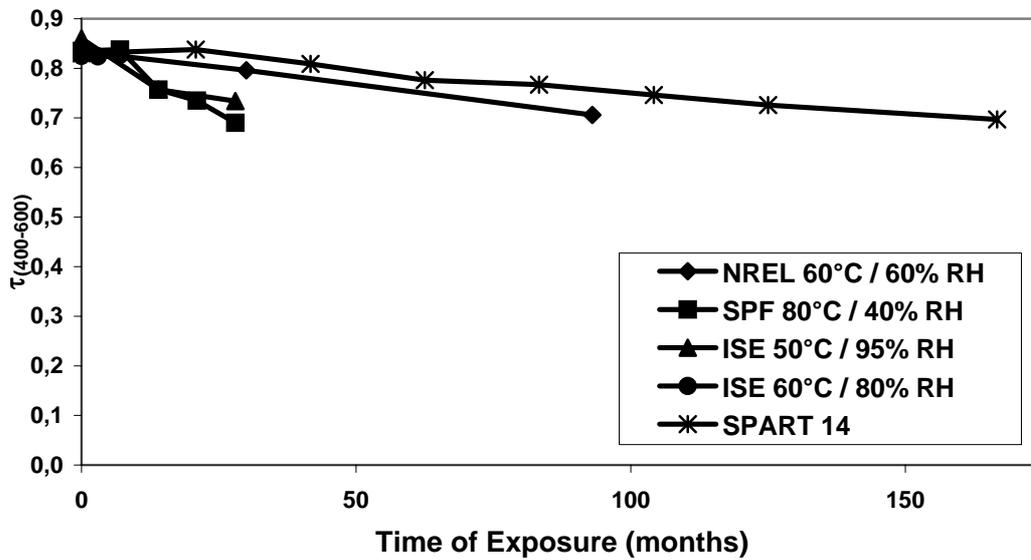


Figure 4: Accelerated exposure test results for APEC 9353 PC

Accelerated exposure test results for Duroglas PVC are provided in Figure 5. Exposure of Duroglas in the unfiltered metal halide chambers at a variety of temperature and RH conditions produced rapid degradation. Results for Ci5000 WOM exposures were less severe, although precipitous degradation did occur in fairly short time periods. Duroglas exposed to the SPART 14 chamber conditions results in considerably less degradation than for the unfiltered metal halide and Ci5000 chamber exposures.

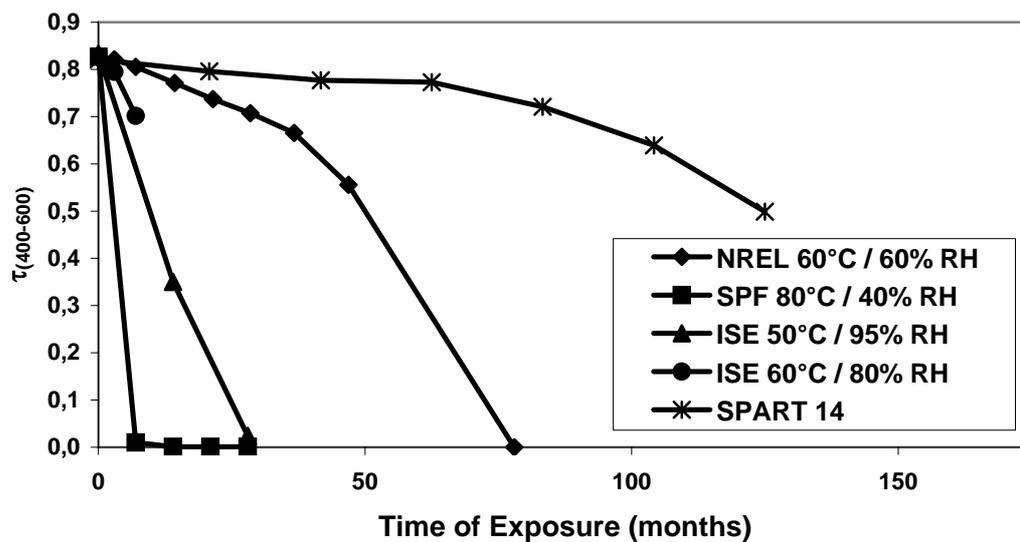


Figure 5: Accelerated exposure test results for Duroglas PVC

The approach developed by the IEA Working Group on Materials for Solar Thermal Collectors [8] is applied below to PVC and UV stabilized PC cover plate materials to illustrate how the general methodology can be used to assess the durability of polymeric-type materials.

1.2.5 Analysis of durability results from accelerated ageing

Using artificially aged samples from screening tests, changes in the key functional properties or the selected degradation indicators are analyzed with respect to the associated changes in the materials. The analyses were made to identify the predominant degradation mechanisms of the materials. Possible mechanisms of degradation of the PC glazing were assumed to be

- (a) photooxidation (PO),
- (b) thermal oxidation, and
- (c) combined photooxidation and hydrolysis.

From the screening tests, it was concluded that only photooxidation contributes significantly to the service life of the glazing. A suitable time-transformation function is:

$$a_{PO} = \frac{\left(I^p \cdot e^{-E/kT} \right)_{acc}}{\left(I^p \cdot e^{-E/kT} \right)_{ref}} \quad (1)$$

where I is the intensity of photoreactive light, T is temperature, E is an activation energy, p is a material dependent constant, “acc” is accelerated test conditions, and “ref” is some set of reference conditions, e.g., use conditions.

For the PVC glazing, degradation mechanisms that could reduce the service life were assumed to be

- (a) dehydrochlorinization,
- (b) photooxidation and
- (c) physical aging.

For (a), the mechanism is a chain reaction type because hydrogen chloride formed from the dehydrogenation reaction acts also as a catalyst for this reaction. The reaction is consequently difficult to model mathematically in a simple way and thus, it is also difficult to express the rate of degradation in terms of a time-transformation function. The best time-transformation function for the PVC degradation was the same general photooxidation time-transformation function used to model the degradation of the PC glazing (Equ. 1).

During life-testing, PC and PVC glazing materials were exposed to the various accelerated conditions discussed above. Hemispherical transmittance measurements were made to characterize the loss in optical performance of the glazing materials during these exposures. Performance-versus-time data were thereafter used to determine the parameters of the time-transformation function (Equ. 1). The results, obtained from a subset of the data accumulated, are shown in Table 1. Values of the activation energies, E , derived are reasonable for photo-thermal degradation mechanisms. The value of $p \sim 2/3$ for PVC indicates that some shielding or rate limiting reactions occur and do not allow all photons to participate in degradation. For the UV-stabilized PC sample, the value of $p = 1$ indicates that exposure of this material follows strict reciprocity. Thus, all incident photons fully contribute to the degradation reactions, even at elevated levels of irradiation.

Table 1: coefficients derived from accelerated exposure for the tested polymeric glazing materials

Polymer Glazing	p	E (kJ/mole)
PVC	0.669	35.3
UV-Stabilized PC	1.093	28.0

1.2.6. Validation of methodology

If it is assumed that the rate in transmittance change is constant if the surface temperature and the UV-light intensity are maintained at the same values during the time interval Δt_i , then the transmittance change $\Delta \tau_i$ may be expressed as

$$\Delta \tau_i = A (I_{UV})^p \Delta t_i e^{-E/kT} \quad (2)$$

using the time-transformation function shown in Equ. 1. The parameter A is a constant independent of surface temperature and light intensity but it is material dependent. It may be determined from the same series of aging tests as used to determine the activation energy E and the parameter p . For $\Delta \tau_i$ equal to the mean global transmittance between an even more narrow bandwidth (400 and 500 nm; chosen to accentuate the region over which degradation occurs, resulting in a more highly sensitive degradation indicator), the values of A were estimated as 2892 $(\text{MJ/m}^2)^{-1}$ for PVC and 5.497 $(\text{MJ/m}^2)^{-1}$ for UV-stabilized PC.

By integrating Equ. 2, Equ. 3 is obtained.

$$\Delta \tau_i(t) = A \int_0^t [I_{UV}(t)]^p e^{-E/kT(t)} dt \quad (3)$$

Applying Equ. 3, the expected transmittance after different time-periods of outdoor exposure may be estimated.

Using the values of the coefficients E and p from Table 1 and the time-monitored values of sample temperature and UV irradiance, the loss in performance was predicted for both the PVC and the UV-stabilized PC as exposed outdoors in Golden, CO, and Phoenix, AZ. Predicted values were then compared with actual measured data for these materials exposed at these sites. The results are shown in Figure 6. The time-dependent changes in the weathering variables result in the irregular shapes of the predicted curves. Excellent agreement is evident between the measured and predicted data. Thus, the phenomenological approach to data analysis is validated i.e., obtaining model coefficients from accelerated test results and then using these coefficients to predict time-variable in-service degradation.

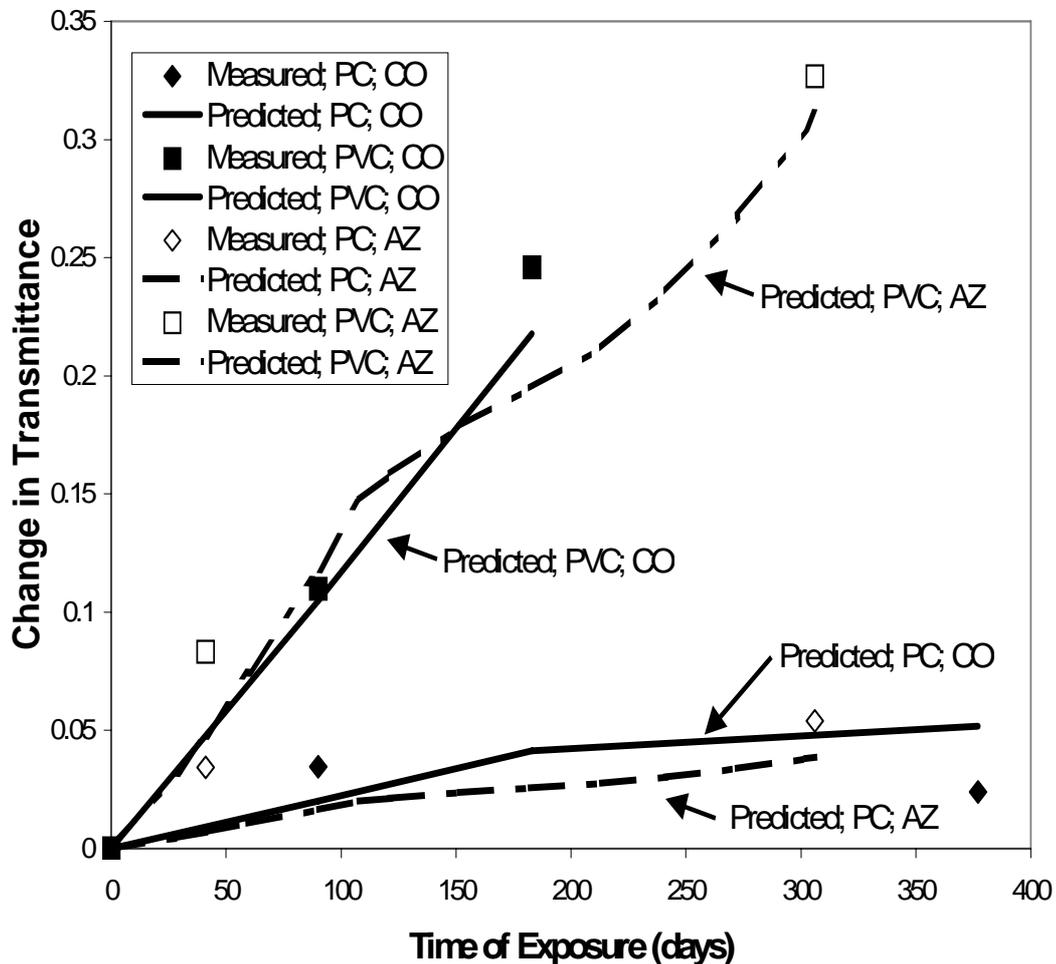


Figure 6: Comparison of the actual and predicted changes (loss) in hemispherical transmittance between 400-500 nm of PVC and PC for exposures of up to 380 days at Golden, CO and Phoenix, AZ.

1.2.7 Conclusions

Durability test data for both accelerated laboratory conditions and outdoor in-service conditions have been presented for PC and PVC glazing materials. Some of the accelerated exposure data were used to demonstrate how to derive damage functions that allow prediction of performance degradation. This methodology also allows the effect of multiple stress factors to be modelled. The usefulness and validity of this approach has then been confirmed by comparing predicted results with actual measured data for samples exposed to variable outdoor conditions. Consequently, highly abbreviated testing times at elevated stress conditions can be substituted for long-time exposures at lower stress levels. The procedure developed allows much shorter development cycle times for

new materials and allows improvements to be identified and readily incorporated into new products.

1.2.8 References

- [1] Davidson, J. H., Mantell, S. C., and Jorgensen, G. J., "Status of Development of Polymeric Solar Water Heating Systems", *Advances in Solar Energy, An Annual Review of Research and Development*, Vol. 15, D. Y. Goswami, Ed., American Solar Energy Society, Inc., Boulder, CO, 2003, pp. 149-186.
- [2] Möller, K., "Identification of New Types of Transparent Polymeric Materials", IEA Task 10 Working Group on Materials in Solar Thermal Collectors Report, November 8, 1996.
- [3] Raman, R. et al, "A Review of Polymer Materials for Solar Water Heating Systems", *Journal of Solar Energy Engineering*, Vol. 122, No. 2, May 2000, pp. 92-100.
- [4] "Solar Hot Water Heating Systems Identification of Plastic Materials for Low Cost Glazings", NREL Subcontract No. TAR-9-29449-02 final report, PolyNEW Inc., Golden, CO, 2000.
- [5] Jorgensen, G. J., et al, "Case Study on Polymeric Glazings", *Performance and Durability Assessment of Optical Materials for Solar Thermal Systems*, A. W. Czamderna, Ed., Elsevier Science, in press.
- [6] SAE J1960, Accelerated Exposure of Automotive Exterior Materials Using a Controlled Irradiance Water-Cooled Xenon Arc Apparatus. Society of Automotive Engineers, 400 Commonwealth Drive, Warrendale, PA 15096.
- [7] Jorgensen G., et al, "Use of Uniformly Distributed Concentrated Sunlight for Highly Accelerated Testing of Coatings", *Service Life Prediction Methodology and Metrologies*, ACS Symposium Series 805, J. W. Martin and D. R. Bauer, Eds., American Chemical Society, Oxford University Press, Washington, DC, 2002, 100-118.
- [8] Carlsson, B., et al, "Weathering of Polymer Products: Assessment of Service Life of Solar Thermal Components by Accelerated Life Testing", *Proceedings of the 1st European Weathering Symposium EWS (XXIIIrd Colloquium of Danubian Countries on Natural and Artificial Ageing of Polymers)*, Gesellschaft für Umweltsimulation e.V., Prague, Czech Republic, September 25-26, 2003.

Case study 2: Reflectors

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The general methodology of project B1 and the contributions from CSTB and SP were used to perform an initial risk analysis for reflectors. The contributions can be found in the annex of the preceding document (r-b3-ISE-MH-Failure mode analysis reflectors-meeting-1-2001) of this working document.

2.1 Structural Analysis

This component is generally made of a multi-layer system on substrates like polymers or aluminium with protective/functional coatings on top. Possible is also silvered glass.

The reflector could be in contact with insulation material or/and the material of the box (polyester, steel, aluminium) using glue, screws or rivets.

Environment

UV

T°C high (170°C)

T°C Low

Thermal shocks

Pollutants (atmospheric: acid)

Air (oxygen, ozone, ...)

Humidity (Rain and condensation)

Shocks (hail, users)

Fluid (Water + antifreeze)

2.2 Specification of end-user and product requirements

Function and general requirements	General requirements for long-term performance during design service time	In-use conditions and severity of environmental stress
Efficiently reflect solar radiation Protect the reflector substrate against the outdoor environment	Loss in material performance should not result in reduction of the solar system performance with more than 5%, in relative sense, during the material service life. No delamination of reflector from substrate Material service life should exceed 25 years	Unprotected reflector UV lowest ambient $<T < 170^{\circ}\text{C}$ Air pollutants Humidity/Wetness Acid rain Mechanical loads (hail, wind, birds, stress from mechanical fixing and due to the own weight) Icing Cleaning as required to maintain system-performance

2.3 Specification of functional properties and requirements on component and its material

Critical functional properties	Test method for determining functional properties	Requirement for functional capability and long-term performance
Reflectance (specular, diffus)	UV-VIS-IR reflectance spectroscopy	ASTM E903-96 „Standard test method for solar Absorptance, Reflectance, and Transmittance of Materials Using Integrating Spheres“ $PC = 0.35 \cdot \Delta\rho_{\text{specular}} + 0.1/C \cdot \Delta\rho_{\text{diffuse}}$
Adhesion between coating and substrate	Adhesion testing ASTM tape test Gitterschnitt	No blistering ISO 4624:2002 „Pull-off test for adhesion“ Adhesion $> 1 \text{ MPa}$ ISO 2409:1992 „Paints and varnishes - Cross cut test“ Degree 0 or 1

2.4 Potential failure modes, critical factors of environmental stress and degradation

Failure/ Damage mode/ Degradation process	Degradation indicator	Critical factors of environmental stress/Degradation factors and severity
Corrosion of the reflecting layer	Reflection spectrum visual inspection TIS	Humidity Temperature Air pollutants (acid) contact with other materials UV
Surface abrasion	visual inspection TIS	Sand, dust, cleaning, icing, hail, touching, scratching
Surface soiling	Reflection spectrum visual inspection TIS	microorganisms, wind, dust, pollutants, chemistry of soiling agent
Degradation of the protective layer	Reflection spectrum visual inspection TIS FTIR Film thickness	Humidity Temperature Air pollutants (acid) UV hail, wind
Degradation of the substrate	visual inspection FTIR mechanical testing	Humidity Temperature Air pollutants (acid) contact with other materials UV
Loss of adhesion of protective coating	visual inspection Gitterschnitt	Air pollutants (acid) Humidity UV, Temperature
Loss of adhesion of reflector from substrate	visual inspection Gitterschnitt	Air pollutants (acid) Humidity UV, Temperature

2.5 Risk assessment and service reliability for commercial AI reflectors

Failure mode / Degradation process	Severity (S) (rating number)	Probability of occurrence(P_O) (rating number)	Probability of discovery(P_D) (rating number)	Rating-number for risk ($RPN = S \cdot P_O \cdot P_D$)
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Severity	Rating number
No effect on product	1
Minor effect on product but no effect on product function	2-3
Risk of failure in product function	4-6
Certain failure in product functioning	7-9
Failure which may affect personal safety	10

Probability of detection	Rating number
Failure which always is noted. Probability for detection > 99.99%	1
Normal probability of detection 99.7%	2-4
Certain probability of detection >95%	5-7
Low probability of detection >90%	8-9
Failures will not be found - cannot be tested	10

Probability of occurrence	Rating number
Unlikely that failure will occur	1
Very low probability for failure to occur	2-3
Low probability for failure	4-5
Moderate probability for failure to occur	6-7
High probability for failure to occur	8-9
Very high probability for failure to occur	10

2.6 Risk assessment and service reliability for reflectors

Failure/Damage mode / Degradation process	Degradation indicator	Critical factors of environmental stress/ Degradation factors and severity	Estimated risk of failure/damage mode from FMEA			
			S	P _O	P _D	Risk RPN
Degradation of the protective layer	Reflectance spectrum visual inspection TIS FTIR Film thickness	Humidity Temperature Air pollutants (acid) UV hail, wind	5	5	2	50
Corrosion of the reflecting layer	Reflectance spectrum visual inspection TIS	Humidity Temperature Air pollutants (acid) contact with other materials UV	8	5	4	160
Surface abrasion	visual inspection TIS	Sand, dust, cleaning, icing, hail, touching, scratching	5	5	2	50
Surface soiling	Reflectance spectrum visual inspection TIS	microorganisms, wind, dust, pollutants, chemistry of soiling agent	4	7	2	56
Degradation of the substrate	visual inspection FTIR mechanical testing	Humidity Temperature Air pollutants (acid) contact with other materials UV	8	2	2	32
Loss of adhesion of protective coating	visual inspection Cross cut	Air pollutants (acid) Humidity UV, Temperature	7	5	2	70
Loss of adhesion of reflector from substrate	visual inspection Cross cut	Air pollutants (acid) Humidity UV, Temperature	7	5	2	70

*In many high temperature applications the limitation in durability is caused by physical loss of stabilisers e.g. antioxidants, UV-absorbers, HALS, etc

**If photooxidation is not important (as for most inorganic coatings) than P_O = 1 and RPN is very low

2.7 Programme for screening testing of reflectors

Possible degradation mechanism	Critical periods of high environmental stress	Suitable accelerated test methods and range of degradation factors
Degradation of the protective layer	<p>- Stagnation conditions of solar system at high levels of solar irradiation (no withdrawal of heat from the collector), High temperature oxidation</p> <p>-At high cumulative dose of solar irradiation, photooxidation, hydrolysis, acid rain</p>	<p>- Constant load high temperature exposure tests in the range of 90-200 °C</p> <p>Weatherometer tests: ISO 4892 „Plastics - Methods of exposure to laboratory light sources“ (UV, temperature and RH) Condensation test+irradiation SPART 14 - an acid rain modification of SAE J1960, which is a Weatherometer test</p> <p>ASTM G155-00ae1 „Standard Practice for Operating Xenon Arc Light Apparatus for Exposure of Non-Metallic Materials”</p>
Corrosion of the reflecting layer	Under humidity conditions involving condensation of water on the reflector	Salt spraying and hostile gases- SP method 2499 A, also corresponding to ISO/CD 21207 method A
Surface abrasion	Wind, hail, cleaning	<p>ASTM D4060-01 „Standard Test Method for Abrasion Resistance of Organic Coatings by the Taber Abraser“</p> <p>ISO 11998:1992 „Paints and varnishes - Determination of wet-scrub resistance and cleanability of coatings“</p>
Surface soiling	Moisture, dust, dirt	ASTM D3274-95 „Standard Test Method for Evaluating Degree of Surface Disfigurement of Paint Films by Microbial (Fungal or Algal) Growth or Soil and Dirt Accumulation”

Degradation of the substrate	Moisture, pollutants, acid rain, hail	<p>Hail: ASTM E822-92(1996) „Standard Practice for Determining Resistance of Solar Collector Covers to Hail by Impact With Propelled Ice Balls”</p> <p>ASTM E1038-98 „Standard Test Method for Determining Resistance of Photovoltaic Modules to Hail by Impact with Propelled Ice Balls”</p>
Loss of adhesion of protective coating	Moisture, pollutants, acid rain, hail, icing, UV, Thermal expansion	<p>Hail: ASTM E822-92(1996) „Standard Practice for Determining Resistance of Solar Collector Covers to Hail by Impact With Propelled Ice Balls”</p> <p>ASTM E1038-98 „Standard Test Method for Determining Resistance of Photovoltaic Modules to Hail by Impact with Propelled Ice Balls”</p> <p>EN 12975-2 Kap 5.10 „Impact resistance test“</p> <p>Icing: Build up of ice layers MIL-STD 810 E, Method 521 "Icing /Freezing rain" ISO 2653, Ice formation, Test C Frost appearance IEC 60068-2-39,Z/AMD, Combined sequential cold, low air pressure and damp heat test</p> <p>Thermal expansion: IEC 60068-2-14, Test N, Change of temperature MIL-STD 810 E, Method 503.3, "Temperature shock" ISO 10545 - Part 9 Ceramic tiles - Determination of resistance to thermal shock</p>

*During outdoor exposure it is, of course, impossible to distinguish between high temperature and photo induced oxidation.

2.8 Suitable accelerated test methods and range of degradation factors

Degradation mechanism	Techniques for analysis of material changes	Expected results
Degradation of the protective layer (High temperature oxidation, Photooxidation, Hydrolysis)	UV-VIS-NIR spectroscopy IR- spectroscopy DSC (OIT) SEM TOF-SIMS/ESCA Mechanical testing AES, GDOS Adhesion testing (Reduction of reflectance in solar range Changes in colour Chemical changes, e.g. formation of OH- groups could be observed Changes in stabilisation Small changes in surface morphology Chemical changes Changes in mechanical properties- adhesion between coating and superstrate
Corrosion of the reflecting layer (High temperature oxidation, Hydrolysis)	UV-VIS-NIR spectroscopy IR- spectroscopy DSC (OIT) SEM TOF-SIMS/ESCA Mechanical testing AES, GDOS Adhesion testing (Reduction of reflectance in solar range Changes in colour Chemical changes, e.g. formation of OH- groups could be observed Changes in stabilisation Small changes in surface morphology Chemical changes Changes in mechanical properties- adhesion between coating and substrate
Surface abrasion	UV-VIS-NIR spectroscopy visual inspection optical microscopy gloss measurement	Reduction in direct reflectance, Changes in gloss
Surface soiling	UV-VIS-NIR spectroscopy IR- spectroscopy visual inspection optical microscopy gloss measurement DSC (OIT) SEM TOF-SIMS/ESCA AES, GDOS	Changes of reflectance in solar/IR range Changes in surface topology Changes in gloss

Degradation of the substrate (High temperature oxidation, Photooxidation, Hydrolysis)	UV-VIS-NIR spectroscopy IR- spectroscopy DSC (OIT) SEM TOF-SIMS/ESCA Mechanical testing AES, GDOS Adhesion testing (Reduction of reflectance in solar range Changes in colour Chemical changes, e.g. formation of OH- groups could be observed Changes in stabilisation Small changes in surface morphology Chemical changes Changes in mechanical properties- adhesion between coating and substrate
Loss of adhesion of protective coating	visual inspection, Gitterschnitt, adhesion testing	Loss of adhesion of protective coating Blistering
Loss of adhesion of reflector from substrate	visual inspection, Cross cut, adhesion testing	Loss of adhesion of reflector from substrate

2.9 Techniques used for measurement of degradation factors at reflectors

Degradation mechanism	Degradation factors/ Measurement variables	Sensors
High temperature degradation	<i>Temperature</i> : Surface temperature of reflector	RTD sensors (Pt-Sensors, Thermocouples)
Photooxidation	Solar irradiation: Outdoor	Radiation sensors (Pyranometer, UV-sensors)
Hydrolysis in combination with photooxidation	<i>Humidity</i> : Measurement of air humidity close to the reflector	Capacitance humidity sensors carefully shielded from solar radiation and thermal radiation of the ambient
Effects of acid rain	<i>Atmospheric corrosivity</i> : Measurement of corrosion mass loss rate of standard metal specimens/coupons. Coupons are exposed close to reflector <i>Air pollutants</i> : Measurement of sulphur dioxide concentration close to reflector.	Metal coupons of carbon steel, zinc and copper and evaluation of corrosion mass loss according to ISO 9226 Exposed metal coupons analysed in respect of the sulphate content of the corrosion products by EDX UV-fluorescence instrument for direct measurement of sulphur dioxide concentration close to reflector.

2.10 Sample selection

Pure Al: The pure Aluminium sample is manufactured by Alanod. It is an aluminium alloy with an content of 99.85% Al and the only fabrication step is degreasing.

Anodized Al: This sample is also manufactured by Alanod. Fabrication steps are degreasing, polishing, anodizing with a thickness of the coating on the front side of 1 to 1.2 μm and on the backside of 0.7 μm .

Miro 4: same as Anodized Al plus e-beam coated Al (99.99%), about 60nm thick, plus SiO₂ (99.9%) reactive with Oxygen, about 80nm, plus TiO₂ (99.8%) reactive with Oxygen, about 50nm thick

Miro 27KK: same as Miro 4, plus Cl/F-protection laquer (about 10-12 μm) on Frontside, standard transparent protection laquer on backside

SO790 (Solaroberfläche790): sample from Alcan (Alusuisse), Al-substrate(Al99,85), anodized (about 200 nm) plus ceramic laquer (Si-based) of about 3-4 μm .

Glass samples: This sample comes from Naugatuck Glass (US), silvered glass sample, thickness is 1.2 mm.

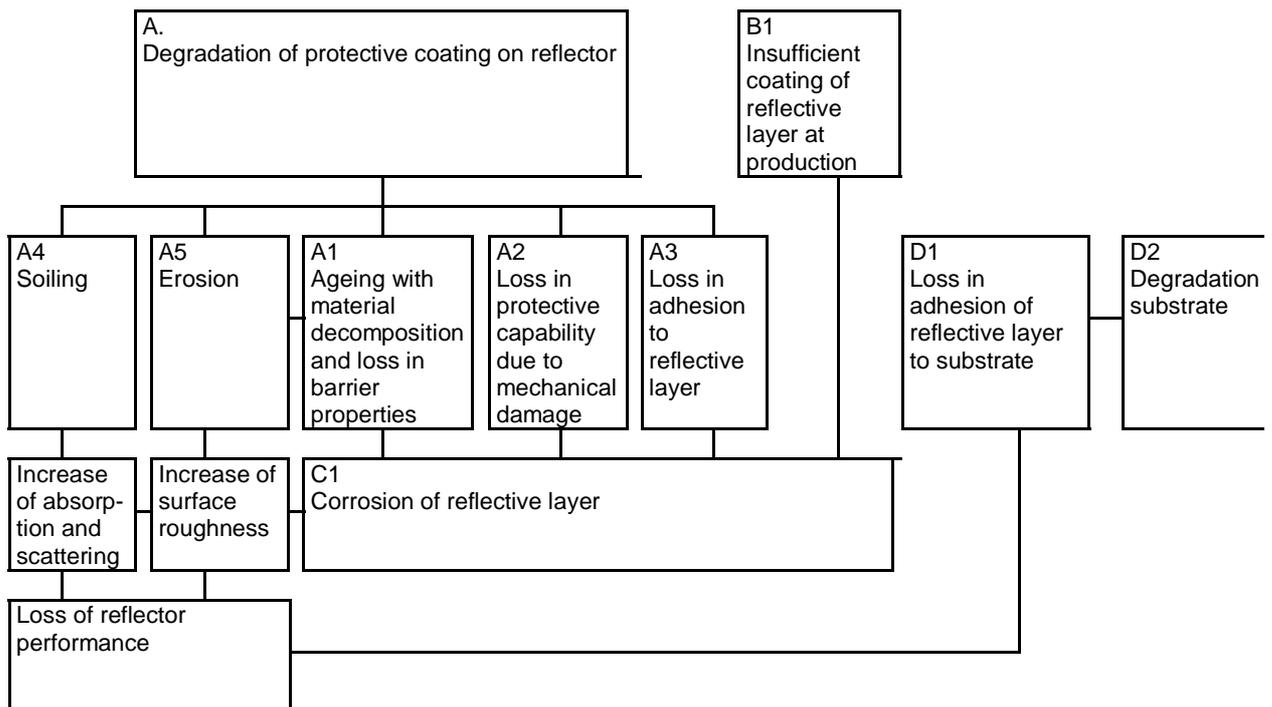
Laminate sample: This experimental material is not yet commercially available in the U.S. and was distributed by NREL. Samples are a laminate construction (UV-screening acrylic film laminated to a silvered polyester film) bonded on an aluminium substrate.

Skultuna #5 (more specular): 250µm Polyester-substrate with 9µm Al-Reflector, protected with 60µm PMMA

Skultuna #6 (more diffuse): 250µm Polyester-substrate with 9µm Al-Reflector, protected with an acrylic varnish

Steel substrate samples: the reflector consist of a foil laminated on steel. The steel grade is in Swedish: "Aluzink B500 A AZ 150" from the steel factory SSAB. The foil comes from Skultuna Flexible, Västerås, Sweden: It consists of from the bottom: PET 15 µm /Al foil 9 µm/metalized Al 200 Å/ PET 59 µm UV-stabilized.

2.11 Fault tree analysis of reflectors



Failure/Damage mode / Degradation process	Degradation indicator	Critical factors of environmental stress	Estimated risk of failure/damage mode from FMEA			
			S	P _O	P _D	RPN
Unacceptable loss in reflector-performance	$PC = -0.35 \cdot \rho_s - 0.1/(1.5 \cdot \rho_d)$					
A. Degradation of protective coating on reflector						
A1. Ageing with material decomposition (may result in A3) and loss in barrier properties resulting in C1	Visual inspection Change in IR characteristics (FTIR, TIS)	Humidity, Temperature, Air pollutants (acid) UV irradiation	5	5	2	50
A2. Loss of protective capability due to mechanical damage resulting in C1	Visual inspection	Mechanical impact				
A3. Surface erosion	Visual inspection Surface morphology (SEM) Film thickness	Sand, dust, cleaning, icing, hail, touching, scratching	5	5	2	50
A4. Surface soiling	Visual inspection, Surface morphology (SEM), Change in VIS IR characteristics (FTIR, TIS), Surface composition (EDX, AES, TOF-SIMS)	microorganisms, wind, dust, pollutants, chemistry of soiling agent	4	7	2	56
A5. Loss of adhesion of protective coating to reflecting layer	Visual inspection, Adhesion	Air pollutants (acid), Humidity, UV, Temperature	7	5	2	70
B1 Insufficient coating of the reflector at production resulting in C1	Film thickness	Human impact				
C1 Corrosion of the reflecting layer	Visual inspection, Surface morphology and composition (SEM and EDX, AES, TIS)	Coating with insufficient protective capability (A1-A3,B1), Humidity, Temperature, Air pollutants (acid) contact with other materials	8	5	4	160
D1. Loss of adhesion of reflector from	Visual inspection, Adhesion	Corroded reflective layer, Degraded substrate	7	5	2	70

For the case-study reflectors samples are exposed in different participating labs:

<u>Indoor</u>	<u>Outdoor</u>
CSTB	ENEA
ISE	INETI
SP	Vattenfall
SPF	
NREL	
UU	

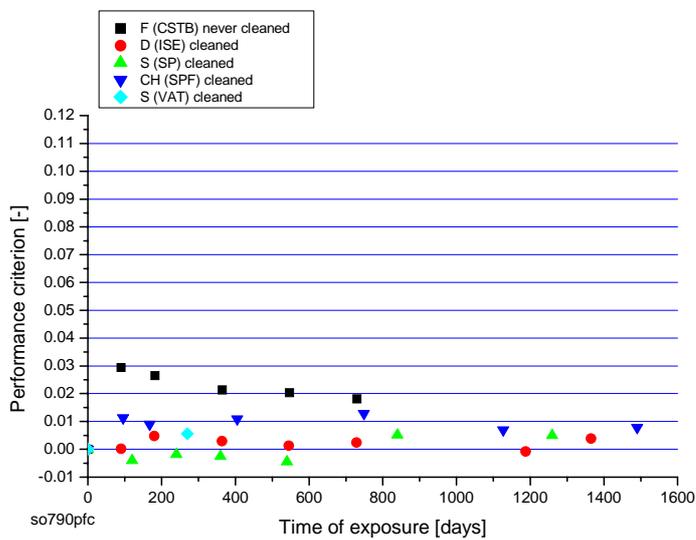
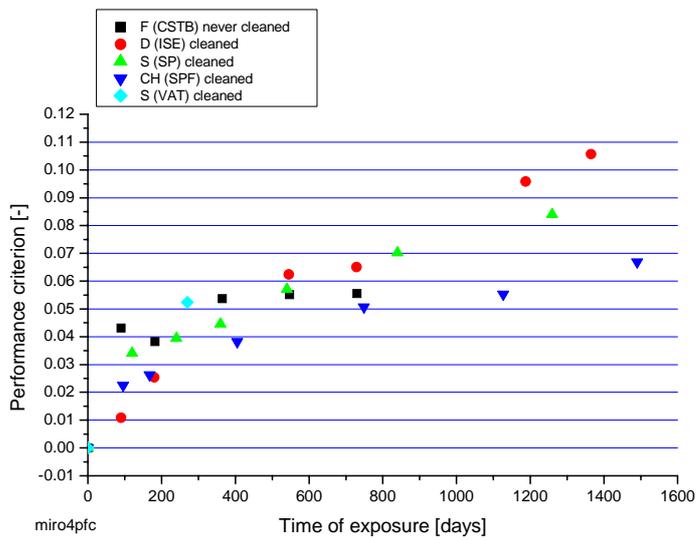
Samples exposed are: pure Al, anodized Al, Miro4, Miro27KK from Alanod, SO 790 from Alusuisse, two different Aluminium foils from Skultuna Flexible AB (Vattenfall, Sweden), thin silvered glass from Naugatuck and an experimental laminated material (NREL). Pure Aluminium and anodized Aluminium are used as reference materials.

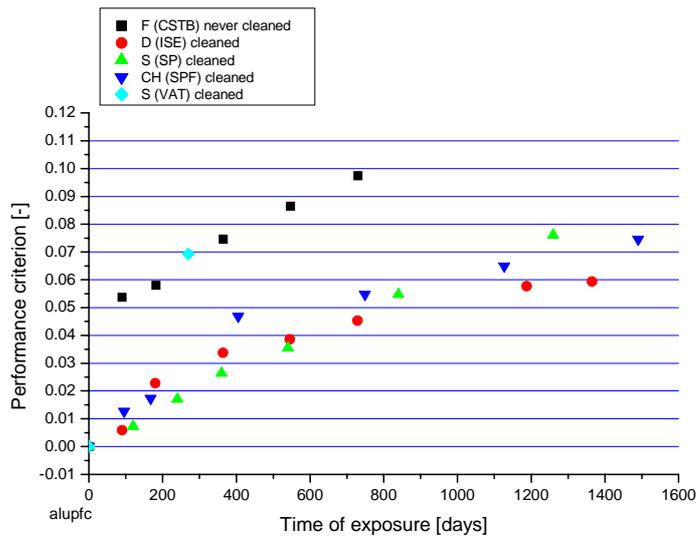
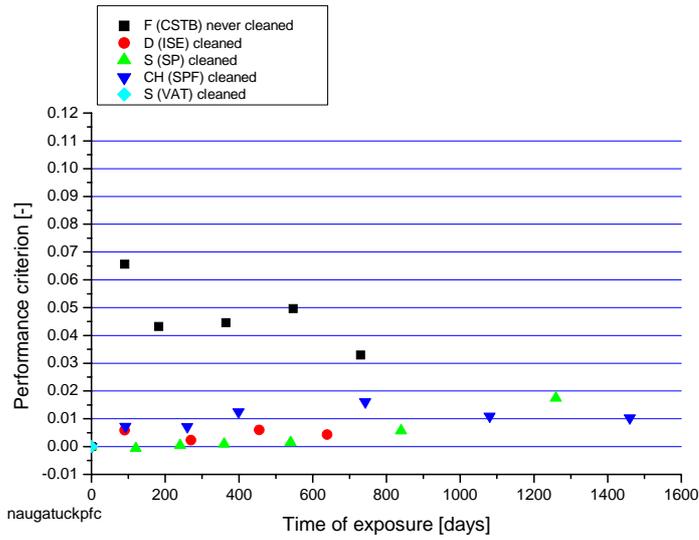
Indoor tests performed in the different labs are:

Lab	Test method
CSTB	WOM test according to ISO 4892: 55°C/50%/UV with 0.5W/m ² @340nm, water spray 18min in 2hours
ISE	condensation at 40°C sample temperature with and without UV and at 60°C sample temperature with UV
SP	pollutants tests according to SP method 2499 A and modified A without salt spray (ISO/CD 21207 -pollutants test in artificial atmosphere-)
SPF	Temperature test at 80°C/UV
NREL	WOM test 60°C/60% relative humidity at a one-sun light intensity
UU	Cycling test 80°C/85% and 40°C/50%

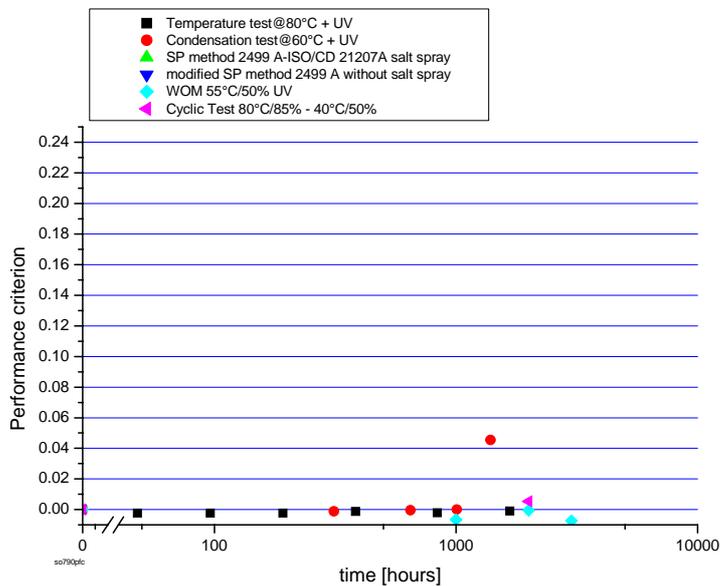
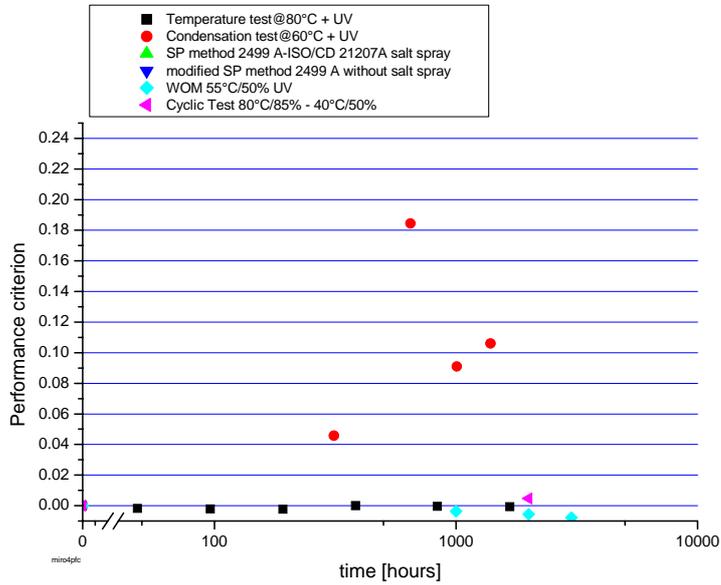
2.12 Some results from outdoor exposure

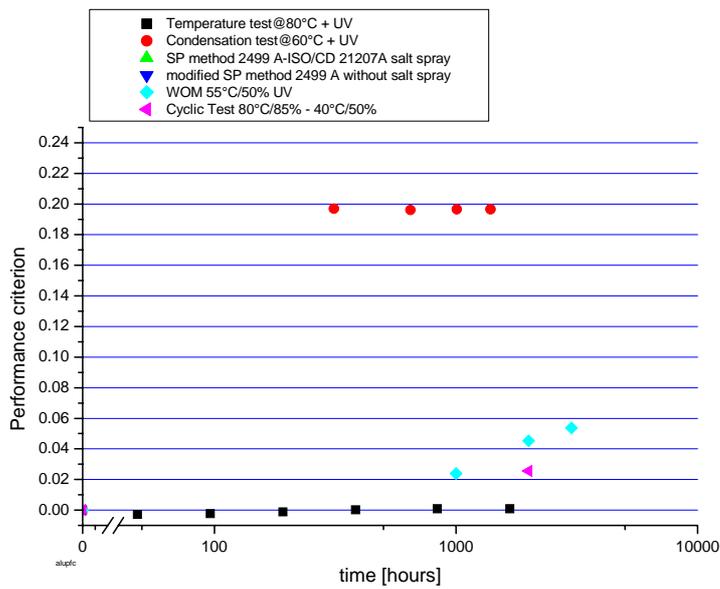
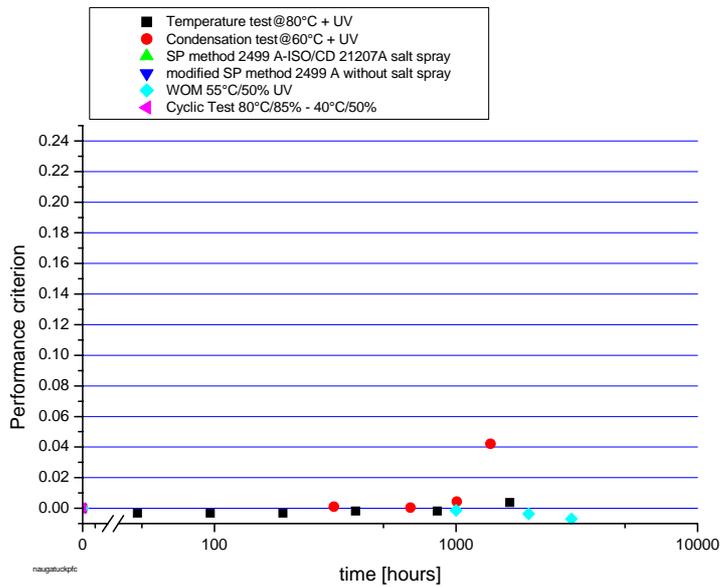
Performance criterion vs. exposure time





The same samples, also performance criterion, but results from indoor tests





2.13 Conclusions

Only two of the tested reflectors showed a promising durability. The test methods are suitable for accelerated life testing.

Case study 3: Absorber

Case-study leader: Stefan Brunold, SPF, Switzerland

3.1 Initial risk analysis of potential failure modes organic absorber coatings

Specification of end-user requirements

Function and general requirements	General requirements for performance and service life	In-use conditions and severity of environmental stress
<p>Efficiently absorb solar radiation</p> <p>Protect the absorber substrate against the outdoor environment - corrosion</p> <p>Retain aesthetic performance properties like colour and gloss</p> <p>Protect the underlying wall construction against the out-door environment</p> <p>Impact resistance</p> <p>Stone-chip resistance</p>	<p>Loss in material performance should not result in reduction of the solar system performance (solar fraction) with more than 5%, in relative sense, during the material service life.</p> <p>No visible loss of colour and gloss</p> <p>No delamination of coating from metal substrate</p> <p>No corrosion of metal substrate</p> <p>Material service life should exceed 25 years</p>	<p>Unprotected solar façade elements</p> <p>Exposed to outdoor environments, which means UV-radiation, humidity, rain, snow, hail, wind loads, air pollutants, high and low temperatures, etc.</p> <p>Exposed to condensation of water (acid rain)</p> <p>Exposed to mechanical loads like tensile stress due to its own weight, wind loads, and thermal expansion, impact of various objects (e.g. birds, stones)</p>

3.2 Specification of functional properties and requirements

Critical functional property	Test method for functional property	Requirement for functional capability or performance
Solar absorptance, α_s Emittance, ϵ	UV-VIS-IR-reflectance spectroscopy	$\alpha_s + 0.25 \leq 0.05$
Colour	As above or CIE, ISO 7724	$E \leq 5$
Gloss	As above or glossmeter	$\leq 20\%$
Adhesion between coating and metal substrate	Tensile testing	≥ 0.05 MPa
Corrosion of metal substrate		No corrosion

3.3 Risk assessment of potential failure modes by use of FMEA applied to polymeric façade absorbers

Failure mode / Degradation process	Severity (S) (rating number)	Probability of occurrence(PO) (rating number)	Probability of discovery(PD) (rating number)	Rating-number for risk (RPN = S · PO · PD)																																						
	<table border="1"> <thead> <tr> <th>Severity</th> <th>Rating number</th> </tr> </thead> <tbody> <tr> <td>No effect on product</td> <td>1</td> </tr> <tr> <td>Minor effect on product but no effect on product function</td> <td>2-3</td> </tr> <tr> <td>Risk of failure in product function</td> <td>4-6</td> </tr> <tr> <td>Certain failure in product functioning</td> <td>7-9</td> </tr> <tr> <td>Failure which may affect personal safety</td> <td>10</td> </tr> </tbody> </table>	Severity	Rating number	No effect on product	1	Minor effect on product but no effect on product function	2-3	Risk of failure in product function	4-6	Certain failure in product functioning	7-9	Failure which may affect personal safety	10	<table border="1"> <thead> <tr> <th>Probability of detection</th> <th>Rating number</th> </tr> </thead> <tbody> <tr> <td>Failure which always is noted. Probability for detection > 99.99%</td> <td>1</td> </tr> <tr> <td>Normal probability of detection 99.7%</td> <td>2-4</td> </tr> <tr> <td>Certain probability of detection >95%</td> <td>5-7</td> </tr> <tr> <td>Low probability of detection >90%</td> <td>8-9</td> </tr> <tr> <td>Failures will not be found - cannot be tested</td> <td>10</td> </tr> </tbody> </table>	Probability of detection	Rating number	Failure which always is noted. Probability for detection > 99.99%	1	Normal probability of detection 99.7%	2-4	Certain probability of detection >95%	5-7	Low probability of detection >90%	8-9	Failures will not be found - cannot be tested	10	<table border="1"> <thead> <tr> <th>Probability of occurrence</th> <th>Rating number</th> </tr> </thead> <tbody> <tr> <td>Unlikely that failure will occur</td> <td>1</td> </tr> <tr> <td>Very low probability for failure to occur</td> <td>2-3</td> </tr> <tr> <td>Low probability for failure</td> <td>4-5</td> </tr> <tr> <td>Moderate probability for failure to occur</td> <td>6-7</td> </tr> <tr> <td>High probability for failure to occur</td> <td>8-9</td> </tr> <tr> <td>Very high probability for failure to occur</td> <td>10</td> </tr> </tbody> </table>	Probability of occurrence	Rating number	Unlikely that failure will occur	1	Very low probability for failure to occur	2-3	Low probability for failure	4-5	Moderate probability for failure to occur	6-7	High probability for failure to occur	8-9	Very high probability for failure to occur	10	
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3.4 Risk assessment and service reliability for polymeric façade absorbers

Failure/Damage mode / Degradation process	Degradation indicator	Critical factors of environmental stress/ Degradation factors and severity	Estimated risk of failure/damage mode from FMEA			
			S	PO	PD	Risk RPN
Unacceptable loss in optical performance Adhesion/delamination	PC = - . . s Changes in colour and gloss Adhesion > 0.15 MPa					
High temperature oxidation	Reflectance spectra UV-VIS-IR Changes in colour and gloss Adhesion testing	High temperature*	6	5	7	210
			8	7	2	112
			8	3	7	168
Photooxidation	Reflectance spectra UV-VIS-IR Changes in colour and gloss Adhesion testing	UV-radiation, high temperature*.	6	5	7	210
			8	7	2	112
			8	3	7	168
Hydrolysis in combination with photooxidation	Reflectance spectra UV-VIS-IR Changes in colour and gloss Adhesion testing	Humidity, condensation, air pollutants	6	3	7	210
			8	5	2	80
			8	3	7	168

*In many high temperature applications the limitation in durability is caused by physical loss of stabilisers e. g. antioxidants, UV-absorbers, HALS, etc

3.5 Programme for screening testing of polymeric façade absorbers

Possible degradation mechanism	Critical periods of high environmental stress	Suitable accelerated test methods and range of degradation factors
High temperature oxidation*	Stagnation conditions of solar façade absorber at high levels of solar irradiation (no withdrawal of heat from the collector)	Constant load high temperature exposure tests in the range of 90-150 °C.
Photooxidation*	At high levels of solar irradiation	Weatherometer tests - ISO 4892 (UV, temperature and RH)
Hydrolysis in combination with photo-oxidation	Under humidity conditions involving condensation of water on the absorber	SPART 14 - an acid rain modification of SAE J1960, which is a Weatherometer test
Corrosion of metal substrate after mechanical damage of coating	Under humidity conditions involving condensation of water on the absorber	Salt spraying and hostile gases- SP method 2499 A, also corresponding to ISO/CD 21207 method A

*During outdoor exposure it is, of course, impossible to distinguish between high temperature and photo induced oxidation.

3.6 Techniques for analysis of material change upon durability testing of polymeric façade absorber

Degradation mechanism	Techniques for analysis of material changes	Expected results
High temperature oxidation	UV-VIS-NIR spectroscopy IR- spectroscopy DSC (OIT) SEM TOF-SIMS/ESCA Mechanical testing	Reduction of absorption in solar range – discolouration Changes in colour and gloss Chemical changes, e.g. formation of OH-groups could be observed Changes in stabilisation Small changes in surface morphology Chemical changes-oxidation Changes in mechanical properties-adhesion between coating and substrate
Photooxidation	UV-VIS-NIR IR- spectroscopy DSC (OIT) SEM TOF-SIMS/ESCA Mechanical testing (Reduction of absorption in solar range Changes in colour and gloss Chemical changes, e.g. formation of OH- groups could be observed Changes in stabilisation Small changes in surface morphology Chemical changes Changes in mechanical properties-adhesion between coating and substrate
Hydrolysis in combination with photooxidation	UV-VIS-NIR spectroscopy IR- spectroscopy DSC (OIT) SEM TOF-SIMS/ESCA Mechanical testing (Reduction of absorption in solar range Changes in colour and gloss Chemical changes, e.g. formation of OH- groups could be observed Changes in stabilisation Small changes in surface morphology Chemical changes Changes in mechanical properties-adhesion between coating and substrate

3.7 Techniques used for measurement of degradation factors at polymeric façade absorbers

Degradation mechanism	Degradation factors/ Measurement variables	Sensors
High temperature degradation	Temperature: Surface temperature of absorber	Pt sensors.
Photooxidation	Solar irradiation: Outdoor	Pyranometer
Hydrolysis in combination with photooxidation	Humidity: Measurement of air humidity close to the absorber	Capacitance humidity sensors carefully shielded from solar radiation and thermal radiation of the ambient.
Effects of acid rain	Atmospheric corrosivity: Measurement of corrosion mass loss rate of standard metal specimens/coupons. Coupons are exposed close to facade Air pollutants: Measurement of sulphur dioxide concentration close to facade.	Metal coupons of carbon steel, zinc and copper and evaluation of corrosion mass loss according to ISO 9226 Exposed metal coupons analysed in respect of the sulphate content of the corrosion products by EDX UV-fluorescence instrument for direct measurement of sulphur dioxide concentration close to façade.

3.8 Constant Load Indoor Tests

For indoor testing different absorbers have been available. Besides the two reference samples (RS1, RS2) these are:

- Colored Sunselect samples on copper (green, red and yellow)
- Sunselect samples on copper (with SnO overcoat) with additional porous SiO₂ Sol-gel overcoat from CIEMAT
- Sunselect samples on copper (without SnO overcoat) with additional dense SiO₂ Sol-gel overcoat from CIEMAT
- Colored selective paint samples on Aluminium from NIC (blue, red)
- Black Chrome on stainless steel (from IEA Task 10)
- Sol-gel coating on Aluminium from CIEMAT
- Sol-gel coating on Aluminium from NIC

Indoor testing was performed at 3 different institutes: corrosion testing at SP (Sweden), condensation testing and high temperature testing at ISE (Germany) and SPF (Switzerland).

3.9 Corrosion Tests

For corrosion testing two different cyclic tests were used:

Corrosion test cycle I

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

- 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
- exposure for 120 h in a test atmosphere containing a mixture of corrosion promoting gases, volume fraction of NO₂ equal to 1,5·10⁻⁶ and of SO₂ equal to 0,5·10⁻⁶, 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 cycle II

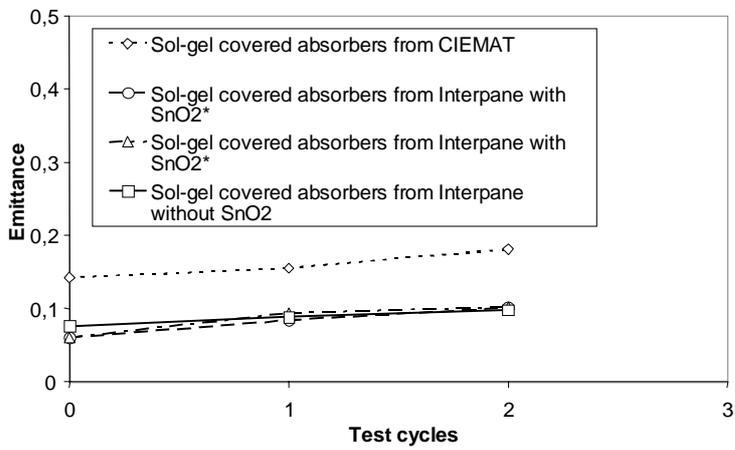
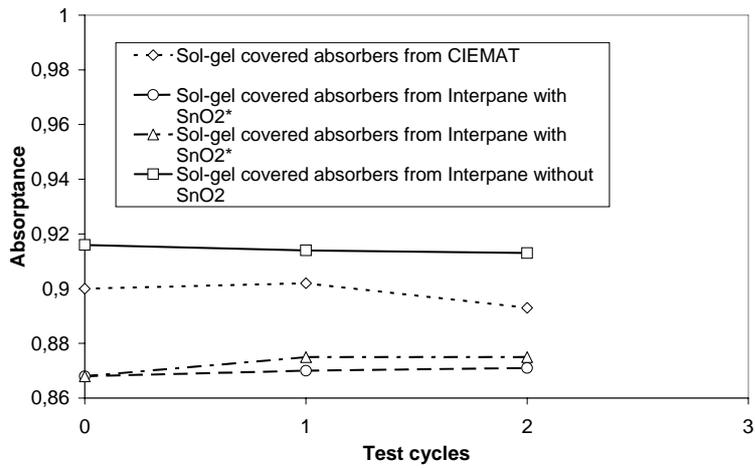
The second was a less corrosive method. It can be described as a slightly modified SP method 2499. A cycle differing from the former in that no salt spray exposure is performed in step a) only drying for 24 h in standard laboratory climate.

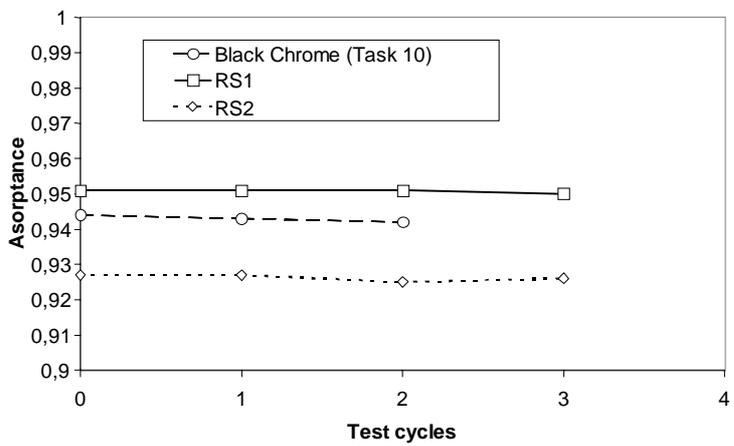
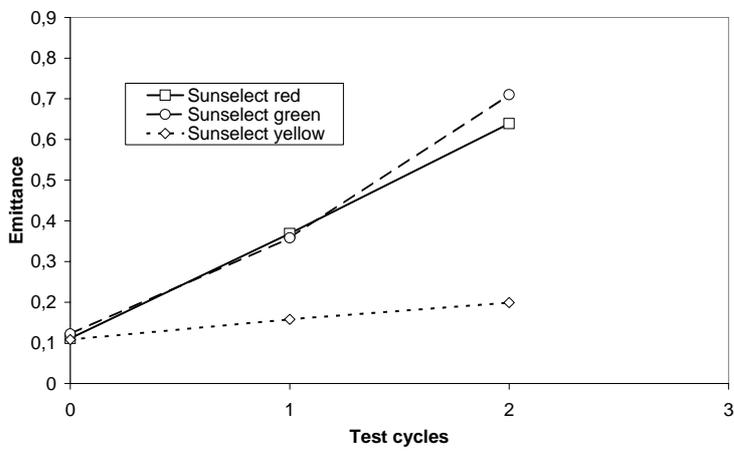
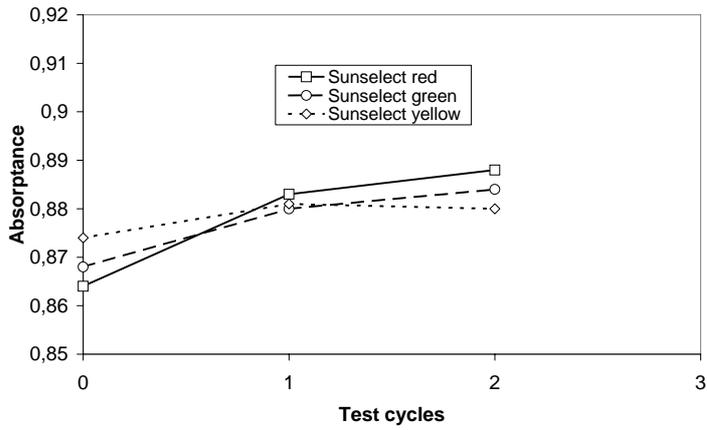
Reference metal specimens

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

The test results obtained with the corrosion test cycles II are shown in Figures 1. In Figure 2 the test results with the corrosion test cycle I are shown. Failure times in corrosion test cycle I for the absorber materials, i.e. when the performance requirement $PC < -\Delta\alpha + 0.25 \cdot \Delta\varepsilon < 0.05$ is no longer met, were also assessed. The results are shown in Table 1. In Table 2 the metallic mass losses of the copper and zinc reference specimens determined after four cycles of testing according to the two corrosion test cycles are given.





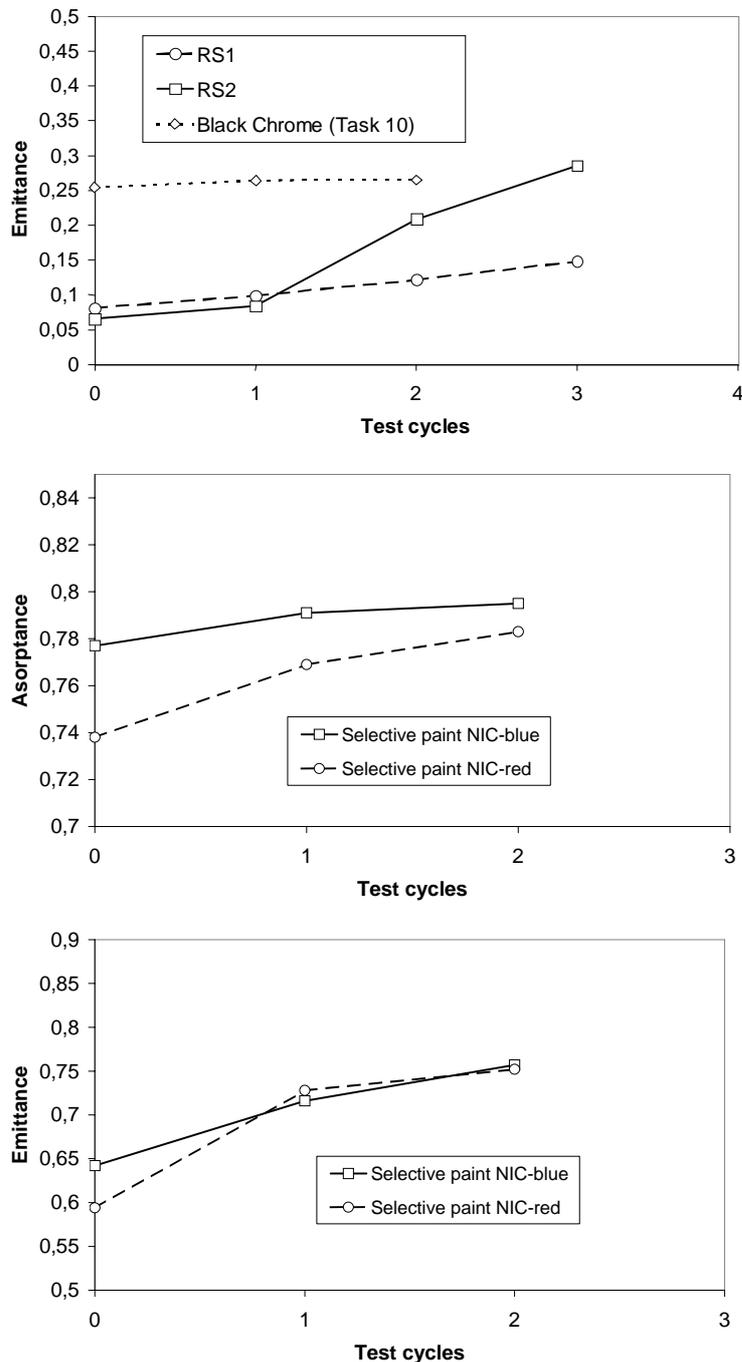
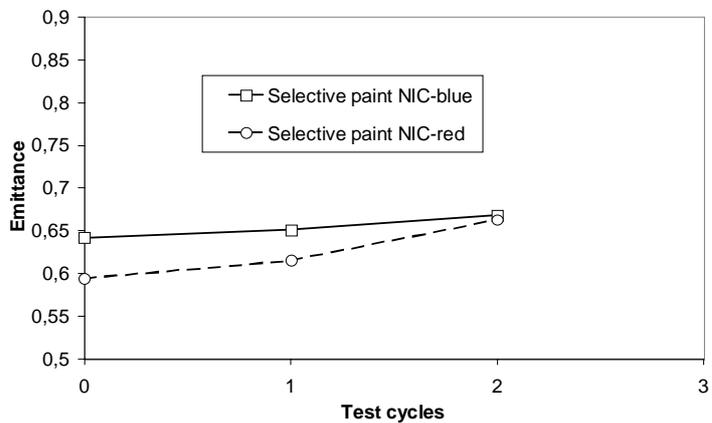
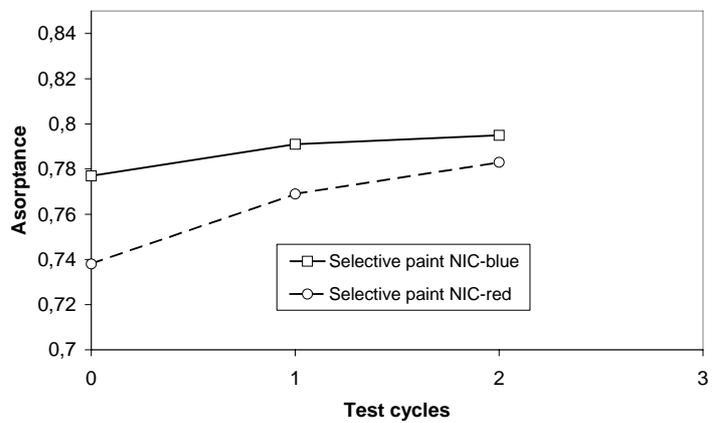
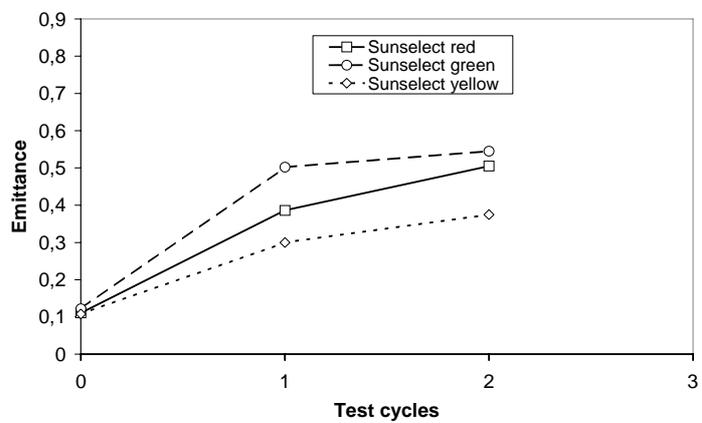
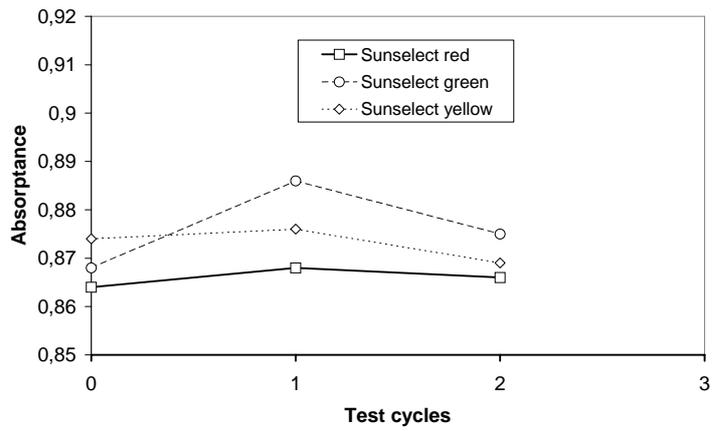


Fig. 1: Solar absorptance and thermal emittance of the absorber materials after corrosion testing according to corrosion test cycle II.

As can be seen in Figure 1, it is only the red and green coloured Sunselect absorber materials that exhibit significant degradation in optical performance upon corrosion testing according to corrosion test cycle II after two weeks. It is mainly the emittance of coatings that is affected. On those samples degradation due to corrosion of the underlying metal substrate can be observed.



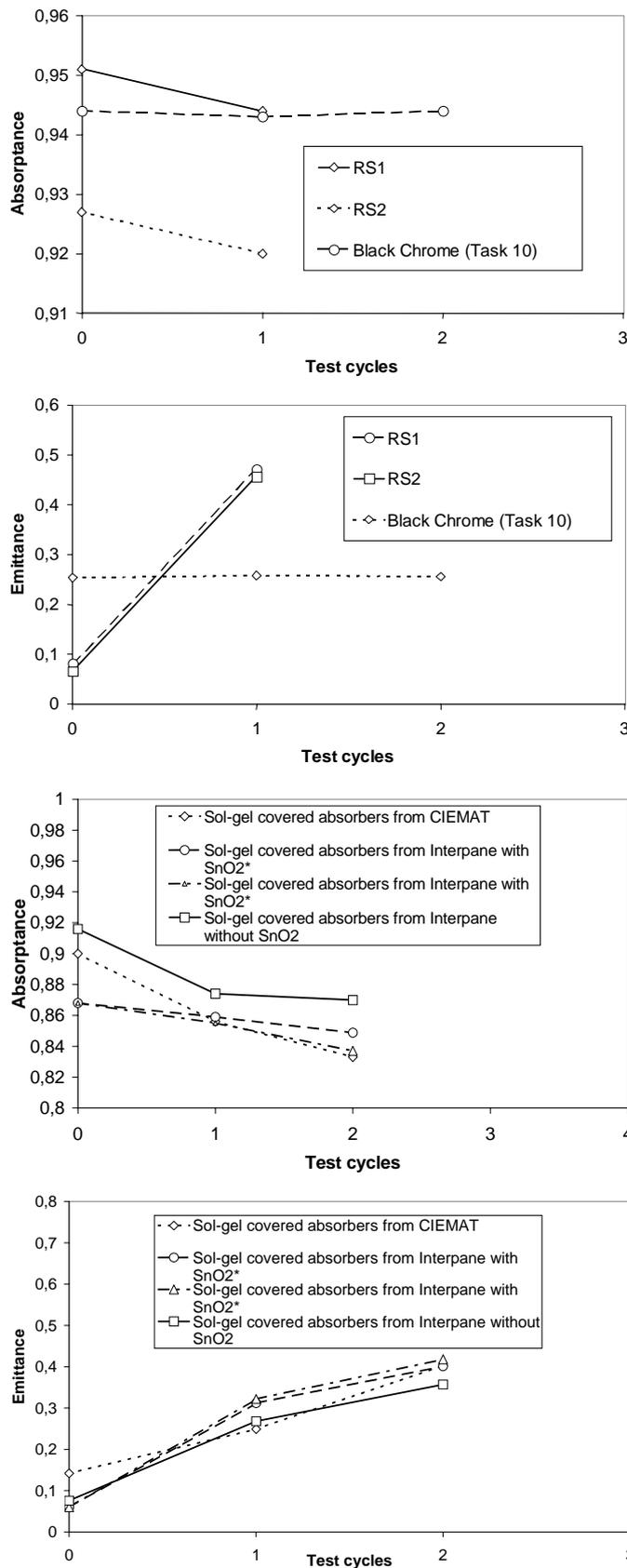


Fig. 2: Solar absorbance and thermal emittance of the absorber materials after corrosion testing according to corrosion test cycle I.

When also salt is added as a corrosion promoting factor as in corrosion test cycle I, see Figure 2, the degradation in optical performance is much more pronounced with the exceptions of the selective paints and the Black Chrome (Task 10) absorber material.

For the rest of the absorber materials you can observe that corrosion has taken place of the underlying metal, which most probably may be due to lost ability of the barrier coatings to protect the underlying metal from corrosion attack by salt and corrosion promoting gases.

Tab. 1: Failure times of the absorber materials in corrosion test cycle I

Absorber material	Failure time (PC =0.05) in corrosion test I (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	0.82	4.5
Sol-gel covered absorbers from Interpane with SnO	0.74	4.1
Sol-gel covered absorbers from Interpane without SnO	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	-	-
RS1	0.57	3.2
RS2	0.47	2.7
Black Chrome (IEA Task 10)	-	-

* When calculating the metal mass loss rate of copper it is assumed that the following relation is valid:

$$M = M1 \cdot tx$$

where M = mass loss, M1 = 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)

Tab. 2: 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 I	18,0	39,0
Corrosion test cycle II	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.

3.10 Condensation and high temperature tests

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 the relative humidity is 95% to assure condensation on the samples. Sample temperature is 65°C and 40°C, respectively. 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). The change of the optical properties solar absorption $\alpha_{AM1.5}$, thermal emission ϵ_{373K} and $pc = -\Delta\alpha + 0.5\Delta\epsilon$ as well as the spectral reflectance is given as a function of testing time in figures 4 - 15 for all samples tested.

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.

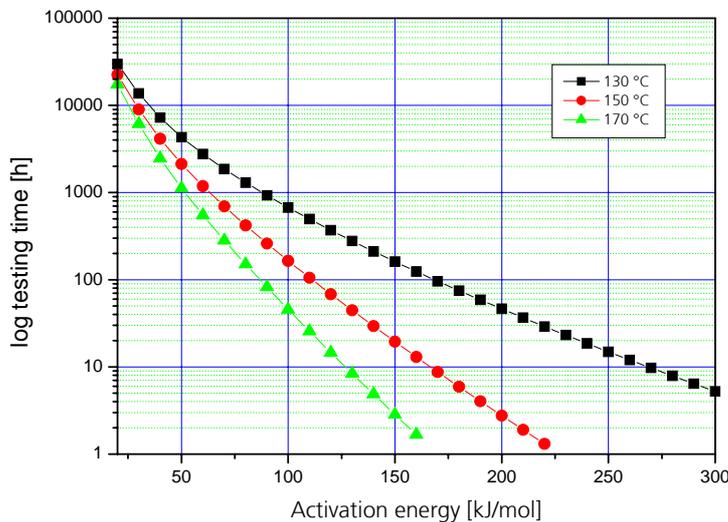


Fig. 3: Testing times for high temperature test.

As a starting point the tests were performed at a sample temperature of 170°C and 150°C, respectively. 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. As light source a “Dr. Hönle Sol 1200” solar simulator was used. 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. However, it has to be re-measured for this specific set-up.

Case study 4: Service life prediction tools for complete Solar Collectors

Case study leader: Manuel Lopes-Prates, INETI, Portugal

The goal of the FMEA methodology is to identify and to prevent problems before they occur in products and processes. So, it is a methodology to analyse and to find out

- all potential failure modes of a proposed or existing product or
- process,
- the effects of these failure modes in the same product or process, and
- the way to correct and/or to mitigate these failures or their effects.

The FMEA methodology was firstly applied about 40 years ago to assure the safety and reliability of products in the aerospace industry, and afterwards in the products of the automotive and chemical processes industries, as a key tool to safety improvement (McDermott, 1996). Meanwhile, the FMEA methodology becomes a key quality tool in the development of new products, to satisfy the needs of a customer in terms of reliability, maintainability, availability and safety (Prates, 2003). Hence, in our days we can distinguish several types of FMEA (Cow, 2002):

- System - focuses on global system functions
- Design - focuses on components and subsystems
- Process - focuses on manufacturing and assembly processes
- Service - focuses on service functions
- Software - focuses on software functions

In terms of standards the first one was adopted in 1974 for ships as a military standard (MIL-STD-1629), expanded in 1980 for all Departments and Agencies of the USA Department of Defense (MIL-STD-1629A), which standard was cancelled in 1998. Meanwhile, were published the standards SAE – J – 1739 and ECSS-Q-30-02A.

Within the IEA-SHC Task 27 the FMEA methodology was firstly applied by CSTB for building products, namely for a flat plate solar collector (Lair, 2002), and after by Aspen Research Corporation in the framework of the project “An Insulating Glass Knowledge Base”, supported by the USA Department of Energy (Hage, 2002; Lair, 2003).

In the framework of the Subproject BC - Service life prediction tools for complete systems - Solar Collectors of the IEA-SHC Task 27 – Performance, durability and sustainability of advanced windows and solar components for building envelopes, INETI is the responsible for applying the FMEA methodology to a low concentrating CPC collector. The present report presents the work done until now.

4.1 FMEA Methodology Brief Review

As a quality tool, the FMEA methodology is a vehicle of communication and documentation which works in full when applied by a multi-disciplinary team with experts from methodology and from the different steps of the development of the product, joining the existing knowledge to identify potential failure modes.

The FMEA methodology lays on the complete identification of (McDermott, 1996):

- the product functions;
- the failure modes of the product;
- the effects of each failure modes;
- the causes of each failure;
- the controls required to identify the potential failures of the product;
- the hazard level (severity) of each failure mode;
- the probability of failure;
- the probability of not detecting the failure.

The FMEA procedure can be divided into several steps as shown in Fig. 1.

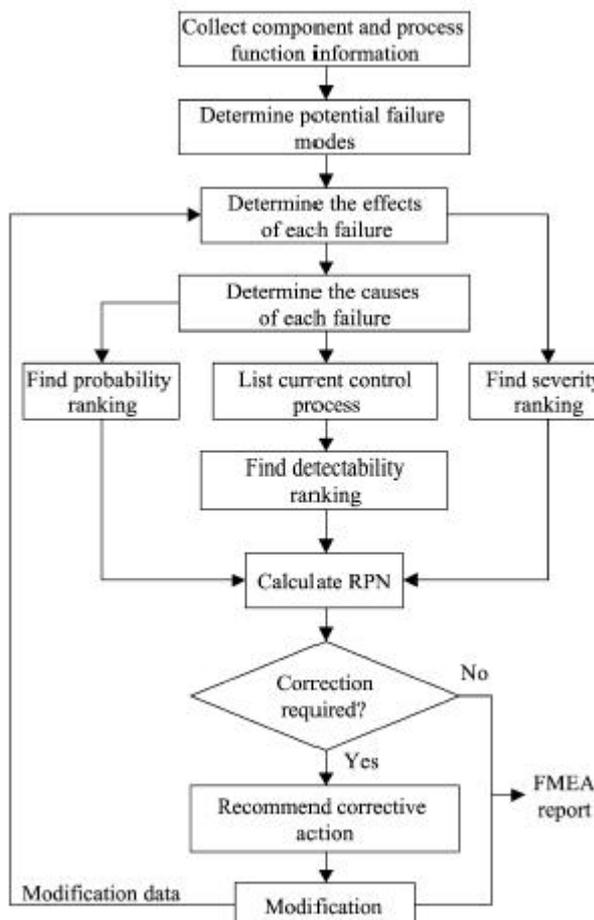


Fig. 1: FMEA process (Pillay, 2003)

For the last three entries scales were established, remembered in Tables 1 to 3 (Pillay, 2003) of Annex A, which permit to calculate a risk priority number (RPN) given by multiplication of the index representing the probability, severity and detectability:

RPN (risk priority number) = S_f (probability of failure) x S (severity of the failure) x S_d (probability of not detecting the failure)

But, as the three factors of RPN have the same five scales and scores of 1-10, the traditional FMEA have the disadvantage of different sets of S_f , S and S_d may produce the same RPN with an obviously risk implication totally different (Pillay, 2003).

Going around this difficulty, the standard ECSS-Q-30-02A define design FMEA/ FMECA requirements and a process risk analysis. The design FMEA/FMECA requirements establish the criticality number (CN) for a specific failure mode as a product of the severity of the failure effects (SN) by the probability of the failure mode occurrence (PN):

$CN = SN \times PN$

For the severity and probability numbers were established scores 1-4, remembered in Tables 1 to 3 (ECSS-Q-30-02A, 2001) of Annex B. In accordance with the requirements of standard ECSS-Q-30-02A, an item of a check-list shall be considered a critical item if the failure mode is classified as

- from FMEA: severity categories 1S (catastrophic with safety impacts), 1 (catastrophic), 2S (critical with safety impacts), and 2 (critical);
- from FMECA: $CN \geq 8$.

The FMEA/FMECA methodology is implemented with the support of worksheets and their results shall be documented, as required by standard ECSS-Q-30-02A.

The process risk analysis (process FMECA) is the application of the FMECA methodology to processes, such as manufacturing, assembly or integration, ground operations, tests, and in-orbit operations, and has as purpose to identify potential weak points and to determine their effects on the product operation and the process itself. As we can read in ECSS-Q-30-02A.

Generally, this method is applied to the mission or safety critical processes as well as to processes which are critical from the programmatic point of view. The inputs required to start the work depend strongly on the process to be analysed. Typical inputs are:

- working and control plan;
- assembly procedure;
- integration procedure;
- test procedure;
- handling procedure (manual).

With the support of a “customer-approved worksheet”, remembered in Annex C, “a small team including a member involved in the process to be analysed”, with “an odd number of

members to facilitate the decision process in the case of different opinion”, the potential weak points shall be evaluated, filling out for each one:

1. Identification number

Identify all process steps.

2. Item

Number the individual process steps.

3. Description

Describe the process step.

4. Failure mode/failure cause

Describe the assumed process step failure mode together with its causes.

5. Failure effects

5.1 the process, and

5.2 the product involved.

Describe all possible effects of the assumed failure modes on:

the process, and

the product involved.

6. Detection means

Describe the existing means and methods by which the effects can be detected.

7. Existing preventive or compensatory provisions

Describe the existing preventive or compensatory provisions to prevent the failure mode, to reduce its effects, or to reduce its probability of occurrence.

8. Severity

Identify the severity of a failure effect by assigning a severity number (SN) according to Table 6.

9. Occurrence

Identify the probability of occurrence of the failure mode by assigning a probability number (PN) according to the Table 7.

10. Detection

Identify the probability of detection of the failure mode by assigning a detection number (DN) according to the Table 8.

11. Criticality

Enter the criticality number (CN) by multiplying $SN \times PN \times DN$.

12. Recommendations and remarks

Describe recommended preventive or compensatory provisions to eliminate the failure mode, to reduce its effects, to reduce its probability of occurrence, or to improve its detectability, as well as any additional information being useful.

The referred tables of standard ECSS-Q-30-02A for the determination of the criticality number (CN) are remembered in Annex D. The same standard establishes that The criticality number (CN) shall be defined as the product of the numbers assigned to failure mode severity, probability of occurrence, and probability of detection according to:

$$CN = SN \times PN \times DN$$

The value of SN, PN, and DN are gained by votes of the team members (engineering judgement).

The CN value is in the range from 1 to 64, whereby the meaning of the extremes is:

- negligible, i.e. there is no risk - if CN = 1;
- extremely critical, i.e. there is an extremely high risk - if CN = 64.

Meanwhile, we have assisted to a theorisation of the traditional empirical model with introduction of new approaches:

- a new technique, based on fuzzy logic, for prioritizing failures for corrective actions in a FMECA (Bowles, 1995);
- a technique of weighted score criticality system applied together with fuzzy logic prioritization of failures (Moss, 1999);
- a fuzzy TOPSIS approach - an alternative multi-attribute decision-making approach for prioritizing failures in FMECA, based on a fuzzy version of the technique for order preference by similarity to ideal solution (Braglia, 2003); and
- a modified failure FMEA using approximate reasoning, which util-ises the fuzzy rules base and grey relation theory (Pillay, 2003).

But, on other hand, to understand better the behaviour of our mechanical equipment we have to consider their five basic failure modes, categorized according to the type of equipment and energy:

- fluid flow equipment (leakage and distorted flow);
- structural system (fracture and excessive deflection);
- thermodynamic systems (overheating and reduction of efficiency);
- kinematic systems (bearing seizure and reduced accuracy of relative movement);
- material properties (incorrect material or geometry).” (Hawkins&Woollons, 1998).

4.2 Structural analysis

Before identifying the product functions, we must start by the structural analysis, identifying each part of the collector and corresponding material used in each of the parts. In our case, this identification is shown in Fig. 2, which can be considered equivalent to a structural diagram too.

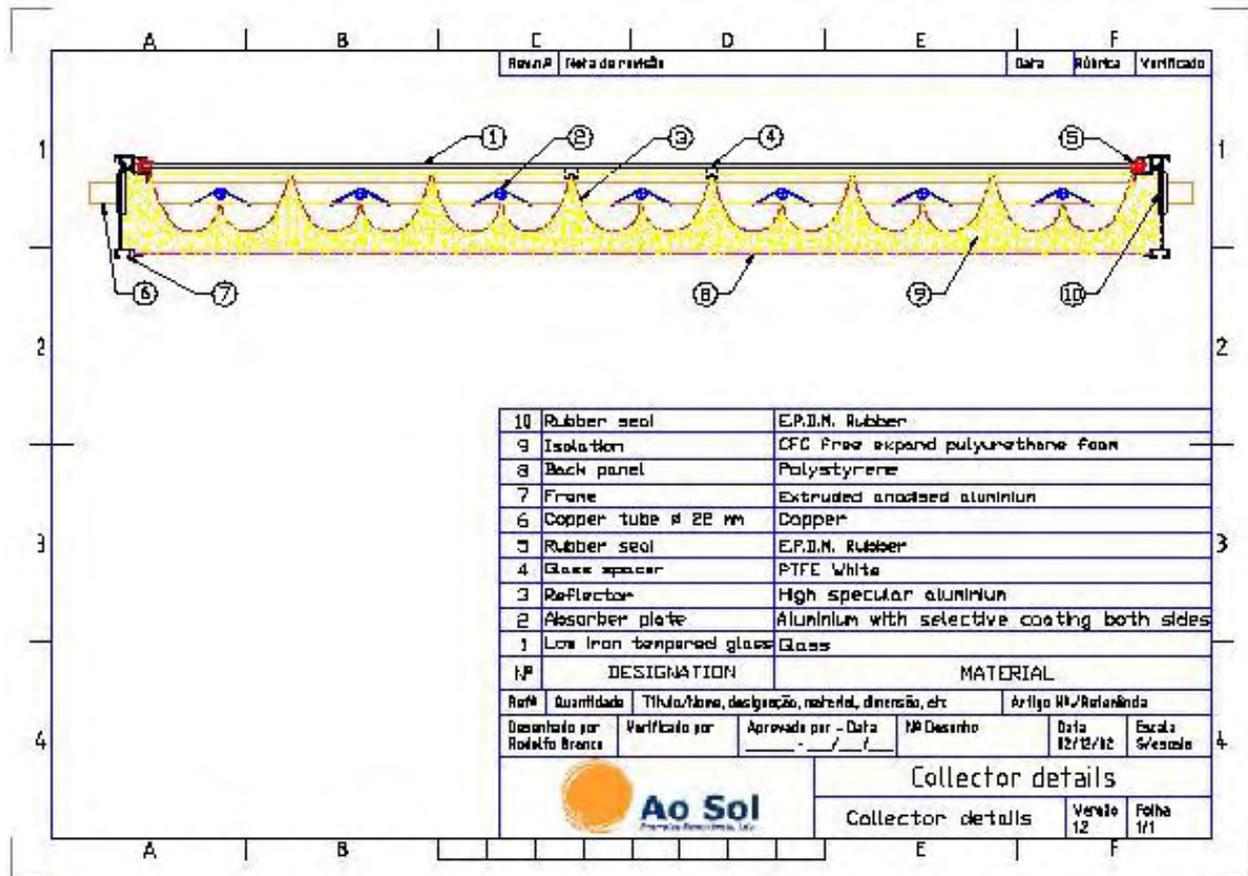


Figure 2: CPC Solar collector cross-section

4.3 Requirements / Failure Modes

The failure modes of the product are related directly with the strength capacity of each one of their components to stresses they are submitted. These stresses can be of environmental or of in-service nature as listed in Fig. 3.

Environmental stresses	In-service stresses
Solar radiation, UV radiation, temperature, high humidity, wind, rain, snow, hail, pollutants (gaseous (sulfur dioxide) and dust), animals (birds), and hazards	Circulating fluid temperature, stagnation temperature, circulating fluid velocity, chemical composition of the circulating fluid

Figure 3: environmental and in-service stresses

For solar collectors, the standard EN 12975-1 identifies the tests to be performed and establishes in clause 5.3.1 the following general pass-criteria (in red actual change proposal):

The term "no major failure", denotes that none of the following occurs:

- Absorber leakage or such deformation that permanent contact between absorber and cover is established;
- Breaking or permanent deformation of cover or cover fixing;
- Breaking or permanent deformation of collector fixing points or collector box;
- Vacuum loss, such that vacuum or subatmospheric collectors may no more be classified as such, according to the definition in EN ISO 9488 (only applicable for vacuum and subatmospheric collectors);
- Accumulation of humidity inside the collector exceeding 5% of the aperture area.

The clause 5.3.4 of EN 12975-1 establishes for the exposure test that when tested in accordance with 5.4 of EN 12975-2:2000, the collector shall not show any major failure according to 5.3.1 and none of the problems constituting major failure shall be graded 2 on the scale given in B.5.5 of EN 12975-2:2000.

The scale given in B.5.5 of EN 12975-2:2000 is remembered in Table 1:

Table 1: Inspection results (EN 12975-2, B.5.5)		
Evaluate each potential problem according to the following scale:		
0 - No problem		
1 - Minor problem		
2 - Severe problem		
• - Inspection to establish the condition was not possible		
Collector component	Potential problem Evaluation	
a) Collector box/fasteners	Cracking/warping/corrosion/rain penetration	
b) Mountings/structure	Strength/safety	
c) Seals/gaskets	Cracking/adhesion/elasticity	
d) Cover/reflector	Cracking/crazing/buckling/delamination/warping/outgassing	
e) Absorber coating Absorber tubes and headers Absorber mountings	Cracking/crazing/blistering Deformation/corrosion/leakage/loss of bonding Deformation/corrosion	
f) Insulation Water	retention/outgassing/degradation	

The maximum fluid temperature to be considered in the design of a solar collector or solar plant is the collector stagnation temperature. Materials to be used in the manufacture of collectors or installations incorporating the collector (expansion tanks, safety valves, etc.) shall be chosen taking into account this temperature.

The stagnation temperature shall be calculated in accordance with C.3 of EN 12975-2:2000 (Approach 2) under the following climate parameters:

- Global irradiance on collector plane 1000 W/m²;
- Surrounding air temperature 30 °C.

The collector shall provide for safe installation and mounting. Sharp edges, loose connections and other potentially dangerous features shall be avoided. If the weight of the empty collector exceeds 60 kg, an anchorage for a lifting device shall be included, except for the collectors that are assembled on the roof. Collectors filled with a heat transfer fluid (irritant to human skin or eyes, or toxic) shall carry a warning label.

4.4 Stresses

The Annex B of EN 12975-1 gives us the main criteria for the correct choice of materials and of design solutions, for guarantee of operational capacity and of long lifetime of a solar collector.

From this Annex B of EN 12975-1, remembered in Annex E, we can extract the major causes driving, first, to degradation and, after, to failure:

- UV radiation,
- environmental temperature (thermal shocks, airborne fire, radiant heat, thermal fatigue)
- internal temperature (stagnation, freezing),
- rain, snow, hail, wind, humidity,
- pollutants (gaseous and dust), bird excrements,
- aggressiveness of heat transfer fluid, and
- internal stresses from manufacturing processes like cutting, brazing, and soldering.

From the Annex C of EN 12975-1, remembered in Annex F, we can extract same precautions for environmental protection, namely that of insulation materials must not have CFC or outgas at the stagnation temperature.

4.5 Functional analysis

The main function (production of heat) of a solar collector can be considered as composed by three distinct functions: energy collection, by the absorber, heat transfer, from the absorber to the circulating fluid, and heat transfer, by the circulating fluid through the pipes. As secondary functions we can distinguish confinement and structural resistance to physical, chemical or mechanical degradation.

The role played by each component is indicated in Fig. 4

Function Component			Energy collection	Heat transfer	Heat transport	Confinement	Resistance to environment
1	Transparent cover	Low iron tempered glass	X			X	X
2	Absorber - coating	selective coating (both sides)	X	X			X
	Absorber - substrate	Aluminium		X			X
	Absorber - pipe	Cooper		X	X		X
3	Reflector	High specular aluminium	X				X
4	Glass spacer	PTFE White	X				X
5	Rubber seal	EPDM rubber				X	X
6	Pipe	Cooper			X		X
7	Frame	Extruded anodized Al				X	X
8	Back panel	Polystyrene				X	X
9	Insulation	CFC free expanded polyurethane foam	X				X
10	Rubber seal	EPDM rubber				X	X

Figure 4: Functional analysis

4.6 FMEA worksheet

FAILURE MODES AND EFFECTS ANALYSIS (FMEA)														
Project:				Owner:				Prepared by:		Document reference:				
Product:				Designer:				Approved by:		Issue:				
System / Equipment:				Installer:				Date:		Page of				
Function	Item	Components	Materials	Failure mode	Failure cause	Failure effects	Severity	Failure detection method / observable symptoms	Compensation provision	Correction actions	Remarks			
Energy collection	1	Transparent cover	Low iron tempered glass	Straching	Cleaning	Decreasing of transmission		Visual inspection / testing	Operator action	Use of clean water				
				Cracking	Schocks	Decreasing of transmission		Visual inspection / testing	Testing	Use of certified material				
				Dirt	Internal stresses	Decreasing of transmission		Visual inspection / testing	Testing	Use of certified material				
					External: dust	Decreasing of transmission		Visual inspection / testing	Operator action	Use of clean water				
					pollutants	Decreasing of transmission		Visual inspection / testing	Operator action	Use of clean water				
					Internal: condensation	Decreasing of transmission		Visual inspection	Design correction	Installer correction				
					binder/insulation	Decreasing of transmission		Visual inspection	Assembling correction	Installer correction				
				2	Absorber - coating	selective coating	Blistering, unstriking, ageing	Corrosion (humidity+ pollutants)	Loss of efficiency		Visual inspection / testing	Testing	Use of certified material	
								Excessive heating						
								3	Reflector	High specular aluminium	Pitting	Corrosion (humidity + pollutants)	Loss of efficiency	Visual inspection / testing
Ageing	Thermal fatigue	Loss of efficiency	Visual inspection / testing								Testing	Use of certified material		
9	Insulation	CFC free expanded polyurethane foam	Confinement	Water absorption	Loss of efficiency	Visual inspection / testing	Testing	Use of certified material						
Heat transfer	2	Absorber - substrate	Aluminium	Pitting	Corrosion (humidity + pollutants)	Loss of efficiency	Visual inspection / testing	Testing	Use of certified material					
				Absorber - pipe	Cooper	Breaking	Damage due to freeze	Ruin	Visual inspection	Maintenance action	new collector			
		Obstruction	Sludge due to corrosion (active agents/chemical incompatibility of fluid)			Decreasing of flow	Visual inspection	operating action	Use of adequate circulating fluid					
		6	Pipe	Cooper	Breaking	Damage due to freeze	Ruin	Visual inspection	Maintenance action	new collector				
Obstruction	Sludge due to corrosion (active agents/chemical incompatibility of fluid)				Decreasing of flow	Visual inspection	operating action	Use of adequate circulating fluid						
			Flow problems	Air trapping, bad control	Loss of efficiency		Visual inspection	operating action	Correct Control system					

FAILURE MODES AND EFFECTS ANALYSIS (FMEA)											
Project:				Owner:				Prepared by:		Document reference:	
Product:				Designer:				Approved by:		Issue:	
System / Equipment:				Installer:				Date:		Page of	
Function	Item	Components	Materials	Failure mode	Failure cause	Failure effects	Severity	Failure detection method / observable symptoms	Compensation provision	Correction actions	Remarks
Confinement	7	Frame	Extruded anodized Al	Pitting	Corrosion (humidity+ pollutants)	Visual impact		Visual inspection / testing	Testing	Use of certified material	
				8	Back panel	Polystyrene	Ageing (cracking, creep)	Thermal fatigue	Visual impact		Visual inspection / testing
	5, 10	Rubber seal	EPDM rubber	Ageing (cracking, creep)	Thermal fatigue	Loss of efficiency		Visual inspection / testing	Testing	Use of certified material	

Note: The secondary function action is considered together with others.

FMECA worksheet

FAILURE MODES EFFECTS AND CRITICALLY ANALYSIS (FMECA)														
			Owner:				Prepared by:				Document reference:			
			Designer:				Approved by:				Issue:			
			Installer:				Date:				Page of			
Item	Components	Materials	Failure mode	Failure cause	Failure effects	Severity	Failure detection method / observable symptoms	Compensation provisions	Severity Number SN	Probability number PN	Critically number CN	Correction actions	Remarks	
1	Transparent cover	Low iron tempered glass	Straching	Clearing	Decreasing of transmission		Visual inspection / testing	Operator action				Use of clean water		
			Cracking	Schocks	Decreasing of transmission		Visual inspection	Testing				Use of certified material		
				Internal stresses	Decreasing of transmission		Visual inspection / testing	Testing				Use of certified material		
			Dirt	External: dust	Decreasing of transmission		Visual inspection / testing	Operator action					Use of clean water	
				pollutants	Decreasing of transmission		Visual inspection / testing	Operator action					Use of clean water	
				Internal: condensation	Decreasing of transmission		Visual inspection	Design correction					Installer correction	
2	Absorber - coating	selective coating	Blistering, unstriking, ageing	Corrosion (humidity+ pollutants) Excessive heating	Loss of efficiency		Visual inspection / testing	Testing				Use of certified material		
3	Reflector	High specular aluminium	Pitting	Corrosion (humidity + pollutants)	Loss of efficiency		Visual inspection / testing	Testing				Use of certified material		
4	Glass spacer	PTFE white	Ageing	Thermal fatigue	Loss of efficiency		Visual inspection / testing	Testing				Use of certified material		
9	Insulation	CFC free expanded polyurethane foam	Confinement	Water absorption	Loss of efficiency		Visual inspection / testing	Testing				Use of certified material		
2	Absorber - substrate	Aluminium	Pitting	Corrosion (humidity + pollutants)	Loss of efficiency		Visual inspection	Testing				Use of certified material		
2	Absorber - pipe	Cooper	Breaking	Damage due to fr	Ruin		Visual inspection	Maintenance action				new collector		
			Obstruction	Sludge due to corrosion (active agents/chemical incompatibility of fluid)	Decreasing of flow		Visual inspection	operating action				Use of adequate circulating fluid		
6	Pipe	Cooper	Breaking	Damage due to fr	Ruin		Visual inspection	Maintenance action				new collector		
			Obstruction	Sludge due to corrosion (active agents/chemical incompatibility of fluid)	Decreasing of flow		Visual inspection	operating action				Use of adequate circulating fluid		
			Flow problems	Air trapping, bad	Loss of efficiency		Visual inspection	operating action				Correct Control system		

FAILURE MODES EFFECTS AND CRITICALLY ANALYSIS (FMECA)														
Project:			Owner:				Prepared by:				Document reference:			
Product:			Designer:				Approved by:				Issue:			
System / Equipment:			Installer:				Date:				Page of			
Function	Item	Components	Materials	Failure mode	Failure cause	Failure effects	Severity	Failure detection method / observable symptoms	Compensation provisions	Severity Number SN	Probability number PN	Critically number CN	Correction actions	Remarks
Confinement	7	Frame	Extruded anodized Al	Pitting	Corrosion (humidity+ pollutants)	Visual impact		Visual inspection	Testing				Use of certified material	
	8	Back panel	Polystyrene	Ageing (cracking, creep)	Thermal fatigue	Visual impact		Visual inspection	Testing				Use of certified material	
	5, 10	Rubber seal	EPDM rubber	Ageing (cracking, creep)	Thermal fatigue	Loss of efficiency		Visual inspection	Testing				Use of certified material	

4.7 Weak points from visual inspection

4.7.1 In service solar installations

In the framework of the Portuguese Public Initiative Solar Heat Water to Portugal they were visited 23 solar installations in different locations of Portugal, from which 8 with CPC solar collectors, similar with that in study. The CPC solar collectors of 6 of these installations were submitted to visual inspection. However the known results were treated all together. As the problems are similar, we present here all the results in Table 2.

Table 2 – Visual Inspection Results of 23 solar installations

Type of problem	Number of solar systems with or without problems			Associated type of failure mode
	With	Without	Not conclusive	
Wrong position for the control sensor	13	8	2	(3) thermodynamic systems
Galvanic corrosion	13	8	2	(5) material properties
Inexistent mechanical protection for insulation	14	7	2	(3) thermodynamic systems
Permanent liaison of primary circuit to network	14	8	1	(3) thermodynamic systems
Defective welding	3	18	2	(2) structural system
Fogginess	12	8	3	(5) material properties
Precoce ageing	12	9	2	(5) material properties
Seal rupture	1	20	2	(5) material properties
Corrosion flakes	5	16	2	(5) material properties
Circuit with non-equilibrium	10	12	1	(3) thermodynamic systems
Control system malfunction	10	13		(3) thermodynamic systems
Air-vent malfunction	20	3		(5) material properties

4.7.2 In tested solar collectors

To understand better both the results obtained from the solar installations visual inspection and the score numbers used by the Task 27 to fulfil the FMEA/FMECA sheets, it seems to be useful to use the summarized results obtained by the INETI Solar Collector Testing Laboratory (LECS/INETI) along the final inspection of the qualification testing procedure (EN 12975-2, Clause 5.11 and Annex B13. These results are presented in the following Tables 3 and 4.

Table 3 – Final Inspection Results of 26 solar collectors qualification testing (EN 12975-2, 5.11, B.13)

Collector component	Potential problem Evaluation	Observed problem Evaluation			
		0	1	2	*
a) Collector box / fasteners	Cracking / warping / corrosion / rain penetration	23	2	1	
b) Mountings/structure	Strength/safety	24	0	2	
c) Seals / gaskets	Cracking / adhesion / elasticity	25	0	1	
d) Cover / reflector	Cracking / crazing / buckling / delamination / warping / outgassing	20	0	6	
e) Absorber coating	Cracking / crazing / blistering	25	1	0	
Absorber tubes and headers	Deformation / corrosion / leakage / loss of bonding	25	1	0	
Absorber mountings	Deformation / corrosion	26	0	0	
f) Insulation	Water retention / outgassing / degradation	26	0	0	

(0 - No problem; 1 - Requirement apart from testing not fulfilled; 2 - Requirements for testing not fulfilled; * - Inspection to establish the condition was not possible)

Table 4 – Final Inspection Results of 26 solar collectors qualification testing (EN 12975-2, 5.11, B.13)

Qualification Test (EN 12975-2)	Number of collectors with scale 2 evaluation (Requirements for testing not fulfilled)
Internal pressure (1st test)	0
High-temperature resistance	0
Exposure	1
External thermal shock (1st test)	0
Internal thermal shock (1st test)	0
Internal pressure (2nd test)	0
External thermal shock (2nd test)	0
Internal thermal shock (2nd test)	0
Rain penetration	4
Freeze resistance	N.A.
Mechanical load	1
Impact resistance (optional test)	2
Thermal performance	0
Final inspection	0

So, using the following criteria for risk assessment of potential failure modes by use of FMEA applied to solar collectors:

Failure mode / Degradation process	Severity (S) (rating number)	Probability of occurrence(P _O) (rating number)	Probability of discovery(P _D) (rating number)	Rating-number for risk (RPN = S · P _O · P _D)
------------------------------------	------------------------------	--	---	---

Severity	Rating number
No effect on product	1
Minor effect on product but no effect on product function	2-3
Risk of failure in product function	4-6
Certain failure in product functioning	7-9
Failure which may affect personal safety	10

Probability of detection	Rating number
Failure which always is noted. Probability for detection > 99.99%	1
Normal probability of detection 99.7%	2-4
Certain probability of detection >95%	5-7
Low probability of detection >90%	8-9
Failures will not be found - cannot be tested	10

Probability of occurrence	Rating number
Unlikely that failure will occur	1
Very low probability for failure to occur	2-3
Low probability for failure	4-5
Moderate probability for failure to occur	6-7
High probability for failure to occur	8-9
Very high probability for failure to occur	10

we have to obtain the results shown in Table 5:

Table 5 – Risk Assessment of Potential Failure Modes versus Final Inspection Results of 26 solar collectors qualification testing (EN 12975-2, 5.11, B.13)

Collector component	Potential problem Evaluation	Observed problem Evaluation				Risk Assessment			
		0	1	2	*	S	P _O	P _D	RPN
a) Collector box / fasteners	Cracking / warping / corrosion / rain penetration	23	2	1		7	4	2	56
b) Mountings/structure	Strength/safety	24	0	2		10	3	6	180
c) Seals / gaskets	Cracking / adhesion / elasticity /loss of performance	25	0	1		7	2	8	112
d) Cover / reflector	Cracking / crazing / buckling / delamination / warping / outgassing	20	0	6		7	6	2	84
e) Absorber coating	Cracking / crazing / blistering	25	1	0		7	1	3	21
Absorber tubes and headers	Deformation / corrosion / leakage / loss of bonding	25	1	0		9	2	2	36
Absorber mountings	Deformation / corrosion	26	0	0		7	1	2	14
f) Insulation	Water retention / outgassing / degradation	26	0	0		6	1	4	24
Total									527

(0 - No problem; 1 - Requirement apart from testing not fulfilled; 2 - Requirements for testing not fulfilled; * - Inspection to establish the condition was not possible)

4.8 Discussion

The main problems encountered in the reported visual inspection of 23 solar installations result from bad design of the solar system or bad installation of the system. This is quite evident from two similar system installed in the same county of Alcácer do Sal to heat water of swimming pools. Both systems have i) 120 m² of CPC collectors of the same manufacturer, ii) a solar system working with a furnace burning biomass. But, as we can see from the pictures below, one doesn't present any evidence of degradation (Torrão) and the other one presents.



Fig.5 Public swimming pools of i) Alcácer do Sal and ii) Torrão

However it is interesting to take a look over the detected problems, showing some evidences from the visual inspection and, when justified, establishing the correspondent fault tree (NUREG-0492, 1981).

a) Wrong position for the control sensor

It's a simple problem of bad design and/or of bad installation. It can be easily identified by visual inspection. So it seems to be necessary a specific form, with a checking list of items to be verified, and to be signed by both the installation designer, and the installer, and by an external auditor.

b) Galvanic corrosion

It results from bad design and/or of bad installation of the solar system. It can be identified by a procedure similar of that proposed in a), using the guide ISO/TR 10217:1989. It is also necessary to implement the training of the installers.



c) Inexistent mechanical protection for insulation

It results from bad design and/or of bad installation. It can be avoided by a procedure similar to that of proposed in a).



d) Permanent liaison of primary circuit to network

It results from bad design and/or from bad installation. It can be avoided by a procedure similar to that of proposed in a).

e) Defective welding

It results from bad design and/or from bad installation. It can be avoided by a procedure similar to that of proposed in a).

f) Fogginess

It can result mainly from

- bad design and/or bad manufacture of the ventilation system of the collector box (see l);
- bad design and/or bad manufacture of the confinement system of the solar collector (see h).

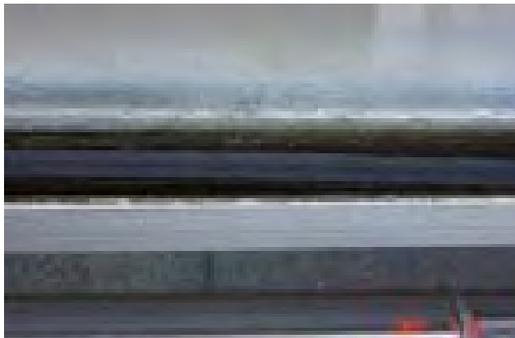
g) Precede ageing

The main causes are the same of that indicated in f).

h) Seal rupture

It can result mainly from

- bad design and/or bad manufacture of the collector;
- inappropriate materials.



The result of the bad design and/or the bad manufacture is detected through the rain penetration test.

But, to avoid the use of inappropriate material it is necessary to include in the qualification tests procedure, after the visual inspection, and the dismounting of the solar collector, the specific tests de-scribed in ISO 9553:1997 and ISO 9808:1990, or to include the requirement of the use of certified materials.

i) Corrosion flakes

The main causes are the same of that indicated in f)

j) Circuit with non-equilibrium

It can be avoided by a procedure similar to that of proposed in a).

k) Control system malfunction

It can be avoided by a procedure similar to that of proposed in a).

l) Air-vent malfunction

By comparison of Tables 2, 3 and 4 we can conclude that the actual set of qualification tests doesn't include an appropriated test to evaluate the behaviour of the ventilation system of the collector box.

It can be avoided by a procedure similar to that of proposed in a).



The work done shows that it is necessary to add to the qualification tests of the collector

- the qualification tests of some important components, namely the qualification tests for absorbers proposed by IEA-SHC Task 27 to CEN, as well those of ISO for rubber seals and sealing compounds (ISO 9553:1997), and for elastomeric materials for absorbers, connecting pipes and fittings (ISO 9808:1990);
- new test procedures for evaluation of the ventilation system of the collector box.

The same data shows that it is necessary to walk towards the certification of medium and large installations to avoid the reported bad design of the system installations as well the bad installation of the systems.

4.9 References

- [1] Bowles J. B. e Enrique C. (1995), Fuzzy logic prioritization of failures in a system failure mode, effects and criticality analysis, Reliability Eng. and System Safe, Vol. 50, pg. 203-213.
- [2] Braglia M., Frosolini M. e Montanari R. (2003), Fuzzy TOPSIS Approach for Failure Mode, Effects and Criticality Analysis, Qual. and Rel. Eng. Int., Vol. 19, pg 425-443
- [3] Carvalho M. J., Collares-Pereira M., Oliveira J. C., Mendes J. F., Haberle A. e Wittwer V. (1995), Optical and thermal testing of a new 1.12X CPC solar collector, Solar Energy Materials and Solar Cells, Vol. 37, pg. 175-190.
- [4] Cow K. (2002), FAILURE MODES AND EFFECTS ANALYSIS (FMEA), available, in September 2004, in <http://www.npd-solutions.com/fmea.html>.
- [5] ECSS-Q-30-02A:2001 - Failure modes, effects and criticality analysis (FMECA), European Cooperation for Space Standardization.
- [6] Hage R. (2002), Capturing Insulated Glass Failure Events Using Failure Modes and Effects Analysis and Event Trees, available, in September 2004, in <http://www.igdurability.org/secure/papers.html>
- [7] Hawkins P.G. and Woolons D.J. (1998), Failure modes and effects analysis of complex engineering systems using functional models, Artificial Intelligence in Engineering, 12, 375-397.
- [8] Lair J. and Hage R. (2003), Failure Mode Effect and Criticality Analysis - Application to windows and solar components, available, in June de 2004, in <http://www.iea-shc-task27.org/>
- [9] Lair J. (2002), r-c2-CSTB-JL-FMEA solar collector (draft3)-2-2002.doc.doc

- McDermott R. E., Raymond J. M. and Michael R. B. (1996), The basics of FMEA, ISBN 0-527-76320-9, Productivity Press.
- [10] Moss T.R. and Woodhouse J. (1999), Criticality analysis revisited, Qual. and Rel. Eng. Int., Vol. 15, pg. 117-121.
- [11] NUREG-0492 (1981), Fault Tree Handbook. U. S. Nuclear Regulatory Commission, available, in Sep-tember 2005, in <http://nrc.gov/reading-rm/doc-collections/nuregs/staff/sr0492/sr0492.pdf>.
- [12] Pillay A. and Wang J. (2003), Modified failure mode and effects analysis using approximate reason-ing, Reliability Engineering and System Safety, Vol. 79, pg. 69–85.
- [13] Prates M. L. and Duarte C. M. (2003), Identity, Quality and Industrial Design, 1st International Meeting of Science and Technology of Design, Senses and Sensibility in Technol-ogy – Linking Tradition to Innovation Through Design, Proceedings Book, Paper 03-039, September 25-26, Lisbon, IADE/ESD.
- [14] SAE - J1739:2002 - Potential Failure Mode and Effects Analysis in Design (Design FMEA) and Potential Failure Mode and Effects Analysis in Manufacturing and Assembly Processes (Process FMEA) and Effects Analysis for Machinery (Machinery FMEA), Society of Automo-tive Engineers.

ANNEX A: Traditional FMEA scales (Pillay, 2003)

Table 1: Traditional FMEA scale for probability of occurrence (Sf)

Probability of occurrence	Rating	Possible failure rate (operating days)
Remote	1	<1:20,000
Low	2	1:20,000
	3	1:10,000
Moderate	4	1:2,000
	5	1:1,000
	6	1:200
High	7	1:100
	8	1:20
Very high	9	1:10
	10	1:2

Table 2: Severity

Severity	<i>Rating</i>
Remote	1
Low	2
	3
	4
Moderate	5
	6
	7
High	8
	9
Very high	10

Table 3: Detectability

Detectability	Rating	Probability of detection (%)
Remote	1	86–100
Low	2	76–85
	3	66–75
	4	56–65
Moderate	5	46–55
	6	36–45
	7	26–35
High	8	16–25
	9	6–15
Very high	10	0–5

ANNEX B: Criticality ranking (ECSS-Q-30-02A, 2001)

Table 1: Severity categories applied at the different levels of analysis

SYSTEM LEVEL FMEA/FMECA	
Severity category	Failure effect
Catastrophic 1S	Loss of life, life threatening or permanently disabling injury or occupational illness, loss of an element of an interfacing manned flight system. Loss of launch site facilities. Long-term detrimental environmental effects.
Catastrophic 1	Loss of system.
Critical 2S	Temporary disabling but not life threatening injury, or temporary occupational illness. Loss of, or major damage to other flight systems, major flight elements, or ground facilities. Loss of, or major damage to public or private property. Short-term detrimental environmental effects.
Critical 2	Loss of mission.
Major 3	Mission degradation.
Negligible 4	Any other effect.
SUBSYSTEM/ASSEMBLY/ EQUIPMENT LEVEL FMEA/FMECA	
Severity category	Failure effect
Catastrophic 1S	Loss of life, life threatening or permanently disabling injury or occupational illness, loss of an element of an interfacing manned flight system. Loss of launch site facilities. Long-term detrimental environmental effects.
Catastrophic 1	Propagation of failure to other subsystems/assemblies/equipment.
Critical 2S	Temporary disabling but not life threatening injury, or temporary occupational illness. Loss of, or major damage to other flight systems, major flight elements, or ground facilities. Loss of, or major damage to public or private property. • Short-term detrimental environmental effects.
Critical 2	Loss of functionality.
Major 3	Degradation of functionality.
Negligible 4	Any other effect.

Note: A severity category shall be followed by a suffix – S, for safety impacts, and R, for redundancy.

Table 2: Severity numbers applied at the different severity categories

Severity category		
1S, 1	catastrophic	4
2S, 2	critical	3
3	major	2
4	negligible	1

Table 3: Probability levels, limits and numbers (for system)

Level	Limits	PN
Probable	$P > 10E-2$	4
Occasional	$10E-4 < P \leq 10E-2$	3
Remote	$10E-5 < P \leq 10E-4$	2
Extremely remote	$P \leq 10E-5$	1

ANNEX C: Process FMECA worksheet (ECSS-Q-30-02A)

Process Failure Modes, Effects and Criticality Analysis (FMECA)											
Project/System/Subsystem/Equipment:		Analysed process/Reference document:				Prepared by: Approved by: Date:		Document ref.: Issue: Page of			
Ident. number	Item	Description	Failure mode/ Failure cause	Failure effects: 1) process 2) product	Detection means	Existing preventive or compensatory provisions	Severity SN	Occurrence PN	Deflection DN	Criticality CN	Recommendations and remarks

Figure 7: Process FMECA worksheet

Figure 1: Process FMECA worksheet

ANNEX D: Determination of the criticality number (CN) (ECSS-Q-30-02A)

Table 1: Severity numbers (SN) for severity of failure effects

SN	Definition
4	Loss of life, life-threatening or permanently disabling injury or occupational illness, loss of an element of an interfacing manned flight system. Loss of launch site facilities. Long-term detrimental environmental effects.
3	Temporary disabling but not life-threatening injury, or temporary occupational illness. Loss of, or major damage to flight systems, major flight elements, or ground facilities. Loss of, or major damage to public or private property. Short-term detrimental environmental effects. Loss of system. Loss of mission.
2	Mission degradation. Deterioration of the analysed process or of associated processes.
1	Any other effect.

Table 2: Probability numbers (PN) for probability of occurrence

PN	Definition
1	Extremely unlikely
2	Unlikely
3	Likely
4	Very likely

Table 3: Detection numbers (DN) for probability of detection

DN	Definition
1	Very likely
2	Likely
3	Unlikely
4	Extremely unlikely

ANNEX E: Description of solar collectors materials and manufacture (EN 12975-1, Annex B)

AE.1 General

The operational ability and long lifetime of solar collectors depend on the correct choice of appropriate materials. Testing of the materials, including accelerated life testing, is very important for the development of new collectors and the prediction of service life. Respective literature is referred to in Annex E.

Solar collectors may be affected by airborne fire or radiant heat. The use of non-combustible materials should be preferred. Collectors should comply with the European regulations to fire classification.

The collector box should be water-tight to prevent penetration of rain water. The collector box should be constructed in such a way, that condensed water does not accumulate in the collector, as this might impair its functional capability and durability. For that purpose the collector should be properly designed to enable ventilation of air through the collector box.

The construction of the collector should ensure that no undue stress is built up in the cover, even at the maximum stagnation temperature of the collector. The materials of collector components should be selected and constructed so, that they can withstand the maximum temperature which may occur at stagnation conditions and the thermal shocks they may be exposed to during the summer period.

The materials of the collector should preferably be resistant to exposure to UV radiation, and in cases where materials selected are not so, they should be protected against, incident and reflected UV-radiation.

Bushings and ducts, leading through the box, should be constructed so that no leakage can occur caused by thermal expansion. The collector box bushings should withstand any damage, if they have to be soldered for assembly. The design of collector should be such, that heat bridges between the collector box and the absorber are avoided.

The components and the materials of the collector should be able to withstand the mechanical loads resulting from the heating up and cooling down of the collector. They should also be resistant to environmental stress from outdoor climate caused by factors such as rain, snow, hail, wind, high humidity and air pollutants.

AE.2 Absorbers

Absorbers should be made from suitable materials to cope with mechanical, thermal and chemical requirements of the application. The effect of the manufacturing processes like cutting, brazing, soldering etc., on the properties of the absorber, should be considered.

The absorber ducts which guide the flow of the heat transfer fluid, including the connection lines, should be designed and constructed in such a way that venting can be effected in the installed condition, thus ensuring the functional capability of the collector.

Absorbers should be dimensioned on the basis of a calculation pressure corresponding to the permissible working overpressure specified by the manufacturer taking into consideration a safety factor of 1,5. The properties of the heat transfer medium should be considered as well.

The effect of the maximum temperature (stagnation temperature) of the absorber should be considered in the selection of material.

In the case of materials with strength characteristics, which vary appreciably with the temperature and/or UV-exposure, the evaluation criteria should be determined individually in each case.

The wetted side of the absorber should withstand corrosion under normal operating conditions and taking into account the admixture of possible additives to the heat transfer fluid. The walls of swimming pool collectors which are wetted by the swimming pool water should be resistant to the additives used for the treatment of the swimming pool water.

Absorber coatings should retain their optical properties under high temperature, high humidity and condensation, and sulfur dioxide at high humidity.

AE.3 Transparent covers

Solar collectors are generally covered with glass or transparent plastic glazings. The durability of glass and tempered glass under the service conditions found in solar collectors is good, but the resistance of plastics and glass treated with a special coating to the combined effects of UV radiation and temperature may be poor. There may be significant degradation with time, and in the case of a reduced transmission in the solar wavelengths, this will lead to degradation in collector performance. A reduction in the tensile strength or impact strength of a cover material may lead to a failure of the collector cover.

The transparency of the covers should not deteriorate appreciably during the service life of the collector, the covers should be resistant to ultraviolet (UV) radiation, air pollution, high humidity and condensate as well as high temperatures depending on the collector design.

AE.4 Insulation materials

Insulation materials should withstand the local temperature arising during stagnation temperature conditions of the collector. At this temperature no melting, shrinkage or outgassing of the insulation with consequent condensation inside the collector cover, or

absorber performance reduction or corrosion of metallic surfaces should occur to the extent of seriously reducing the collector performance.

Water or humidity absorption by the insulation material may shortly or permanently reduce the insulation performance of the material.

Thermal expansion of the material used in the collector due to the wide range of temperatures should be taken into consideration because of different thermal expansion coefficients. Furthermore transparent insulation materials or teflon layers used, should not deteriorate appreciably, both mechanically and optically, during the service life of the collector due to ultraviolet (UV) radiation, high temperature and humidity.

AE.5 Reflectors

Reflectors, diffuse or specular, are reflecting surfaces used to increase the radiation, incident on the absorber. The reflecting surface should be resistant to environmental influences such as air pollution and to corrosion through humidity or rain. Outside the collector box reflectors should resist also mechanical loads through wind, snow and hail, whereas inside reflectors should withstand high temperatures.

AE.6 Diffusion barriers

Diffusion barriers are materials used between absorbers and insulation material to prevent diffusion into or out of the insulation material. They should be able to withstand the absorber high temperatures and the incident UV radiation without shrinking and the high humidity or condensate accumulated remaining tight.

**11. ANNEX F: Environmental protection
(EN 12975-1, Annex B (informative))****AF.1 Heat transfer fluid**

The heat transfer fluid used should not be toxic, seriously irritant to the human skin or eyes, or water polluting and it should be fully biodegradable.

AF.2 Insulation materials

For the collector insulation no materials should be used, which have been manufactured using or containing CFCs. Furthermore, the insulation materials should not contain components, which outgas at the stagnation temperature, specified in clause 6, which are toxic and seriously irritant to the human skin or eyes.

AF.3 Recycling of the collector materials

Solar collectors are mainly used to save energy and reduce pollution. Therefore the design of the collectors should take into consideration the possibility to recycle the materials used. Materials which are not to be recycled should be avoided or used to the lowest possible extent.

Case study 5: Window/Wall interface

Case study leader: Michael Köhl, Fraunhofer ISE, Freiburg, Germany

5.1 Introduction

Unfortunately the originally planned cooperation with other Task27 partners was not possible because of missing funding. Therefore the investigations were only carried out in ISE, Germany.

The main aim was the detection of thermal bridges and water vapour leakages in the window/wall-interface.

5.2 The detection system

The temperature was measured with an Infrared camera (see figure 5.1). An optical sensor was applied for the humidity measurements. The working principle is to measure the reflected light at the water-absorption band at $1.4 \mu\text{m}$. The incident light and the measured light are transferred by a wave-guide to the supply and detection electronics (see figure 5.2).

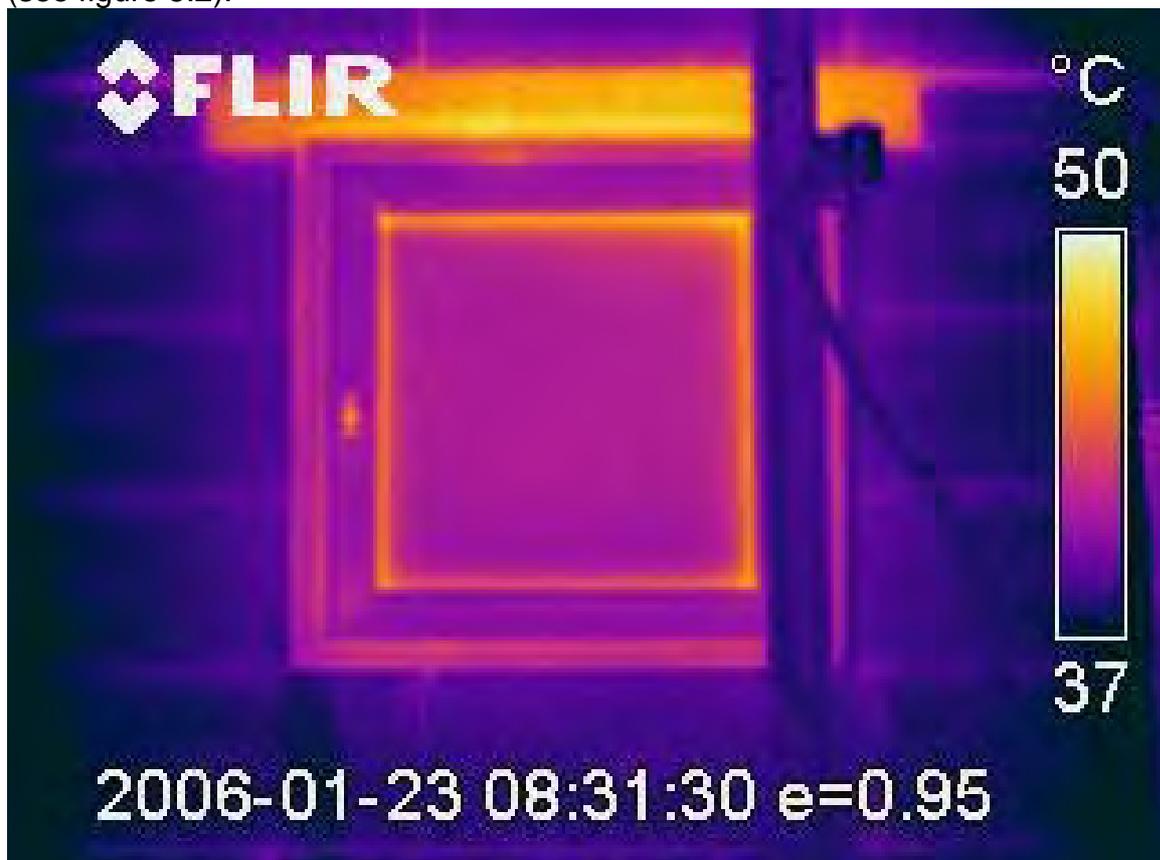


Figure 5.1: Temperature distribution at the window/wall interface. The bar at the right side of the window belongs to the scanner of the humidity sensor.



Figure 5.2: The humidity sensor mounted on the scanner

The waveguide was fixed on the arm of a 2-dimensional scanner which was constructed for scanning an area of 2 m times 2 m in usually in steps of 1 cm. One scan around the window needed about 20 min.

5.3 The subject

A commercially available window was mounted in a wall (Dimension 165cm x 215cm x 15cm), as shown in figure 5.3, which was placed between the two parts of the double climatic chamber of the ISE (see figure 5.4).



Figure 5.3: Window in the wall to be tested



Figure 5.4: Climatic chamber and sample holder, which allows the installation of samples with dimensions of more than 1.8 m times 1.5 m.

The window-wall interface was sealed by PU-foam covered by a Silicon layer. The climatic conditions at the both sides of the wall could be set independently.

5.4 Results

After waiting for drying out of the wall the outside of the wall was exposed to 95% relative humidity at 60°C. The other side was not conditioned. The monitoring of the climatic conditions is shown in figure 5.5.

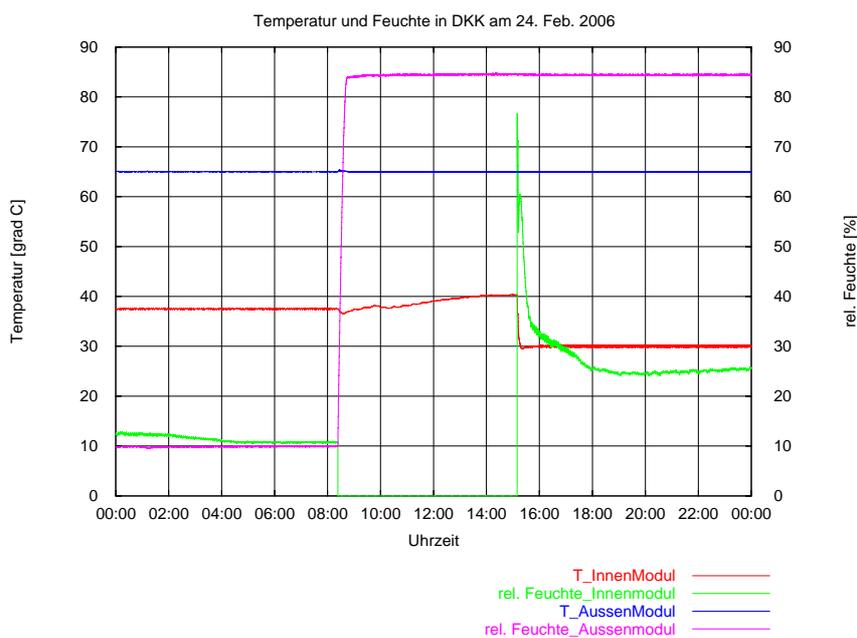


Figure 5.5: Temperature (inside in red, outside in blue) and relative humidity in the two chambers.

The measurements with scanner and IR camera are shown in figure 5.6 and 5.1.

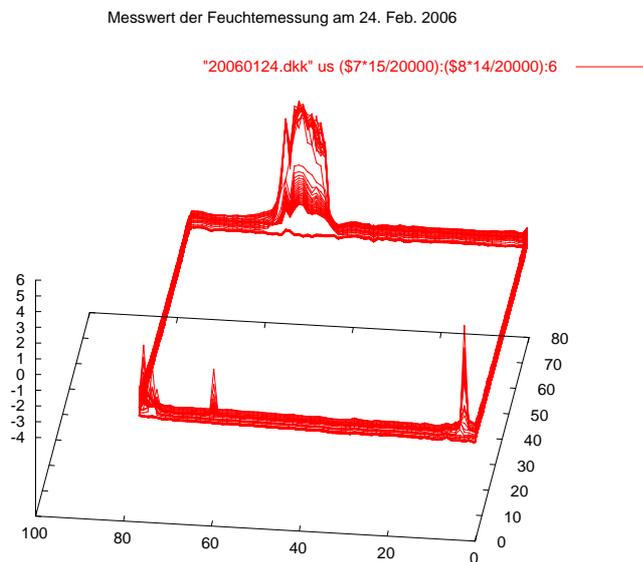


Figure 5.6: Signal of the humidity sensor by scanning the window-wall interface frequently. The upper lines come from the top part.

Four leaks became visible after some time. The 3 smaller leaks at the low part came from water droplets which penetrated through the frame sealant and were sucked by the wall (see figure 5.7). The leakage at the top-side resulted from a ventilation opening. This opening can be identified in the infrared picture (figure 5.1) as well.



Figure 5.7: Condensation in the window frame and wetting of the wall at the bottom side.



Figure 5.8: Condensation in the window frame, ventilation opening and wetting of the wall at the top side.

5.5 Conclusions

The optical humidity sensor combined with a xy-scanner allows the detection of water leaks. Further investigations should assess the potential for using the scanner in-situ during long-term durability tests for the detection of growing leaks.