

IEA SHC Task 27: Durability assessment of solar energy materials based on general methodology of accelerated life testing: Introduction

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The search for quantitative methods in durability assessment

One of the most crucial steps in component design is estimating the risk and cost of possible material or component failures. Such work most often requires methods for accelerated life testing to be applied in order to be able to predict expected service life or service reliability of a particular component or material.

In the past, it was performance and short-term reliability that were the main interests in the development of products, components and materials. Long-term performance aspects, such as durability, were mainly considered in a qualitative and generally non-predictive way. Long-term stability was considered mainly in connection with long-term tests under service conditions or in conjunction with comparative short-term durability tests to select the best materials or product component design. Failure analysis was seldom employed in a systematic way to predict potential causes of failures.

As industry is paying greater attention to minimising lead times, the need to predict the service life of products has grown in order better to optimise processes and products. As a consequence, methods of predicting long-term performance or durability have become more quantitative in nature.

This includes the development of methods for:

- Quantitative characterisation of environmental stress in terms suitable for service life prediction.
- Test tailoring in environmental resistance testing.
- Performance analysis to elaborate relations between component performance and material properties.
- Predictive failure analysis to investigate relationships between failure, degradation and life-limiting processes in terms of chemical change of materials.
- Risk analysis to estimate the effect of different failure modes with respect to reliability and safety.

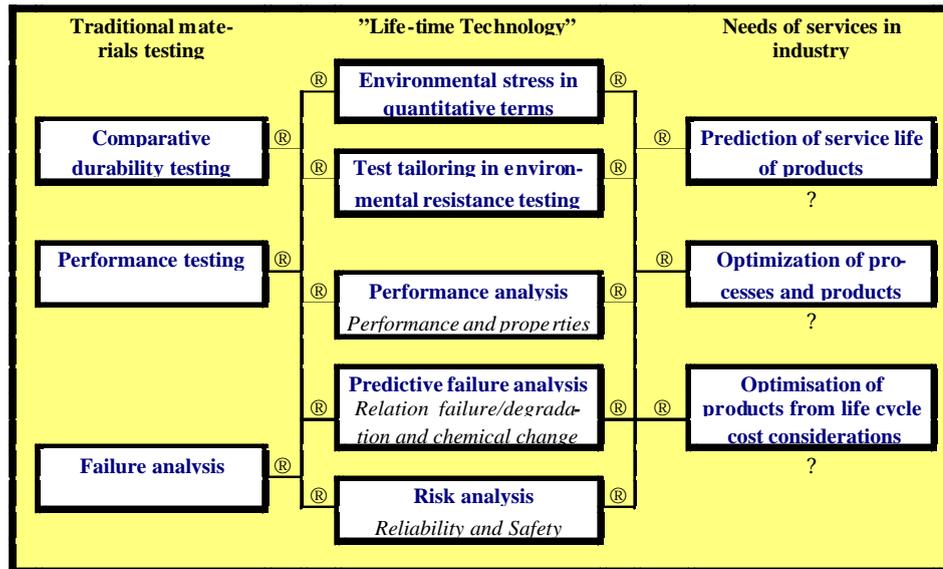


Fig. 1 From traditional qualitative testing to quantitative testing in durability assessment

Many efforts have been made to develop systematic approaches to service life prediction based on accelerated testing so that all essential aspects of the problem will be taken into consideration, see e.g. Gaines *et.al.* (1977), Sjöström (1985), CIB W 80/RILEM 71-PSL (1986), ISO 15686-1(2000) and ISO 15686-2 (2001).

In Task 27 of the IEA Solar Heating and Cooling Programme, the work on durability has two main objectives. The first is to develop a general methodology for durability and service lifetime prediction (SLP) that are applicable to the wide variety of advanced optical materials and components used in energy efficient solar thermal and buildings applications. The second is to apply this general methodology to specific materials/components to allow prediction of service lifetime and to generate proposals for international standards.

This paper reviews briefly the general methodology which has been adopted by Task 27 to meet the first objective. A more thorough description of the methodology can be found in a Working Document of IEA Solar Heating and Cooling Task 27 (Carlsson *et.al.* 2001).

The general methodology for durability assessment adopted by Task 27

In the general methodology adopted by Task 27, a predictive failure modes and effect analysis serves as the starting point for service life prediction from accelerated life test results as is illustrated schematically in Fig. 1. The analysis is made on the component level.

The diagram in Fig. 2 is based on a similar scheme developed for the purpose of accelerated life testing of selective solar absorber surfaces in a joint case study of Task 10 of the IEA Solar Heating and Cooling Program (Carlsson *et.al.* 1994).

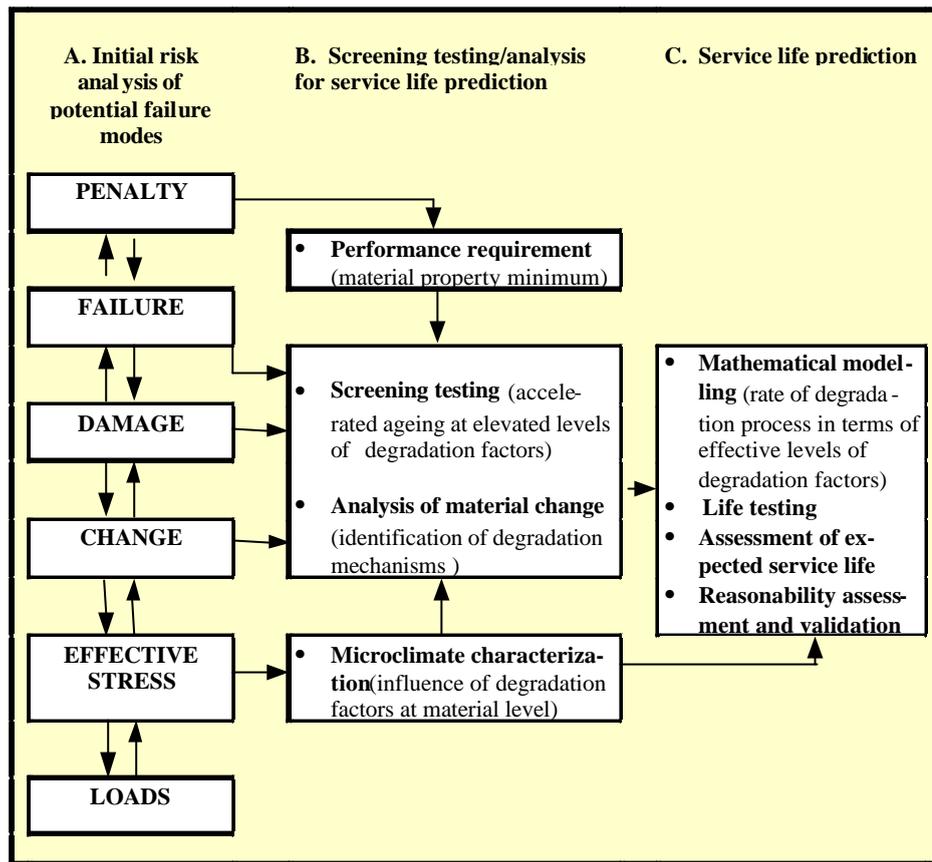


Fig. 2 Failure mode analysis for planning of accelerated tests for service life prediction

- **PENALTY** is the level at which an assessment is made of the economic effects of a component failure. Based on this assumption, it is possible to set a reliability level that must be maintained for a given number of years.
- **FAILURE** is the level at which performance requirements are determined. If the requirements are not fulfilled, the particular component or part of 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.
- **DAMAGE** describes the stage of failure analysis at which various types of damage, each capable of resulting in failure, can be identified.
- **CHANGE** is related to the change in the material composition or structure that can give rise to the damage of the type previously identified.
- **EFFECTIVE STRESS** is the level at which various factors in the microclimate, capable of being significant for the durability of the component and its materials, can be identified. An important point here is that it is possible to make quantitative characterisation.
- **LOADS**, finally, is the level that describes the macro-environmental conditions (climatic, chemical, mechanical), and which is therefore a starting point for description of the microclimate or effective stress as above

Each step in the scheme on the left hand side of Fig.2 may be related to the subsequent step by an appropriate deterministic or statistical relationship. The relation should define the expected results of all the various activities involved in accelerated life testing, as indicated on the right hand side of Fig.2.

Initial risk analysis of potential failure modes

The first step in the scheme illustrated in Fig. 2 is an analysis of potential failure modes with the aim of obtaining:

- a)** 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,
- b)** a framework for the selection of test methods to verify performance and service life requirements,
- c)** 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
- d)** a framework for compiling and integrating all data on available component and material properties and material degradation technology.

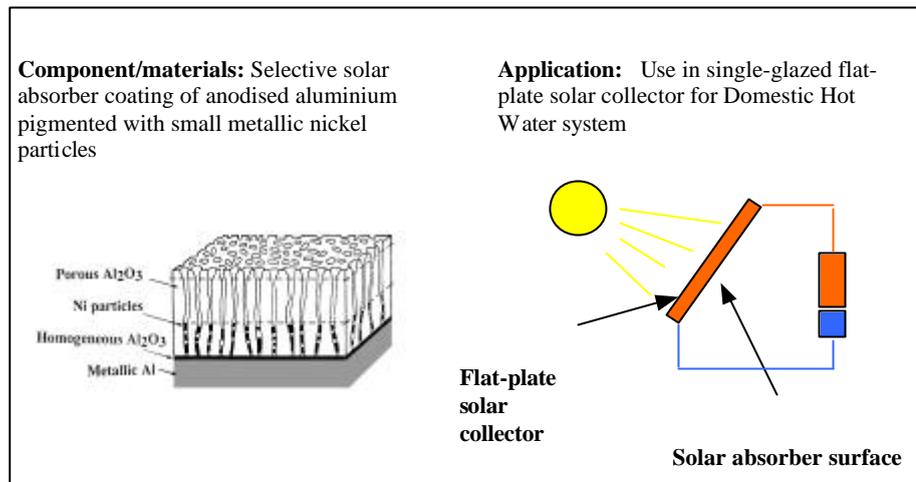
From a practical point of view, but also from an economic viewpoint, an assessment of durability or service life has to be limited in its scope and focused on the most critical failure modes. An important part of the initial step in such an assessment is therefore estimating the risk associated with each of the potential failure modes of the component.

The programme of work in the initial step of service life assessment may be structured into the following activities (Carlsson, 1993):

- a)** 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;
- b)** 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;
- c)** 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. When identifying potential failure modes, it is important to distinguish between 1) failures initiated by the short-term influence of environmental stress, the latter representing events of high environmental loads on the component and its materials, 2) failures initiated by the long-term influence of environmental stress, the latter causing material degradation so that the performance and sometimes also the environmental resistance of the component and its materials gradually decrease.
- d)** Estimation of risks associated with different failure modes

Table 1

Example of result from an initial risk analysis of potential failure modes based on information taken from the IEA Task 10 case study on selective solar absorber surfaces.



A. Specification of end-user and product requirements on component

<i>Function and general requirements</i>	<i>General requirements for long-term performance during design service time</i>	<i>In-use conditions and severity of environmental stress</i>
<ul style="list-style-type: none"> -Efficiently convert solar radiation into thermal energy -Suppress heat losses in the form of thermal radiation 	<ul style="list-style-type: none"> -Loss in optical performance should not result in reduction of the solar system energy performance (solar fraction) with more than 5%, in relative sense, during a design service time of 25 years 	<ul style="list-style-type: none"> - Behind glazing in contact with air. - Casing of collector exchange air with the ambient, meaning that airborne pollutants will enter collector. - If the collector is not rain tight the humidity level of air in the collector may become high - Maximum temperature 200 °C

B. Critical functional properties and requirements on component and its materials

<i>Critical functional properties</i>	<i>Test method for determining functional property</i>	<i>Requirement for functional capability and long-term performance</i>
<ul style="list-style-type: none"> -Solar absorptance (α) -Thermal emittance (ϵ) -Adhesion (ad) 	<ul style="list-style-type: none"> ISO CD 12592.2 ISO CD 12592.2 ISO 4624 	<p>Functional capability</p> <ul style="list-style-type: none"> $\alpha > 0.92$ $\epsilon < 0.15$ ad > 0.5 MPa <p>Long-term performance</p> <ul style="list-style-type: none"> PC = $-\Delta\alpha + 0.25 \Delta\epsilon \leq 0.05$

C. Service reliability/service life

<i>Failure/Damage mode / Degradation process</i>	<i>Degradation indicator</i>	<i>Critical factors of environmental stress/ Degradation factors and severity</i>	<i>Estimated risk of failure/damage mode from FMEA</i>			
			<i>S</i>	<i>P_O</i>	<i>P_D</i>	<i>Risk RPN</i>
<p>Unacceptable loss in optical performance</p> <p>(A) High temperature oxidation of metallic nickel</p> <p>(B) Electrochemical corrosion of metallic nickel</p> <p>(C) Hydratization of aluminium oxide</p>	<p>PC = $-\Delta\alpha + 0.25 \Delta\epsilon$;</p> <p>Adhesion</p> <p>Reflection spectrum Vis-IR</p> <p>Reflection spectrum Vis-IR</p> <p>Reflection spectrum IR</p>	<p>High temperature</p> <p>High humidity, sulphur dioxide (atmospheric corrosivity)</p> <p>Condensed water, temperature</p>	S	P _O	P _D	Risk RPN
			7	2	8	112
			7	5	5 ¹	175
			7	7	4 ¹	196

¹ Result of glazing failure

The result of the initial risk analysis of potential failure modes may be documented as shown in Table 1 and Table 2 using information from a case study on accelerated life testing of selected solar absorbers performed in Task 10 of the IEA Solar Heating and Cooling Programme (Carlsson et.al. 1994).

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, see Table 1.

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. Defining performance requirement should be accompanied by an assessment of the economic effects of a component failure. Based on this, it is possible to define a service life requirement or set a reliability level that must be maintained for a given number of years.

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 kinds of failures for a particular component. The different damage mechanisms, which may lead to the same kind of failure of the component, may sometimes be quite numerous.

The objective of analysis is to identify potential failure/damage modes and mechanisms that may lead to material degradation and the development of damage, and associated critical factors of environmental stress or degradation factors, see the example in Table 2.

Table 2 Risk assessment of potential failure modes by use of FMEA applied to the selective absorbers studied in IEA Task 10, see Table 1.

<i>Failure mode / Degradation process</i>	<i>Severity (S) (rating number)</i>	<i>Probability of occurrence (P_O) (rating number)</i>	<i>Probability of discovery (P_D) (rating number)</i>	<i>Rating-number for risk (RPN = S × P_O × P_D)</i>

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

The risk or risk number associated with each potential failure/damage mode identified can be estimated by use of the methodology of FMEA

(Failure Modes and Effect Analysis) in a simplified way, see IEC Standard (1985) for a review of the FMEA methodology. The estimated risk number is taken as the point of departure to judge whether a particular failure mode needs to be further evaluated or not. The estimated risk number may also be used to determine what kind of testing is needed for qualification of a particular component and its materials, see the example in Table 2.

Screening testing by accelerated ageing

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.

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, see example in Table 3.

Table 3 Programme for screening testing in the IEA solar absorber case study.

<i>Possible degradation mechanism</i>	<i>Critical periods of high environmental stress</i>	<i>Suitable accelerated test methods and range of degradation factors</i>
(A) High temperature oxidation of metallic Ni particles	Stagnation conditions of solar collector at high levels of solar irradiation (no withdrawal of heat from the collector)	Constant load high temperature exposure tests in the range of 200-500 °C
(B) Electrochemical corrosion of metallic Ni particles at high humidity levels and in the presence of sulphur dioxide	Under starting-up and under non-operating conditions of the solar collector when the outdoor humidity level is high	Exposure tests at constant high air humidity (75 - 95 % RH), constant temperature (20- 50 °C), and in the presence of sulphur dioxide (0-1 ppm)
(C) Hydratization of aluminium oxide and electrochemical corrosion of metallic Ni particles by the action of condensed water	Under humidity conditions involving condensation of water on the absorber surface	Exposure tests under constant condensation (sample surface cooled 5 °C below surrounding air which is kept at 95 % RH) and temperature conditions ranging from 10 - 90 °C

Analysis of material change during ageing

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. In Table 4 an example from the IEA absorber surface case study is shown that demonstrates how different techniques for analysing material changes resulting from ageing can be used to get information on what material degradation mechanisms are contributing to deterioration in performance.

Table 4

Techniques that were used in the IEA Task 10 solar absorber case study for analysis of material change upon durability testing

<i>Degradation mechanism</i>	<i>Techniques for analysis of material changes</i>	<i>Results</i>
(A) High temperature oxidation of metallic Ni particles	- UV-VIS-NIR reflectance spectroscopy - AES depth profiling - SEM-EDX - XRD	- Reduction of absorption in solar range corresponding to reduction in metal concentration - Formation of Ni oxides - Small changes in surface morphology - Formation of NiO
(B) Electrochemical corrosion of metallic Ni particles at high humidity levels and in the presence of sulphur dioxide	- UV-VIS-NIR reflectance spectroscopy - FTIR-IR reflectance spectroscopy - AES depth profiling - SEM-EDX	- Reduction of absorption in solar range corresponding to reduction in metal concentration - Formation of sulphate - Increase in surface concentration of Ni accompanied with sulphur at the surface - Surface morphology affected and detection of sulphur
(C) Hydratization of aluminium oxides and electrochemical corrosion of the metallic particles by the action of condensed water	- UV-VIS-NIR reflectance spectroscopy - FTIR-IR reflectance spectroscopy - AES depth profiling - SEM-EDX	- Some changes hard to explain - Formation of hydrated forms of aluminium oxide leading to increased thermal emittance - Change in surface structure - Considerable change in surface morphology

Microclimate characterisation for service life prediction

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. In Table 5 measurement techniques that were used in the IEA Task 10 absorber case study previously reviewed are given as an example of what factors were needed to take into consideration in this study. It is of extreme importance to characterize the service conditions in terms relevant for the most important degradation mechanisms identified for the materials of the component but also in terms relevant for and convertible into the test conditions for the environmental resistance tests to be used for accelerated life testing.

Table 5

Techniques that were used in the IEA Task 10 absorber case study for measurement of degradation factors in solar collectors operating under service conditions.

<i>Degradation mechanism</i>	<i>Degradation factors/ Measurement variables</i>	<i>Sensors</i>
(A) High temperature oxidation of metallic Ni particles	<i>Temperature</i> : Surface temperature of absorber plate	Pt sensors in holders screwed directly on the absorber plate. To accomplish a good thermal contact heat conducting compound was used.
(B) Electrochemical corrosion of metallic Ni particles at high humidity levels and in the presence of sulphur dioxide	<i>Atmospheric corrosivity</i> : Measurement of corrosion mass loss rate of standard metal specimens <i>Air pollutants</i> : Measurement of sulphur dioxide concentration inside and outside of the solar collector.	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 in the air outside and inside of the solar collector
(C) Hydratization of aluminium oxide and electrochemical corrosion of metallic Ni particles by the action of condensed water	<i>Humidity</i> : Measurement of air humidity in the air gap between the absorber plate and glazing cover of the collector <i>Time of condensation</i> : Measurement of specular reflectance of absorber surface <i>Surface humidity</i> : Measured relative air humidity converted to relative humidity on surface by use of measured surface temperatures	Capacitance humidity sensors carefully shielded from solar radiation and thermal radiation of the ambient. Special designed reflectance mode condensation sensor

Distribution functions of single degradation factors or combinations of degradation factors

If only the dose of a particular environmental stress is important then the distribution or frequency function of a degradation factor is of interest. In the IEA absorber case study, only the distribution in the absorber temperature during service conditions was needed for predicting the service life limited by high temperature degradation, see Fig.3, left diagram. In case of service life prediction considering degradation caused by the action of high humidity and condensed water, both air humidity and surface temperature were taken into account, see Fig. 3, right diagram.

Mathematical modelling for service life prediction from results of accelerated ageing

To perform an accelerated test, D , means that the level of at least one stress factor, X , causing degradation is kept at a higher level relative to the situation in service. Consequently this means the time to failure in the accelerated test, $\tau_{f,D}$, will be shorter relative to service life, τ_s . The ratio between the latter and the former is commonly referred to as the acceleration factor, A . If the applied stress is constant in time also for service conditions, the acceleration factor A can in the case of only one stress factor contributing to degradation be expressed as:

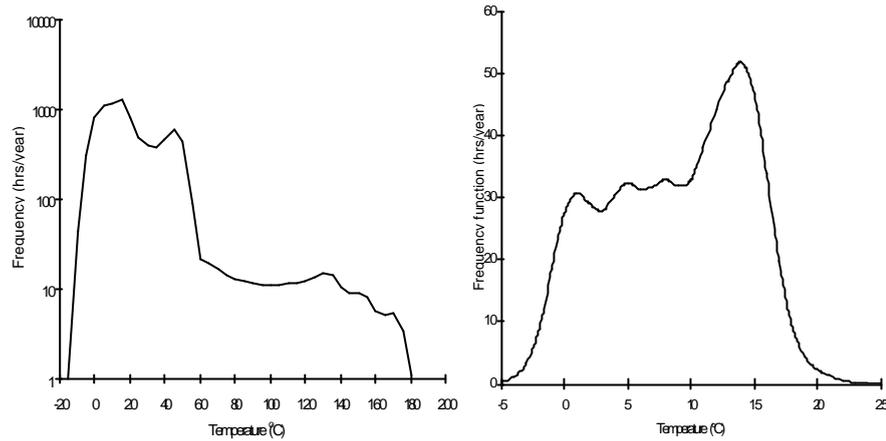


Fig. 3

Results from measurement of microclimate for the absorber in the IEA absorber surface case study - Left diagram: Absorber temperature frequency function for one year. For one month of the year the collector was under stagnation conditions - Right diagram: Absorber temperature frequency function when $RH \geq 99\%$ of that year. Metallic mass loss due to corrosion of zinc was determined to 0.3 g/m^2 , year.

$$A = \tau_s / \tau_{f,D} = a_x = g(\underline{X}_D) / g(\underline{X}_S) \quad (1)$$

where the expression $g(\underline{X}_D) / g(\underline{X}_S)$ is called the time transformation function or the acceleration factor function. Examples of time transformation functions can be found in e.g. reports by Martin (1982), Carlsson et. al. (1988 and 2001). The time transformation functions, a_x , used in the IEA absorber case study are shown in Table 6.

Accelerated life testing and assessment of expected service life

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 in terms of the mathematical models set up to characterize the different degradation mechanisms identified. Life testing therefore requires conducting a series of tests.

The accelerated test programme also provides an opportunity to validate whether the predominant degradation mechanism or mechanisms identified during screening testing change when the level of stress is changed. It is particularly important to clarify this for tests with the lowest possible stress levels in respect of the longest available testing time.

The following equations may therefore be helpful for evaluation of the results of the test program:

If the accelerated tests truly reflect the service degradation behaviour, the change in performance ΔP with service time y_s should be described by the same function as the change in performance with testing time y_D for a test with acceleration factor A , *i.e.*

$$\Delta P = f(y_s) = f(A \cdot y_D) \quad (2)$$

Table 6

Estimated service life of the nickel- pigmented anodised aluminium absorber surface in the IEA solar absorber case study. Values are given for the different degradation mechanisms and assuming that the different degradation mechanisms are acting alone.

<i>Degradation mechanism</i>	<i>Time transformation function (a_x)</i>	<i>Estimated service life with $PC = -Da + De < 0.05^1$ (years)</i>
(A) High temperature oxidation of metallic Ni particles	$a_T = \exp [-(E_a / R) \cdot (1/T_D - 1/T_s)]$ E_a = activation energy R = general gas law constant T_D = temperature of test (K) T_s = effective mean temperature at service (K)	$>10^5$
(B) Electrochemical corrosion of metallic Ni particles at high humidity levels and in the presence of sulphur dioxide	$a_{Co} = \tau_{M,S} / \tau_{M,D}$ $\tau_{M,S}$ = time to reach a certain extent of corrosion of reference metal in service $\tau_{M,D}$ = time needed to reach the same extent of corrosion of reference metal in test D (zinc used as reference metal)	12 (The coating is assumed to be installed in a non-airtight highly ventilated collector) 34 (The coating is assumed to be installed in an airtight collector with controlled ventilation)
(C) Hydratization of aluminium oxide and electrochemical corrosion of metallic Ni particles by the action of condensed water	$a_{T,H}^{-1} = \tau_H \cdot \exp \left(\frac{E_{H,T}}{R} \left(\frac{1}{T_{eff}} - \frac{1}{T} \right) \right)$ $T_{H,eff}$ = effective mean temperature of the absorber surface when the relative humidity in the air gap is equal to or higher than 99 %. τ_H = the time fraction of the year, time-of-wetness, during which the relative humidity in the air gap is equal to or higher than 99 %. $E_{H,T}$ = Arrhenius activation energy	9 (The coating is assumed to be installed in a non-airtight highly ventilated collector)

By introducing the inverse function f^{-1} , equation (2) may be rewritten as

$$y_D = (1/A) \cdot f^{-1}(\Delta P) \quad (3)$$

or

$$\ln(y_D) = -\ln(A) + \ln(f^{-1}(\Delta P)) \quad (4)$$

Equation (4) forms the basis for the determination of the parameters in the time-transformation or acceleration factor equation and also for checking whether the performance versus transformed-time relation is the same irrespective of the stress level. General problems when applying equation (4) for evaluating the results of tests are: For high stress level tests the performance versus time curve may be difficult to determine for small ΔP values - the degradation process is too fast. However, for low stress level tests, the appearance of the performance versus time curve at high ΔP values may be difficult to determine because the testing time may be too long. Those restrictions limit the range, in which it is possible to check, whether the relation between the performance and the transformed time is the same irrespective of the stress level of test.

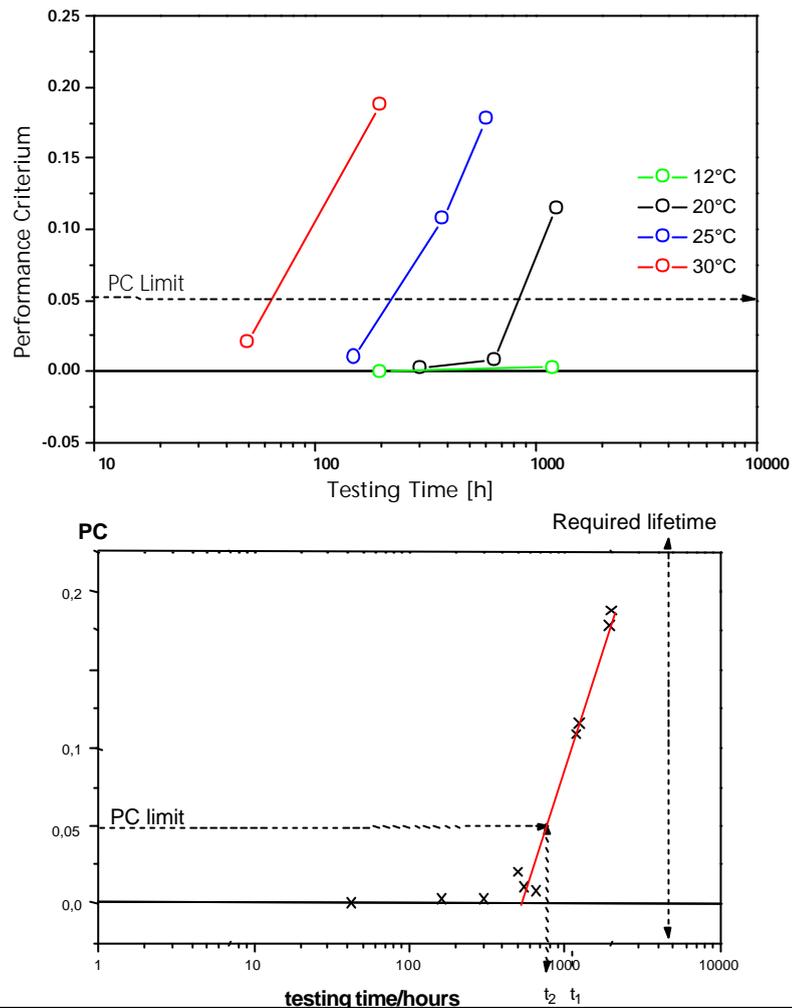


Fig. 4

Example from the IEA solar absorber case study on accelerated testing of a nickel pigmented anodised aluminium absorber surface in respect of its resistance to the action of condensed water on its surface.

Upper diagram: Results of a series of constant condensation tests at different temperatures.

Lower diagram: All test results from upper diagram transformed to the 20°C test condition by use of the performance versus time relation given in the table below.

Material	Nickel pigmented anodised aluminium absorber surface
Degradation mechanisms	Hydratization of aluminium oxide and electrochemical corrosion of metallic Ni particles by the action of condensed water
Degradation indicator	$PC = -\Delta\alpha + 0.25 \Delta\varepsilon$ α = solar absorptance, ε = thermal emittance
Environmental resistance tests	Exposure tests under constant condensation (sample surface cooled 5 °C below surrounding air which is kept at 95 % RH) and temperature conditions ranging from 12-30 °C
Performance versus time relation	$\ln(\text{testing time}) = \frac{E_{HT}}{R} (T^4 - T_R^4) + \ln \sum_{n=0}^{\infty} d_n \cdot (\Delta\varepsilon)^n$ T = testing temperature; $T_R = 20$ °C

How equation (4) may be applied is illustrated in Fig 4 where an example from the IEA solar absorber case study is shown. It should be mentioned

that at above 40 °C a phase change reaction occurs, which completely changes the kinetics of the degradation process.

From the accelerated life test results the parameters of the assumed model for degradation are determined and the service life then estimated by extrapolation to service conditions. If the service conditions vary, effective mean values of stress need to be assessed from measured service stress data (Carlsson et.al. 1994 and 2001), see also Annex 1.

As a result, it may be possible to express the importance of different degradation mechanisms in terms of expected service life values, see example from the absorber surface case study in Table 6.

Reasonability assessment and validation

By use of accelerated life testing, potential degradation mechanisms limiting the service life of a component may be identified. However, it is important to point out that it is only the service life determined by the material degradation mechanisms observed in the accelerated tests at relative high levels of stress that can be assessed. Life-limiting degradation mechanisms may exist that cannot be identified by way of accelerated life testing because the knowledge and experience in what may cause degradation of a particular material in a component may be too limited.

The best approach in validating an estimated service life from accelerated testing, therefore, is to use 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 order to validate the predicted service life data from accelerated life testing in the IEA absorber case study the actual service degradation in optical performance of the nickel pigmented anodised aluminium absorber coating was investigated (Carlsson et al 2000). Samples from the coating taken from collectors used in solar DHW systems for time periods of ten years or more were analysed for that purpose. It could be concluded that the agreement between degradation data determined for the absorber samples from the DHW systems and that from accelerated life testing from the Task 10 study was astonishingly good both from a quantitative and a qualitative point of view. For the absorber coating in a properly designed solar collector, the service life seems good enough. For the absorber coating in a not air tight solar collector, probably because of glazing failures, the humidity level is raised to such high levels that the service life is reduced to an unacceptable level.

Some general characteristics of six solar DHW-systems from which nickel-pigmented anodised aluminium absorber samples were analysed.

DHW-system and location	Age	Collector	Remark
DK 1 (Copenhagen, Denmark)	12 years	BATEC 22 SEL	
DK 2 (Zealand, Denmark)	11 years	BATEC 22 SEL	Frost burst, one fin replaced
DK 3 (Karlsunde, Denmark)	10 years	BATEC 22 SEL	
DK 4 (Zealand, Denmark)	10 years	BATEC 22 SEL	Frost burst, one fin replaced
CH 1 (Gisikon, Switzerland)	15 years	Mühlemann Einbau	Collector leaky 1993
CH 2 (Frauenfeld, Switzerland)	15 years	SOLTOP Einbau	Plastic cover replaced 1988 Collector leaky 1990

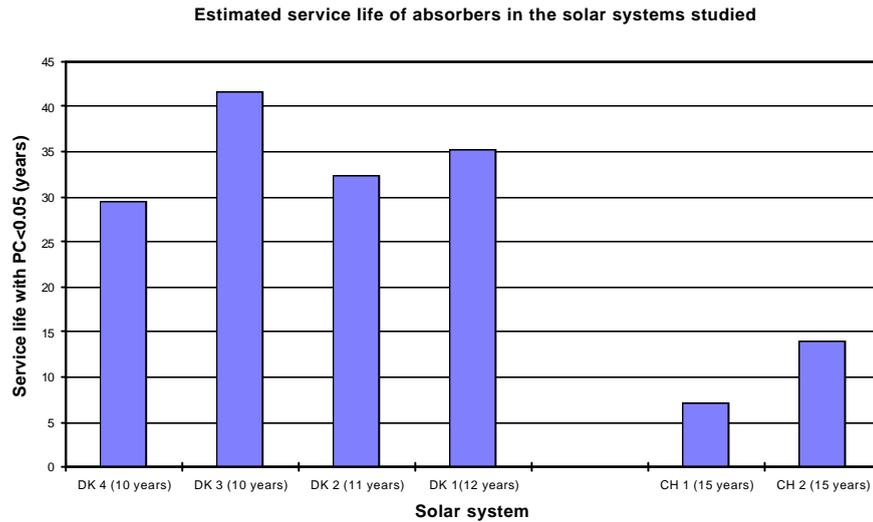


Figure 5 Service life for the absorber coatings in the different solar DHW systems estimated from measurements on samples from the different systems

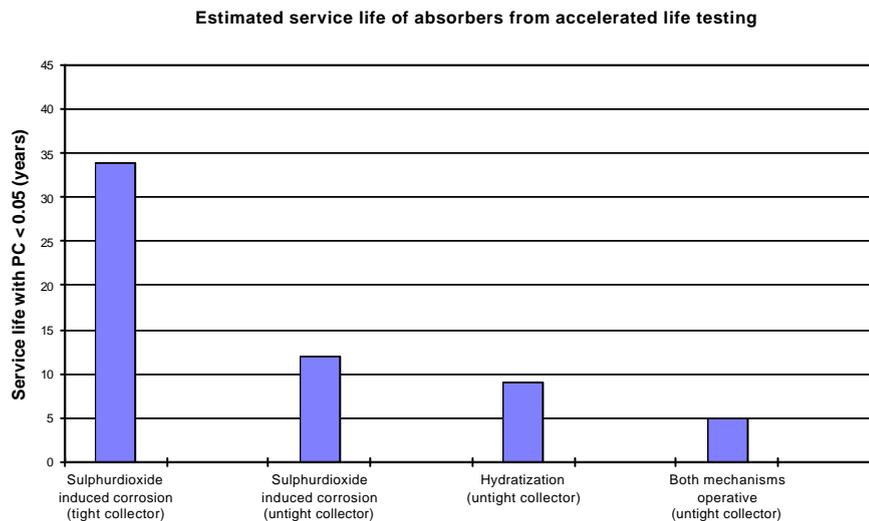


Figure 6 Service life, of absorber coating as determined from results of accelerated life testing, see Table 6.

Figure 5:6 Comparison between estimated service life of absorber coating from actual service exposure and from the result of accelerated life testing (from Carlsson et al 2000).

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Annex 1: Effective mean values of stress factors or combinations of stress factors

The acceleration factor approach as represented by equation (1) can directly be applied only when the level of the degradation factor considered is constant in time. If the degradation factor varies with time under service conditions an effective mean value, $X_{S,EFF}$, has to be used, *i.e.*

$$A = \tau_S / \tau_{i,D} = a_X = g(\underline{X}_D) / g(X_{S,EFF}) \quad (A1)$$

If the stress factor under service conditions varies periodically with time, the following equation may be derived

$$\int_0^{t_S} g(X_S) \cdot dt = n \cdot \int_0^{y_p} g(X_S) \cdot dt \quad (A2)$$

where y_p is the length of the period, e.g. one year, and n is the number of periods until failure is reached.

If, when calculating the extent of degradation, only the time period at a certain state of environmental influence is of importance, not the history of changes in the environmental stress factor with time, equation (A2) may be written as

$$\int_0^{t_S} g(X_S) \cdot dt = n \cdot y_p \cdot \int_{X_{S,min}}^{X_{S,max}} g(X_S) \cdot f(X_S) \cdot dX_S \quad (A3)$$

where

$f(X_S)$ = frequency function for distribution of X_S within one time-period of length y_p .

An effective mean value, $X_{S,EFF}$, can therefore be introduced defined by

$$g(X_{S,EFF}) = \int_{X_{S,min}}^{X_{S,max}} g(X_S) \cdot f(X_S) \cdot dX_S \quad (A3)$$

If X_S denotes absolute temperature and the Arrhenius equation is used as a basis for expressing the temperature dependence of the rate of degradation, eq. (A3) becomes

$$\exp[-(E_a / R) \cdot (1/T_{EFF})] = \int_{T_{min}}^{T_{max}} \exp[-(E_a / R) \cdot (1/T)] \cdot f(T) \cdot dT \quad (A4)$$

where

E_a = Activation energy (J/mol)

R = General gas law constant (J/K,mol)

As is obvious from equation (A4), the effective mean value of a stress factor is usually material dependent.

The activation energy dependence of the effective mean temperature means that primarily periods with relatively high temperatures are of importance. In the IEA solar absorber case study on accelerated lifetime testing, it could be concluded that the period when a solar collector is under stagnation conditions more or less solely determined the effective mean temperature of the absorber in a solar collector although it represented only one month of the year, see Fig. A1

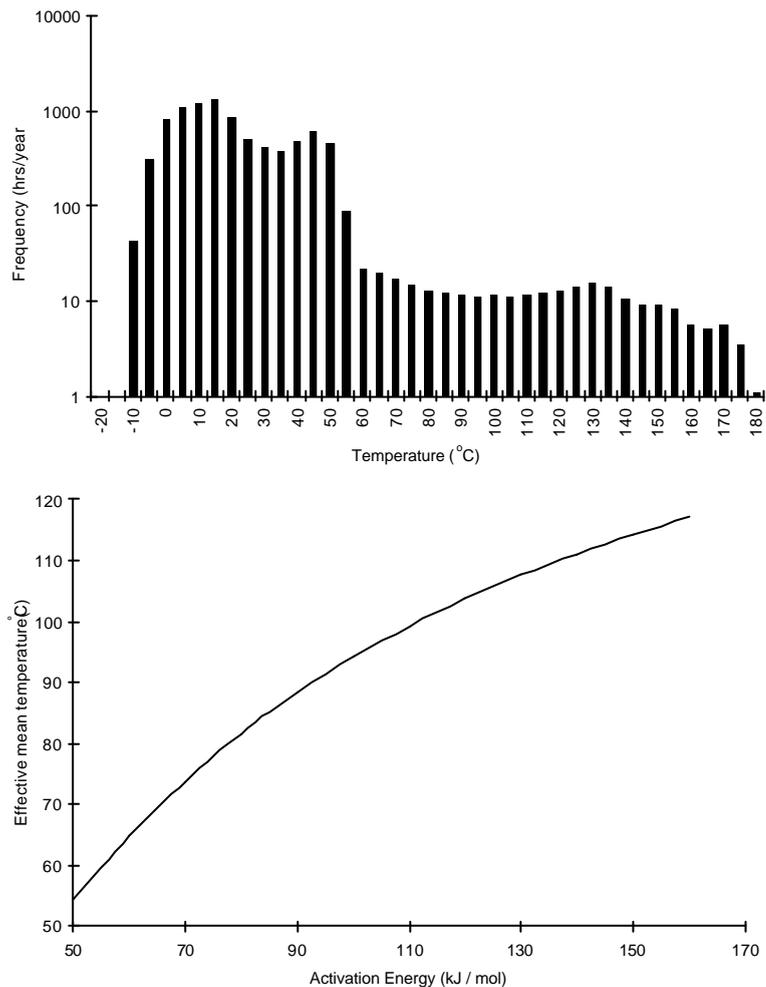


Fig. A1

Upper figure - Absorber temperature frequency function for one year valid for a typical single glazed flat-plate solar collector. For one summer month of the year the collector is under stagnation conditions.

Lower figure - Effective mean temperature vs activation energy for the thermal load profile illustrated in the upper figure.

(Data from the IEA solar absorber case study, see Carlsson et.al. 1994)

If the variation in more than one stress factor needs to be taken into account, combined time-transformation functions are used. IN the IEA absorber case study the effective mean temperature during time-of-wetness conditions for a selective solar absorber surface in a solar collector was

calculated from measured absorber temperatures and corresponding air humidity data for one year by the use of the following expression:

$$\exp\left(-\frac{E_{H,T}}{R} \cdot T_{H,\text{eff}}^{-1}\right) = \int_{T_{H,\text{min}}}^{T_{H,\text{max}}} \exp\left(-\frac{E_{H,T}}{R} \cdot T_H^{-1}\right) \cdot f_H(T_H) dT_H \quad (\text{A5})$$

where

$f_H(T_H)$ is the yearly-based frequency function for the service temperature of the absorber surface in a solar collector when the relative humidity level exceeds 99%, being the time fraction of a year when the service temperature is in the interval T to $T+dT$ and the relative humidity level exceeds 99%, see Fig. 3, right diagram.

$T_{H,\text{max}}$ in K is the maximum service temperature of the absorber surface in a collector, when the relative humidity level exceeds 99%.

$T_{H,\text{min}}$ is equal to 273 K, as below this temperature ice is formed on the surface of absorber.

$E_{H,T}$ is the Arrhenius activation energy expressing the temperature dependence for a possible degradation reaction of the absorber surface caused by condensation.

The acceleration factor for a constant load condensation test D - a T_{H} - could therefore be expressed as previously shown in Table 6, *i.e.*

$$a_{T,H}^{-1} = \tau_H \cdot \exp\left(-\frac{E_{H,T}}{R} (T_{H,\text{eff}}^{-1} - T_D^{-1})\right) \quad (\text{A6})$$

where

$T_{H,\text{eff}}$ is the effective mean temperature of the absorber surface in K, defined by eq.(A5)

τ_H is the time fraction of the year, time-of-wetness, during which the relative humidity in the air gap is equal to or higher than 99 %.

In the IEA absorber case study, the Arrhenius activation energy $E_{H,T}$ was determined from a series of constant load condensation tests performed at varying temperatures, as illustrated in Fig. 4.