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 B1: Durability assessment methodology development

October 2007

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PROJECT B1: "Durability assessment methodology development"

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November 2003

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1   Foreword

This report is the result of a joint effort in Task 27 " Performance, durability and sustainability of advanced windows and solar components for building envelopes" of the International Energy Agency Solar Heating and Cooling Programme.

The members of project B1 on durability assessment methodology development have prepared the work presented in the report. The main contributors have been:

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2   Abstract

To achieve successful commercialisation of new advanced windows and solar fa-çade components for buildings, the durability and reliability of these need to be demonstrated prior to installation by use of reliable and well-accepted test methods.

In Task 27 Performance of Solar Facade Components of the IEA Solar Heating and Cooling Programme work has therefore been undertaken with the objective to de-velop a general methodology for durability test procedures and service lifetime pre-diction (SLP) methods adaptable to the wide variety of advanced optical materials and components used in energy efficient solar thermal and buildings applications.

As the result of this joint work a general methodology has been developed. The pro-posed methodology 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.

The working scheme to be employed in the development of durability test procedures is illustrated in the report with results from the previous IEA research in materials research on accelerated life testing of selective solar absorber surfaces.

In the report also the results of another validation study is presented performed by the Task 27 group by applying the proposed general methodology to service life prediction of PVC and PC polymeric glazing materials as collector cover in flat plate solar collectors. Previous results from IEA work are also here utilized for the analysis.

The examples on durability assessment of selective solar absorber surfaces and on polymeric glazing materials both show the great applicability of the general methodology for accelerated life testing.

The usefulness and validity are also confirmed by comparing predicted results with actual measured data for samples exposed under real in-service conditions. Consequently, very abbreviated testing times at elevated stress conditions can be substituted for long-time exposures at lower stress levels in durability assessment. This will allow much shorter development cycle times for new products and will allow improvements to be identified and readily incorporated in new products prior to market introduction.

3   Introduction

To achieve successful and sustainable commercialisation, solar building products must meet three important criteria, namely minimum cost, sufficient performance, and demonstrable durability.

Durability assessment directly addresses all three segments of this triad. First, it permits analysis of life cycle costs by providing estimates of service lifetime, O&M costs, and realistic warranties. Understanding how performance parameters are affected by environmental stresses (for example by failure analysis) allows improved products to be devised. Finally, mitigation of known causes of failure directly results in increased product longevity. Thus, accurate assessment of durability is of paramount importance to assuring the success of solar thermal and building products.

Data on durability of materials and service life of components or parts of components can be obtained or estimated from different kinds of sources, for example:

- feedback from practice,
- results of long-term tests under in-use conditions,
- estimates based on accelerated life testing.

In the case of components with traditional materials in conventional applications, feedback data from practice are often available in the form of actual service life of materials and parts of components and such data can serve directly as an aid for material selection in component design. A problem, which may arise, however, is that environmental factors contributing to material degradation vary with time and location. This makes it difficult, as a rule, to transfer this kind of life data from one climate to another.

Long-term tests under in-use conditions are one way of generating service life data for components or parts of components with new or substitute materials or for com-ponents or parts of components with traditional materials in new applications. How-ever, it may take a long time to obtain results from these types of tests, unless changes in the properties of the materials can be detected at an early stage of deg-radation.

One alternative to long-term testing under in-service conditions is accelerated life testing in which test the stress levels of one or more degradation factors are kept higher relative to in-use conditions. As a result, the testing time can be selected much shorter than the expected service life. For the development of components with new materials, accelerated life testing is, as a rule, the only realistic way to get information on the long-term performance of the components prior to their market introduction in new products.

Early efforts to develop accelerated methods for material ageing were often aimed at attempting to speed up, under laboratory conditions, degradation of the materials to as great an extent as possible. In many cases, the exposure conditions employed in the laboratory tests were altogether too extreme, resulting in damage to the materi-als of a type that would not be observed under normal conditions of use. The suit-ability of these laboratory tests varied from one type of materials to another.

A feature of the development of present-day accelerated method of ageing is that the work has become more mechanism-related. When developing a new method, it is important to be sure the same type of ageing mechanisms are at work in the mate-rials during the accelerated testing as during normal service conditions. A quantita-tive approach, and a general methodology that allows for all the factors associated with the work are necessary in order to be able to forecast the expected service life of component and the limitations in the service life set by the durability of its materi-als.

Within the IEA Solar Heating and Cooling Programme, Task 27 Performance of So-lar Facade Components started at the beginning of the year 2000 with the objectives of developing and applying appropriate methods for assessment of durability, reliability and environmental impact of advanced components for solar building facades.

For the work on durability in Task 27 there have been two main objectives. The first was to develop a general framework for durability test procedures and service life-time prediction (SLP) methods that are applicable to a wide variety of advanced opti-cal materials and components used in energy efficient solar thermal and buildings applications. The second is to apply the appropriate durability test tools to specific materials / components to allow prediction of service lifetime and to generate proposals for international standards.

This final report of project B1 "Durability assessment methodology development" of Task 27, presents the general methodology to meet the first objective.

4   General methodology

Many efforts have been made to develop systematic approaches to service life prediction of components, parts of components and materials so that all essential aspects of the problem will be taken into consideration [1-11].

In one such methodology, which will be focused on in this report, a predictive failure modes and effect analysis serves as the starting point for service life prediction from accelerated life test results as is illustrated diagrammatically in Figure 1. The analysis is made on the component level.

The diagram in Figure 1 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 X of the IEA Solar Heating and Cooling Program [10].

- 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

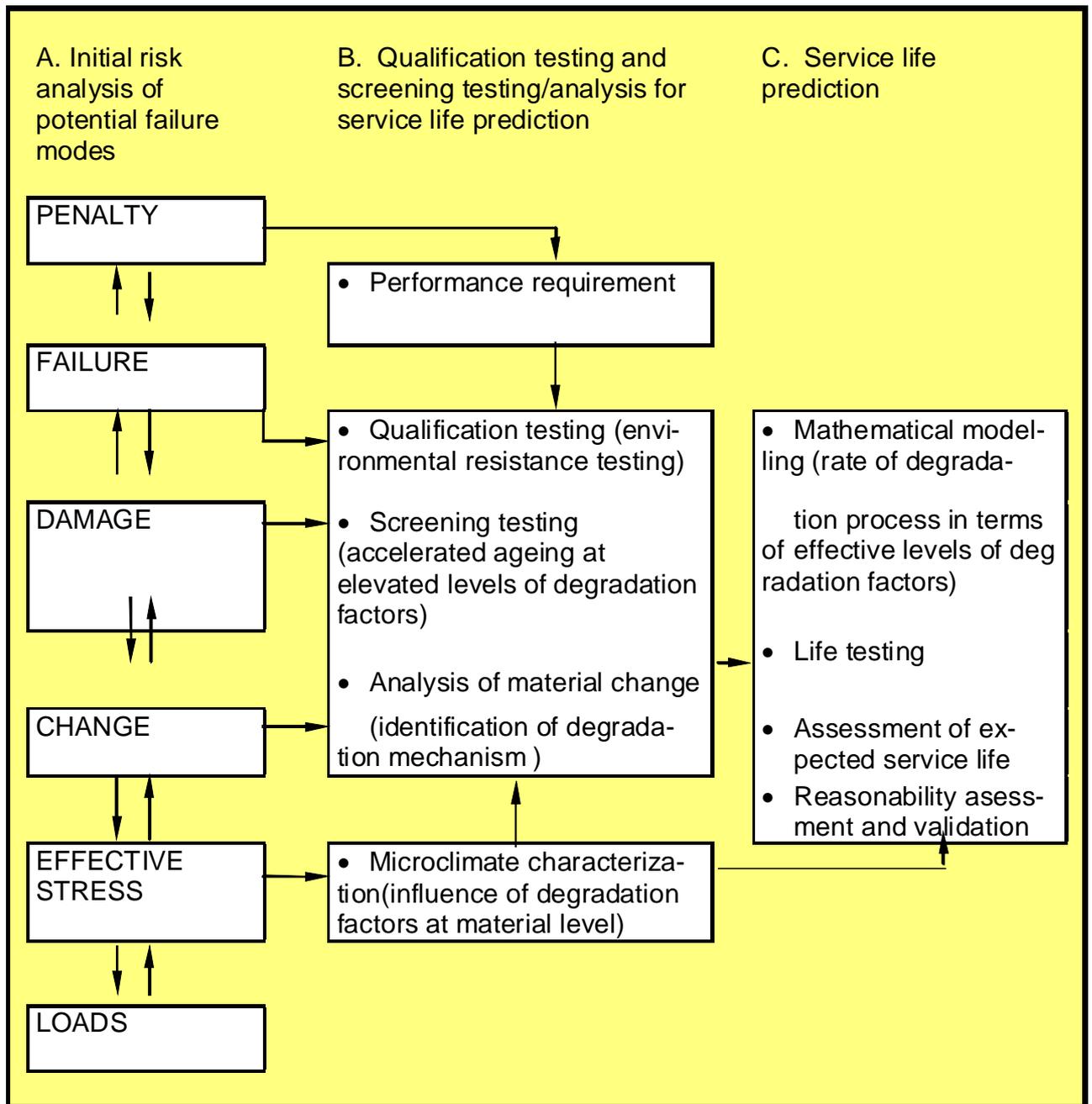Fig.1   Failure mode analysis for planning of accelerated tests for service life prediction

Each step in the scheme on the left hand side of Figure 1 may be related to the sub-sequent 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 Figure 1.

5   Initial risk analysis of potential failure modes

The first step in the scheme illustrated in Figure 1 is an analysis of potential failure modes 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 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:

- 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 in respect of 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
- Estimation of risks associated with different failure modes

The result of the initial risk analysis of potential failure modes may be documented as exemplified in Table 1.

5.1 Penalty/Failure

The first activity is specifying in general terms the function of the component and service life requirement from an end-user and product point of view, and from that identifying 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.

It may be important to understand the consequences of different failures - PENALTY - to define general requirements for performance and service life, as failure is defined to occur below that performance level at which satisfactory functioning can not be guaranteed. Thus, 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. For failure modes characterised by a gradual deterioration in performance, the consequences of failure may not be very significant shortly after the service life requirement is no longer met. For catastrophic types of failure modes, however, the intended functional capability of the component or some part of the component may be completely lost. 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.

An example on how these first steps in the initial risk analysis of potential failure modes may be documented is given in Table 2.

Table 1: Examples of how the results from an initial risk analysis of potential failure modes may be documented

A. 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

B. Specification of functional properties and requirements on component and its materials

Critical functional properties	Test method for determining functional properties	Requirement for functional capability and long-term performance

C. 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

5.2 Failure/Damage/Change/Degradation indicators

Potential failure modes and important degradation processes should be identified after failures have been defined in terms of minimum performance levels.

When identifying potential failure modes, it is important to distinguish between

- failures initiated by the short-term influence of environmental stress, the latter rep-resenting events of high environmental loads on the component and its materials,
- failures initiated by the long-term influence of environmental stress, the latter causing material degradation so that the performance and sometimes also the environ-mental resistance of the component and its materials gradually decrease.

In the first case catastrophic failures occur, whereas in the second case, both grad-ual and catastrophic types of failures may occur.

In general, there exist many kinds 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.

Fault tree analysis is a tool, which provides a logical structure relating failure to various damage modes and underlying chemical or physical changes. The use of fault tree analysis to describe the potential degradation pattern of an organic coating system for metals is illustrated in Figure 2.

The objective of analysis is to identify potential failure/damage modes, degradation mechanisms or mechanisms which may lead to material degradation and the development of dam-age, and associated critical factors of environmental stress or degradation factors.

Table 2: 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 [10]

Component/materials: Selective solar absorber coating of anodised aluminium pigmented with small metallic nickel particles

Application: Use in single-glazed flat-plate solar collector for Domestic Hot Water system

Porous Al2O3
Ni particles
Homogeneous Al2O3
Metallic Al

Flat-plate solar collector

Solar absorber surface

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

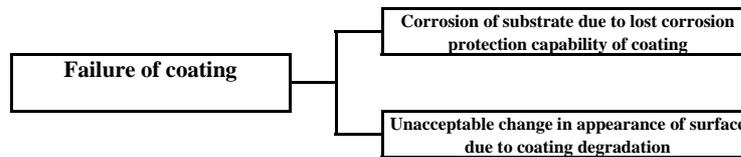| Function and general requirements	General requirements for long-term performance during design service time	In-use conditions and severity of environmental stress
-Efficiently convert solar radiation into thermal energy -Suppress heat losses in the form of thermal radiation	-Loss in optical performance 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	- 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. Specification of functional properties and requirements on component and its materials

Critical functional properties	Test method for deter-mining functional property	Requirement for functional capability and long-term performance
-Solar absorptance (α) -Thermal emittance (ε) -Adhesion (ad)	ISO CD 12592.2 ISO CD 12592.2 ISO 4624	Functional capability $\alpha > 0.92$ $\varepsilon < 0.15$ ad >0.5 MPa Long-term performance - $\Delta\alpha + 0.25\ \Delta\varepsilon \leq 0.05$

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                                          ┌─────────────────────────────────────┐
                                          │ Corrosion of substrate due to lost   │
                                     ┌────│ corrosion protection capability of   │
                                     │    │ coating                              │
┌──────────────────────┐            │    └─────────────────────────────────────┘
│   Failure of coating  │───────────┤
└──────────────────────┘            │    ┌─────────────────────────────────────┐
                                     │    │ Unacceptable change in appearance of │
                                     └────│ surface due to coating degradation   │
                                          └─────────────────────────────────────┘
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Degradation indicator

Uniform corrosion of coated substrate	Degree of rusting
Blistering	Degree of blistering
Adhesion loss/ undercorrosion at defect or damage of coating	Creep of corrosion defects from mechanical damage
Partial or total adhesion loss	Adhesion/Degree of flaking
Cracking	Degree of cracking
Colour Change	Colour change in CIE system (ΔE)
Gloss change	Specular reflectance change
Degradation caused by chemicals	Various
Soiling	Colour change in CIE system (ΔL)

Failure/Damage modes

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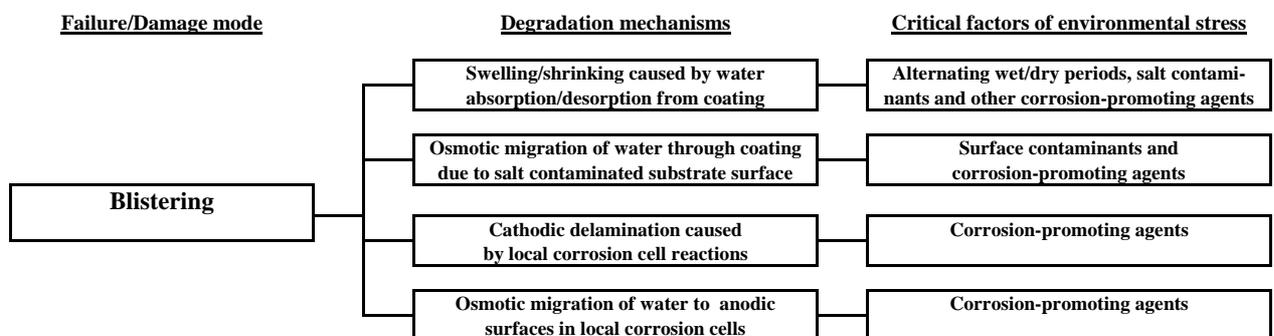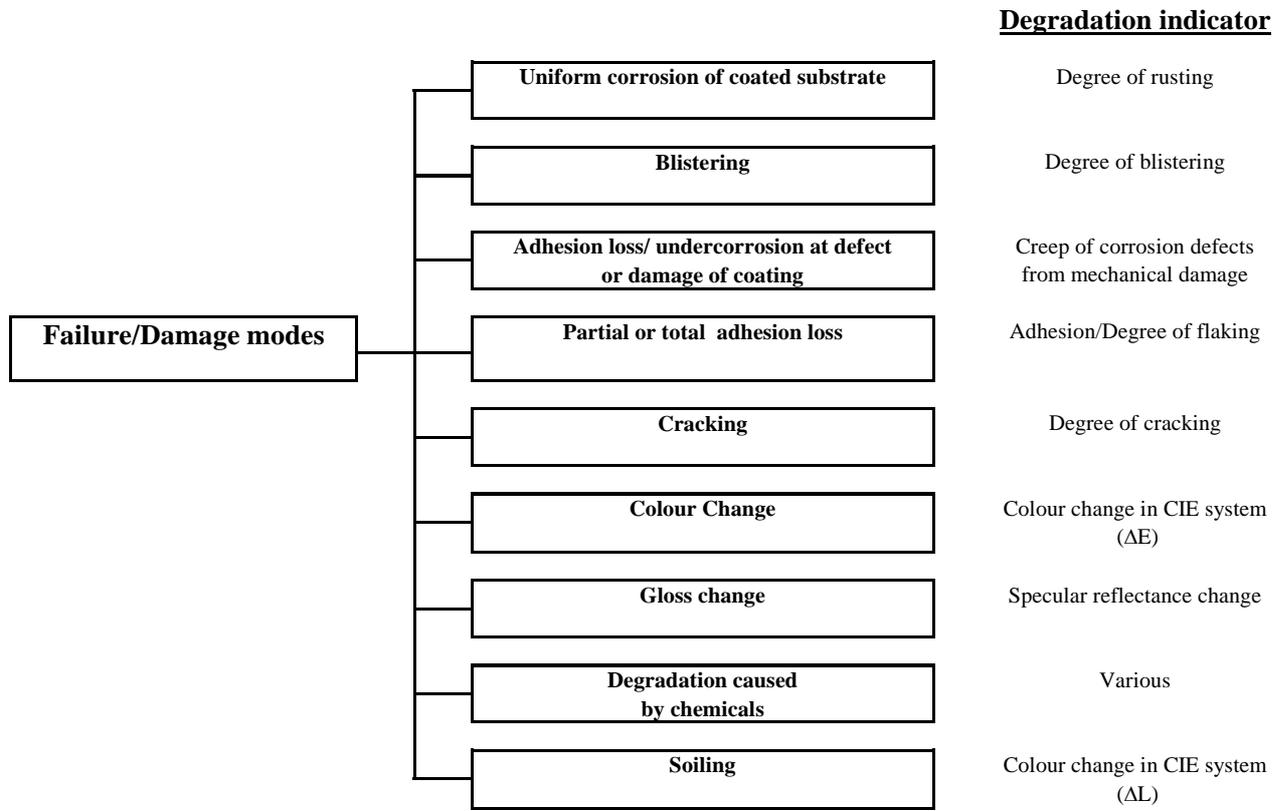| **Failure/Damage mode**	**Degradation mechanisms**	**Critical factors of environmental stress**
Blistering	**Swelling/shrinking caused by water absorption/desorption from coating**	**Alternating wet/dry periods, salt contaminants and other corrosion-promoting agents**
	Osmotic migration of water through coating due to salt contaminated substrate surface	**Surface contaminants and corrosion-promoting agents**
	Cathodic delamination caused by local corrosion cell reactions	**Corrosion-promoting agents**
	Osmotic migration of water to anodic surfaces in local corrosion cells	**Corrosion-promoting agents**

Fig. 2 Examples of the use of fault tree analysis to represent potential failure/ damage/ change relationships to identify suitable degradation indicators and critical factors of environmental stress/degradation factors for organic coatings on metals [13]

For the purpose of service life prediction, it is important also to select suitable degradation indicators for the different potential failure modes so that failure may be assessed properly and if possible, the degradation process behind this failure may also be followed, see example in Figure 2.

5.3 Load/Effective stress/ Degradation factors

To identify potential failure modes the kind of environmental stress factors and their severity under service conditions must be known.

For the purpose of service life prediction, in-use conditions representing a worst case may be selected. Alternatively, in-use condi-tions may be determined by measuring environmental stress under varying service conditions and selecting data from the most rep-resentative case as a basis for service life prediction.

In the initial phase of service life prediction, however, the most important issue is to identify first the most critical in-use conditions and environmental stress factors which may contribute to material degradation and cause failure to occur. Based on this knowledge potential degradation mechanisms and failure/damage modes are identified; see Table 1

Literature research is recommended after potential failure modes, degradation processes and critical factors of environmental stress have been initially identified. The objective of this research is to look for reports on durability and available service life data on similar components and materials in the same kind of application as the present or on the specific component and materials of the component in other applications and in-use environments as the present, see Table 3

Table 3: Available service life data of relevance to the actual case.

Component / Materials	Available service life data	Remark

5.4 Risk analysis according to FMEA

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 [13, 14] 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.

The risk number associated with a particular failure mode is estimated by use of the following factors:

Severity (S)   Probability of occurrence (P_O)   Probability of discovery (P_D)

The risk number RPN is the product of all these factors, namely

$$RPN = S \cdot P_O \cdot P_D$$

The first factor, Severity, is a measure on the consequences of a particular failure from safety and economic viewpoints, when treating the component and its materials as part of a product or system. For rating Severity a scale with ten degrees may be used, see Figure 3.

The second factor, Probability of occurrence, is a measure of how probable it is that failure according to the particular mode will occur during the design service life of the component and its materials. For rating also a ten-degree scale may be used, see Figure 3. The third factor, Probability of detection, takes into account how probable it is to detect a damage/failure mechanism and thereby prevent failure to happen. The ten-degree scale may also be used here, see Figure 3.

The risk assessment may be documented as shown in Table 4. In the risk assessment of potential failure modes, the relevance of durability and life data found in the literature for the component and its materials must be taken into account. The risk assessment should most advantageously be performed by a group of experts.

How reasonable it is to set the design service life of the component or parts of the component at the same level as that of the product may also be questioned during the risk assessment. During maintenance or repair work, the component or parts of the component may be replaced, which may considerably lower the requirement on the service life of the component or some of its replaceable parts.

It should be pointed out that the risk assessment made at this initial stage of service life prediction is only but qualitative in nature. The main purpose is to limit the scope of the service life evaluation to be able to focus on the most important failure modes. The rating numbers may be used mainly as an aid to reduce the number of critical failure modes in the subsequent evaluation of the service life of the component.

Table 4: Risk assessment of potential failure modes

Failure mode / Degradation process	Severity (rating number)	Probability of occurrence (rating number)	Probability of discovery (rating number)	Rating-number for risk

An example on the result of an initial risk analysis based on information from the IEA Task 10 absorber surface case study referred to in Table 2, is shown in Table 5

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 occurance	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

Failure/Damage modes of coating	S	P_o	P_d	RPN
Uniform corrosion of coated substrate	6	6	2	72
Blistering	4	7	5	140
Adhesion loss/ undercorrosion at defect or damage of coating	4	9	3	63
Partial or total adhesion loss	7	6	2	84
Cracking	4	6	5	120
Colour Change	7	7	7	343
Gloss change	7	8	8	448
Degradation caused by chemicals	8	4	3	96

Fig. 3 Rating scales for FMEA analysis in respect of severity, probability for detection, and probability for occurrence in the assessment of the risk number for a particular failure/damage mode. In the lower table, an example is given on how the rating of different failure modes may be assessed for organic coatings on metals, see also Figure 2

C. Potential failure modes, critical factors of environmental stress and degradation, risk assessment by FMEA

Table 1: Example on the result of an initial risk analysis with information from the IEA Task 10 case study on selective solar absorber surfaces (see Table 2 and Figure 3)

Failure/Damage mode / Degradation process	Degradation indicator	Critical factors of environmental stress/ Degradation factors and severity	Estimated risk of failure/damage mode from FMEA (see Figure 3)			
			S	P_O	P_D	Risk RPN
Unacceptable loss in optical performance	PC = $-\Delta\alpha + 0.25 \Delta\varepsilon$; Adhesion					
(A) High temperature oxidation of metallic nickel	Reflection spectrum Vis-IR	High temperature	7	2	8	112
(B) Electrochemical corrosion of metallic nickel	Reflection spectrum Vis-IR	High humidity, sulphur dioxide (atmospheric corrosivity)	7	5	5^1	175
(C) Hydatization of aluminium oxide	Reflection spectrum IR	Condensed water, temperature	7	7	4^1	196
[1] Result of glazing failure						

6   Qualification testing and screening testing/analyses for service life prediction

The combined stress and failure/damage mode analysis forms the basis also for identifying suitable durability tests, see example given in Figure 4. Sometimes relevant durability tests for the application considered can be found and used directly for qualification testing as described in 3.1. Most often, however, durability tests for accelerated life testing have to be tailor-made, as will be described in more detail later in this report.

6.1   Qualification testing

In case of durability assessment of a product, component or material, it is important to distinguish between :

a)   resistance against the short-term influence of environmental stress representing events of high environmental loads,

b)   resistance against the long-term influence of environmental stress, which may cause material degradation with the result that the performance and sometimes also the environmental resistance of the product, component and materials gradually decreases

In the first case catastrophic failures occur, whereas in the second case both gradual and catastrophic type of failures may occur.

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Durability test methods   **Failure/Damage modes (RPN)**

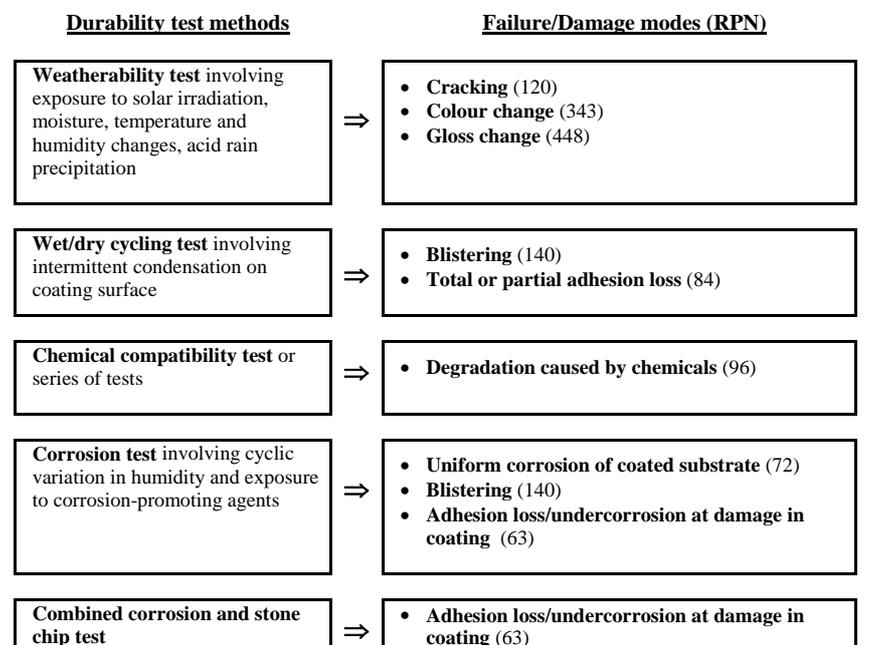|	
Weatherability test involving exposure to solar irradiation, moisture, temperature and humidity changes, acid rain precipitation	⇒ • **Cracking** (120) • **Colour change** (343) • **Gloss change** (448)
Wet/dry cycling test involving intermittent condensation on coating surface	⇒ • **Blistering** (140) • **Total or partial adhesion loss** (84)
Chemical compatibility test or series of tests	⇒ • **Degradation caused by chemicals** (96)
Corrosion test involving cyclic variation in humidity and exposure to corrosion-promoting agents	⇒ • **Uniform corrosion of coated substrate** (72) • **Blistering** (140) • **Adhesion loss/undercorrosion at damage in coating** (63)
Combined corrosion and stone chip test	⇒ • **Adhesion loss/undercorrosion at damage in coating** (63)

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Fig. 4 Identification and ranking of suitable durability tests for organic coatings on metals based on risk assessment of potential failure/damage modes from Figure 3 (Risk- numbers estimated for different failure/damage modes from Figure 3 are given in brackets)

6.1.1 Short-term environmental influence characterised by high environmental loads

For qualification durability testing in respect of case a), where gradual material degradation due to ageing does not affect the results of the test, the general practice used in environmental resistance testing of products is recommended, see e.g. SEES Environmental Engineering Handbook [16]

6.1.1.1 Environmental factors, characterization and specification of severities of stress

The standard IEC 600721 published by the International Electrochemical Commission for classification of environmental conditions is used as the starting point. The basic idea behind this environmental classification is that it is necessary to have a general reference frame when specifying the environmental loads on products. It is therefore common that IEC 600721 is used for classification. IEC has also published a standard on basic environmental testing procedures, IEC 60068-2, which merely treats test methods.
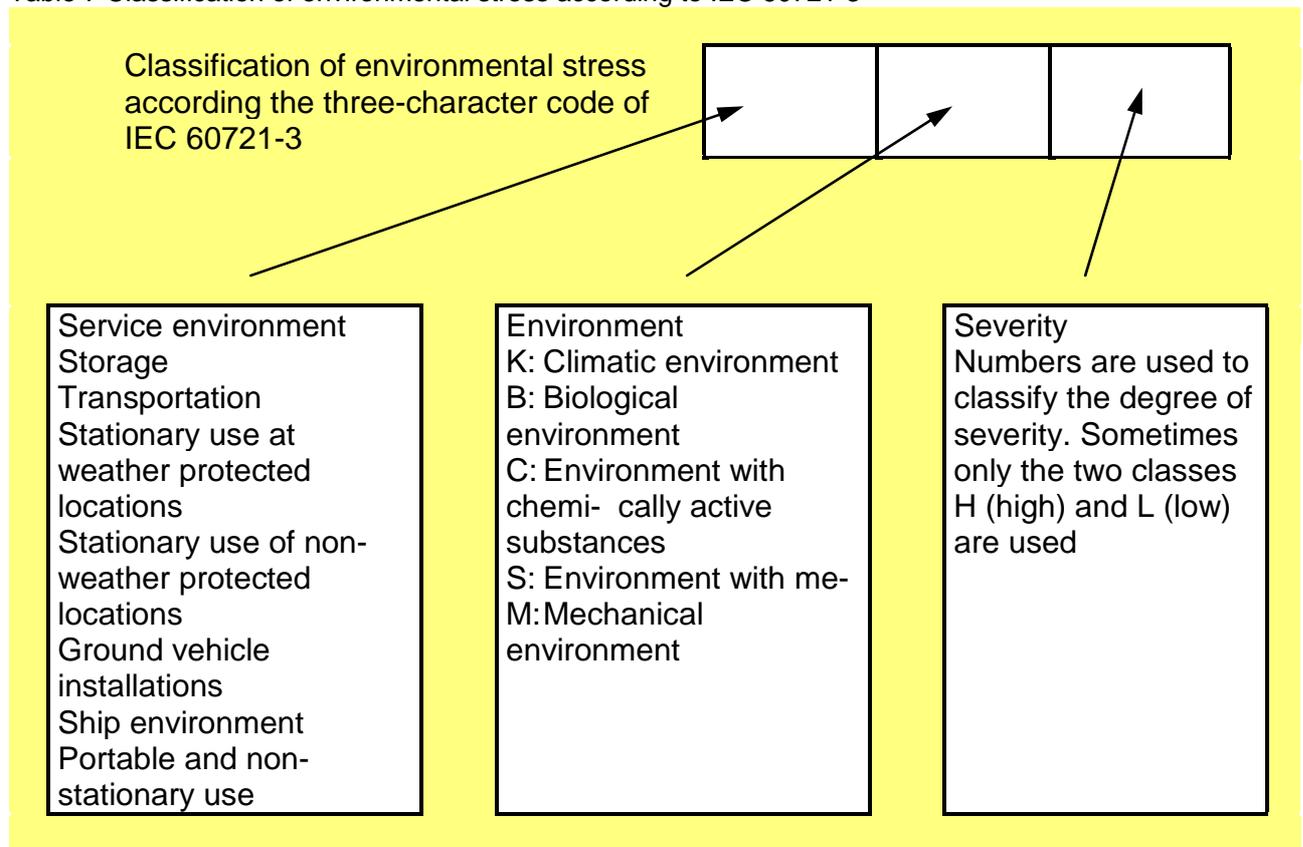
IEC 600721 is intended for assessing the requirements on environmental resistance of products and for the establishment of the environmental life cycle profile for a product. However, in most cases, it is necessary to perform a careful tailoring process for correctly specifying the severity of environmental stress. As guidance, it can be mentioned that the American MIL-STD 810 describes both a methodology for the tailoring process and the test methods.

Table 6: Classification of environmental conditions according to IEC 600721

IEC 600721-1 Classification of environmental parameters and their severity
Introduction to the standard

IEC 600721-2 Environmental conditions appearing in nature
Temperature and humidity, precipitation and wind, air pressure, solar radiation and temperature, dust, sand, salt mist/wind, earthquake vibrations and shocks, fauna and flora

IEC 600721-3 Classification of groups of environmental parameters and their severities
Storage, transportation, stationary use at weather protected locations, stationary use of non-weather protected locations, ground vehicle installations, ship environment, portable and non-stationary use

In IEC 600721, the severity for the single environmental factors are maximum values, to which the product may be exposed to. The severity generally represents conditions, which will be exceeded with 1 % probability. The classification does not give any information on duration or statistical distribution of the stress factor. To select the severity for an accelerated test from the given values in the standard is often not possible. The standard therefore can be used as an aid mainly in determining product resistance against the short-term environmental influence of extreme events and not in cases where degradation of materials gradually occurs, successively reducing the environmental resistance of a product.

Table 7 Classification of environmental stress according to IEC 60721-3

Classification of environmental stress according the three-character code of IEC 60721-3

Service environment Storage Transportation Stationary use at weather protected locations Stationary use of non-weather protected locations Ground vehicle installations Ship environment Portable and non-stationary use	Environment K: Climatic environment B: Biological environment C: Environment with chemi- cally active substances S: Environment with me- M: Mechanical environment	Severity Numbers are used to classify the degree of severity. Sometimes only the two classes H (high) and L (low) are used

6.1.1.2 Environmental resistance tests and reliability acceptance testing

With the aid of the severity determined by use of IEC 60721 or by use of measured severity of stress for factors contributing to degradation, the environmental resistance of a product may be verified by use of a number of available standard environmental resistance tests as are exemplified in Table 8. Most tests given in the table are from the standard IEC 60068-2 or from MIL-STD 810. Some of the tests given, however, can not directly be applied for testing on the component or material scale, but the table illustrates the great variety of tests that are sometimes needed for the assessment of the environmental resistance of a product. It should be mentioned that the IEC technical committee TC 104 "Environmental conditions, classification and methods of test" is presently working on methods on how to transform the condition classes of IEC 60721-3 into test conditions for suitable methods of IEC 60068-2.

It should also be mentioned that some of the tests in Table 8 are for assessment of environmental resistance also in case of long-term influence of environmental stress, which may lead to gradual material degradation and subsequent failure. This is dealt with in section 3.1.2.

Table 8: Some standard tests for assessing environmental resistance of products against environmental stress factors

Environmental factor (mechanical)	Specification	Examples of standard test methods[1]	Examples of possible damage
Mechanical sine vibration	Direction for verification, mounting of test object, frequency, amplitude and duration should be specified.	a) IEC 60068-2-6, Test Fc, Vibration (sinusoidal) b) MIL-STD-810E, Method 514.4 "Vibration"	Fracture Permanent deformation Fatigue Wear
Mechanical random vibration	Acceleration density as a function of frequency, vibration level where function is required, duration of test.	a) MIL STD-810 E, Method 514.4 "Vibration" b) ISO 2041, Vibration and shock	Crack initiation, crack growth Material loss (wear) Plastic flow Creep
Mechanical random sounds	Sound level, frequency contents and duration of test. Type of sound field, measuring and analysis methods should also be specified.	a) MIL STD 810 E Method 515.4 "Acoustic noise". b) IEC 68 Test Fg, Vibration acoustically induced	Injuries and discomfort to people from high air pressure levels Vibration damages in mechanical structures caused by sound waves
Mechanical shock waves	Maximum pressure of the shock pulse, its duration and number of pulses	a) IEC 60068-2-27"Test Ea, Shock" b) MIL STD 810 E, Method 516.4 "Shock"	Mechanical damages caused by the pressure of the shock wave on the surface of product Vibration damages in mechanical structures caused by the shock wave
Earthquake	Acceleration level, frequency contents, duration, number of earth quakes the product must withstand	a) IEEE STD 344, Recommended practice for seismic qualification of nuclear power generating system b) IEEE STD 501, Seismic testing of relays c) IEEE STD 693, Recommended practice for seismic design of substations	Mechanical (effect of high amplitude of single load, fatigue due to repeated load cycles)
Shock in vehicles	Response spectrum of shock. When the test shall be carried out with some standard pulse its peak acceleration and duration are stated	a) IEC 60068-2-27, Test E a, Shock b) MIL STD 810 E, Method 516.4	Fatigue or wear Instantaneous fracture Plastic deformation

[1]IEC International Electrotechnical Commission, http://www.iec.ch; MIL STD Department of Defense Standards, Philadelphia, PA 19111-5094, United States; IEEE Institute of Electrical and Electronics Engineers Inc., http://standards.ieee.org; ISO International Standardization Organization, http://www.iso.ch;

Table 8(cont.) Some standard tests for assessing environmental resistance of products against environmental stress factors

Environmental factor (mechanical)	Specification	Examples of standard test methods[1]	Examples of possible damage
Linear acceleration	Acceleration values in different directions must be stated as well as duration.	a) IEC 60068-2-7 Test Ga, Acceleration, Steady state b) MIL-STD-8100 Method 515.3	Fracture Plastic deformation (plastic flow)
Angular acceleration	Acceleration magnitude and duration, its direction relative to the test object.	a) IEC 60068-2-7,Test G a, Acceleration, Steady state b) MIL-STD-810 D, Method 515.3 "Acceleration"	Fracture Plastic deformation (plastic flow)
Free fall	Fall height, orientation of test object, if the object shall be packaged or not during the test	a) IEC 60068-2-32, Test Ed, Free fall b) MIL-STD 331 A, Tests 103.1,111.1, and 117 c) DEF STAN07-55, Test A9 "Free fall"	Mechanical (fracture, permanent deformation)
Drop and topple connected to bench	See free fall	a) IEC 60068-2-31 Test Ec, Drop and topple, primarily for equipment-type specimen b) MIL-STD-810 E, Method 516.4 Shock: Procedure IV "Transient drop", Proce- dure VI "Bench handling"	Mechanical (fracture, permanent deformation)
Shake	Mounting of the test object in the shaker, mode of operation of test object during test	a) MIL-STD 810 E Method 516.4 "Shock" b) IEC 60068-2-29,Test E b; Bump	Fracture Permanent deformation Fatigue
Bounce	Mounting of the test object during test, if the object shall be packaged or not during the test, movement of the platform of the bounce machine.	a) MIL-STD 810 E, Method 514.4 "Vibration; Category 3 Loose cargo transport" b) IEC 60068-2-55,Test E e: Bounce	Fracture Permanent deformation Fatigue
Tumbling	Number of falls, see free fall	a) IEC 60068-2-32 "Test E d, Free fall" b) MIL-STD-331 Test 102 "Tumble"	Mechanical (fracture, permanent deformation)

[1]IEC International Electrotechnical Commission, http://www.iec.ch;
MIL STD Department of Defense Standards, Philadelphia, PA 19111-5094, United States;

Table 8 (cont.) Some standard tests for assessing environmental resistance of products against environmental factors

Environmental factor (climatic)	Specification	Examples of standard test methods[1]	Examples of possible damage
Precipitation	*Rain:* Rain intensity, drop size, duration, angle of impact *Snow:* The load which a snow cover may constitute for an object *Hail:* Specified only exceptionally *Dew and frost:* See "Moisture" and "Ice formation" (Composition of water should also be specified eg. salts, pH)	a) MIL-STD-810 E, Method 506.3 "Rain" b) IEC 60068-2-18, Test R "Water"	Mechanical (permanent deformation) Erosion Chemical (see "Moisture") Misfunction of electric components
Moisture	Humidity and temperature levels, duration, alternatively number of cycles for cyclic tests	a) MIL-STD-810 E, Method 507.3 b) IEC 60068-2-3, Test C a: Damp heat, Steady state c) IEC 60068-2-30 Test D b: Damp heat, cyclic	Metals: Corrosion Polymeric materials: Fatigue caused by swelling and shrinking due to water absorption / desorption, chemical degradation caused by hydrolysis, chemical degradation due to extraction of stabilizers from material surface Misfunction in electric function
Water	*Dripping water:* Fall height, duration *Spraying:* Water flow, pressure, nozzle diameter, duration *Immersion in water:* Water depth, duration	a) IEC 60068-2-18, "Test R, Water" b) MIL-STD 810 E, Method 506.3 "Rain"	Most damage mechanisms mentioned under "Moisture" and "Precipitation" apply also to "Water"

Ice formation	Degree of icing (thickness of ice coating), procedure how to accomplish icing, e.g. rain/cooling, water spray/cooling, duration	Build up of ice layers
		a) MIL-STD 810 E, Method 521 "Icing
		   /Freezing rain"
		b) ISO 2653, Ice formation, Test C
		   Frost appearance
		c) IEC 60068-2-39,Z/AMD, Combined
		   sequential cold, low air pressure and
		   damp heat test
			Mechanical due to volume expansion during freezing
			Mechanical due to increased load from ice coating

[1]IEC International Electrotechnical Commission, http://www.iec.ch; MIL STD
Department of Defense Standards, Philadelphia, PA 19111-5094, United States; ISO
International Standardization Organization, http://www.iso.ch;

Table 8 (cont.) Some standard tests for assessing environmental resistance of products against environmental factors

Environmental factor (climatic)	Specification	Examples of standard test methods[1]	Examples of possible damage
Temperature	Temperature histogram or effective mean temperature and duration, maximum and minimum temperatures	a) IEC 60068-2, Part 2, Test B "Heat" b) MIL-STD 810 E, Method 501.3 "High temperature"	Mechanical due to thermal expansion and thermomechanical stresses Physical due to phase change reactions or irreversible changes in material properties with temperature (physical ageing) Chemical (all chemical reactions are influenced by temperature)
Temperature change	Levels of temperatures and time characteristics of temperature cycle, number of cycles in test	a) IEC 60068-2-14, Test N, Change of temperature b) MIL-STD 810 E, Method 503.3, "Temperature shock"	Fracture/cracking due to thermo-mechanical stress
Solar irradiation	Spectrum of light source and intensity of light at the surface of the test object, surface temperature, time-characteristics of test cycle and test duration.	a) IEC 60068-2-5,Sa, Simulated solar radiation at ground level b) IEC 60068-2-9 "Guidance for solar radiation testing" c) MIL-STD 810 E, Method 505.3 "Solar radiation"	Chemical and physical changes due to an increased surface temperature, see "Temperature" Photochemical degradation caused mainly by UV-radiation, which may result in deterioration of mechanical properties, optical properties (e.g. colour, gloss) of materials.
UV-irradiation and outdoor climate	Spectrum of light source and intensity levels in test cycle, black standard temperature, humidity levels, frequency of water spraying (composition), duration of test in light dose.	a) ISO 4892, Plastics - Methods of sure to laboratory light sources b) SAE J 1960, Accelerated exposure of automotive exterior materials using controlled irradiance water cooled xenon-arc lamp c) SP-method 2710, Accelerated weather-ing test with simulation of acid rain	As above but also damages caused by the combined action of UV radiation, temperature, moisture, and in SP-method 2710 also of acid rain

[1]IEC International Electrotechnical Commission, http://www.iec.ch; MIL STD Department of Defense Standards, Philadelphia, PA 19111-5094, United States; ISO International Standardization Organization, http://www.iso.ch; SAE Society of Automotive Engineers Standards, http://www.sae.org; SP Swedish National Testing and Research Institute, http://www.sp.se

Table 8 (cont.) Some standard tests for assessing environmental resistance of products against environmental factors

Environmental factor (climatic)	Specification	Examples of standard test methods[1]	Examples of possible damage
Low atmospheric pressure	Lowest pressure, limits for pressure change and pressure cycling, time-characteristics of pressure cycle, duration of test	a) IEC 60068-2-13, Test M "Low air pressure" b) MIL-STD 810 E, Method 500.3 "Low pressure"	Mechanical due to pressure gradients Misfunction in electric components like contacts, resistors and transformers Wear due to evaporation of lubricants
Sand and dust	Reference to standard method and suitable severity of the test in terms of test dust(hardness, size distribution, concentration), particle velocity, temperature and humidity	a) IEC 50B (Sur.) 286 (Test L) "Dust and sand" b) MIL-STD 810 E, Method 540.3 "Dust and sand"	Wear Misfunction in electric components due to sand penetration
Wind	Maximum wind speed, limits for wind cycling	a) US Army Material Command AMPC 706-116, Engineering Design Hand- book, Environmental Series, Part Five, Natural Environmental Factors, 1975	Mechanical damages due to high mechanical load

[1]IEC International Electrotechnical Commission, http://www.iec.ch; MIL STD
Department of Defense Standards, Philadelphia, PA 19111-5094, United States;

Environmental factor (chemical)	Specification	Examples of standard test methods[1]	Examples of possible damage
Salt mist and saline atmosphere	Reference to standard method, duration of test or alternatively required corrosivity dose in terms of metallic mass loss of reference metals to be used in the standard test (Test a)-c) is mainly for quality control)	a) ISO 9227, Salt spray tests b) IEC 60068-2-11, Test Ka, Salt mist c) IEC 60068-2-52, Test Kb, Salt mist cyclic d) ISO 11474, Accelerated outdoor test by intermittent spraying of a salt solution e) VDA 611-415 Prüfung des Korrosions-schutzes von Kraftfahrzeuglacklerun- f) ISO/DIS 16701 Accelerated corrosion test involving exposure under control- led conditions of humidity cycling and	Corrosion of metals and alloys Degradation of organic coatings which may give rise to various kinds of damages, see Figure 2:2 Misfunction in electric components
Sulphuric atmosphere samt andra gasformiga luftfröroreningar	Reference to standard method, duration of test	a) IEC 60068-2-42, Test c, Sulphur dioxide test for contacts and connections" b) IEC 60068-2-43, Test d, Hydrogen sulphide test for contacts and connec-tions"	Se below
Mixtures of pollutants in	Reference to standard method, duration of test or alternatively required corrosivity dose in terms of metallic mass loss of reference metals to be used in the standard test	a) IEC 60068-2-60, Part 2, Test Ke, Flowing mixed gas test b) SP-method 2499 Accelerated corrosion testing involving alternate exposure for corrosion promoting gases, neutral salt c) ISO 10062, Corrosion tests in artificial atmosphere at very low concentrations of polluting gas(es)	Corrosion of metallic materials including metals protected by organic and inorganic coatings Acidic hydrolysis of polymeric materials

[1]IEC International Electrotechnical Commission, http://www.iec.ch; MIL STD
Department of Defense Standards, Philadelphia, PA 19111-5094, United States; ISO
International Standardization Organization, http:// www.iso.ch; VDA Verband der
Automobilindustrie E.V., http://www.vda.de ; SP Swedish National Testing and
Research Institute, http://www.sp.se

Table 8 (cont.) Some standard tests for assessing environmental resistance of products against environmental factors

Environmental factor (chemical)	Specification	Examples of standard test methods[1]	Examples of possible damage
Contaminating liquids	All possible contaminating liquids the product will come in contact with during its life cycle should be specified and severity limits given	a) ISO 175 Plastics - Methods of test for the determination of the effects of immersion in liquid chemicals) b) ISO 1871 Rubber, vulcanised - Deter-mination of the effect of liquids	Chemical (possible degradation mechanisms are dictated by the specific contaminating liquid)
Explosive atmosphere	Requirements for intrinsic safety stated in standards	a) IEC Publication 79, Electric apparatus for explosive gas atmospheres	
Fire	Prediction of the resistance to fire is dictated by its use and controlled by a number of regulations both regarding design and use	a) IEC Publication 695, Fire hazard testing	Damage from a fire may originate from the high temperature, water for extinguishing the fire and corrosive gases (hydrogen chloride, sulphur dioxide) produced by the fire

[1]IEC International Electrotechnical Commission, http://www.iec.ch; ISO International Standardization Organization, http://www.iso.ch;

Environmental factor (biological)	Specification	Examples of standard test methods[1]	Examples of possible damage
Micro-biological organisms	Kind of micro-biological organisms that are of relevance for the product durability are listed, eg bacteria one-cell fungi one-cell algae protozoa	a) IEC 60068-2-10, Test J, "Mould	Microbiological corrosion of metallic materials Discolouring of organic coatings due to algae and fungi growth Rot attack of wood due to mould fungus
Macro-biological organisms	Kind of macro-biological organisms that are of relevance for the product durability are listed, as e.g. rodents, birds, insects, dogs	a) US Army Material Commend, AMCP 706-116, Engineering design handbook	Attack on wood of e.g. termites, booring beetles, ants Gnawn-of material losses, e.g. insulation, caused by rats and mice Corrosion induced by dog urine or bird excrements

[1]IEC International Electrotechnical Commission, http://www.iec.ch; ISO International Standardization Organization, http://www.iso.ch;

6.1.2 Long-term environmental influence leading to gradual material degradation

For qualification durability testing in respect of case b), where gradual material degradation due to ageing is important, the general procedure as outlined in Table 9 may be followed.

Table 9 General procedure for qualification or acceptance testing based on accelerated testing

Qualification or acceptance lifetime testing
1) Identify critical failure mode and degradation process to be assessed by way of accelerated testing.
2) Select appropriate accelerated test to study the importance of that failure mode.
3) Select suitable functional property to be used as degradation indicator and from the performance requirement, evaluate the lowest tolerable level of this to define failure
4) Choose most appropriate set of test conditions for the accelerated test.
5) From the service life requirement and information on the in-use conditions estimate acceptable failure time in the accelerated test.
6) Perform the test and determine actual failure time of test specimens. Analyse test specimens in respect of expected degradation caused by the assumed failure mode.
7) From the results obtained conclude whether the tested component or material shall be considered qualified or not in respect of its durability.

Appropriate accelerated tests to be used for qualification testing have to be tailor-made in this case to correspond to the particular environmental conditions, but at an enhanced level of stress. This requires firstly, that the test should be able to reproduce the same kind of degradation pattern as observed under real service conditions. Secondly, that the acceleration factor, i.e. the ratio between the time to reach a certain extent of degradation in service and the time to reach the same extent of degradation in the accelerated test, should be independent of the extent of degradation at which this comparison is made.

The main difficulty after an appropriate accelerated test has been identified, is to estimate the relationship between testing time and service time for a component or parts of the component in a particular application. The design service life of the component or parts of the component has to be converted into an acceptable failure time for the component or parts of it in the accelerated test.

Because of the difficulties mentioned, it is seldom that an accelerated test can be found, which can be directly used as a lifetime test for the purpose of qualification testing. Lifetime tests, for service life prediction therefore usually need to be developed.

6.2   Screening testing by accelerated ageing

Screening testing is the first step in accelerated life testing and is 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.

The main purpose is to identify which stress factors contribute to deterioration in performance of the studied component or part of component. From the result of the tests also the most suitable range for the different degradation factors for the purpose of life testing may be determined.

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 10.

Table 10 Programme for screening testing in the IEA case study on selective solar absorber surface previously reviewed, see Table 2 and 5

Possible degradation mechanism	Critical periods of high environmental stress	Suitable accelerated test methods and range of degradation factors
(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 $^{\circ}$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 $^{\circ}$C below surrounding air which is kept at 95 % RH) and temperature conditions ranging from10 - 90 $^{\circ}$C

Test methods that can be employed for screening testing are essentially the same as used for qualification testing, see Table 7. The general scheme for testing as presented in Table 8 may be followed. However, an acceptable failure time in test in this case may be just a rough estimate.

6.3   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 in respect of associated material changes. This is made in order to identify the predominant degradation mechanisms of the material. 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 change due to ageing may vary considerably. In Table 11 some techniques for surface analysis and their general characteristics are listed together with references for further information.

Table 11 Some suitable techniques for surface analysis that can be useful in the study of material change caused by ageing

Technique	Characteristics	References
Fourier Transform Infrared Spectroscopy (FT-IR)	Detailed chemical information	Griffiths, P.R., Chemical Infrared Fourier Transform Spectroscopy, John Wiley & Sons, New York, 1975
Ultraviolet-Visible-Near Infrared Spectroscopy (UV-VIS-NIR)	Chemical information	Hobart, H.W., et. al. Instrumental Methods of Analysis, 7th Ed., Wadsworth Publishing Company, Belmont, California, 1988.
Scanning Electron Microscopy (SEM)	High magnification images	Watt, I.M., The Principles and Practice of Electron Microscopy, Cambridge University Press, Cambridge, 1985
Energy Dispersive X-ray Spectroscopy (EDX) in SEM	Micrometer depth surface analysis, elemental information, elemental mapping	Loretto, M.H., Electron Beam Analysis of Materials, Chapman and Hall, London, 1984, See also Watt above
Auger (Photo) Electron Spectroscopy (AES)	Nanometer depth surface analysis, elemental information, high lateral resolution mapping, depth profiling, only conducting samples	Briggs, D. and Seah, M.P., Practical Surface Analysis by Auger and X-ray Spectroscopy, John Wiley & Sons, New York, 1983
X-ray Photo Electron Spectroscopy (XPS) or Electron Spectroscopy for Chemical Analysis (ESCA)	Nanometer depth surface analysis, elemental information with some chemical information due to chemical shifts	See above
Time of Flight - Secondary Ion Mass Spectrometry (TOF-SIMS) (Static SIMS)	Nanometer depth surface analysis, detailed chemical information, high lateral resolution mapping, depth profiling	Briggs, D., Brown, A. and Vickerman; J.C., Handbook of Static Secondary Ion Mass Spectrometry, 1989

In Table 11 an example from the IEA absorber surface case study is shown on how different techniques for analysing material changes resulting from ageing can be used to get information on what material degradation mechanisms that are contributing to deterioration in performance.

Table 12 Techniques that were used in the IEA Task 10 solar absorber case study for analysis of material change upon durability testing as described in Table 10 ; see also Table 2.

Degradation mechanism	Techniques for analysis of material changes	Results
(A) High temperature oxidation of metallic Ni particles	- UV-VIS-NIR reflectance spectroscopy - AES depth profiling - SEM-EDX - XRD	- Reduction of absorption in solar - 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 - Formation of sulphate -Increase in surface concentration of Ni accompanied with sulphur at the - 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 alu- - Change in surface structure - Considerable change in surface morphology

6.4   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.

Although the general standard IEC 60721, see section 3.1.1, contains recommendations for classifying the severity of stress for various climatic, mechanical, chemical, biological and electrical environments, it does not contain recommendations on how to measure the characteristic environmental stress factors. The reader has to go to the literature to identify suitable measurement techniques and sensors.

In Table 13 measurement techniques that were used in the IEA Task 10 absorber case study previously reviewed are given as an example on 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 degradations 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 13 Techniques that were used in the IEA Task 10 absorber case study for measurement of degradation factors in solar collectors operating under service conditions, see also Table 2 and 10

Degradation mechanism	Degradation factors/ Measurement variables	Sensors
(A) High temperature oxidation of metallic Ni particles	*Temperature:* Surface temperature of absorber plate	Pt sensors in holders screwed directly on the absorber plate. To accomplish a good thermal contact heat sink compound was used.
(B) Electrochemical corrosion of metallic Ni particles at high humidity levels and in the presence of sulphur dioxide	*Atmospheric corrosivity*: Measurement of corrosion mass loss rate of standard metal specimens Air pollutants: 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-fluoresence 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	*Humidity:* Measurement of air humidity in the air gap between the absorber plate and glazing cover of the collector *Time of condensation:* Measurement of specular reflectance of absorber surface *Surface humidity:* Measured relative air humidities 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

6.4.1 Time variations and the importance of amplitudes and frequencies of changes in stress levels

It is the degradation process that determines not only what degradation factors should be measured but also what form of data that is of interest. The changes with time of the environmental load may be important and determine what form of data you need in respect of time resolution during monitoring of environmental stress factors.

Sometimes, it may be just maximal or minimum values of a certain environmental stress factor that are necessary to assess. It is, however, seldom that the arithmetic mean value of a degradation factor is useful for evaluating environmental resistance, but more often the duration of some critical time period of kind of environmental stress. Corrosion occurs only when the humidity level and temperature are above critical threshold values. Accordingly, the time of wetness, which is defined as the time of the year when the relative humidity is above 80% and the temperature is above 0°C, has been introduced as a simple measure for characterizing the atmospheric corrosivity of different climates. In the case mentioned it is assumed that it is only the time period when materials are exposed for some critical climatic conditions of degradation factors, that is important for characterizing degradation and not the history of changes in some degradation factor. The dose that should be measured in such cases may, however, be hard to define properly when very complex degradation mechanisms are involved.

Reference materials or reference components may therefore in some cases be used, e.g. characterization of atmospheric corrosivity by use of standard metal specimens, see ISO 9226, and characterization of UV-irradiation and temperature during outdoor or artificial ageing conditions by use of polystyrene standard specimens as reference, see SAE J1885.

For some materials, with a fatigue type of degradation/failure mechanism, it is the number of changes or cycles of changes in the environmental conditions that are of importance for the service life. Concrete durability, e.g. may be defined in the number of freeze-thaw cycles a material may resist. To perform and interpret the results of mechanical vibration tests information on the dynamics of the mechanical loads under service conditions are needed; see Table 7.

For the purpose of service life prediction, it is the data on the local environmental stress for the materials of the component that are needed. Such data may sometimes be difficult to obtain and therefore environmental stress on the materials of a component has to be calculated from information on the overall environmental load.

6.4.2 Distribution functions of single degradation factors or combinations of degradation factors

If only the dose is important then the distribution or frequency function of a degradation factor is of interest. By use of frequency functions and knowledge how the rate of degradation depends on the degradation factors, the extent of degradation is possible to estimate as will be dealt with in section 4.1.2.
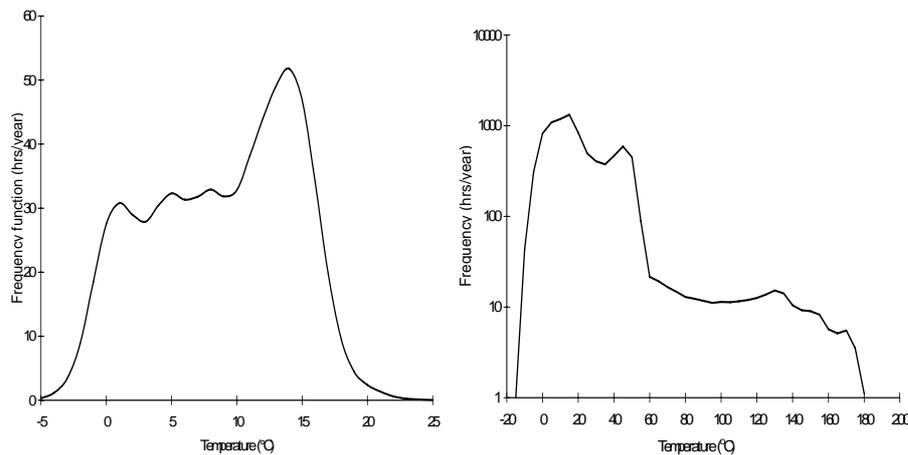

Fig. 5 Results from measurement of microclimate for the absorber in the IEA absorber surface case study, see Table 13.
Right diagram: Absorber temperature frequency function for one year. For one month of the year the collector is under stagnant conditions;
Left diagram: Absorber temperature frequency function when RH   99% of that year. Metallic mass loss due to corrosion of zinc was determined to 0.3 g/m2, year

Sometimes it is the distribution function of a single degradation factor that is used for the purpose of service life prediction. In other cases more than one degradation factor needs to be taken into account, which means that those degradation factors have to be measured simultaneously with an accurate time resolution.

In the IEA absorber case study, previously referred to, only the distribution in the absorber temperature during service conditions was needed for predicting the service life limited by high temperature degradation, see Figure 5, 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 Figure 5, right diagram.

Dose functions may also vary in such a way that a function of more than one degradation factor needs to be used for the purpose of service life prediction. In case of photochemical degradation of a polymeric material during outdoor use, it may not only be the dose of UV-radiation that needs to be taken into account. The combined action of UV irradiation and thermal load should be taken into account and therefore UV irradiation and surface temperature need to be measured simultaneously. The variable used to describe service environmental stress conditions might therefore be the product of UV irradiation level, I, and e.g. an Arrhenius type of expression, exp (Ea/RT), see (a) and (e) in Table 15.

As mentioned in the previous section reference test specimens may be used to describe environmental stress where complex degradation mechanisms are involved. In such cases, the dose function will correspond to the extent of degradation of the reference specimens of course. In the absorber case study use was made of metallic test specimens of zinc as an indicator or sensor for atmospheric corrosivity; see text of Figure 5.

7   Service life prediction from results of accelerated ageing

7.1   Mathematical modelling

To mathematically treat the results of accelerated tests to evaluate the service life of a component and its materials means:

Define the performance requirement for the component or materials in terms of a level for at east one measurable functional property or performance variable (degradation indicator).

Find a numerical expression, which relates the change in this degradation indicator to the environmental stress factors - degradation factors - contributing to the deterioration in the performance of the component and its materials.

Characterise the degradation factors under service conditions in order to be able to extrapolate the results of the accelerated tests to a service life for the component and its materials.

Two different kinds of approach to mathematical modelling of lifetime data can be found in the literature – the deterministic approach and the probabilistic or statistical approach. The difference between the two, however, seems to be merely a question of how to formulate the service life requirement for the pertinent component or its parts.

The service life requirement can be formulated in such a way that the variation in service life is not taken into account and therefore the mean service life should be of a certain value. A so called deterministic approach is the right level of mathematical modelling. But, the service life requirement can also be formulated in such a way that a certain population fraction should survive beyond a given age and in this case a probabilistic approach has to be used, taking into account the distribution in service life also.

Table 14 Deterministic and probabilistic approach in defining service life and service reliability

> Deterministic viewpoint
> Requirement on service life in terms of mean or median service life
>
> Probabilistic viewpoint:
> Requirement on minimum service reliability (e.g. 90%) after certain service time

However, in the prediction of service life from data obtained in accelerated life testing, not only does the mathematical treatment but the testing procedures between the deterministic and probabilistic approach also differ.

The deterministic mathematical models based on the time-transformation or acceleration factor approach will be focused on in this report. Such models consist mainly of numerical expressions, which relate the change in time the degradation indicator to the environmental degradation factors or stress factors contributing to the degradation of the materials in the component. The numerical expressions are set up to model the results from accelerated tests carried out at elevated levels of stress.

The problem here is to find an expression that takes into account the influence of all the environmental stress factors contributing to degradation under service conditions. Another problem is that the mechanism of degradation or the rate-determining step may be different at elevated stress levels compared to the situation under service conditions. In such cases, the numerical expressions set up to model accelerated life data may give erroneous results when used for extrapolation.

The probabilistic models that can be used for accelerated life testing are more complex. The problems of finding kinetic models that can be used to transfer accelerated life data to service life data are the same. However, as the variation in component properties and environmental stress are also taken into account, the results obtained will be more realistic and useful for material selection in component design to match the specific requirements of a certain application.

For a more detailed review on the use of deterministic and probabilistic mathematical models to describe accelerated life data, the reader is referred to references [19, 20]. Here the acceleration factor or time-transformation approach will be presented.

7.1.1 Accelerated testing and time transformation functions

To perform an accelerated test, D, means that the level of at least one stress factor 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 be expressed as [1]

$$A = \tau_s / \tau_{f,D} = g(\underline{S_D}) / g(\underline{S_s}) \qquad (1)$$

where the expression $g(\underline{S_D}) / g(\underline{S_s})$ is called the time transformation function or the acceleration factor function.

When more than one stress factor has to be taken into account, the function $g(\underline{S})$ can often be approximated to a product function of the following type:

$$g(\underline{S}) = h_1(S_1) \cdot h_2(S_2) \ldots \ldots \qquad (2)$$

Thus, from equation (2)

$$A = [h_1(S_{1,D}) / h_1(S_{1,s})] \cdot [h_2(S_{2,D}) / h_2(S_{2,s})] \cdot \ldots \qquad (3)$$

or

$$A = a_{S1} \cdot a_{S2} \cdot a_{S3} \ldots \ldots \qquad (4)$$

where $a_{S1} \cdot a_{S2} \cdot a_{S3}$ are the acceleration factors for stress S_1, S_2 and S_3, respectively.

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[1] The assumption for equation (1) to be valid is that the deterioration in performance (P) with time (t) in the interval $\underline{S_D}$ to $\underline{S_s}$ can be described by a product function of the following type: $\dfrac{dP}{dt} = k(\underline{X}) \cdot g(\underline{S})$

where $\underline{X}$ is a vector specifying a set of inherent property parameters of the material, which are of importance for the performance variable P, see reference [10]

In a series of ageing tests, varying the level of one stress factor and keeping the levels of the other stress factors constant can determine the parameters of the time transformation functions.

In the Table 15, some examples of acceleration factor equations are given for different stress factors.

To accelerate the degradation process by increasing the temperatures is by far the most frequently applied method in accelerated testing. Most often the results are analysed in terms of the Arrhenius equation, see eq. (a) in Table 15. Examples of materials that can be tested and evaluated this way are elastomers and plastic materials, see e.g. [22-24]. The method has been adopted in connection with solar energy applications to analyse test results for e.g. plastic absorber materials of HPDE and selective inorganic absorber coatings [10].

The success of using the Arrhenius equation in chemical reaction kinetics is well documented, although its theoretical meaning is vague even when studying elementary reactions. However, its success for describing the temperature dependence of material degradation processes, in many cases seems to be associated with its numerical form. If the degradation mechanism is known the order of magnitude of the activation energy can often be found in the literature.

However, in accelerated testing of a material it is recommendable to determine the activation energy for the degradation process from the results of a series of tests performed at varying elevated temperature levels.

The Eyring equation, e: g. (b) in Table 15, contains an additional parameter and can be derived from statistical mechanical principles. It is, however, more seldom used in modelling of temperature dependence of material degradation in lifetime testing.

To assess the importance of initial corrosion of electronic components by accelerated lifetime testing, the Eyring-Flood equation, see eq.(c) in Table 15, in combination with the Arrhenius equation have frequently been used for modelling. The overall acceleration factor is expressed as:

$$A = a_H \cdot a_T = \exp\left[B(1/RH_D - 1/RH_s)\right] \cdot \exp\left[-(E_a / R) \cdot (1/T_D - 1/T_s)\right] \tag{5}$$

From a series of constant load tests at elevated levels of temperature and relative humidity, firstly the two parameters B and E_a are determined and then the expected service life assessed by use of eq. (1).

Eq.(d) in Table 15 has also been used in combination with the Arrhenius equation for predicting the in-service loss in optical performance of a nickel-pigmented anodized aluminium, selective solar absorber surface due to hydratisation of aluminium oxide. In this case a series of constant condensation tests at varying temperatures was used as basis for the evaluation of service life [10].

Table 15: Examples of time-transformation functions for different kinds of stress factors

Stress factor	Time-transformation function	Remarks
Thermal stress	$a_T = \exp[-(E_a / R)\cdot(1/T_D - 1/T_s)]$ E_a = activation energy R = general gas law constant T_D = temperature of test T_s = temperature at service $a_T = (T_D/T_s)^w \cdot \exp[G(1/T_D - 1/T_s)]$ G = material dependent constant w = material dependent constant T_D = temperature of test T_s = temperature at service conditions	Based upon the Arrhenius equation for expressing the temperature dependence of the rate constant of a chemical reaction. Based upon the Eyring equation for expressing the temperature dependence of the rate constant of a chemical reaction, see e.g. [7, 21]
Humidity stress	$a_H = \exp[B(1/RH_D - 1/RH_s)]$ B = material dependent constant RH_D = relative humidity of test RH_s = relative humidity at service	Eyring-Flood time-transformation function recommended for describing degradation caused by initial corrosion of metals in the relative humidity interval 60 - 95%, see e.g. [16]
Condensed water	$a_{ToW} = (\tau_{ToW,D} / \tau_{ToW,s})$ $\tau_{ToW,D}$ = time fraction-of-condensation in test cycle $\tau_{ToW,s}$ = time fraction-of-condensation under service cycle	The assumption is that degradation only occurs under condensation, time-of-wetness, conditions, see [10]
Photoactive light	$a_I = (I_D / I_s)^p$ p = material dependent constant I_D = intensity of photoactive light in test I_s = intensity of photoactive light in service	When p = 1 the rate of degradation is limited by a single photochemical reaction, see e.g. [7, 21]
Electrical stress	$a_e = (V_D / V_s)^p$ p = material dependent constant V_D = applied elevated electrical potential in test V_s = applied electrical potential in service	Based upon Levenbach's equation to describe failure caused by electrical stress of electrical insulating fluids, see e.g. [25]

Table 15 cont. Examples of time-transformation functions for different kinds of stress factors [3,4]

Stress factor	Time-transformation function	Remarks
Mechanical stress	$a_\sigma = \exp[b(\sigma_{f,D} - \sigma_{f,s})]$ b = material dependent constant $\sigma_{f,D}$ = applied elevated mechanical stress in test $\sigma_{f,s}$ = mechanical stress in service $a_\sigma = [((\sigma_{f,D} - \sigma_{f,\infty})/(\sigma_{f,s} - \sigma_{f,\infty}))]^{1/q}$ q = material dependent constant $\sigma_{f,\infty}$ = the largest value of mechanical stress such that the life time is infinite $\sigma_{f,D}$ = applied elevated mechanical stress in test $\sigma_{f,s}$ = mechanical stress in service $a_\sigma = (\sigma_{f,D}/\sigma_{f,s})^{-n}$ n = material dependent constant $\sigma_{f,D}$ = applied elevated mechanical stress in test $\sigma_{f,s}$ = mechanical stress in service	Based upon equation which has been used to model degradation of amorphous polymers caused by mechanical stress at temperatures below the glass transition point, see e.g. [21]]. Based upon equation which has been used to model degradation of amorphous polymers caused by mechanical stress at temperatures above the glass transition point, see e.g. [21]. Based upon equation which has been used to model degradation of solar mirrors caused by mechanical stress, see e.g.[26]
Chemical stress	$a_C = (c_{i,D}/c_{i,s})^n \cdot (c_{j,D}/c_{j,s})^m \ldots\ldots$ $c_{i,D}$, $c_{j,D}$ = concentrations in test of the chemical compounds i and j. $c_{i,s}$, $c_{j,s}$ = concentrations in service of the chemical compounds i and j. n, m = reaction order constants	Based on the well known general rate equation in chemical reaction kinetics [7]
Stress from corrosive environments	$a_{Co} = \tau_{M,s}/\tau_{M,D}$ $\tau_{M,s}$ = 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	Based upon the principle of comparative testing. The choice of reference metal may be crucial [10]

When $p = 1$ in eq. (d) in Table 15, this reflects that the turnover in a photochemical reaction is proportional to the light dose absorbed by a photoactive species. When $p \neq 1$ the reaction scheme is more complex and consists most probably of both photochemical and thermochemical steps.

The influence of chemical stress, equation (j) in Table 15 can sometimes be taken into account by applying the general rate equation in chemical reaction kinetics. However, this equation is only relevant for those cases when a chemical compound in the environment acts as a reactant or catalyst in a chemical degradation reaction.

For other cases of chemical stress, the role played by the chemical compound may not be directly coupled to a chemical reaction. An example of the appearance of chemical stress in different roles is the degradation of carbon steel by way of atmospheric corrosion. The most important degradation factors here are atmospheric oxygen, pollutants such as sulphur dioxide and chlorides and the degradation factor of moisture. Atmospheric oxygen is the reactant. Sulphur dioxide is a catalyst, which reacts chemically in the corrosion process. Moisture acts by way of being adsorbed at the surface and thereby creating a liquid film so that the electrochemical process of corrosion can take place. Chlorides in the air, which will be deposited on the surface, increase the electrical conductivity of the adsorbed film when present, which in turn will increase the corrosion rate. Deposited chlorides on the surface are hygroscopic also, which will lower the critical humidity level for corrosion. This will increase time-of-wetness and thus the time of corrosion.

It should be mentioned that atmospheric corrosion of carbon steel can be described quite well in terms of these four degradation factors. Accordingly, the corrosion rate in different climates can be estimated, see ISO 9223. However, the example shows that when chemical stress is involved, detailed knowledge of the degradation mechanisms is necessary before reasonably proceeding with mathematical modelling of the degradation processes.

Atmospheric corrosion comprises quite complex degradation mechanisms and therefore the principle of comparative testing using standard metals as references may sometimes be applied in such cases, see eq. (k) in Table 15. This kind of approach has been used in accelerated testing of selective solar absorber surfaces [10]. In accelerated lifetime testing of electronic components, metallic copper is frequently used for this purpose, see e.g. [27]. In the developing work of the standard test method described in [27], laboratory tests were designed to reproduce the in-service corrosion behaviour of metallic copper in respect of extent of corrosion, composition of corrosion products, and rate limiting step in the corrosion process. Sometimes more than one reference metal is used to relate laboratory test conditions to different service conditions. In ISO/DIS 16701, a cyclic general accelerated corrosion test is presented in which both zinc and carbon steel are used as reference metals [28].

7.1.2 Varying levels of stress with time during an ageing process

So far, the acceleration factor approach as represented by equation (1) can be applied only when the levels of the degradation factors are constant in time and can be assumed to act independently from each other. If this is not true, it may be useful to introduce some approximations.

If the stress varies periodically with time during an ageing process and the stress factors can be assumed to act independently of each other, the following equation may be derived

$$\int_0^{\tau_f} g(\underline{S}) \cdot dt = n \cdot \int_0^{y_p} g(\underline{S}) \cdot dt = n \cdot \int_0^{y_p} (h_1(S_1) \cdot h_2(S_2) \ldots \ldots) \cdot dt \qquad (6)$$

where y_p is the length of the period and n is the number of periods until failure is reached.

If firstly, only the variation in one stress factor, S_1, needs to be taken into account, and secondly, 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 factors with time, eq. (6) may be written as

$$\int_0^{\tau_f} g(\underline{S}) \cdot dt = n \cdot C(S_{2,c}, S_{3,c}, ..) \cdot \int_0^{y_p} h_1(S_1) \cdot dt = n \cdot C(S_{2,c}, S_{3,c}, ..) \cdot$$

$$y_p \cdot \int_{S_{1,min}}^{S_{1,max}} h_1(S_1) \cdot f(S_1) \cdot dS_1 \qquad (7)$$

where
$f(S_1)$ = frequency function for distribution of S_1 within one time-period of length y_p
$C(S_{2,c}, S_{3,c}, ..)$ = constant dependent on the time-invariant levels of stress of $S_2, S_3, ..$

An effective mean value, $S_{1,EFF}$, can also be introduced defined by

$$h_1(S_{1,EFF}) = \int_{S_{1,min}}^{S_{1,max}} h_1(S_1) \cdot f(S_1) \cdot dS_1 \qquad (8)$$

or if the acceleration factor is introduced, eq. (8) may be rewritten as

$$\cdot a_{S1}(S_{1,EFF}, S_{1,c,D}) = \int_{S_{1,min}}^{S_{1,max}} a_{S1}(S_1, S_{1,c,D}) \cdot f(S_1) \cdot dS_1 \qquad (9)$$

If S_1 denotes absolute temperature and the Arrhenius equation is used as a basis for expressing the time-transformation function, eq. (30) becomes

$$\exp[-(E_a / R) \cdot (1/T_{EFF})] = \int_{T_{min}}^{T_{max}} \exp[-(E_a / R) \cdot (1/T)] \cdot f(T) \cdot dT \qquad (10)$$

As is obvious from eq. (10), 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. From the study of accelerated lifetime testing of selective solar absorber surfaces [10], 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 Figure 6
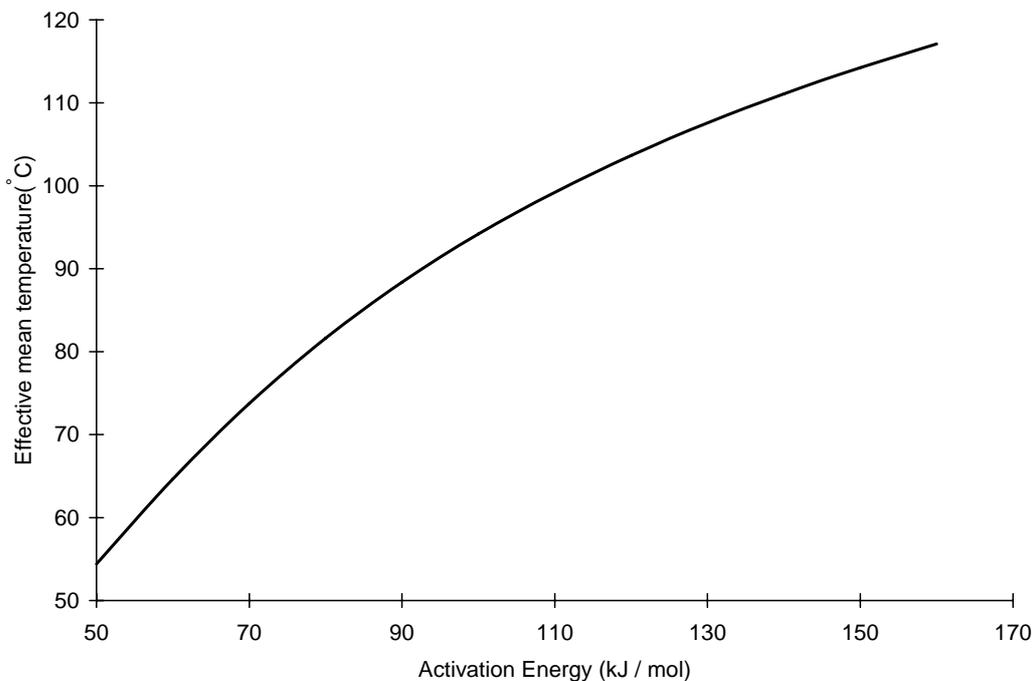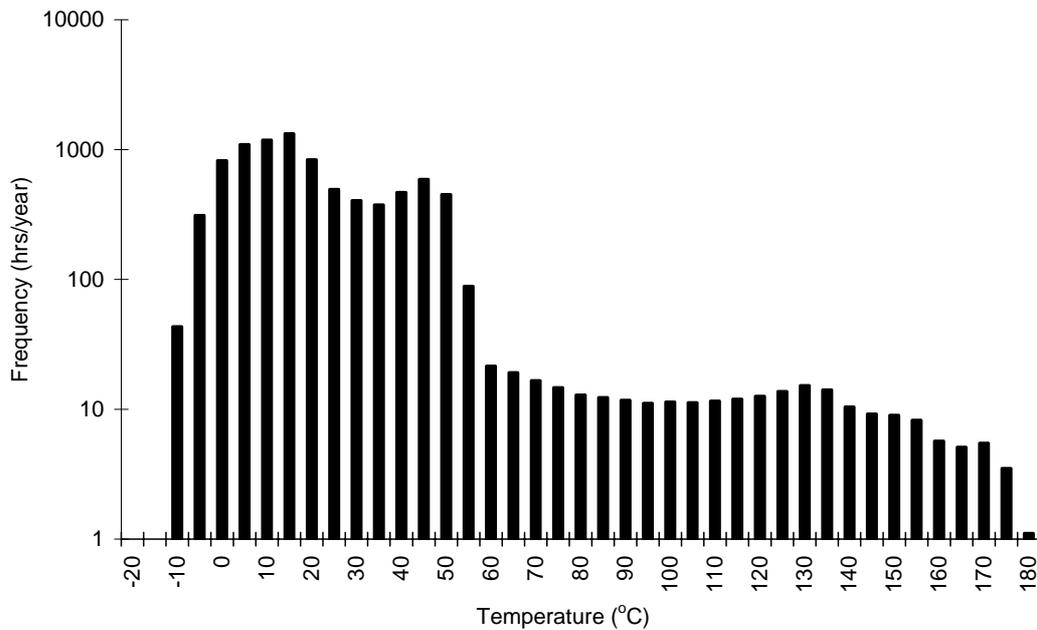

Fig. 6: Upper figure - Absorber temperature frequency function for one year valid for a typical single glazed flat-plate solar collector. For one summer month of the year the collector is under stagnation conditions [10]. Lower figure - Effective mean temperature vs activation energy for the thermal load profile illustrated in the upper figure.

If the variation in more than one stress factor needs to be taken into account, combined time-transformation functions are used. The effective mean temperature during time-of-wetness conditions for a selective solar absorber surface in a solar collector was for example calculated from measured absorber temperatures and corresponding air humidity data for one year by the use of the following expression, see [10]

$$\exp\left(-\frac{E_{H,T}}{R}\cdot T_{H,eff}^{-1}\right) = \int_{T_{H,min}}^{T_{H,max}} \exp\left(-\frac{E_{H,T}}{R}\cdot T_H^{-1}\right)\cdot f_H(T_H)\,dT_H \qquad (11)$$

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%.

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

$T_{H,min}$ 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 a combination of eqs. (a) and (d) in *Table 15, i.e.*

$$a_{T,H}^{-1} = \tau_H\cdot \exp\left(-\frac{E_{H,T}}{R}\left(T_{H,eff}^{-1} - T_D^{-1}\right)\right) \qquad (12)$$

where

$T_{H,eff}$ is the effective mean temperature of the absorber surface in K, defined by eq.(11)

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 %.

The Arrhenius activation energy $E_{H,T}$ was determined from a series of constant load condensation tests performed at varying temperatures.

7.1.3 More than one degradation reaction

In cases where two or more degradation reactions contribute to the deterioration in performance, simplifications need to be introduced which can be exemplified by the model developed for accelerated life testing of solar absorber surfaces in IEA Task X [10].

In that study a constant-load accelerated ageing test programme was set up taking into account different environmental stress factors that might generate loss in the optical performance of selected coatings. Included in the programme were three different kinds of ageing tests related to (A) high-temperature degradation, (B) degradation caused by sulphur dioxide at high humidity, and (C) degradation by the action of condensed water, see Table 10.

To distinguish between processes induced by test conditions (A) and (B), it was assumed that there exists a certain threshold value for the relative humidity, RHc, such that for humidity levels below this value the effect of water vapour on the rate of degradation is negligible.

For modelling, it was found reasonable to assume that the different processes of degradation (A), (B), (C) proceed in parallel and independently of each other and that the contributions of the different processes to the changes in performance were additive.

If n denotes the overall service life in number of years, it then follows that

$$\frac{1}{n} = \sum_{i=A,B,C} \int_0^{y_i} (g_i\ (S)\ /g_i\ (S_{c,Di})\ \cdot (1/\tau_{f,Di})\ dt \tag{13}$$

Where

y_i = time period of a year when service conditions according to test category
    i (A, B or C) prevail.

Eq. (13) may also be expressed as

$$\frac{1}{n} = \frac{1}{n_A} + \frac{1}{n_B} + \frac{1}{n_C} \tag{14}$$

The quantity $1/n_A$ represents testing according to category A and service conditions when the relative humidity is less than RH_C; the quantity $1/n_B$, represents testing according to category B and service conditions when the relative humidity is between RH_C and 100 %, and the quantity $1/n_C$, represents testing according to category C and service conditions during condensation.

From the above, it can be concluded that the parameter n_A is the expected service life when only processes of category A contribute to the overall degradation. The parameters n_B and n_C are the corresponding reaction times when processes of categories B and C respectively act alone. The tentative model described enables processes of each category A, B or C to be evaluated separately. Reference constant-load tests can also be selected for each humidity interval, so that the acceleration factor or time-transformation functions will be as simple as possible.

7.1.4 Change of mechanism with varying levels of stress

One complication in connection with extrapolation of accelerated test results is that the mechanism of degradation or the rate-determining step in the degradation process is different at elevated stress levels compared to the situation under service conditions. In such cases, however, both the mechanistic and non-mechanistic approach most probably lead to erroneous results. However, an approach based on a physical and chemical model of the degradation process seems preferable in general because extrapolation should be more accurate. However, if many competing mechanisms of degradation are involved, it may not be possible to design reasonable mechanistic models and a more general numerical approach may be preferable.

7.2   Accelerated life testing and assessment of expected service life

Accelerated life testing means firstly 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 the conduction of a series of tests.

The conduction of the accelerated test programme means also an opportunity to validate if the predominate degradation mechanism or mechanisms identified during screening testing do not change when the level of stress is changed. This is particularly important to clarify for tests with the lowest possible stress levels in respect of the longest available testing time.

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

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.

$$\Delta P = f(y_s) = f(A \cdot y_D) \qquad (15)$$

By introducing the inverse function f^{-1}, equation (15) may be rewritten as

$$y_D = (1/A) \cdot f^{-1}(\Delta P) \qquad (16)$$
or

$$\ln(y_D) = -\ln(A) + \ln(f^{-1}(\Delta P)) \qquad (17)$$

Equation (17) 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 (17) 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.

How equation (17) may be applied is illustrated in Figure 7, where an example from the IEA absorber surface case study is shown [10]. It should be mentioned that at above 40°C a phase change reaction occurs, which completely changes the kinetics of the degradation process.
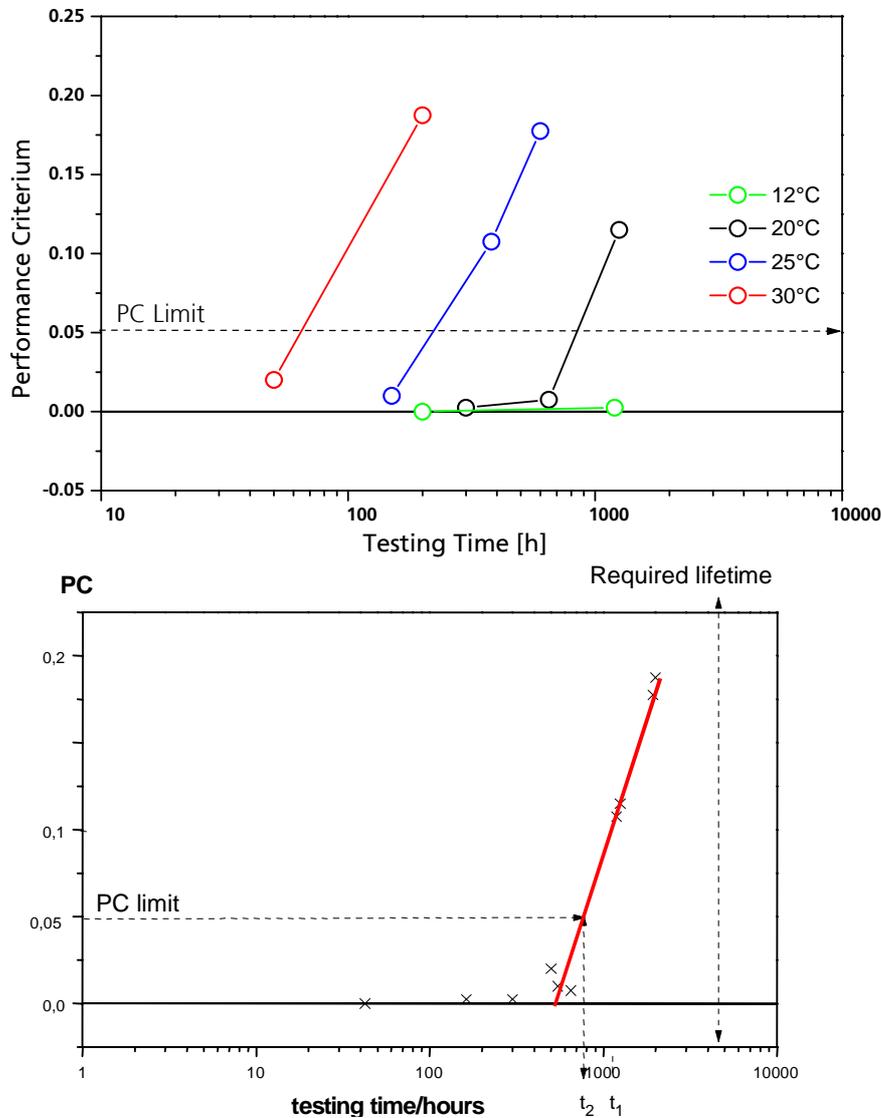

Fig. 7 Example from accelerated testing of a nickel pigmented anodised aluminium absorber surface with respect to its resistance to the action of condensed water on its surface, see Table 10.

Upper diagram: Results of a series of constant condensation tests at different temperatures
Lower diagram: All test results from the upper diagram transformed to the 20 °C test condition by use of the performance versus time relation given in the table below.

Component / Materials	Nickel pigmented anodized 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 ºC
Performance versus time relation	ln (testing time) T = $\dfrac{E_{H,T}}{R}$ (T_D^{-1} - T_s^{-1}) + ln($\sum\limits_{n=0}$ d_n $\cdot(\Delta(PC))^n$) T_D= testing temperature; T_s = 20 °C (see (a) in *Table 15*)

After it has been concluded that the assumed model for degradation is applicable, the service life determined by the pertinent degradation mechanism is 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, see section 4.1. 2.

As a result, it may be possible to express the importance of different degradation mechanisms in terms of expected service life values, which are valid only under the assumption that each degradation mechanism acts alone, see example from the absorber surface case study in Table 16. To estimate the overall service life when two or more degradation reactions contribute to deterioration in material performance, some guidance is given in section 4.1.3.

Table 16 Estimated service life of the nickel- pigmented anodised aluminium absorber surface due to different degradation mechanisms and if the different degradation mechanisms were acting alone [10]

Degradation mechanism	Time transformation function (see Table 15)	Estimated service life with $PC = -\Delta\alpha + \Delta\varepsilon < 0.05$ [1] (years)
(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 T_s = effective mean temperature at service	$>10^5$
(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 corro- sion 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	$a_{T,H}^{-1} = \tau_H \cdot \exp\left(-\dfrac{E_{H,T}}{R}\left(T_{H,eff}^{-1} - T_D^{-1}\right)\right)$ $T_{H,eff}$ = 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 an non-airtight highly ventilated collector)

[1] PC = 0.05 corresponds to a decrease in the solar system performance of 5%

In cases when the degradation process is very complex and the rate of degradation is hard to model mathematically in terms of measurable degradation factors, the use of reference materials or components in life testing may be applied, see example in Table 16, mechanism (B). Other examples on how reference materials are used in connection with atmospheric corrosion testing can be found in [27,28]

7.3   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 advantage with such an approach is of course that deviations from predicted performance may early give an indication that the presumptions made on life-limiting degradation processes are not fully correct and the result might indicate that some important process of degradation has not been foreseen.
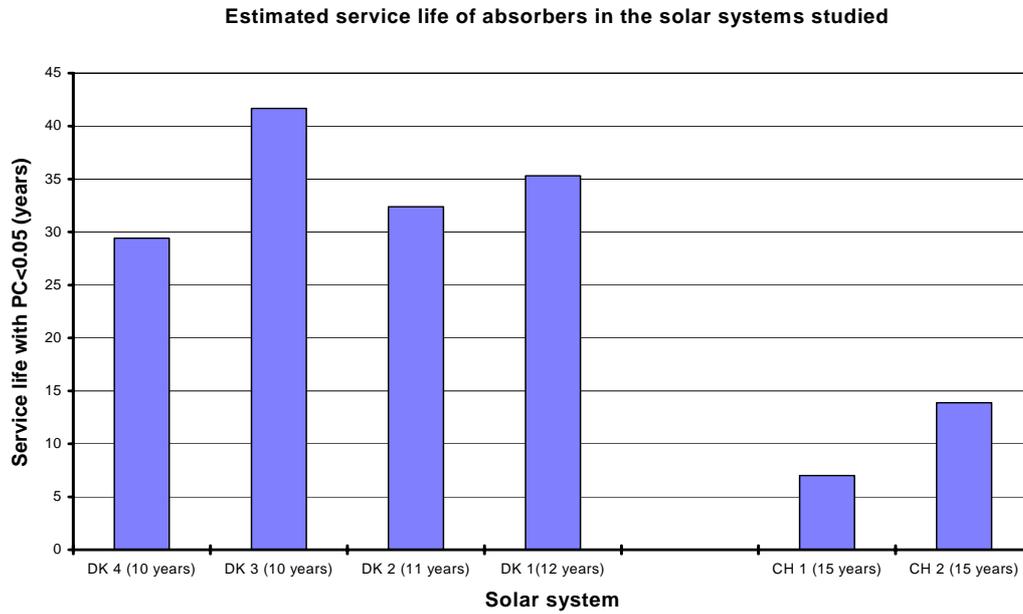
The results of validation tests therefore can be used to revise a predicted service life and form the starting point also for improving the component tested in respect of environmental resistance, if so required. It should be remembered that the main objective of accelerated life testing is to try to identify those failures, which may lead to an unacceptable 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 value.

How the predicted service life of the nickel-pigmented anodised aluminium absorber coating was validated in the absorber surface case study is illustrated in Figure 8. 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 (Karlslunde, 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

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

Estimated service life of absorbers in the solar systems studied

Service life of absorber coating as determined from results of accelerated life testing, see Table 15.

Estimated service life of absorbers from accelerated life testing

Fig. 8 Comparison between estimated service life of absorber coating from actual service exposure and from the result of accelerated life testing [29]

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9.   ANNEX 1: Adoption of the general methodology for durability and service life prediction to polymeric glazing materials

A1.1   Introduction

Polymeric glazing materials offer significant potential for cost savings both as direct substitutes for glass cover plates in traditional collector systems and as an integral part of all-polymeric systems. This savings includes both base material cost and costs associated with shipping, handling and installation (due to their lightweight and lack of fragility). Glazing materials should have high transmittance across the solar spectrum and must be able to resist long term (25 years) exposure to service conditions under solar ultraviolet (UV) light and elevated temperature loads sometimes exceeding 80 C under shorter periods of stagnation conditions of a solar collector. They must retain mechanical integrity (for example, impact resistance and flexural rigidity) under these harsh environmental stresses.

Recent efforts have emphasized

1)   identification of new/improved candidate glazing materials and
2)   evaluation of optical and mechanical durability during exposure to actual and simulated service conditions.

Such work was performed in the IEA Working Group Materials in Solar Thermal Collectors with the aim of developing durability test procedures for polymeric glazing materials. Mainly PVC and UV stabilized PC glazing materials were studied by the IEA Working Group and a lot of results on those materials are available [1]. For validating the applicability of the general methodology on durability assessment developed in project B1 of IEA Task 27, it was therefore decided to make use of the results from this previous IEA polymeric glazing study.

The outcome of this analysis is presented in the following annex.

A1.2   Initial risk analysis of potential failure modes of polymeric glazing materials

The first step in the general methodology for durability assessment adopted by the IEA Task 27 Group is an analysis of potential failure modes and this work structured into the following steps:

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 specify also in more general terms 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 in respect of 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,

d)   Estimate the risks associated with the different failure modes identified;

As the polymeric glazing materials should be evaluated with respect to their suitability as cover plate materials for flat plate collectors, the end-user requirements would be specified as presented in Table A1.

Table 17 A1.2 Specification of end-user requirements for cover plates in flat plate solar collectors for DHW systems

Function and general requirements	General requirement for long term performance and service life	In-use conditions and severity of environmental stress
Efficiently transmit solar radiation to the absorber Suppress heat losses by creating an insulating air gap Protect the absorber against the outdoor environment	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 service time of 25 years	Above solar absorber, which means sometimes exposure to high temperatures (exceeding 80 ºC at stagnation conditions) Exposed to condensed water Exposed to outdoor environments, which means UV-radiation, humidity, rain, snow, hail, wind loads, air pollutants, high and low temperatures, etc. Exposed to mechanical loads like tensile stress due to its on weight, wind loads, and thermal expansion, impact of various objects (e.g. hails, birds, stones)

The next step is the translation of the end-user requirements into requirements for specific cover plate functional properties and critical material properties as presented in Table A2. In this table also data for two cover plate materials: APEC 9353 (UV-stabilized polycarbonate (PC)) and Duroglas (polyvinylchloride (PVC) previously studied by the IEA Solar Material Working Group are shown.

One of the most critical material properties related to the use of polymeric materials as solar collector covers is the maximum recommended service temperature for the material or in this case the closely related deflection temperature of the material under mechanical load. This requirement, set by the maximum cover temperature observed when the collector is under stagnation conditions, narrows down the number of possible polymeric materials considerably. As can be seen from Table A2, the PC glazing material meets this requirement but the PVC material is not, because its glass transition takes place already around 80°C. The PVC material does neither meet the requirement on minimum service temperature.

The mechanical properties of a polymeric glazing material may also be critical when used as a collector cover. Especially as an effect of ageing the mechanical properties of the polymeric materials may deteriorate to a level at which failure may occur induced by e.g. wind or snow loads and because of impacts from flying objects like hail. By use of reliability tests on solar collectors, see e.g. EN 12975-2 [14] or SPF programme on quality labelling of solar collectors [4], the effect of mechanical loads on the collector can be assessed.

From the requirements given in those collector tests, accordingly, corresponding requirements on mechanical properties of the cover material can be derived, see Table 18. As can be concluded from the data given for the PC and PVC materials, only the PC material seems qualified with respect to its mechanical properties. The effects of ageing on the mechanical properties of the polymeric materials, however, also need to be taken into account.

When used as cover plate material, it is assumed that the level of the critical extension of the polymeric materials will not be exceeded for none of the two materials considered.

Table 18 A1.2 Specification of functional properties and requirements for the polymeric glazing materials

Critical functional property	Test method for functional property	Requirement for functional capability	Material data UV-stab. PC (APEC 9353) (thickness 4 mm)	Material data PVC (Duroglas) (thickness 1 mm)
Solar transmittance τ	ASTM D 1003	$\tau > 0.80$ $-\Delta\tau_{25 \text{ years}} \leq 0.05$	0.80 [2)] To be determined by testing at a later stage of evaluation	0.83 [2)] To be determined by testing at a later stage of evaluation
Deflection temperature under mechanical load	ASTM D 648	> 80°C *	161°C (1.82 MPa) 173 °C (0.46 MPa)	82 °C max. rec. service temp.
Thermal expansion κ	ASTM D696		66 e-6/K	50-80 e-6/K[1)]
Critical extension		$> 100 \cdot \kappa$	OK	OK
Yield tensile strength	ASTM D638	> 30 Pa (4 mm) > 60 Pa (3mm) **	66 MPa	80 MPa
Impact strength	ASTM D256	> 6 J/cm	6.50-9.50 J/cm	0.22 -1 J/ cm[1)]
Brittleness temperature		< - 30 °C	$\approx$ -100 °C min. service temp.	$\approx$ -10 °C[1)] min. service temp.

1) General data from the material data base Idemat for PVC, hard [2]
2) Measured value, see [13]
*   Estimated maximum temperature of a polymeric cover of a single glazed flat plate solar collector under stagnation conditions [3]
** Value based on the requirement that the cover shall resist on overpressure of 1000 Pa according to EN 12975-2 (Cover dimension 1m x 2m x thickness) [14]. Data calculated for the case of cylindrical bending with uniformly loaded rectangular plates with built-in edges [5]
*** Estimated value based on the requirement that the cover shall resist a falling steel ball (150 g) from a height of 2.0 m [6]

To summarize the analysis on the critical functional properties of the two polymeric glazing materials, it is evident that the PVC glazing material does not qualify for use as a solar collector material. However, the PC material is qualified at this stage of evaluation at least prior to the next phase of evaluation when ageing effects are taking into account also.

The third step in the initial risk analysis is to identify potential failure modes and degradation mechanisms. In Table A3 the result for the PC material and in Table A4 the result for the PVC material are shown.

Two kinds of failures are considered, one related to a gradual decrease in the optical performance of the cover material and one related to insufficient mechanical strength of the material leading to either breakage or plastic deformation of the cover so that it cannot protect the absorber from the outdoor environment or act as a barrier towards heat losses.

A1.3 Potential failure modes and estimated risks of failure for the PC cover plate

A1.3.1 Unacceptable loss in optical performance

Reduction in the optical performance of a PC glazing may be due to yellowing, see e.g. [7] for a review. The mechanisms in the colour formation proceed from two main routes:
a)   the Fries photoreaction and
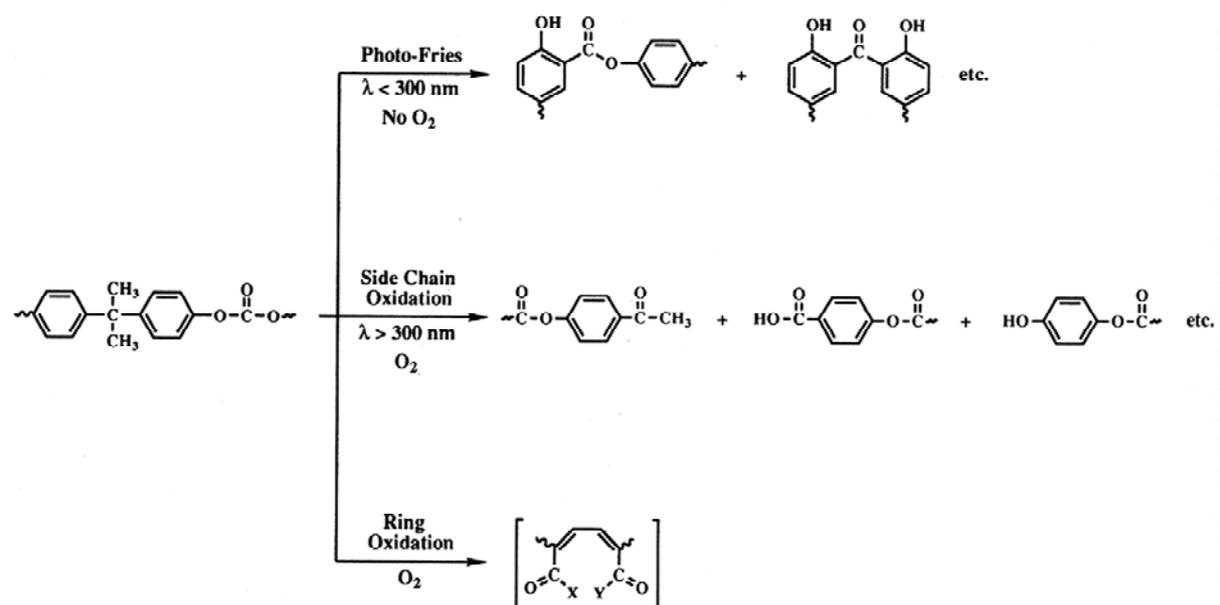b)   the oxidative attack of dimethyl groups, see Figure A1.

Fig. 19 A.1 Mechanisms of yellowing of a PC material

Most likely the mechanism responsible for yellowing starts with the action of light above 300nm and with the action of oxygen. Methyl groups are the vulnerable part of the structure attacked by the UV, leading to oxidation products such as phenols, esters, acids, which impart the yellow coloration to the material. The yellow colour appears at the end of the oxidising route, which can be thermal or photo-activated.

Polycarbonate is quite stable in air with a recommended maximum service temperature of around 130°C or for some qualities even higher. The problem of yellowing, however, increases with temperature and therefore it is important to use UV-stabilized PC materials for collector covers. It should be mentioned that APEC 9353 considered in this analysis is a UV- stabilized PC material.

A1.3.2   Mechanical breakage or plastic deformation of the cover making the collector not rain tight

Chemical degradation of a PC material due to photo-oxidation or thermal oxidation may also result in deterioration in the mechanical properties of the material, which may result in a breakage of the cover when subjected to a high mechanical load.

Estimated risks associated with the different identified degradation processes of the PC material are shown in Table A3. It is believed that photo-oxidation and thermal oxidation resulting in an unacceptable optical performance are the most important and need to be further studied the importance of by ageing testing. Failures resulting from an insufficient mechanical performance caused by ageing are believed to be of less probability of occurrence. The initial values of the most critical mechanical properties are well above the required levels for the PC glazing material but not for the PVC glazing material.

Table 20 A3. Potential failure modes, critical factors of environmental stress and degradation, risk assessment by FMEA related to the use of the PC material for collector cover

Failure/Damage mode / Degradation process	Degradation indicator	Critical factors of environmental stress/ Degradation factors	Estimated risk of failure/damage mode from FMEA [1]			
			S	P_O	P_D	Risk RPN
A. Unacceptable loss in optical performance	PC = - $\Delta\tau$		7	$\Downarrow$	7	
i) High temperature oxidation	Transmittance spectra UV-VIS-IR	High temperature	7	5	7	245
ii) Photooxidation	Transmittance spectra UV-VIS-IR	UV-radiation, high temperature	7	8	7	392
iii) Hydrolysis in combination with photooxidation	Transmittance spectra UV-VIS-IR	Humidity, condensation, air pollutant and UV-radiation	7	3	7	147
iv) Soiling	Transmittance spectra UV-VIS-IR	Solid air pollutants	7	6	2	84
v) Contamination by outgas- ing products	Transmittance spectra UV-VIS-IR	Outgassing products from insulation materials, etc	7	3	6	126
B. Mechanical breakage of the cover	Visual observation		9	$\Downarrow$	2	
vi) Mechanisms i, ii, and iii, see above	see above	Additional stress caused by wind and snow loads	9	3	7	189
vii) Mechanisms i, ii, and iii, see above	see above	Additional stress of mechanical impact from hail, birds, etc	9	3	7	189
viii) Irreversible change in microstructure causing brittleness	DSC characteristics	Low temperature (below min. service temperature)	9	1	7	63
ix) Mechanisms i, ii, and iii, see above	see above	Additional stress caused by temperature changes (Thermal shock)	9	3	7	189
C. Plastic deformation of	Visual observation		$\Downarrow$	$\Downarrow$	2	
x) Change in microstructure	DSC characteristics	High temperature (above max. recommended service temperature) and mechanical stress	8	1	7	56

A1.3.3   Unacceptable loss in optical performance

The optical performance of a PVC glazing material may be deteriorated by dehydrochlorination causing yellowing, see e.g. [7] for a review.

The dehydrochlorination reaction is a primary step in PVC thermal or photodegradation leading to the formation of polyenes, see Figure A2. Polyenes are coloured and depending on the number of conjugated double bonds, their colour shifts gradually from yellow to black with increasing extent of degradation of the PVC material, see route 1 in Figure A2. In the presence of oxygen, however, the polyenes are in an early stage of degradation attacked by radicals leading to the formation of carbonyl groups and acids instead of polyenes with an increasing number of conjugated double bonds, see route 2 in Figure A.2. As a result of route 2, the PVC material is discoloured. Radical formation may also lead to chain scissions and crosslinking causing brittleness of the PVC material, reaction 3.
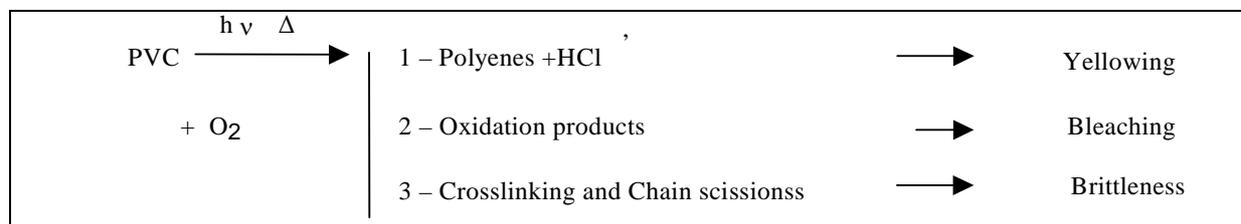

Fig. 21 A.2 Reactions involved in the degradation of PVC [7]

So, two main routes are involved in the degradation of PVC. Depending on the conditions of ageing, UV light intensity and temperature, route 1 or 2 can be more or less favoured.

Clear PVC as the considered Duroglas is generally less weather resistant than polycarbonate. Ageing may result in reduced optical performance due to yellowing but also to mechanical failures as breakage of the cover when subjected to a high mechanical load.

Estimated risks associated with the different identified degradation processes of the PVC material are shown in Table A3. The lowest as well as the highest expected cover temperature for the considered application are outside of the recommended service temperature interval of PVC, Mechanical failures due to that most likely will occur. But, it is also believed that dehydrochlorination and photooxidation resulting in an unacceptable optical performance are important and need to be further studied by ageing testing. Failures resulting from an insufficient mechanical performance caused by ageing are believed to be of second order interest.

A1.4   Screening testing/analyses for service life prediction

Screening testing is the first step in accelerated life testing and is 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. How the program of screening testing was designed following the recommendations made in the general methodology described in the main report is presented in Table A4.

Table 22 A4. Potential failure modes, critical factors of environmental stress and degradation, risk assessment by FMEA related to the use of the PVC material for collector cover

Failure/Damage mode / Degradation process	Degradation indicator	Critical factors of environmental stress/ Degradation factors	Estimated risk of failure/damage mode from FMEA [1]			
			S	P_O	P_D	Risk RPN
A. Unacceptable loss in optical performance	PC = - $\Delta\tau$		7	$\Downarrow$	7	
i) Dehydrochlorination and formation of polyenes	Transmittance spectra UV-VIS-IR	High temperature	7	8	7	392
ii) Photooxidation	Transmittance spectra UV-VIS-IR	UV-radiation, high temperature	7	8	7	392
iii) Acid catalysed dehydro-chlorination	Transmittance spectra UV-VIS-IR	Humidity, condensation, air pollutant	7	2	7	98
iv) Soiling	Transmittance spectra UV-VIS-IR	Solid air pollutants	7	6	2	84
v) Contamination by outgas- ing products	Transmittance spectra UV-VIS-IR	Outgassing products from insulation materials, etc	7	3	6	126
B. Mechanical breakage of the cover	Visual observation		9	$\Downarrow$	2	
vi) Mechanisms i, ii, and iii, see above	see above	Additional stress caused by wind and snow loads	9	3	7	189
vii) Mechanisms i, ii, and iii, see above	see above	Additional stress of mechanical impact from hail, birds, etc	9	5	7	315
viii) Irreversible change in microstructure causing brittleness	DSC characteristics	Low temperature (below min. service temperature)	9	10	7	630
ix) Mechanisms i, ii, and iii, see above	see above	Additional stress caused by temperature changes (Thermal shock)	9	3	7	189
C. Plastic deformation of	Visual observation		$\Downarrow$	$\Downarrow$	2	
x) Change in microstructure due to glass transition	DSC characteristics	High temperature (above max. recommended service temperature) and mechanical stress	8	10	7	560

[1] See section 2.4 in the main report

Table 23 A4 Programme for screening testing in the IEA MSTC polymeric glazing case study

Possible degradation mechanism	Critical periods of high environmental stress	Accelerated test methods used and range of degradation factors
High temperature oxidation of PC

Thermal dehydrochlorination of PVC | Stagnation conditions of solar collector at high levels of solar irradiation (no withdrawl of heat from the collector) | A)   Constant load temperature exposure tests in the range of 40°C to 80 °C [1].

B)   Xe-arc-radiation tests at intensities of 2X AM 1.5 solar spectrum and the use of a UV-filter [8] |
| Photooxidation of PC and PVC

Photochemical dehydrochlorination of PVC | At solar irradiation | C)   Xe-arc-radiation tests at intensities of 2X AM 1.5 solar spectrum [8] |
| Hydrolysis in combination with photooxidation of PC | At solar irradiation under high humidity conditions | D)   UV-radiation tests at varying levels of temperature and humidity [1] |
| Acid catalysed dehydro-chlorination of PVC

Hydrolysis in combination with photooxidation of PC | At solar irradiation under high humidity conditions and exposure to rain | E)   Xe-arc-radiation test (intensity of 1X 1.5 AM solar spectrum) with cyclic water and acid rain spraying SPART 14 [9] |

The results from the screening test program conducted by the IEA Group MSTC are summarized in Table 24.

Table 24 A4 Observed change in performance during screening testing of PC and PVC in the IEA MSTC polymeric glazing case study

Degradation mechanism	Observed changes	Conclusions
	PC glazing	
Photooxidation	Reduction of transmittance -yellowing - in test C at higher rate than observed in test B, see Table A5	Photooxidation seems to be the life limiting mechanism of degradation in optical performance. The effect on photochemical ageing on the mechanical performance should also be studied
High temperature oxidation	Reduction of transmittance - yellowing - in test B but at a much lower rate than in test C	High temperature oxidation seems to be a much less important mechanism of degradation than photooxidation.
Hydrolysis in combination with photooxidation	Reduction of transmittance -yellowing - in test E at a rate, which slightly exceeds half of that in test C. Reduction of transmittance observed also in tests D but the test results also suggest that the temperature dependence of the rate of degradation is relatively small. The effect of humidity on the rate of degradation seems very small or none.	Hydrolysis seems not to have an important role in the photooxidation of PC
	PVC glazing	
Photochemical dehydrochlorination	Reduction of transmittance -yellowing - in test C at higher rate than observed in test B, see Table A5	Photochemical dehydrochlorination seems to be the life limiting mechanism of the degradation of PVC.
Thermal dehydrochlorination	Reduction of transmittance - yellowing - in test B but at a lower rate than in test C. In the series of tests A yellowing is observed first for the test at 80 °C.	Thermal dehydrochlorination is an important mechanism of degradation only close to or above the glass transition temperature at 80 °C, i.e. above the maximum recommended service temperature.
Acid catalysed photochemical dehydro-chlorination	Reduction of transmittance -yellowing - in test E at a rate, which is less than half of that in test C.	Acidic catalysis seems not important in the photochemical dehydrochlorination of PVC

From the screening tests it could be concluded that the dominating mechanism of degradation of the PC glazing material was photooxidation and in the case of the PVC

material photochemical dehydrochlorination. The two most dominating degradation factors were thus temperature and UV-radiation.

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. This was done by the IEA MSTC Group using techniques as described in e.g. [10].

A1.5   Service life prediction from results of accelerated ageing

A1.5.1   Mathematical modelling

Because only the degradation mechanism of photooxidation seemed to contribute significantly to the service life of the PC glazing, the time-transformation function as shown in

Table 25 was set up for the modelling of accelerated test data. This function is a combination of the time-transformation functions (a) and (e) of Table 14 in the main report.

Concerning the PVC glazing, photochemical dehydrochlorination seems to be the life limiting mechanism of the degradation. Thermal dehydrochlorination is a less important mechanism of degradation and seems to contribute only significantly at temperatures close to or above the glass transition temperature of PVC at 80   C, i.e. above the maximum recommended service temperature of PVC.

Dehydrochlorination is a complex process of degradation as briefly reviewed in section A2.2. The reaction rate dependence on environmental stress factors contributing to degradation is consequently hard to mathematically model from a theoretical viewpoint. The study of the IEA Working Group MSTC, however, showed that an adequate time-transformation function for the PVC degradation was the general photooxidation time-transformation function used to model the degradation of the PC glazing, see Table 25 and 26.

Table 25 Time-transformation function and estimated service life of the PC glazing material

Degradation mechanism	Time transformation function	Estimated service life with PC = $-\Delta\tau < 0.05$ [1] (years)
Photooxidation	$a_{PO} = [I^p \cdot \exp\,[-(E_a / RT)]]_{EFF,D} / [\,I^p \cdot \exp\,[-(E_a /(RT)]]_{EFF,s} = PO_{EFF,D} / PO_{EFF,s}$ a_{PO} = acceleration factor for photooxidation I = intensity of photoactive light p = material dependent constant which value has to be determined by accelerated testing E_a= activation energy R = general gas law constant T = temperature [K] s = index for service; D = index for test EFF = effective mean value	5 years (Golden, Colorado) 6 years (Phoenix, Arizona) At outdoor exposure with glazing inclined 45° and facing south

[1] PC = 0.05 corresponds to a decrease in the solar system performance of 5%

Table 26 Time transformation function and estimated service life of the PVC glazing material

Degradation mechanism	Time transformation function	Estimated service life with PC = -$\Delta\tau$ < 0.05 [1] (years)
Photochemical and thermal dehydrochlorination	a_{PO} = [I^p ·exp [-(E_a / RT)]] $_{EFF,D}$ / [I^p·exp [-E_a /(RT)]] $_{EFF, s}$ = PO $_{EFF,D}$/ PO $_{EFF, s}$ see above and moreover I = intensity of photoactive light p = material dependent constant which value s = index for service; D = index for test EFF = effective mean value	around 1/2 (Golden, Colorado) around 3/4 (Phoenix, Arizona) At outdoor exposure with glazing inclined 45° and facing south

[1] PC = 0.05 corresponds to a decrease in the solar system performance of 5%

This time-transformation function is characterized by two material dependent constants p and E_a which have to be determined by conducting a series of accelerated ageing tests at varying levels of intensity of photo activating light and temperatures of the glazing material tested. The conduct of this program of testing referred to as life testing was performed by NREL starting from the test denoted C in Table 24.

A1.5.2   Accelerated life testing and assessment of expected service life

During life-testing the two glazing materials were exposed by Jorgensen et.al in an Atlas Ci-5000 WeatherOmeter (having a UV intensity of about 2 x compared to typical outdoor terrestrial levels) and at 50 x and 100 x using a UV concentrator in a series of tests at varying light intensities and surface temperatures [11,12]. Hemispherical transmittance measurements were made to characterize the loss in optical performance of the glazing materials during exposures. Performance-versus-time data were thereafter used to determine the parameters of the time-transformation function. The results are shown in Table A9. Values of activation energies (E_a) derived are reasonable for photo-thermally driven degradation mechanisms. A value of p ~ 2/3 for PVC implies that exposure to 50-100 x light intensities had a net effect of only 15-25 x, suggesting that some shielding or rate limiting reactions occur that do not allow all photons to participate in degradation. For the UV-stabilized PC sample, a value of n≈1 suggests that exposure of this material follows strict reciprocity even up to 100 x; all incident photons fully contribute to degradation reactions that proceed at twice the rate undergone at 50 x exposure and 50 times the rate experienced at 2 x exposure.

Table 27 A9 Coefficients derived for the tested polymeric glazing materials [11]

Polymer Glazing	A	p	E_a (kcal/mole-K)
Polyvinyl Chloride	2892	0.669	8.440
UV-Stabilized Polycarbonate	5.497	1.093	6.688

The determined values of p and E_a and measured climatic data of surface temperatures and UV-light intensities from two locations Golden, Colorado and Phoenix, Arizona, were thereafter used.

Firstly, the effective yearly main values of PO $_{EFF, s}$, see *Table A7* and *A8*, for the two locations were determined, see eq. (8) in the main report. Secondly, the expected service life with PC< 0.05 of the glazing materials was estimated from

{Estimated service life with PC<0.05} =
PO $_{EFF,D}$/ PO $_{EFF, s}$ · {Determined failure time for PC = 0.05 in reference test D}

where PO $_{EFF,D}$ refers to the reference test D.

The results are shown in Table A7 for PC and in Table A8 for PVC.

The results indicate the long-term performance requirement as regards optical performance is not met by any of the two glazing materials. Even if a decrease in the solar transmittance of 10 % is considered acceptable, the estimated service life with PC < 0.10 for the PC glazing will be in the order of ten years instead of 25 years. This means that if a service time of 25 years is considered it seems necessary to exchange a PC solar collector cover at least once during this time period to maintain the performance level at a reasonable level.

As expected the PVC glazing material is far from fulfilling the requirements on long-term optical performance.

A1.5.3   Reasonability assessment and validation

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

$$-\Delta\tau_i = A\,(I_i)^{\,p}\cdot\exp\left[-(E_a / RT_i)\right] \tag{A1}$$

using the time-transformation function shown in Table 25. The parameter A is a constant independent on surface temperature and UV-light intensity but material dependent. It may be determined from the same series of ageing tests as used to determine the activation energy E and the parameter n. For - $\Delta\tau_i$ equal to the mean global transmittance between 400 and 500 nm the values of A was estimated by Jorgensen et.al. to 2892 for PVC and 5.497 for UV-stabilized PC [11].

By integrating equation (A.1) with the respect to time, the following equation is obtained

$$-\ \tau_i\,(t)\ = A\int_{0}^{t}\ (I_i)^{\,p}\cdot\exp\left[-(E_a / RT_i)\right]dt \tag{A2}$$

where I_i and T_i are all functions of time.

By using this equation and measure data for I_i and T_i, the expected transmittance after different time-periods of outdoor exposure may be estimated by numerical integration.

Using the values of the coefficients E_a and p from Table 27 and time-monitored values of sample temperature and UV irradiance, the loss in performance was predicted for both the PVC and the PC as exposed outdoors in Golden, Colorado , and Phoenix, Arizona. Predicted values were then compared with actual measured data for these materials exposed at these sites. The results are presented in Figure A2. Time-dependent changes in weathering variables produce the irregular shapes of the predicted curves. Excellent agreement is evident between the measured and predicted data, thereby validating the phenomenological approach to data analysis (using accelerated test results to obtain model coefficients, and then the use of these coefficients to predict time-variable real-world degradation), and the assumed damage function model.
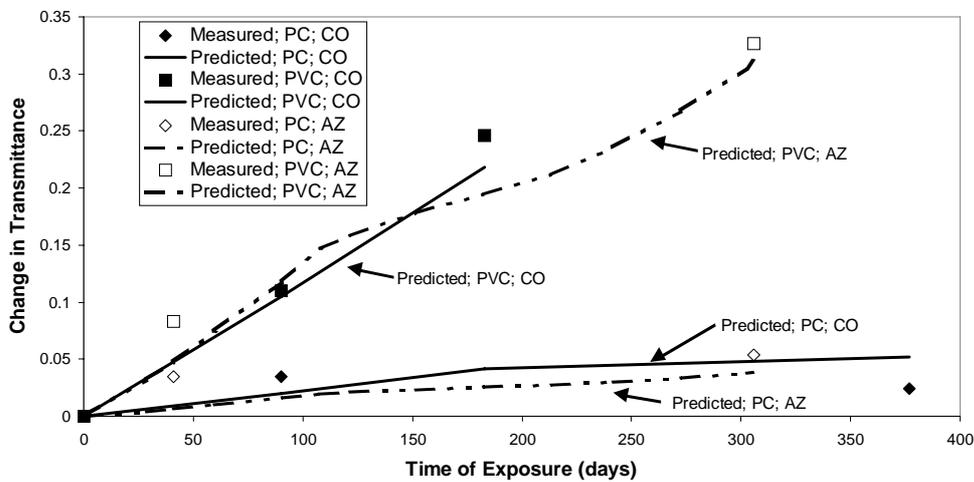

Fig. 9 A3 Measured vs. predicted change in hemispherical transmittance between 400-500 nm for the PC and PVC glazing materials of the IEA Working Group MSTC glazing case study [11]

A1.6 Conclusions

The general methodology has proved to be applicable to durability assessment of PC and PVC glazing materials by way of accelerated life testing. The usefulness and validity of this approach has also been confirmed by comparing predicted results with actual measured data for samples exposed to variable outdoor conditions. Consequently, very abbreviated testing times at elevated stress conditions can be substituted for long-time exposures at lower stress levels. This will allow much shorter development cycle times for new products and will allow improvements to be identified and readily incorporated.

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10.   Appendix I: Adaptation of general durability test procedures from B1 to chromogenic materials

A. Specification of end-user requirements

Function and general requirements	General requirements for performance and service life	In-use conditions and severity of environmental stress
Optimal use of solar energy in buildings due to variable TSET value Optimal use of daylight Minimal glare Good thermal insulation Mechanical properties as for conventional IGU´s Homogeneous appearance Fire resistance as for conventional IGU´s Colour rendering Minimal blur Safety	High solar gain when heating is required – Low solar gain when cooling is required Sufficiently high τ_{vis} Sufficiently low τ_{vis} Acceptable switching times (minutes) Low U value 20 years service life Acceptable power consumption	Outdoor ambient temperatures between –20 °C and 45 °C Outer pane T: -20°C - ~80 °C Indoor T: 5 °C – 35 °C Solar radiation: 0 - ~ 1100 W m^{-2} UV radiation: 0 – 50 Wm-2 Glazed unit in frame EC: laminate (in DGU) GC: GC-DGU (in TGU) Mechanical loads as for conventional glazing (wind, snow, structural, thermal shock/stress) condensation Thermal stress between shaded and unshaded glazing Electrical loads (EMC)

B. Specification of functional properties and requirements

Critical functional property	Test method for determining functional property	Requirement for functional capability or performance (benchmarks) and determination methods
TSET (g value) for different states	Calorimetric or component method from $\tau(\lambda)$, $\rho(\lambda)$	Postulate: $TSET_{max}$: $TSET_{min}$> 3 Benchmark: 10% saving in <u>building energy demand</u> (heating+cooling+lighting) compared to good solar control or low-e glazing for location and "reference office". Determination method: building energy simulation; illuminance on work plane and/or room temperature as control parameters; parameter sensitivity study to variation in $TSET_{max}$: $TSET_{min}$ coupled with realistic variation of $\tau_{vis,max}$:$\tau_{vis,min}$
α_{sol} for different states	Spectrophotometric	max. α_{sol} for T_{max} < 75 °C at specified location Determination method: temperature distribution in window under extreme environmental conditions

τ_{vis} for different states	Spectrophotometric or luxmeter	From ASTM standard test method E2141-01: photopic transmittance ratio of at least 4:1 Benchmark: 10% saving in building energy demand (heating+cooling+lighting) compared to good solar control or low-e glazing for location and "reference office". Determination method: building energy simulation; illuminance on work plane and/or room temperature as control parameters; parameter sensitivity study to variation in $\tau_{vis,max}$:$\tau_{vis,min}$ coupled to realistic variation of $TSET_{max}$: $TSET_{min}$ _____ Postulate: $\tau_{vis,min}$< 0.1 Benchmark: <u>increase of 10% duration in "tolerable" (low-glare) VDU working conditions</u> in specified geometric configuration compared to good solar control or low-e glazing for location and "reference office". Determination method: lighting simulation coupled to energy simulation; illuminance on work plane and/or room temperature as control parameters; parameter sensitivity study to variation in $\tau_{vis,min}$ for constant $\tau_{vis,max}$:$\tau_{vis,min}$ coupled to realistic variation of $TSET_{max}$ Postulate: $\tau_{vis,min}$> 0.05 Benchmark: minimum "tolerable" availability of daylight Determination method: standards for natural lighting of offices

Degree of glare, described by transmission components derived from BTDF (REVIS result)	photogoniometric	Threshold value for transmission components. Benchmark: degradation not faster than for good solar control or low-e glazing for location and "reference office". Determination method: durability study on switchable and conventional glazing
View retention index (REVIS result)	equation using transmission components	Threshold value for transmission components. Benchmark: degradation not faster than for good solar control or low-e glazing for location and "reference office". Determination method: durability study on switchable and conventional glazing
$d\tau_{vis}/dt$ for different states	Spectrophotometric or luxmeter	Postulate: $t(\tau_{vis,max})$-$t(\tau_{vis,min})$ < 10 minutes. Benchmark: <u>increase of 10% duration in "tolerable" (low-glare) VDU working conditions</u> in specified geometric configuration compared to good solar control or low-e glazing for location and "reference office". Determination method: lighting simulation coupled to energy simulation; illuminance on work plane and/or room temperature as control parameters; parameter sensitivity study to variation in $t(\tau_{vis,max})$-$t(\tau_{vis,min})$ for constant $\tau_{vis,max}$ and $\tau_{vis,min}$ coupled to realistic values of TSET

Colour rendering index	Spectrophotometric or luxmeter	Postulate: delta E* < ? Benchmark: "acceptable" colour Determination method: comparison with "accepted" conventional glazing _____ Postulate: <u>Colour shift: <5 in delta E</u>* (CIE) (with time), <1 in delta E* between windows Benchmark: "Tolerable" colour difference Determination method: study on perception of colour in association with glazing
Homogeneous appearance	visual inspection, luxmeter	<u>Tolerances for visible defects</u> as specified in guidelines to assess the visible quality of insulating glass units or laminated safety glass, prepared by national glazing trade associations (e.g. DIN EN ISO 12543-6)
Homogeneous switching between panes	visual inspection, photo-documentation	Benchmark: "inhomogeneous" duration < 10 minutes per switching process
Control unit adaptability	monitoring window operation	Postulate: correct operation for periods in one state ranging from 1 hour to 1 day, glazing temperatures between -20 °C and 80 °C, accumulated cycles between 1 and 14000 Benchmark: < 10 % duration in "incorrect" state for lighting Determination method: parameter variation in building lighting simulation
Control unit reliability	Monitoring window transmittance in operation	Benchmark: 95 % availability
U value	Hot-box, hot-plate or calculations from components	e.g. EN673, EN674, EN675, ISO ... Benchmark: $U_{cog} < 1.1 \ Wm^{-2}K^{-1}$

Thermal comfort	determination of "operative temperature" from air and surface temperatures, and incident radiation	Benchmark: "tolerable" comfort Determination method: comparison with "accepted" conventional glazing, statistical study with twin cells
Privacy	determination of view obstruction from outside to inside under determined lighting conditions	Benchmark: view obstruction of light curtains or screens
Mechanical properties as for conventional glazing	Testing methods as in standards for conventional glazing	prEN 1279
Power consumption	power meter	Benchmark: < 10 % of the building energy saved in comparison to good solar control or low-e glazing for location and "reference office". Determination method: as specified above by building energy simulation

C. Potential failure modes, critical factors of environmental stress and degradation

Failure/Damage mode / Degradation process	Degradation indicator	Critical factors of environmental stress/ Degradation factors/Suitable accelerated tests
Glazing remains dark Glazing remains light Switching becomes unacceptably slow Switching range decreases Appearance is not homogeneous (critical in "steady state", less critical during switching) Switching range increases Shift in upper and lower transmittance values Delamination Haze, blur Yellowing Colour shift	$\tau_{vis}(t) = \tau_{vis,min}$ $\tau_{vis}(t) = \tau_{vis,max}$ $d\tau_{vis}/dt$ $TSET_{max} - TSET_{min}$ Spatial differences in τ_{vis} Visual observation of film degradation (spots, crazing, etc.)	Elevated temperatures (more critical for coloured state) UV radiation Sudden temperature changes (laminated devices, not all solid-state with EVA or PVB) Gradients in spatial temperature distribution Leakage of air (O_2, H_2O, pollutants) into EC laminate or GC-DGU High humidity Condensation Inappropriate control strategies Mechanical deformation (short-circuiting in coating) due to pressure differences, vibration Switching frequency Continuous duration in a given state (memory effects)

11.   Appendix II: Relevant durability testing standards

(October, 2003)
International
- DIN EN ISO 12543-1 Glass in building - Laminated glass and laminated safety glass - Part 1: Definitions and description of component parts (1998-08)
- DIN EN ISO 12543-2 Glass in building - Laminated glass and laminated safety glass - Part 2: Laminated safety glass (1998-08)
- DIN EN ISO 12543-3 Glass in building - Laminated glass and laminated safety glass - Part 3: Laminated glass (1998-08)
- DIN EN ISO 12543-4 Glass in building - Laminated glass and laminated safety glass - Part 4: Test methods for durability (1998-08) Summary: Testing at elevated temperature (100°C), high air humidity (100% at 50 °C), UV-enhanced simulated solar radiation (900 Wm^{-2}), monitoring by visual observation and visible transmittance measurement
- DIN EN ISO 12543-5 Glass in building - Laminated glass and laminated safety glass - Part 5: Dimensions and edge finishing (1998-08)
- DIN EN ISO 12543-6 Glass in building - Laminated glass and laminated safety glass - Part 6: Appearance (1998-08)

Europe
- DIN EN 410; Glass in building – Determination of luminous and solar characteristics (1998-12)
- DIN EN 673; Glass in building – Determination of thermal transmittance (U value) – calculation method (including Amendment A1:2000) (2001-01)
- DIN EN 1096; Glass in building - Coated glass
- DIN EN 1096-1 Part 1: Definitions and classification (Section 6; Visual faults) (1999-01)
- DIN EN 1096-2 Part 2: Requirements and test methods for durability of A, B and S coatings (2001-05)
- DIN EN 1096-3 Part 3: Requirements and test methods for durability of class C and D coatings (2001-05)
- The DIN EN 1096 family of standards is applied to test the durability of thin films.
  The following tests are included:
  Condensation resistance
  Acid resistance
  Neutral salt spray resistance
  Abrasion resistance
  Solar radiation resistance

- prEN1279 – Glass in Building; Insulating Glass Units
  (It is anticipated that this standard will come into force by the end of 2001.)
- Summary of aspects which may be relevant for accelerated testing of chromogenic glazing
- prEN1279-1; Generalities, dimensional tolerances and rules for the system description (1995-09)
  The following characteristics are treated:
  resistance to fire
  reaction to fire
  external fire performance

bullet resistance: shatter properties and resistance to attack
explosion resistance: shatter properties and resistance to impact
burglar resistance: shatter properties and resistance to attack
pendulum body impact resistance: shatter properties (safe breakability) and
resistance to impact
mechanical resistance: resistance against sudden temperature changes and
temperature differentials (prEN 1863-1, prEN 12150-1, prEN 12337-1, prEN
WI00129055-1)
mechanical resistance: resistance against wind, snow, permanent load and/or
imposed loads of the glass unit (prEN 13474)
mechanical resistance: resistance against wind, snow, permanent load and/or
imposed loads of the edge seal where required (e.g. for structural sealant glazing)
(prEN 13022)
direct airborne sound reduction
energy conservation and heat retention; thermal transmittance (U value) (EN 673)
energy conservation and heat retention; light transmittance and reflection (EN 410)
energy conservation and heat retention; total solar energy transmittance (solar
factor) (EN 410)
optical and visual quality for bubbles, optical distortions, bows, etc (prEN 1096,
prEN 12150, WI00129055, WI00129..., prEN 1863, EN 12543-6)

prEN1279-2; Long-term test method and requirements for moisture penetration (1994-08)
Section 5 describes a climate test which must be passed by any gas-filled, insulating glass
unit. It is designed as an accelerated test for moisture penetration into a sealed glass unit.
The high humidity/temperature test procedure consists of two parts.
The first part consists of 56 temperature cycles, each lasting 12 hours. After an initial
temperature decrease at 14 °C/h from room temperature to –18 °C, one complete cycle is
defined as follows: 1 h at –18 ±1°C, 5 h temperature increase of (14±2)°C/h, 1 h at
53±1°C, 5 h temperature decrease of –(14±2)°C/h (to -18±1 °C). While the temperature is
lower than +10 °C, the relative humidity is not specified, but a value less than 20 % is
implied. At +10 °C, the relative humidity should be 20 %, and then increase with the
temperature until a value exceeding 95 % is held while the temperature exceeds 42 °C (a
total of 4 hours). The relative humidity should then decrease with the temperature until the
value of 20 % is again reached when the temperature is +10 °C.
The second part consists of maintaining the samples at a constant temperature of 58 °C
and relative humidity exceeding 95 % for seven weeks.
The dew point and moisture content of the sealed glass unit are measured before and
after the climate test, and the average moisture penetration index is determined.
This test does not include exposure to UV or solar simulator radiation.

prEN1279-3; Long-term test method and requirements for gas leakage rate and for gas
concentration (1995-08)
tolerances
The climate test employed here is as specified in prEN1279-2, with the following
modifications: the number of cycles is reduced to 28, and the time at a constant
temperature of 58°C is reduced to 4 weeks.
The gas leakage rate at 20 °C is determined after subjecting the test specimen to the
climate test.

prEN1279-4; Methods of test for the physical attributes of edge seals (1996-10)
Section 5.1.3 describes ageing regimes which must be applied to any gas-filled, insulating glass unit. They are intended as accelerated ageing tests for the adhesion and cohesion of edge seals (glass-sealant-glass joints).
The test specimens are glass-sealant-glass joints (without a gas-filled cavity).
The test consists of three parts; heat exposure, water immersion and UV exposure.
Different test specimens are used for each test, i.e. the tests are not cumulative.
The test specimens are heat aged in a closed oven at 60±2 °C for 168±5 h.
The test specimens are immersed in distilled or de-ionised water for 168±5 h.
The test specimens are exposed for 96±4 h to UV irradiation perpendicular to the glass at an intensity in the UVA range (315 nm-380 nm) of 40±5 Wm^{-2}.
The tensile strength is measured for unexposed specimens and for specimens exposed to each type of ageing condition.

prEN1279-5; Evaluation of conformity (2001-10)
From Table 1: Characteristics of interest for factory production control:
periodic, low-frequency tests and inspections:
visual inspection of the seal geometry
short climate test (21 days at T=58 °C, r.h. ≥ 95 %)
check of gas concentration
gas permeability test
fogging test results

prEN1279-6; Factory production control and periodic tests (1997-04)
From Annex C: Fogging test
This test checks whether unacceptable condensation appears on the glass surfaces facing the unit cavity, due to release of volatile substances. The release of gaseous substances is achieved by applying heat at a point on the relevant organic component. Condensation is achieved by cooling a spot of the glass surface.
The heated surface temperature nearest to 20 – 30 % of the relevant component is to be held between 50 and 60 °C.
The cold spot, which is to have an area of 10 % of the unit surface, is to be 27 – 33 K lower than the heated surface temperature, as specified above.
The test duration is 168±4 h.
The test specimens are examined for fogging or permanent condensation visually in a specified viewing box.

DIN EN 1863-1; Glass in building; Heat strengthened soda lime silicate glass – Part 1: Definition and description (2000-03)
DIN prEN 1863-2; Glass in building - Heat strengthened soda lime silicate glass - Part 2: Evaluation of conformity (2001-09)

DIN EN 12150-1; Glass in building – Thermally toughened soda lime silicate safety glass - Part 1: Definition and description (2000-11)
DIN prEN 12150-2; Glass in building - Thermally toughened soda lime silicate safety glass - Part 2: Evaluation of conformity (2001-09)

DIN EN 12337-1; Glass in building – Chemically strengthened soda lime safety glass - Part 1: Definition and description (2000-11)
DIN prEN 12337-2; Glass in building – Chemically strengthened soda lime safety glass - Part 2: Evaluation of conformity (2001-09)

prEN 12975-2 Thermal solar systems – Collectors – Part 2: Test methods (1998-01)

DIN EN 12898 Glass in building – Determination of the emissivity (2001-04)

DIN prEN 13022; Glass in building – Structural sealant glazing – Part 3: Sealants, test methods (1998-01)

prEN 13474; Glass in building – Design of glass panes – Part 2: Design for uniformly distributed loads (2000-05)

prEN WI00129055-1; Glass in building – Heat soaked thermally toughened soda lime silicate safety glass

National:
France
MO3 Humidity test for coated IGU (In-house test developed and conducted by CEBTP or OMV)
MO 08 Adherence test for coated IGU (In-house test developed and conducted by CEBTP or OMV)
MO20 Compatibility of sealants with glass coating (In-house test developed and conducted by CEBTP or OMV)
(Source of MO standards
CEBTP
M.Moïse Riotteau (Dep. Fenêtres et Fassades)
Domaine de Saint-Paul
B.P. 37
78470 Saint-Rémy-Lès-Chevreuse
France
Tel. 01.30.85.23.32, Fax 01.30.85.23.20)

Germany
DIN 1286-1 Insulating glass units; air filled; ageing behaviour (1994-03)
DIN 1286-2 Multiple-walled insulating glazing units; gas filled; ageing behaviour, limiting deviations of gas volume fraction (1989-05)
DIN 52 293 Testing of glass; testing the gas tightness of gas-filled insulating glass units (1987-12)
DIN V 52 293 Part 2 Testing of glass; testing the gas tightness of gas-filled multiple-walled insulating glazing units; determination of the loss in gas by gas chromatography and thermal conductivity detector (1988-11)
DIN 52 294 Testing of glass; determination of the loading of desiccants in multiple –walled insulating glazing units (1988-11)
DIN 52 344 Testing of glass; testing the effect of alternating atmosphere on multi-layer insulating glass (1984-05)
DIN 52 345 Testing of glass; determination of dew point temperature of insulating glass units; laboratory test (1987-12)

<u>Japan</u>
In Japan, JIS (Japanese Industrial Standard) is the only national standard related to this issue, which is listed below. However, this is the only necessary minimum and mostly specifications are determined between manufacturers and customers.

List of JIS related to glazing and its testing procedures
A-5759:Adhesive Films for Glazings
B-4111:Solar Water Heater for Dwellings
B-7751:Glass-Enclosed Carbon-Arc Type Apparatus for Artificial Light Exposure Tests
B-7752:Light-and-Water-Exposure Apparatus (Enclosed Carbon-Arc Type)
B-7753:Light-and-Water-Exposure Apparatus (Open-Flame Sunshine Carbon-Arc Type)
B-7754:Light-Exposure and Light-and-Water-Exposure Apparatus (Xenon-Arc Lamp Test)
R-3106:Testing Method on Transmittance and Reflectance for Daylight and Solar Radiation and Solar Heat Gain Coefficient of Flat Glass
R3211:Safety Glass for Road Vehicles
R3212:Test Method of Safety Glass for Road Vehicles

<u>USA</u>
ASTM Standard E 2141-02 "Standard Test Methods for Assessing the Durability of Absorptive Electrochromic Coatings on Sealed Insulating Glass Units" (2002)
Summary: Exposure of electrochromic windows (ECW) to simulated solar irradiance in a temperature- and humidity-controlled chamber at selected sample temperatures ranging from 70°C to 105°C while the ECW's are cyclically coloured and bleached, monitoring of the photopic (visible) transmittance at ~22°C and the elevated temperatures.

ASTM Standard E 2240-02 "Standard Test Method for Assessing the Current-Voltage Cycling Stability at 90°C (194°F) of Absorptive Electrochromic Coatings on Sealed Insulating Glass Units" (2002)

ASTM Standard E 2241-02 "Standard Test Method for Assessing the Current-Voltage Cycling Stability at Room Temperature of Absorptive Electrochromic Coatings on Sealed Insulating Glass Units" (2002)

ASTM Draft E GGG (Draft 1a, 6/12/2003) "Standard Guide for Assessing the Durability of Absorptive Electrochromic Coatings within Sealed Insulating Glass Units" (2003)

ASTM Draft E UUU (Draft 1a, 6/12/2003) "Standard Test Method for Measuring the Uniformity of an Absorptive Electrochromic Coating on a Glazing Surface" (2003)

1. Fenestration Component Test Methods and Specifications
1.1   Perimeter Sealants
1.1.1 AAMA 808.3 "Specifications for Exterior Perimeter Sealing Compounds
1.1.2 ASTM C 920 "Specification for Elastomeric Joint Sealants"
1.1.3 ASTM C1085 "Standard Specification for Butyl-Based Solvent-Release Sealants"
1.1.4 AAMA 803.3 "Specification for Narrow Joint Seam Sealers"
1.1.5 ASTM C1311 "Standard Specification for Solvent-Release Sealants"
1.1.6 ASTM C834 "Standard Specification for latex Sealants"
1.2   Glazing Compounds
1.2.1 ASTM C669 "Standard Specification for Glazing Compounds for Back Bedding and Face Glazing of Metal Sash"

1.2.2   ASTM C797 "Standard Practices and Terminology for Use of Oil and Resin Based Putty and Glazing Compounds"

1.2.3   ASTM C741 "Standard Test Method for Accelerated Aging of Wood Sash Face Glazing Compound"

1.2.4   AAMA 802.3 "Specification for Ductile Back Bedding Compound"

1.2.5   AAMA 805.2 "Specification for Bonding Type Bedding Compound"

1.2.6   AAMA 804.3; 806.3; 807.3 "Specifications for Back Bedding Mastic Type Glazing Tapes"

1.2.7   ASTM C1281 "Standard Specification for Performed Tape Sealants for Glazing Applications"

1.2.8   AAMA 810.1 "Specification for Expanded Cellular Glazing Tapes"

1.3   Gaskets

1.3.1   ASTM C509 "Standard Specification for Cellular Elastomeric Preformed Gasket and Sealing Material"

1.3.2   ASTM C864 "Specification for Dense Elastomeric Compression Seal Gaskets, Setting Blocks and Spacers"

1.4   Spacers

1.4.1   SIGMA A-200 "Voluntary Test Methods and Voluntary Performance Quality Assurance Criteria for Spacers for Sealed Insulating Glass Units"

1.5   Insulating Glass Units

1.5.1   ASTM E-774 "Standard Specification for Sealed Insulating Glass Units"

1.6   Glass

1.6.1   ASTM C1036 "Standard Specification for Flat Glass"

1.6.2   ASTM C1048 "Standard Specification for Heat-Treated Glass"

1.6.3   ASTM C1172 "Standard Specification for Laminated Architectural Flat Glass"

1.6.4   ASTM E1300 "Determining Load Resistance of Glass in Buildings"

1.7   Desiccant

SIGMA A2801 "Recommended Voluntary In-Plant Test Methods and Performance Criteria for Desiccants for Sealed Insulating Glass Units"

2.   Fenestration Assembly Tests

2.1   A number of fenestration tests currently exist for determining performance criteria. These tests include Water Penetration (ASTM E-547 or ASTM E-331); Thermal Transmission (ASTM C1199 or AAMA 1503.1); Structural Strength (ASTM E-330); and Chromogenic Functionality (ASTM-TBD). Chromogenic functionality will include but not be limited to maximum controllability in the colored and bleached states, their visual appearance, switching time, and photopic contrast ratio between the colored and bleached states.

2.2   To meet the requirement of this practice, a product shall be tested to meet the requirements of a nationally recognized product performance standard (see AAMA/NWWDA 101/IS2-97) in the following sequence.

2.2.1   The specimen shall be tested in accordance with ASTM E283.

2.2.2   The specimen shall be tested in accordance with ASTM E547 (or E331).

2.2.3   If specified, the specimen shall be tested in accordance with ASTM C1199 (or AAMA 1503).

2.2.4   The specimen shall be tested in accordance to ASTM E330 (at designated pressures for design classification).

2.2.5   The test specimens shall be chosen in accord with Section 8.

2.2.6   The test specimen must pass a qualification test, which simulates a sudden rainstorm (water-spray) when the device is operating, by maintaining its chromogenic functionality.

2.3   The specimen shall then be exposed to the following accelerated tests (in sequence).
2.3.1   The specimen shall be exposed to 1/2 of the specified cycles as referenced in AAMA 910-93 "Voluntary Life Cycle Specifications and Test Methods for Architectural Grade Windows and Sliding Glass Doors."
2.3.2   The specimen shall be tested for 100 cycles at 0.75 (75%) of the designated pressure for the design classification in accordance with ASTM E-1233 "Standard Test Method for Structural Performance of Exterior Windows, Curtain walls, and Doors by Cyclic Static Air Pressure."
2.3.3   The specimen shall be exposed to the remaining half of the specified motion cycles as reference in AAMA 910-93 "Voluntary Life Cycle Specifications and Test Methods for Architectural Grade Windows and Sliding Glass Doors"

2.4   Upon completion of the accelerated tests, the specimen shall be tested in accordance with Section 2.2.1, 2.2.2, and 2.2.3.
The results of these tests shall be reported in Section 9.

Useful web sites

www.afnor.fr Association française de normalisation
(Information provided in French and English on NF and EN standards)
www.din.de   Deutsche Industrie Norm
(Information provided in German and English on DIN and EN standards)
www.jisc.org Japanese Industrial Standards Committee
(Information provided in Japanese and English on JIS standards)
global.ihs.com   Global Engineering Documents
(Information in English on international and national standards)
www.iso.ch   International Organization for Standardization

12.   Appendix III: Durability Testing Facilities for Advanced Glazing

Within Task 27, Project B2, the work on testing the durability of advanced glazing required special modifications to existing climatic chambers, and the development of a new testing box for outdoor exposure.

Climatic Chambers for Accelerated Ageing
Durability tests at elevated air temperatures, with or without simulated solar radiation, were made in climatic chambers at three research institutes; Fraunhofer ISE in Freiburg, Germany, CSTB in Grenoble, France and NREL in Golden, USA. The most important characteristics of the climatic chambers are summarised in Table 1. Of specific interest in the characterisation of glazing is the measurement of the glazing transmittance. At CSTB, visible transmittance is measured on-line in the chamber by determining the signal ratio of luxmeters located in front of and behind the glazing, at equal distances from a light source (Figures 1 and 2). At Fraunhofer ISE, the visible transmittance was determined spectrophotometrically off-line, or LED's can be used to monitor the transmittance at a single wavelength on-line. The approach taken at NREL is to determine the visible transmittance from off-line spectrophotometric measurements.

Table 1: Characteristics of climatic chambers used for durability testing of advanced glazing.

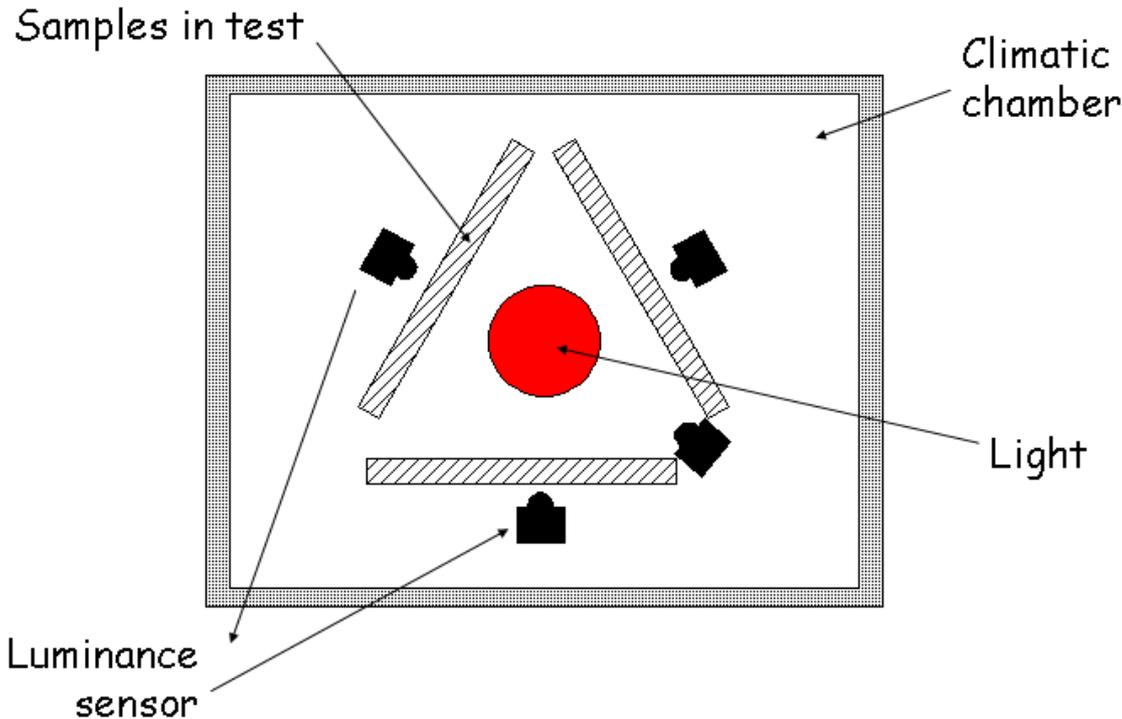|	CSTB	Fraunhofer ISE	NREL
Climatic chamber	single chamber, manufactured by Weiss Umwelttechnik	double chamber, manufactured by Weiss Umwelttechnik	single chamber, Atlas XR260
Sample position	vertical	vertical	horizontal
Max. sample capacity (area)	3 @ 400 x 400 mm² (see Fig. 1) Chamber volume : 680x540x820 mm^3 (≈300 litres)	max. 1800 mm x 1500 mm, can be subdivided as required	max. 1200 mm x 1800 mm, can be subdivided as required
Temperature range	-40 – +180 °C	-40 - +100 °C and -20 - +100 °C	-40 - +95 °C
Relative humidity	5 -98%	10 - 95 %	5 - 95 %
Solar simulator spectrum	Daylight OSRAM DULUX L 24W/19-250 1200 lm	app. AM1, global	app. AM1.5 global
Solar simulator intensity in sample plane	-	1100 - 1600 Wm^{-2}	1 - 1.5 kWm^{-2}
Transmittance measurement	with luxmeters: one reference and behind each sample, spectrophotometric off-line if required	monochromatic with LED's or spectrophotometric on-line, spectrophotometric off-line	spectrophotometric off-line

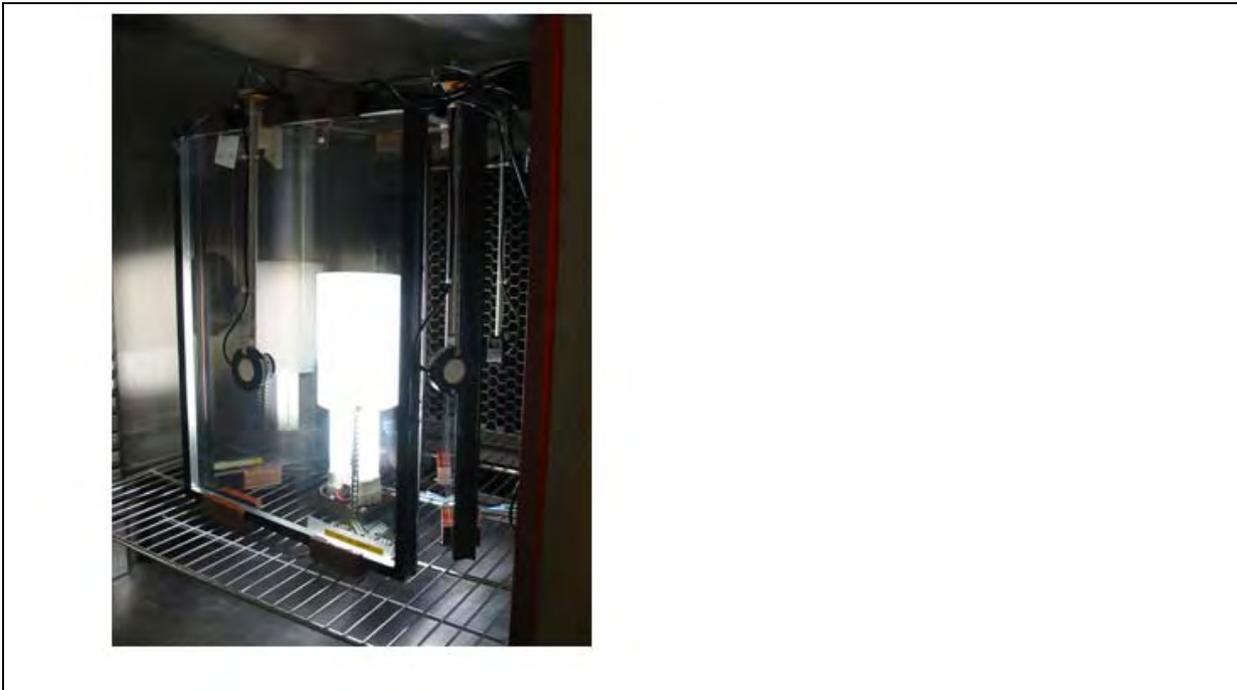Fig. 1: Horizontal cross-section of the climatic chamber used at CSTB.

Fig. 2: Advanced glazing samples mounted for testing in the climatic chamber at CSTB.

Fig.3: Double climatic chamber at Fraunhofer ISE.

Fig.4: Interior view of the climatic chamber at NREL, showing the scanning radiometer for homogeneity measurements.

Figures 2 to 4 illustrate the test box developed and used at Fraunhofer ISE and CSTB for exposing insulated glazing units (IGU's) to natural weathering conditions. The IGU is mounted to form the upper cover of the text box. The interior walls are lined with highly reflective foil to simulate a box of "infinite lateral dimensions". Multiple reflections between the base of the box and the tested IGU are minimised by the base construction, consisting of an anti-reflectively coated glass pane and a separate absorber, which is cooled by natural ventilation. Air temperatures at various points within the box and the glazing surface temperatures were measured with thermocouples at CSTB and Pt100 resistance temperature probes at Fraunhofer ISE. The ratio of the luxmeter in the box to one mounted in a parallel plane (tilted at 45 °, orientated to the south) was used to determine the glazing transmittance.

If required, an angle-dependent function was applied to correct for the different incident angles of the sun, which was used as the light source for the luxmeter measurements.

The same measurement principle is applied for the determination of the spectral transmittance, using integrating spheres connected to diode-array spectrometers. Four IGU's, each with an area of 590 mm x 895 mm, can be tested in parallel in such a test box.
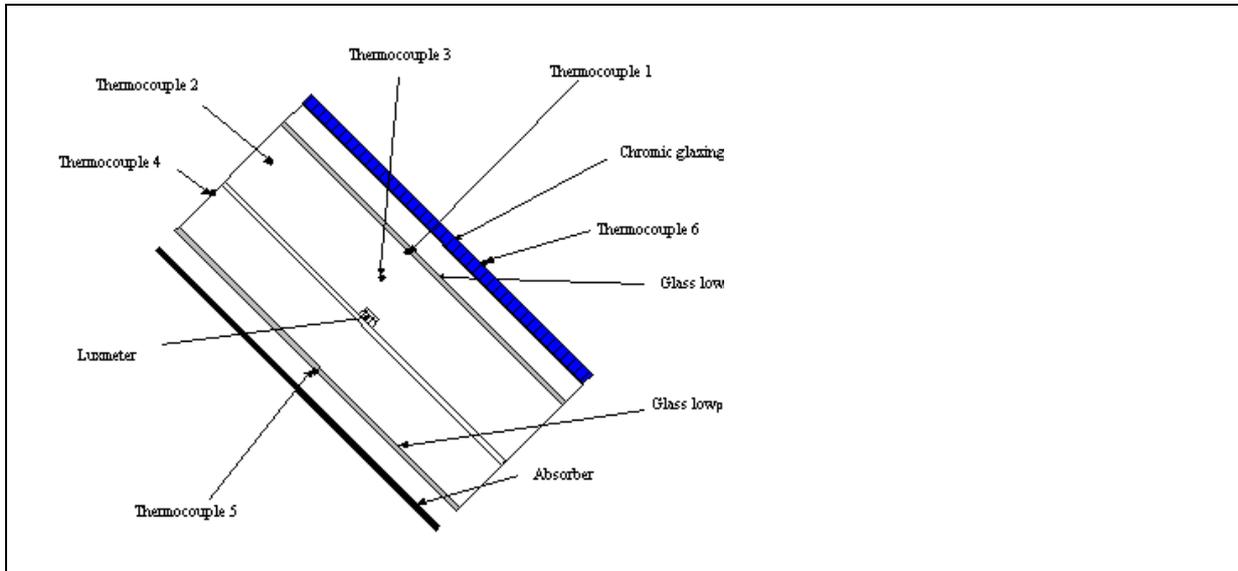

Fig. 5: Vertical cross-section through the test box as installed at CSTB and Fraunhofer ISE. Instrumentation as at CSTB.

Fig. 6: View of the test box for outdoor exposure and meteorological instruments at CSTB

Fig. 7: View of the test box for outdoor exposure in Freiburg (back absorber plate removed for better visibility).

For more detailed information on the test facilities described, readers are invited to contact the following persons:

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