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Solar energy — Collector components and materials —

Part 3: Absorber surface durability

Energie solaire — Composants et matériaux du collecteur —

Partie 3: Durabilité de la surface de l'absorbeur

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Foreword

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The committee responsible for this document is ISO/TC 180, *Solar energy*.

ISO 22975 consists of the following parts, under the general title *Solar energy — Collector components and materials*:

— *Part 3: Absorber surface durability*

The following parts are under preparation:

— *Part 1: Evacuated tubes – Durability and performance*

— *Part 2: Heat-pipe for solar thermal application — Durability and performance*

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Introduction

To effectively select, use and maintain a material in a given application, its degradation under service conditions must be predicted prior to use. Preferably, the durability of the material should be expressed quantitatively in terms of an expected service life. Durability in this case is the ability of a material to withstand deterioration caused by external factors in the environment, which may influence the performance of the material under service conditions. Service life is defined as the period of time after installation during which specific material properties important for the performance of the material meet or exceed minimum acceptable values.

The service life of a material is, thus, not solely dependent on its physical and chemical properties, but also on its performance requirement in the application considered, and on the external environmental factors, which influence performance under service conditions. In design work, the important question is if a specific material can be expected to have a service life longer than a certain value, the so-called design service life; the latter dictated by life cost considerations taking into account the total system. Service life assessment may be based on feed-back data from practice or on results from so-called qualification or acceptance durability tests.

The present recommended qualification procedure for solar absorber surface durability is based on the conduct of a series of short-term durability tests. During a test the optical performance of the absorber surface tested is determined by measuring its solar absorptance and thermal emittance. From the loss in optical performance of the absorber surface, its failure time in the test performed is assessed and compared with the shortest acceptable failure time set by the design service life of the absorber. Design service life, performance requirement defining failure time in terms of loss in optical performance, classification of type and levels of environmental stress are set under the assumption, that the absorber surface tested will be installed in a vented flat plate solar collector for use in domestic hot water systems and combisystems or under similar operating conditions.

The recommended qualification procedure may favourably be used in the development and validation of new kinds of absorber surfaces. From the results of tests, it can be concluded whether it is likely that an absorber surface tested may meet the requirement for an acceptable service life also in practice. The recommended durability testing procedure has proved to give results in fairly good agreement, both qualitatively and quantitatively, with what has actually been observed on absorber surfaces tested for longer time periods in solar collectors working under conditions corresponding to that in a typical domestic solar hot water system or combisystem. Nevertheless, if the tested absorber could not be qualified by present procedure, a more comprehensive investigation on durability is recommended and can still lead to a qualification.

The present procedure consists of three parts to test the absorber with respect to its stability against high temperature, against high humidity and condensation and against corrosion caused by atmospheric sulfur dioxide. The three parts are independent and can be assessed individually.

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Solar energy — Collector components and materials —

Part 3: Absorber surface durability

1 Scope

This part of ISO 22975 is applicable to the determination of the long term behaviour and service life of selective solar absorbers for use in vented flat plate solar collectors working under conditions corresponding to that in a typical solar domestic hot water system or combisystem.

This part of ISO 22975 specifies a failure criterion of a solar absorber based on changes in optical performance of the absorber. The optical properties of interest are solar absorptance and thermal emittance.

This part of ISO 22975 specifies durability testing procedures focused on resistance to high temperatures and condensation of water on the absorber surface as well as high humidity in the presence of sulfur dioxide.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 4624, *Paints and varnishes — Pull-off test for adhesion*

ISO 8407, *Corrosion of metals and alloys — Removal of corrosion products from corrosion test specimens*

ISO 9050, *Glass in building — Determination of light transmittance, solar direct transmittance, total solar energy transmittance, ultraviolet transmittance and related glazing factors*

ISO 10062, *Corrosion tests in artificial atmosphere at very low concentrations of polluting gas(es)*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

3.1
design service life
time period of exposure under service conditions after installation during which the absorber surface is expected to meet the performance requirement

3.2
failure time
time period of exposure in the test at which the performance requirement limit is reached

3.3
solar absorptance, α_S
fraction of solar radiation energy absorbed by an absorber surface

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3.4
thermal emittance, ε
ratio between the energy per unit area radiated by a surface at a given temperature and the corresponding energy radiated by a perfect black body at the same temperature

3.5
performance criterion function
PC
change in performance of an absorber surface in terms of changes in solar absorptance and thermal emittance

4 Requirements and classification

4.1 For classification of the durability of the absorber surface, the following performance requirement shall apply:

$$PC = -\Delta\alpha_s + 0{,}50\Delta\varepsilon \leq 0{,}05 \quad (1)$$

where

$\Delta\alpha_s$ is the change in the solar absorptance defined as

$$\Delta\alpha_s = \alpha_{s,t} - \alpha_{s,i} \quad (2)$$

with $\alpha_{s,t}$ equal to the value of the solar absorptance at the actual time of the test or at service, and

with $\alpha_{s,i}$ equal to the initial value of solar absorptance

where

$\Delta\varepsilon$ is the change in the thermal emittance

$$\Delta\varepsilon = \varepsilon_t - \varepsilon_i \quad (3)$$

with ε_t equal to the value of the thermal emittance at the actual time of the test or at service and

with ε_i equal to the initial value of thermal emittance.

NOTE 1 This performance criterion function is primarily based on location averaged values of the performance of typical solar domestic hot water systems and combisystems.[4] But, in the IEA Task 10 testing procedure referred to, a slightly different definition of PC is used, namely PC = $-\Delta\alpha_s - 0{,}25 \times \Delta\varepsilon$. Investigations made by the IEA MSTC group, however, showed that a weighting factor of 0,5 for the thermal emittance is more appropriate.[9]

NOTE 2 Higher values for the PC function may be used if considered more appropriate. PC < 0,10 should mean that the optical performance of absorber surface, and thus also the performance of solar domestic hot water system and combisystems, is allowed to be reduced to a level equal to 90 % of its original value during the design service life time period.[4]

4.2 Before durability testing of an absorber surface, all test specimens, sampled and prepared as specified in 5.1, shall be characterized with respect to their value for solar absorptance, determined as specified in 5.2, and their value for thermal emittance, determined as specified in 5.3.

To be qualified for testing, the set of test specimens shall have a standard deviation in the determined values for solar absorptance of less than 0,01 and for the determined values of thermal emittance a standard deviation less than 0,04.

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4.3 For coated absorber surfaces, three extra test specimens shall be prepared and the adhesion of coating on those test specimens shall be assessed, as specified in 5.5.

For the absorber to be qualified for testing, the adhesion of coating shall be > 0,15 MPa for all test specimens (ISO 4624).

NOTE If considered accurate enough, the adhesion of the coating may be assessed by a more simple method. The method of ISO 2409[1] may be used and the requirement for satisfactory adhesion be set at the degree of 1. Alternatively, some suitable method in ISO 2819[2] may be used.

4.4 For an absorber surface to be qualified with respect to its thermal stability, the procedure of durability testing as specified in Clause 6 shall be applied.

An absorber surface with sufficient thermal stability shall meet the requirement for test results as is specified in 6.4.

4.5 For an absorber surface to be qualified with respect to its resistance to condensed water when used in a non-airtight solar collector with more or less uncontrolled ventilation of air in the solar collector, the procedure of durability testing as specified in Clause 7 shall be applied.

An absorber surface with sufficient resistance to condensed water shall meet the requirements for test results as are specified in 7.4.

4.6 If an absorber surface should be qualified with respect to its resistance to degradation caused by sulfur dioxide as an airborne pollutant, the procedure of durability testing as specified in Clause 8 shall be applied (optionally).

An absorber surface may be qualified for use in two classes of solar collectors; the two classes representing different severity classes as regards atmospheric corrosivity.

Solar collector of type A: Airtight solar collector or solar collector with controlled ventilation of air in the space between the absorber surface and the cover plate. At the top and at the bottom of the frame of the solar collector, it should be equipped with ventilation holes. The atmospheric corrosivity at the bottom part of the solar collector under service conditions may typically correspond to a corrosion rate of zinc of 0,1 g/m^2 per year.

Solar collector of type B: Non-airtight solar collector with more or less uncontrolled ventilation of air in the solar collector. The atmospheric corrosivity at the bottom part of the solar collector under service conditions corresponds to a corrosion rate of zinc of 0,3 g/m^2 per year.

An absorber surface with sufficient resistance to degradation caused by sulfur dioxide in high humidity air, either regarding only a type A solar collector or regarding both type A and type B solar collectors, shall meet the requirements for test results as are specified in 8.6.

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5 Test methods for assessing material properties as measure of absorber performance

5.1 Sampling and preparation of test specimens

For durability testing, test samples with an absorber surface area of preferably (50 × 50) mm shall be prepared. Sampling from larger pieces of absorber plate shall be made in such a way that variation in the optical properties between the different test specimens is minimized. Three extra test samples are also required for the assessment of the adhesion of the coating of un-aged test samples. For execution of the complete programme of durability tests of this recommended procedure, a minimum of 18 test samples are required.

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5.2 Sample conditioning

Determine the mean of solar absorptance and the mean of thermal emittance of three samples. Determine the possible maximum absorber temperature for a collector covered with anti-reflection (AR) coating according Table B.1. Temper all 18 samples at this maximum absorber temperature for at least 5 h with an apparatus similar to that described in 6.2. Test three test samples for adhesion according to 5.5 and proceed with the other 15 test samples if they pass the test.

5.3 Solar absorptance

Determine the value of the solar absorptance for each of the 15 test samples from reflectance measurements as specified in A.1. For the complete set of test samples calculate also the mean value and standard deviation of solar absorptance.

5.4 Thermal emittance

Determine also the value for the thermal emittance for each of the 15 test samples as is specified in A.2. For the complete set of test samples calculate also the mean value and the standard deviation of thermal emittance.

5.5 Adhesion

Determine the adhesion of the absorber coating either according to ISO 4624 (use the general method for testing both rigid and deformable substrates when selecting test assembly and use test cylinders with a diameter of 20 mm) or by means of a simpler method for assessment of adhesion (see 4.3) and proceed as specified in the relevant standard.

6 Tests for assessing the thermal stability of absorber surfaces

6.1 Principle

6.1.1 High-temperature ageing is frequently used in many technical application areas for the assessment of thermal stability of materials. A high temperature accelerates all kinds of processes, normally leading to an increased rate of degradation of materials. For a selective absorber coating composed of small metal particles, a high temperature enhances oxidation of metal decreasing mainly the absorptance of coating.

6.1.2 When installed in a single-glazed flat plate solar collector, an absorber surface is exposed to a temperature which may vary greatly; in the extreme case from −20 °C up to more than 200 °C. As a measure of the level of thermal load, the effective mean temperature, T_{eff}, during one year of service for an absorber surface is used here. It is defined by the following expression:

$$\exp\left(-\frac{E_{\text{T}}}{R}T_{\text{eff}}^{-1}\right)=\int_{T_{\min}}^{T_{\max}}\exp\left(-\frac{E_{\text{T}}}{R}T^{-1}\right)f(T)\,\mathrm{d}T \tag{4}$$

where

$f(T)$ is yearly based frequency function for service temperature of absorber surface in solar collector, meaning the time fraction of a year when service temperature is in the interval T to T+dT;

$T_{\max}$ is the maximal service temperature of absorber surface in the solar collector in kelvin (K);

$T_{\min}$ is the minimal service temperature of absorber surface in the solar collector in kelvin (K);

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E_T is the Arrhenius activation energy expressing the temperature dependence of a thermal degradation reaction of absorber surface;

R is the ideal gas law constant equal to 8,314 J/(mol·K).

6.1.3 The yearly based frequency function $f(T)$ is determined by the external climatic load acting on the solar collector and the optical properties of the solar absorber surface and the glazing.

In this recommended procedure it is assumed that the solar collector is under operating conditions for 11 months of a year and then producing tap water during daytime when the solar collector temperature exceeds 40 °C. For one month of a year, during summer, the solar collector is under stagnation conditions. From a thermal ageing point of view it is only during the sunny days when the solar collector is under stagnation that the temperature load on the solar absorber surface will result in significant thermal degradation. The reference thermal load or temperature frequency function for one year representing service conditions in this recommended procedure corresponds therefore to 30 sunny days when the solar collector is under stagnation; see Figure B.1.

The temperature load acting on the solar absorber surface depends also on the optical properties of the absorber surface and so does the maximum solar absorber surface temperature during stagnation conditions. The maximum solar absorber surface temperature is in this recommended procedure determined from the solar absorptance and the thermal emittance by use of interrelations shown in Table B.1. The reference thermal load in terms of an effective mean temperature is thereafter calculated as a function of the activation energy for thermal degradation by making use of the maximum absorber surface temperature.

NOTE If found more appropriate, another temperature frequency function may be used to represent service conditions. The new effective mean temperature corresponding to a specific activation energy may be calculated by use of Formula (4).

6.1.4 To assess the thermal stability of the absorber surface, short-term tests, enhancing thermal degradation of the absorber surface at a constant high temperature, are used. To convert the design service life of 25 years into a shortest acceptable failure time, t_R, for a constant temperature test to be executed at the temperature T_R, the following time-transformation function is used:

$$t_R = 25 \times 8\,760 \exp\left[-\frac{E_T}{R}\left(T_{eff}^{-1} - T_R^{-1}\right)\right] \quad (5)$$

where

T_{eff} is the effective mean temperature, in kelvin (K), of absorber surface defined by Formula (4).

The effective mean temperature will vary with the activation energy and so will also the shortest acceptable failure time for a specific constant temperature test.

6.1.5 To conclude whether an absorber surface is qualified or not, the results from at least two different constant temperature tests are needed unless the optical performance of solar absorber surface tested is unaffected during the first test. The qualification scheme and the conditions for the temperature tests are given in Figures B.2 to B.4 and Table B.2, respectively.

6.2 Apparatus

6.2.1 Testing chamber to be used for assessing the thermal stability of the absorber surface shall be constructed so that:

a) Constant temperature tests can be executed up to a temperature of at least 380 °C.

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NOTE 1 Testing chambers with circulating air heating are recommended in favour of those based on radiative heating, because the temperature difference between the sensor and the test samples will be less because of more uniform temperature condition in testing chambers of the former type.

NOTE 2 When radiative furnaces are used, the temperature of the test samples and the temperature of the temperature sensor strongly depend on the radiation exchange with the heater and therefore also on their optical properties. It is in this case preferable to measure the temperature of the test sample for heating control.

b) The temperature is maintained at level of ±1 °C after stabilized conditions have been reached after start of test.

NOTE 3 Even a symmetrical variation around the set temperature results in a higher effective mean temperature with respect to thermal degradation.

c) The temperature in the chamber is so uniform that the variation between absorber specimens tested simultaneously is within the range of ±1 °C; see NOTE 1 and 2.

d) During cooling down of chamber after high temperature exposure, the rate of temperature decrease shall be at least 10 °C/min (from 200 °C to 100 °C). If the chamber does not meet this requirement, the test samples shall be taken out of the chamber immediately after the specified testing time has been reached; see 6.3.4.

6.2.2 Instruments for measuring of optical properties of absorber surfaces complying with the requirements as are specified in Annex A.

6.2.3 Tensile tester and test cylinders for measurement of adhesion of absorber coating in accordance with ISO 4624 as specified in 5.5. If a simpler method for assessment of adhesion is used, see 4.3, use equipment complying with the requirements given in the relevant standard for assessment of adhesion.

6.3 Procedure for execution of high temperature tests

6.3.1 Select three test samples of absorber surface with known solar absorptance and thermal emittance and qualified for testing according to 4.2.

6.3.2 Increase the temperature of the testing chamber to the specified level of test. After this temperature has been reached, place the test samples of room temperature in the testing chamber.

6.3.3 Keep the test samples at this temperature level for the specified time period of test.

6.3.4 After the specified time period of test or of interruption for measurement of the extent of degradation, decrease the temperature of the testing chamber down to room temperature. The cooling rate should be at least −10 K/min until the temperature has dropped to 40 °C or to 100 K below the testing temperature, whichever is met first.

If the testing chamber does not meet the requirement for minimum rate of cooling down as specified above, the test samples shall be taken out of the testing chamber immediately after the specified time period of test has been reached. The hot test samples shall after they have been taken out of the testing chamber be placed on a thermally insulating material to minimize damages, which may result from the thermal shock the test samples are exposed to during cooling down.

6.3.5 Determine the solar absorptance and the thermal emittance of test samples as specified in Annex A.

6.3.6 Calculate from the change in solar absorptance and thermal emittance of test samples, the value of the PC function for each panel tested by use of Formula (1). Calculate also the mean value of the PC function for the different test samples.

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6.3.7 If the test was interrupted only for measurement of extent of degradation, reintroduce the test samples after measurement into the climatic chamber after stabilized test conditions at the specified levels have been confirmed.

6.4 Qualification procedure

6.4.1 Determine from the mean values of the solar absorptance and the thermal emittance of the solar absorber surface to be tested the expected maximum absorber surface temperature T_{max} by use of Table B.1 for the case of anti-reflection (AR) coating (line 1 of Table B.1); see also Figure B.2.

6.4.2 Determine from the T_{max} value the temperature T1 of the first test to be performed making use of Table B.2.

6.4.3 With a set of three test samples perform a test, as specified in 6.3, at T_1 and measure α_s and ε after the testing times of 18, 36, 75, 150, 300 and 600 h or until PC ≥ 0,05 is reached. If PC > 0,05 after 18 h of testing the solar absorber surface is not qualified with respect to its thermal stability. In all other cases, introduce the time t_1, which is the last testing/measuring time with PC ≤ 0,05.

6.4.4 If PC ≤ 0,015 after 600 h of testing, check whether the absorber surface meets the adhesion requirements as specified in 5.5. If the requirement on adhesion is met the absorber surface is qualified with respect to its thermal stability.

6.4.5 If t_1 ≥ 300 h and PC > 0,015, check whether the absorber surface meets the adhesion requirement as specified in 5.5. If the requirement on adhesion is met proceed as follows: Use Table B.2 to determine the T_3 value which corresponds to the previously determined T_{max} value. Determine also from Table B.2 the testing time t_3 which corresponds to the previously determined t_1 value; see also Figure B.3.

With a new set of three test specimens, perform a test at T_3 for a time period of t_3 and measure α_s and ε to determine PC.

If PC (T_3, t_3) ≥ PC (T_1, t_1) the absorber surface is qualified with respect to its thermal stability.

6.4.6 If t_1 ≤ 150 h proceed by using Table B.2 to determine the T_2 value which corresponds to the previously determined T_{max} value. Determine also from Table B.2 the testing time t_2 which corresponds to the previously determined t_1 value; see also Figure B.4.

With a new set of three test specimens perform a test at T_2 for a time period of t_2 and measure α_s and ε to determine PC.

If PC (T_2, t_2) ≤ PC (T_1, t_1) check whether the absorber surface meets the adhesion requirement as specified in 5.5. If the requirement on adhesion is met the solar absorber surface is qualified with respect to its thermal stability.

7 Tests for determining the resistance to condensed water of absorber surfaces

7.1 Principle

7.1.1 High humidity and the effect of moisture and condensed water on materials may initiate many kinds of degradation reactions. Selective absorber coatings composed of inorganic oxides may sometimes undergo hydratization reactions increasing the thermal emittance of coating. High humidity must prevail for electrochemical corrosion to occur causing oxidation of metal and as a result the optical performance of the coating may decrease.

7.1.2 As the casing of a flat plate solar collector is usually ventilated, this means that the absorber surface is in contact with the ambient air. Humid air from the ambient therefore enters the solar collector

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and sometimes the temperature of the solar collector inside is so low related to the humidity level that condensation of water takes place. Some solar collectors are not raintight, this means, an absorber surface has to resist periods of exposure in very humid atmospheres during its service life. An absorber surface should therefore to be qualified according to this procedure resist a humidity load representative for a non-airtight solar collector with more or less uncontrolled ventilation of air in the solar collector.

The yearly time fraction, when the relative air humidity in the gap between absorber and cover plate exceeds 99 %, is used as a measure of the severity of the humidity at service conditions. The severity depends, however, also on the effective mean temperature during such time periods of high humidity. The effective mean temperature during high humidity conditions is defined as in Formula (4). In this case Formula (3) will, accordingly, contain the parameters given below with the following meaning:

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

$T_{H,max}$ is the maximal service temperature, in kelvin (K), of the absorber surface in the solar collector, when the relative humidity level exceeds 99 %.

$T_{H,min}$ is equal to 273,15 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 absorber surface caused by the action of condensed water.

In Figure C.1, the function $f_H(T)$ of this recommended procedure is shown.

NOTE If found more appropriate other humidity/ temperature data may be used to represent service conditions. The new effective mean temperatures for specific activation energy values may be calculated by use of Formula (3).

7.1.3 To assess the resistance to condensed water of absorber surface, short-term tests at different temperatures of absorber surface are performed. To obtain constant condensation of water on the surface of absorber during testing, the surrounding air is kept at a temperature 5 K above the temperature of absorber surface and at a relative humidity of 95 %. To convert the design service life, set at 25 years, into a shortest acceptable failure time for a short-term test, Formula (4), is also here applied.

In Figure C.2, the shortest acceptable failure time, as function of activation energy, is shown for a series of constant condensation tests.

7.1.4 To conclude whether an absorber surface is qualified or not, the results from at least two different constant condensation tests performed at two different temperatures are needed. For this recommended procedure the conduct of tests at absorber surface temperatures of 40 °C and 30 °C or at 40 °C and 60 °C are contained.

7.2 Apparatus

7.2.1 Climatic chamber to be used shall be constructed so that:

a) climatic conditions ranging from room temperature and 50 % RH up to at least 65 °C and 95 % RH can be obtained, controlled and monitored during test;

b) the temperature can be maintained at a level of ±1°C and the relative humidity at a level of ±3 % RH relative to the specified climatic conditions during test.

7.2.2 Cooled sample holder for temperature control of test samples in climatic chamber is to be constructed so that:

a) the test samples can be fixed to it so that the test samples will be electrically insulated from each other and the sample holder;

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b) the test samples will be in good thermal contact with the sample holder, which is used for cooling and control of the temperature of the test sample;

c) the test samples will be positioned at an angle of 45° relative to the horizontal plane;

d) the temperature of sample holder can be measured for control of test temperature. This can preferably be made by use of Pt 100 polyamide foil sensor which adheres to the surface of the sample holder and which is additionally protected by means of a self-adhesive PTFE -film;

e) a temperature constancy over time for the sample holder of ±0,5 °C is provided.

A suitable sample holder made of aluminium and which can be used for the purpose of this test is specified in Annex D.

NOTE The crucial point in ensuring a high reproducibility of the condensation tests is the careful mounting of the test samples on the sample holder. A thin layer of an electrically insulating heat sink compound in combination with a foil for distance control, made of e.g. PTFE, can preferably be used to guarantee good thermal contact. The arrangement made means that bimetallic corrosion will be prevented too.

7.2.3 Instruments for measuring of optical properties of absorber surfaces complying with the requirements as are specified in Annex A.

7.2.4 Tensile tester and test cylinders for measurement of adhesion of absorber coating in accordance with ISO 4624, see 5.5. If a simpler method for assessment of adhesion is used, see 4.3, use equipment complying with the requirements given in the relevant standard for assessment of adhesion.

7.3 Procedure for execution of constant condensation tests

7.3.1 Select three test samples of absorber surface with known solar absorptance, thermal emittance, and qualified for testing according to 4.2.

7.3.2 Adjust the temperature of the climatic chamber at a level of 5,0 K above the specified test temperature for test samples and set the relative humidity level of climatic chamber at 95 % RH. Adjust also the temperature of the thermostatic bath so that the temperature of the sample holder placed in the climatic chamber will reach the specified test temperature.

7.3.3 After stabilized conditions have been obtained, fix the test samples to the sample holder. The testing time period starts when condensation of water is first observed on the surface of the test samples.

7.3.4 After the specified time period of the test or of interruption for measurement of extent of degradation, take out the test samples from the climatic chamber and remove gently the excess of condensed water on the surface of the test samples by a clean water absorbing paper.

7.3.5 Condition the test samples under normal laboratory climatic conditions for at least 2 h. Determine the solar absorptance and the thermal emittance of the test samples as specified in Annex A.

7.3.6 Calculate from the change in solar absorptance and thermal emittance of the test samples, the value of the PC function for each panel tested by use of Formula (1). Calculate also the mean value of the PC function for the different test samples.

7.3.7 If the test was interrupted only for measurement of extent of degradation, reintroduce the test samples after measurement into the climatic chamber after stabilized test conditions at the specified levels have been confirmed.

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7.4 Qualification procedure

7.4.1 With a set of three test samples perform test, as specified in 7.3, at T_1 = 40 °C and measure α_s and ε after the testing times 18, 36, 75, 150, 300, and 600 h or till PC ≥ 0,05 is reached. If PC > 0.05 after 18 h of testing the solar absorber surface is not qualified with respect to its resistance to condensed water. In all other cases introduce the time t_1, which is the last testing/measuring time with PC ≤ 0,05; see also Figure C.2.

7.4.2 If PC ≤ 0,015 after 600 h of testing check whether the absorber surface meets the adhesion requirements as specified in 5.5. If the requirement on adhesion is met the absorber surface is qualified with respect to its resistance to condensed water.

7.4.3 If t_1 ≥ 300 h and PC > 0,01 and if the absorber substrate is not made of aluminium check whether the absorber surface meets the adhesion requirement as specified in 5.5. If the requirement on adhesion is met proceed as follows: Use Table C.2 to determine the testing time t_3 which corresponds to the previously determined t_1 value; see also Figure C.3.

With a new set of three test specimens perform a test at T_3 = 60°C (see Table C.2) for a time period of t_3 and measure α_s and ε to determine PC.

If PC (T_3, t_3) ≥ PC (T_1, t_1) the absorber surface is qualified with respect to its thermal stability.

7.4.4 If t_1 ≤ 150 h or if the absorber substrate is made of aluminium proceed by using Table C.3 to determine the testing time t_2 which corresponds to the previously determined t_1 value for the second testing temperature T_2 = 30 °C; see also Figure C.4.

With a new set of three test specimens perform a test at T_2 for a time period of t_2 and measure α_s and ε to determine PC. If PC (T_2, t_2) ≤ PC (T_1, t_1) check whether the absorber surface meets the adhesion requirement as specified in 5.5. If the requirement on adhesion is met the solar absorber surface is qualified with respect to its resistance to condensed water.

8 Test for determining absorber surface corrosion resistance to high humidity air containing sulfur dioxide

8.1 Principle

8.1.1 Many airborne pollutants, such as sulfur dioxide present in air as a trace substance, accelerate highly, as well known, electrochemical corrosion of most metallic materials at high humidity As a solar collector exchanges air with the ambient, this means also that airborne pollutants will be transported from the ambient into the solar collector and the absorber surface. Airborne pollutants may, therefore, influence the long-term optical performance of an absorber by promoting corrosion attacks on the metallic substrate. Airborne pollutants may also cause loss in the optical performance of selective absorber coatings pigmented with small metallic particles, due to oxidation/corrosion of the metal particles.

8.1.2 Due to the complex nature of degradation caused by air pollutants, atmospheric corrosivity, as defined from exposure of standard panels of metals as specified in ISO 9226[3], is used here. More precisely, the corrosion rate of zinc is taken as a measure for severity of environmental stress on absorber surface in solar collectors and sulfur dioxide is considered the dominating airborne pollutant as regards degradation of absorber surface. As specified in 4.6, two severity classes are used here related to two kinds of solar collectors for which corrosion rates for zinc are defined.

NOTE If found more appropriate other levels of atmospheric corrosivity may be used to represent service conditions. The new levels of atmospheric corrosivity may be expressed also in terms of corrosion rates of other metal than zinc, if found more appropriate.

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8.1.3 To assess the atmospheric corrosion resistance of the absorber surface, exposure in high-humidity air containing small concentrations of sulfur dioxide (10^{-6}) is adopted. To convert the design service life of 25 years into shortest acceptable failure times relevant for the two severity classes defined, the principle of comparative testing is applied. This means that the time transformation function for degradation of optical performance of absorber surface is assumed to be the same as the one for the corrosion of zinc.

NOTE In the study of nickel pigmented anodized aluminium absorber coatings as specified in reference [4], it was roughly assumed that the time transformation function for degradation of the nickel-pigmented anodized aluminium coatings was the same as for the corrosion of zinc. The reasonableness of this assumption was supported by results from measurements of deposited amounts of sulfur dioxide on this kind of coatings both during laboratory tests, involving exposure in high humidity air containing sulfur dioxide, and during in-service tests of absorbers in solar collector.[7]

8.1.4 To conclude whether an absorber surface is qualified or not, the results from one test, involving exposure in circulating air of a relative humidity of 95 % RH, temperature of 20 °C, and with a volume fraction of sulfur dioxide of 10^{-6}, are needed. The test is essentially performed as specified in ISO 10062.

8.2 Apparatus

8.2.1 Climatic cabinet with inner chamber and gas flow system, shall comply with the requirements of ISO 10062. An example of a suitable design is shown in Annex D.

The equipment used for testing shall be constructed so that:

a) the inner chamber and gas flow system consist of inert materials, e.g. PTFE or glass, to avoid or minimize adsorption of sulfur dioxide on surfaces other than of that of the test samples;

b) the air flow and sulfur dioxide injection system are designed to ensure uniform test conditions in the inner chamber or working space of the cabinet;

NOTE 1 In the most common design of test equipment, the test atmosphere in the working space is obtained by continuously introducing the necessary quantity of sulfur dioxide into a damp air flow to obtain the required concentration. Sulfur dioxide and conditioned air are mixed outside the cabinet. The conditioned air is taken from the outer chamber of the climatic cabinet. The air flow after injection of sulfur dioxide is then mixed with a flow of recirculated test atmosphere and the resulting gas flow admitted into the inner chamber or working space of the cabinet. Half of the flow of the test atmosphere through the inner chamber may be recirculated.

To ensure uniform test conditions in the working space, the test atmosphere is normally supplied to the working space from the bottom and the outlet is placed at the top. Perforated plates are placed in front of the openings to ensure uniform air flow through the working space.

c) uniformity of temperature in the working space shall be better than ±1 °C and uniformity of relative humidity better than ±3 %. In terms of corrosivity, as expressed in terms of corrosion rates of standard metals, the uniformity shall be not less than 5 %;

NOTE 2 The uniformity of the test conditions in the working space may be checked regularly by exposing a number of copper coupons, placed at different positions in the working space during sulfur dioxide exposure. The differences in weight change of the metal coupons indicate if the uniformity of test conditions is within specified range.

d) the damp air flow shall be within the tolerance for the specified temperature ±1 °C and relative humidity ±3 % and the linear flow rate of air shall be in the range of 1 mm/s to 5 mm/s. The damp air flow shall be free of water droplets or aerosols;

NOTE 3 In the most common design of test equipment, the air is introduced to the outer chamber of the cabinet after filtration and purification by activated charcoal and a particulate filter. The sulfur dioxide gas may be taken from a pressurized cylinder filled with high-purity sulfur dioxide gas at a volume fraction of 10^{-3} in high-purity nitrogen gas.

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e) for exposure of test samples in the working space, a specimen holder shall be used so the test samples do not shield one another or disturb the uniformity of the flow of air across the chamber;

f) the temperature, relative humidity, and concentration of sulfur dioxide in the air flow at the outlet of the working space are monitored so that they reflect the true test conditions for the test samples.

8.2.2 Instruments for measuring of optical properties of absorber surfaces complying with the requirements as are specified in Annex A.

8.2.3 Tensile tester and test cylinders for measurement of adhesion of absorber coating in accordance with ISO 4624; see 5.5. If a simpler method for assessment of adhesion is used, see 4.3, use equipment complying with the requirements given in the relevant standard for assessment of adhesion.

8.3 Reference test specimen

For measurement of corrosivity in the working space during testing, standard test samples of zinc shall be used.

The test sample of zinc may preferably has a dimension of 50 mm × 100 mm × 1 mm, and shall have an impurity level at or lower than 0,5 %.

Before testing, the test samples shall carefully be cleaned with a hydrocarbon solvent in order to remove all marks of dirt, oil, or other foreign matter capable of influencing the result from the corrosion rate determination. After drying the panel, it shall be possible to weigh to the nearest 0,1 mg.

After testing, the corrosion products on the zinc panel shall be removed as specified in ISO 8407 and the mass loss of the metal be determined. Use for removal of corrosion products a solution with a mass fraction of 5 % of acetic acid in distilled water. During chemical removal of corrosion products, work at room temperature with cleaning cycles with a length of around 2 min. Express mass loss of metallic zinc in mg/m^2.

8.4 Procedure for execution of corrosion test in high humidity air containing sulfur dioxide

8.4.1 Select three test samples of absorber surface with known solar absorptance, thermal emittance, and qualified for testing according to 4.2.

8.4.2 Prepare the climatic cabinet for test by firstly adjusting temperature to 20 °C, air humidity to 95 % RH and air flow rate at a selected value between 1 mm/s and 5 mm/s. After stable conditions have been reached, adjust the sulfur dioxide gas flow to the specified level so that the sulfur dioxide volume fraction in the inlet air flow to the working space will be at a level of 10^{-6}.

8.4.3 When stabilized conditions have been reached also after this step, open the door to cabinet and place the test and reference panels quickly in the working space. After a testing time period not more than 5 % of the specified time period of test, the concentration of sulfur dioxide in the outlet air flow from the working space shall not be less than 90 % of that in the inlet flow of air. If the concentration of sulfur dioxide in the outlet air flow is lower, this probably means the total area of the test samples in the cabinet is too large. During the test, check the exposure conditions regularly and, if necessary, make adjustments to the specified levels.

8.4.4 After the specified time period of test or interruption for measuring the extent of degradation in optical performance of the test samples, take out the test samples from the working space of the cabinet and place them in a desiccator over silica gel for at least 2 h. Determine the solar absorptance and the thermal emittance of the test samples as specified in Annex A.

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8.4.5 Calculate from the change in solar absorptance and thermal emittance of the test samples, the value of the PC function for each panel tested by use of Formula (1). Calculate also the mean value of the PC function for the different test samples.

8.4.6 If the test was interrupted only for measurement of extent of degradation, reintroduce the test samples after the measurement into the working space after stabilized test conditions at the specified levels have been confirmed.

8.5 Determination of shortest acceptable failure times in test by use of reference test specimens

8.5.1 If the corrosion rate of zinc, under the test conditions specified in 8.4, is not known from previous exposures in the test equipment used, proceed as follows.

8.5.2 Perform a corrosion test as specified in 8.4 with three pairs of reference test samples of zinc with known initial mass, see 8.3. Make interruptions of the test after 90 h, 180 h and 360 h and take out from cabinet at each interruption of test one pair of zinc panels for determination of mass loss in metallic zinc caused by corrosion during test, see 8.3.

8.5.3 Assume the mass loss in metallic zinc versus the testing time period is linear and determine by least square fitting, the mean corrosion rate of zinc, r_{Zn}, during the test conditions specified in 8.4. Express r_{Zn} in $mg/m^2/h$.

8.5.4 Use the mean corrosion rate of zinc and determine the following shortest acceptable failure times in hours of the test according to 8.4 as follows.

a) For a type A solar collector, see Clause 4: Shortest acceptable failure time, $t_{f,A} = 2{,}5/r_{Zn}$

b) For a type B solar collector, see Clause 4: Shortest acceptable failure time $t_{f,B} = 7{,}5/r_{Zn}$

8.6 Qualification procedure

8.6.1 The qualification scheme for testing the corrosion resistance of solar absorber surfaces, similar to the schemes of Figures B.2 and C.2 can be found in [5]. Perform a corrosion test as specified in 8.4 for $t_{f,B}$ h, including also one interruption of the test for measurement of extent of degradation after $t_{f,A}$ h. If only qualification for the type A solar collector severity class is required, complete the test after $t_{f,A}$ h.

8.6.2 If a coated absorber surface is tested, measure, as specified in 5.5, also the adhesion of the coating on all the panels after the test.

If the requirement on adhesion as specified in 4.3 is not met the absorber surface is not qualified with respect to long-term performance.

8.6.3 Dependent on the PC mean value obtained after the two testing times of 8.6.1, the following shall be concluded regarding corrosion resistance of absorber surface:

a) If after $t_{f,A}$ h of test, PC < 0,05, the absorber surface is qualified for the type A solar collector severity class if, when coated, it also fulfils the requirement of 8.6.2.

b) If after $t_{f,B}$ h of test, PC < 0,05 too, the absorber surface is qualified also for the type B solar collector severity class if, when coated, it also fulfils the requirement of 8.6.2.

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9 Test report

The test report shall give the following information:

a) reference to this part of ISO 22975;

b) the type and designation of the tested product of absorber surface;

c) any deviations from the prescribed testing method;

d) method for assessing adhesion if appropriate and used requirement for acceptable adhesion;

e) test results;

f) selected or defined maximum stagnation temperature;

g) testing laboratory;

h) dates for start and completion of tests.

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Annex A
(normative)

Procedure for determination of solar absorption and thermal emittance of absorber surfaces

A.1 Assessment of solar absorptance

A.1.1 Scope

This procedure specifies a method for determination of the directional solar absorptance α_s, for near-normal incidence, i. e. 8° to 10° to the surface normal, from spectral directional absorptance $\alpha(\lambda)$ values in the spectral range 0,30 µm – 2,5 µm. The spectral directional absorptance $\alpha(\lambda)$ values are determined from spectral (near-normal) directional/hemispherical reflectance $\rho(\lambda)$ values measured on opaque samples of solar absorber surfaces at room temperature.

A.1.2 Apparatus

Spectral (near-normal) directional/hemispherical reflectance $\rho(\lambda)$ values shall be determined by photometric integration by use of a spectrophotometer equipped with an integrating sphere. The wall of sphere shall be coated with a highly and diffusely reflecting coating, e.g. $BaSO_4$ In the photometric integration the specular component of reflected radiation has to be included.

The sphere shall be designed so that the sample is part of sphere wall during the measurement. The detector shall be positioned so that it is shielded against radiation received directly from the sample.

The geometry of the sphere shall preferably be so that the comparison method can be used, i.e. sample and reference are simultaneously part of the sphere wall.

When using the substitution method, i.e. sample and reference are alternately covering the measuring port, the sphere error must be corrected for by measuring the respectively corresponding brightness of the sphere wall.

For calibration purposes a diffusely reflecting white standard (e.g. provided by NIST) shall be used as reference.

A.1.3 Measurement of reflectance values

Solar absorptance shall be assessed by use of the weighted ordinates method; see A.1.5.

The reflectance shall be measured at al least 40 wavelengths in the range 0,30 µm to 2,50 µm.

A.1.4 Evaluation of spectral absorptance values

Calculate the near normal/hemispherical spectral reflectance of sample, $\rho(\lambda)$, by use of the following expression:

$$\rho(\lambda) = \frac{R_s(\lambda)}{R_r(\lambda)} \cdot \rho_r(\lambda) \qquad \text{(A.1)}$$

where

$R_s(\lambda)$ is the recorded reflectance value of sample;

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$R_r(\lambda)$ is the recorded reflectance value of reference;

$\rho_r(\lambda)$ is the near-normal/hemispherical reflectance of reference.

The spectral directional absorptance $\alpha(\lambda)$ values are calculated as:

$$\alpha(\lambda) = 1 - \rho(\lambda) \tag{A.2}$$

A.1.5 Evaluation of solar absorptance

The solar absorptance, α_s, is calculated from the following expression:

$$\alpha_s = \frac{\sum_{i=1}^{n} (\alpha(\lambda_i) \cdot S_{\lambda i} \cdot \Delta\lambda_i)}{\sum_{i=1}^{n} (S_{\lambda i} \cdot \Delta\lambda_i)} \tag{A.3}$$

where

the set of λ_i are the selected measuring wavelengths;

$\Delta\lambda_i$ is the respective wavelength interval.

The values of $\alpha(\lambda_i)$ shall be determined by interpolation for the selected wavelengths of ISO 9050:2003, Table 2.

A.1.6 Crucial factors in the assessment of solar absorptance

When assessing the solar absorptance of absorber surface according to this procedure, attention shall be paid to possible anisotropy of the samples, i.e. the samples shall be marked to allow mounting of the samples at the measuring port using the same orientation and ensuring that the same areas of samples are re-measured. When establishing degradation-over-time relationships in a durability test, measurements of extent of degradation at different testing times should be performed on one and the same sample.

A.2 Assessment of thermal emittance

A.2.1 Scope

This procedure specifies methods for determination of:

a) Total directional emittance $\varepsilon_n(T)$ for near-normal incidence;

This quantity is elaborated from measurements of total hemispherical/directional reflectance $\rho(T)$ for thermal radiation incident from a black-body radiator at the temperature T. The total emittance for near-normal incidence is given by

$$\varepsilon_n(T) = 1 - \rho(T) \tag{A.4}$$

b) Spectral near-normal directional emittance $\varepsilon(\lambda)$.

To determine this quantity spectral directional/hemispherical reflectance $\rho(\lambda)$ is firstly measured yielding the directional spectral emittance as $\varepsilon_n(\lambda) = 1 - \rho(\lambda)$. By weighted integration with a Planck-distribution for a black body radiator at a chosen temperature, T, finely, $\varepsilon_n(T)$ is obtained as specified in A.2.3.

Whenever the reflection method is used, transmittance has to be zero within spectral range measured.

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The relevant spectral range is 2,0 µm to 50,0 µm. The angle of incidence or emission is restricted to near-normal, i. e. 8° to 10° to the surface normal. The temperature of sample is room temperature.

NOTE Most IR-spectrometers are limited to smaller wavelength ranges. Then an extrapolation procedure to higher wavelengths has to be employed; See A.2.3.

A.2.2 Apparatus

For determination of emittance quantities from spectral measurements, a spectrophotometer equipped with diffusely reflecting gold coating as sphere wall shall be used for photometric integration. In photometric integration the specular component of reflected radiation shall be included.

The requirements on sphere design are the same specified in A.1.2.

For calibration purposes, highly specular reflecting references (e.g. gold or aluminium) are recommended:

A.2.3 Assessment of thermal emittance

For assessment of $\varepsilon_n(T)$ based on spectral measurements in the wavelength range 2,0 µm to 50,0 µm, the following procedure should be used.

Calculate the near normal/hemispherical spectral reflectance of sample $\rho(\lambda)$, by use of the following expression:

$$\rho(\lambda) = \frac{R_s(\lambda)}{R_r(\lambda)} \cdot \rho_r(\lambda) \tag{A.5}$$

where

$R_s(\lambda)$ is the recorded reflectance value of sample;

$R_r(\lambda)$ is the recorded reflectance value of reference;

$\rho_r(\lambda)$ is the near-normal/hemispherical reflectance of reference.

As no correction of possible distortion of the measured result when a specular component of the reflected radiation exists, the spectral directional emittance, $\varepsilon(\lambda)$ is calculated as:

$$\varepsilon(\lambda) = 1 - \rho(\lambda) \tag{A.6}$$

The total emittance from spectral measurements, $\varepsilon(T)$ is convoluted with the Planck function $P_\lambda(T)$ for a black-body radiator with temperature of T, as:

$$\varepsilon(T) = \frac{\sum_{i=1}^{n} \varepsilon(\lambda_i) \cdot P_{\lambda i}(T) \cdot \Delta\lambda_i}{\sum_{i=1}^{n} P_{\lambda i}(T) \cdot \Delta\lambda_i} \tag{A.7}$$

where

the set of λ_i are the selected measuring wavelengths.

$\Delta\lambda_i$ is the respective wavelength interval.

$P_{\lambda i}(T)$ is the value of the Planck function for black body radiation at the selected wavelengths and temperature.

NOTE 1 Values for the Planck function can be found for example in most handbooks in physics.

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The temperature T shall be 100 °C if not otherwise specified.

NOTE 2 If data for $\varepsilon(\lambda)$ are only available for wavelengths up to a limit of e.g. 25 µm, $\varepsilon(\lambda)$ may be considered constant and equal to that at this limit up to 50 µm and $\varepsilon(T)$ be calculated from Formula A.7.

A.2.4 Crucial factors in the assessment of thermal emittance from spectral measurement

When assessing the thermal emittance of absorber surface from spectral measurements, attention shall be paid to the same factors as specified in A.1.

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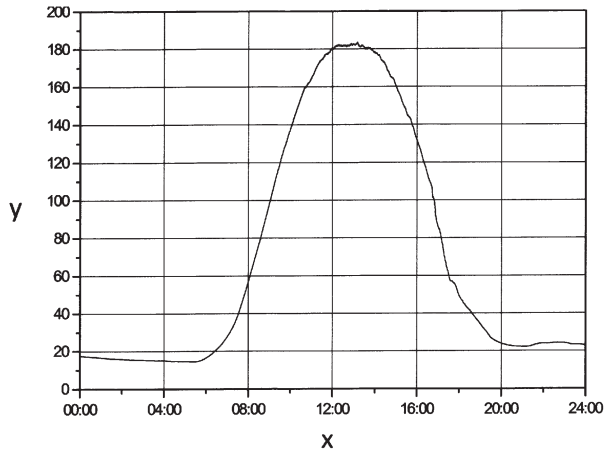
Annex B
(normative)

Temperature and failure time characteristics in assessment of thermal stability of absorber surface

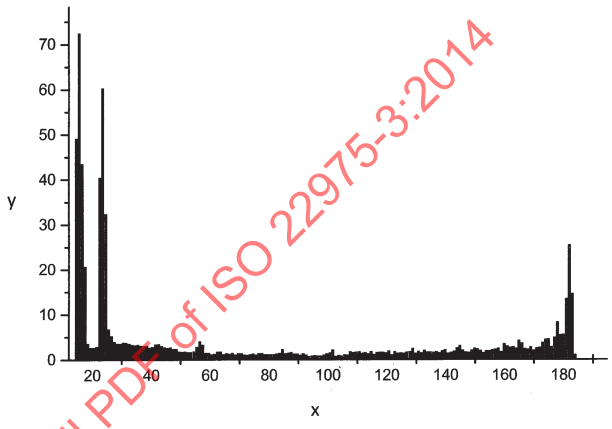


a) Measured solar absorber surface temperatures at stagnation condition during one day of clear sky conditions

Key

x time in hours

y T_{abs} in °C



b) Corresponding temperature frequency function for 30 days with clear sky conditions

Key

x T_{abs} in °C

y f in hours

Figure B.1 — Reference thermal load for assessment of thermal stability of absorber surface

The temperature profile of the selective absorber surface (α_s = 0,94 and ε = 0,06) was measured in a commercial flat plate solar collector installed in Freiburg/Germany, facing south with a tilt angle of 45°. The profile was recorded 25th of August 1997 with a maximum global radiation of about 930 W/m^2, measured in the solar collector plane. The maximum stagnation temperature was 184 °C.

The maximum possible solar absorber temperature, T_{max} shall be chosen according to Table B.1, showing the relation between optical properties of a solar absorber surface and T_{max}. The line entitled "α(AR)" shall be used.

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Table B.1 — Relation between optical properties of a solar absorber surface and possible maximum solar absorber temperature, T_{max}

α(AR)→	1,00	0,99	0,98	0,97	0,96	0,95	0,94	0,93	0,92	0,91	0,90	0,89	0,88	0,87	0,86	0,85	0,84	0,83	0,82	0,81	0,80					
ε↓ α→						1,00	0,99	0,98	0,97	0,96	0,95	0,94	0,93	0,92	0,91	0,90	0,89	0,88	0,87	0,86	0,85	0,84	0,83	0,82	0,81	0,80
0	238	236	235	233	231	229	228	226	224	222	220	219	217	215	213	211	210	208	206	204	202	200	199	197	195	193
0,01	233	232	230	228	227	225	223	222	220	218	216	215	213	211	209	208	206	204	202	201	199	197	195	193	192	190
0,02	229	228	226	224	223	221	219	218	216	214	213	211	209	208	206	204	203	201	199	197	196	194	192	190	189	187
0,03	226	224	222	221	219	218	216	214	213	211	209	208	206	204	203	201	199	198	196	194	193	191	189	188	186	184
0,04	222	221	219	218	216	214	213	211	210	208	206	205	203	202	200	198	197	195	193	192	190	188	187	185	183	182
0,05	219	218	216	215	213	211	210	208	207	205	204	202	200	199	197	196	194	193	191	189	188	186	184	183	181	179
0,06	216	215	213	212	210	209	207	206	204	203	201	200	198	196	195	193	192	190	189	187	185	184	182	181	179	177
0,07	214	212	211	209	208	206	205	203	202	200	199	197	196	194	193	191	190	188	186	185	183	182	180	179	177	175
0,08	211	210	208	207	205	204	202	201	199	198	196	195	193	192	190	189	187	186	184	183	181	180	178	177	175	174
0,09	209	207	206	204	203	202	200	199	197	196	194	193	191	190	189	187	186	184	183	181	179	178	176	175	173	172
0,10	207	205	204	202	201	200	198	197	195	194	192	191	190	188	187	185	184	182	181	179	178	176	175	173	172	170
0,11	205	203	202	200	199	198	196	195	193	192	191	189	188	186	185	183	182	181	179	178	176	175	173	172	170	169
0,12	203	201	200	199	197	196	194	193	192	190	189	187	186	185	183	182	180	179	177	176	175	173	172	170	169	167
0,13	201	199	198	197	195	194	193	191	190	189	187	186	184	183	182	180	179	177	176	175	173	172	170	169	167	166
0,14	199	198	196	195	194	192	191	190	188	187	186	184	183	182	180	179	177	176	175	173	172	170	169	167	166	165
0,15	197	196	195	194	192	191	190	188	187	186	184	183	181	180	179	177	176	175	173	172	170	169	168	166	165	163
0,16	196	195	193	192	191	189	188	187	185	184	183	181	180	179	177	176	175	173	172	171	169	168	166	165	164	162
0,17	194	193	192	191	189	188	187	185	184	183	181	180	179	177	176	175	173	172	171	169	168	167	165	164	162	161
0,18	193	192	190	189	188	187	185	184	183	181	180	179	177	176	175	174	172	171	169	168	167	165	164	163	161	160
0,19	192	190	189	188	187	185	184	183	181	180	179	178	176	175	174	172	171	170	168	167	166	164	163	162	160	159
0,20	190	189	188	187	185	184	183	182	180	179	178	176	175	174	173	171	170	169	167	166	165	163	162	161	159	158
0,21	189	188	187	185	184	183	182	180	179	178	177	175	174	173	171	170	169	168	166	165	164	162	161	160	158	157
0,22	188	187	185	184	183	182	180	179	178	177	175	174	173	172	170	169	168	166	165	164	163	161	160	159	157	156
0,23	187	185	184	183	182	181	179	178	177	176	174	173	172	171	169	168	167	165	164	163	162	160	159	158	156	155
0,24	185	184	183	182	181	179	178	177	176	175	173	172	171	170	168	167	166	165	163	162	161	159	158	157	155	154
0,25	184	183	182	181	180	178	177	176	175	174	172	171	170	169	167	166	165	164	162	161	160	158	157	156	155	153
0,26	183	182	181	180	179	177	176	175	174	173	171	170	169	168	166	165	164	163	161	160	159	158	156	155	154	152
0,27	182	181	180	179	178	176	175	174	173	172	170	169	168	167	166	164	163	162	161	159	158	157	156	154	153	152
0,28	181	180	179	178	177	175	174	173	172	171	170	168	167	166	165	163	162	161	160	158	157	156	155	153	152	151

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Table B.1 *(continued)*

0,29	180	179	178	177	176	175	173	172	171	170	169	167	166	165	164	163	161	160	159	158	156	155	154	153	151	150
0,30	179	178	177	176	175	174	172	171	170	169	168	167	165	164	163	162	161	159	158	157	156	154	153	152	151	149
0,31	178	177	176	175	174	173	172	170	169	168	167	166	165	163	162	161	160	159	157	156	155	154	152	151	150	149
0,32	178	176	175	174	173	172	171	170	168	167	166	165	164	163	161	160	159	158	157	155	154	153	152	150	149	148
0,33	177	176	174	173	172	171	170	169	168	166	165	164	163	162	161	159	158	157	156	155	153	152	151	150	149	147
0,34	176	175	174	173	171	170	169	168	167	166	165	163	162	161	160	159	158	156	155	154	153	152	150	149	148	147
0,35	175	174	173	172	171	169	168	167	166	165	164	163	161	160	159	158	157	156	154	153	152	151	150	148	147	146
0,36	174	173	172	171	170	169	168	166	165	164	163	162	161	160	158	157	156	155	154	153	151	150	149	148	147	145
0,37	173	172	171	170	169	168	167	166	165	163	162	161	160	159	158	157	155	154	153	152	151	150	148	147	146	145
0,38	173	172	170	169	168	167	166	165	164	163	162	160	159	158	157	156	155	154	152	151	150	149	148	146	145	144
0,39	172	171	170	169	168	166	165	164	163	162	161	160	159	157	156	155	154	153	152	151	149	148	147	146	145	143
0,40	171	170	169	168	167	166	165	164	162	161	160	159	158	157	156	155	153	152	151	150	149	148	146	145	144	143

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Test conditions for the different accelerated temperature tests used in the qualification of solar absorber surface are shown in Table B.2.

Table B.2 — Test conditions for the different accelerated temperature tests used in the qualification of solar absorber surface

T_{max} (°C)	T_1 (°C)	T_2 (°C)	t_2 (h) (t_1 = 18 h)	t_2 (h) (t_1 = 36 h)	t_2 (h) (t_1 = 75 h)	t_2 (h) (t_1 = 150 h)	T_3 (°C)	t_3 (h) (t_1 = 300 h)	t_3 (h) (t_1 = 600 h)
< 90	137	107	361	493	689	953	167	83	221
91–100	149	119	321	443	627	877	179	88	233
101–110	160	130	283	397	570	808	190	93	244
111–120	172	142	251	356	519	746	202	98	256
121–130	184	154	222	320	474	690	214	103	267
131–140	196	166	198	289	434	641	226	108	278
141–150	208	178	177	262	400	598	238	114	289
151–155	215	185	168	250	384	578	245	116	294
156–160	221	191	159	239	369	559	251	119	299
161–165	227	197	151	229	355	542	257	121	304
166–170	233	203	144	219	342	525	263	124	309
171–175	240	210	137	210	330	510	270	127	314
176–180	246	216	131	201	319	495	276	129	319
181–185	252	222	125	193	308	481	282	132	323
186–190	259	229	120	186	298	468	289	134	328
191–195	265	235	114	179	289	456	295	136	333
196–200	272	242	110	173	280	444	302	139	337
201–205	278	248	105	166	272	433	308	141	342
206–210	285	255	101	161	264	423	315	144	346
211–215	291	261	97	155	256	413	321	146	350
216–220	298	268	94	150	249	403	328	148	355
221–225	304	274	90	146	243	394	334	151	359
226–230	311	281	87	141	236	386	341	153	363

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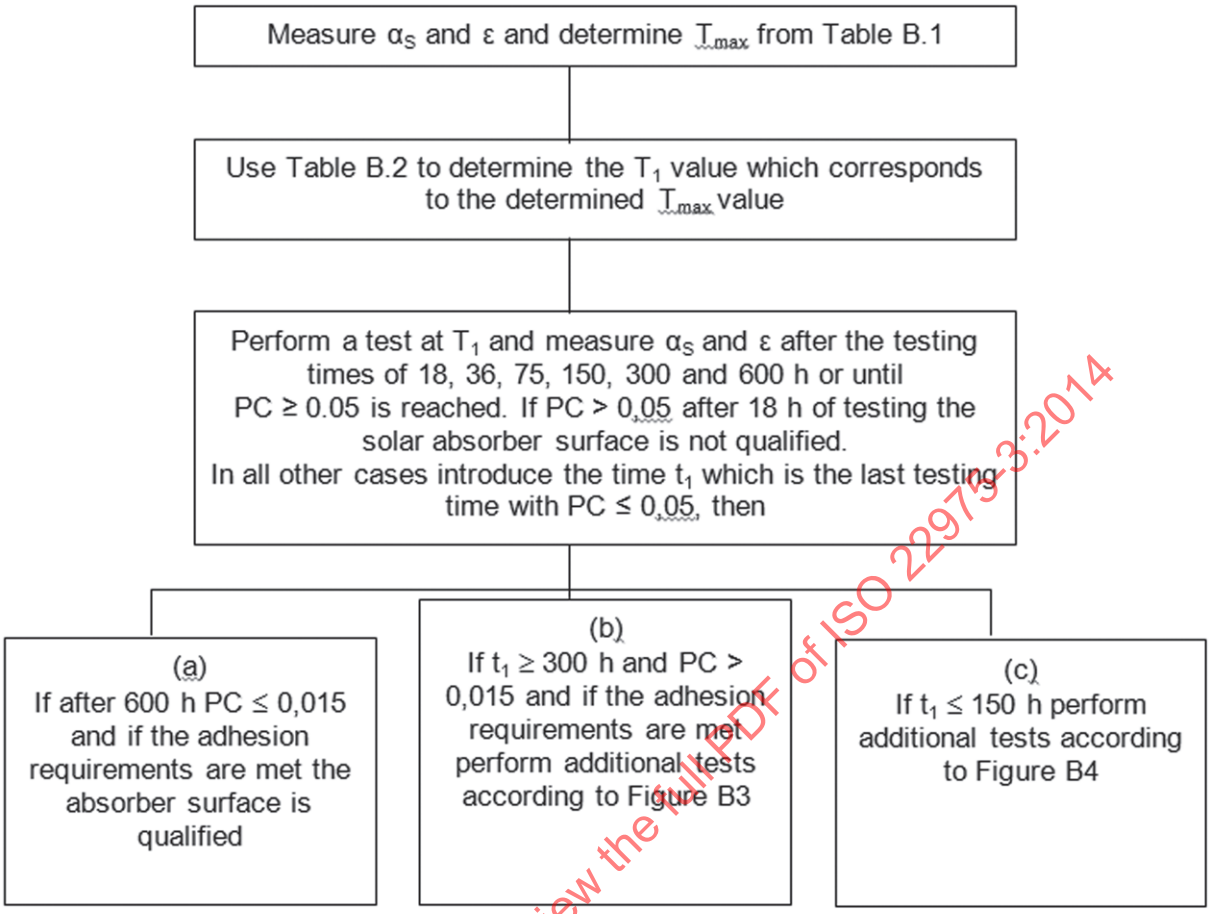

Figure B.2 — Qualification scheme for testing the thermal stability of solar absorber surfaces

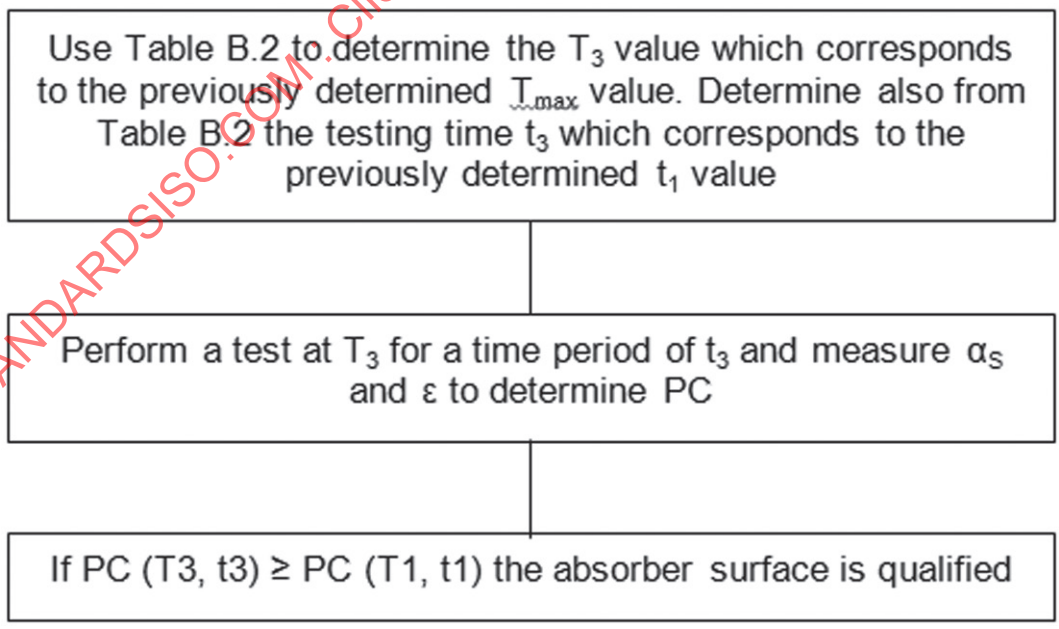

Figure B.3 — Continuation of the qualification scheme in Figure B.2 for the (b) option

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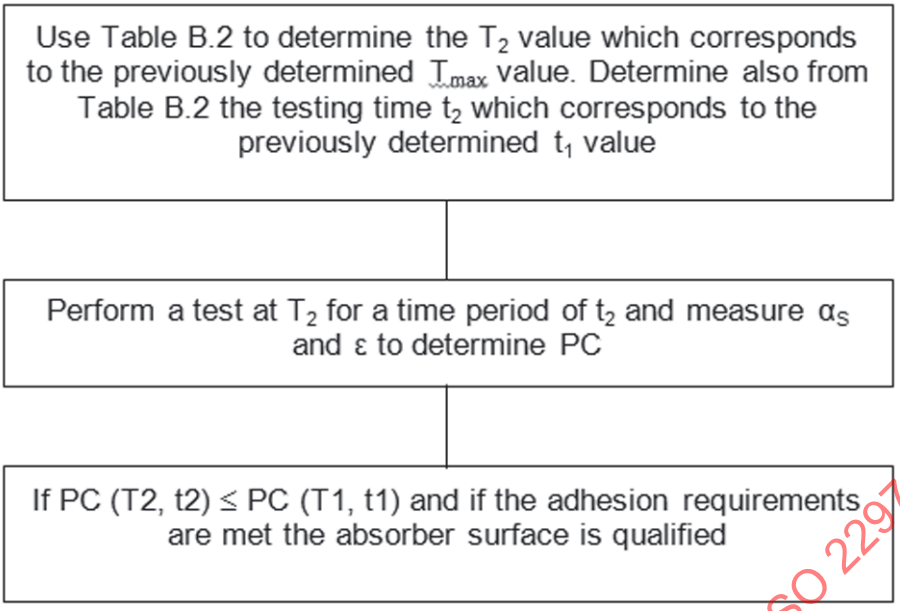

Figure B.4 — Continuation of the qualification scheme in Figure B.2 for the (c) option

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