Accelerated Aging Test and Service Life Time Estimation for Solar Collectors

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Abstract

Based the loads and degradation observed on flat plate collectors exposed in the period from 2012 to 2020 at different locations (Kochi (India), Negev (Israel), Gran Canaria (Spain), Beijing (China), Zugspitze (Germany), Freiburg (Germany) and Stuttgart (Germany)) accelerated aging tests were developed and carried out on identical solar collectors to simulate the degradation that occurred at the exposure sites and thus estimate the service life of the solar collectors.

After and during the multi-year exposure of 7 to 8 years, the performance of the solar collectors was tested according to ISO 9806 to determine the performance degradation caused by the loads. Based on these measurements and the loads measured at the exposure sites, a model for service life estimation of flat-plate collectors was developed.

Keywords: Accelerated aging test, service life prediction, solar thermal collector

1. Introduction

In the SpeedColl (www.speedcoll.de) and SpeedColl2 (www.speedcoll2.de) projects, a consortium consisting of Fraunhofer ISE, the Institute for Building Energy, Thermotechnology and Energy Storage at the University of Stuttgart (IGTE) and representatives from industry investigated the loads and developed tests to simulate the loads for solar thermal collectors and their components. For this purpose, first test specimens were exposed outdoors for a long time at various locations (Kochi (India), Negev (Israel), Gran Canaria (Spain), Beijing (China), Zugspitze (Germany), Freiburg (Germany) and Stuttgart (Germany)). Next accelerated ageing tests were developed and carried out in the laboratory on solar collectors of identical construction to simulate the degradation that occurred at the exposure sites and thus estimate the service life of the solar collectors. Figure 1 shows an overview of the different test locations.

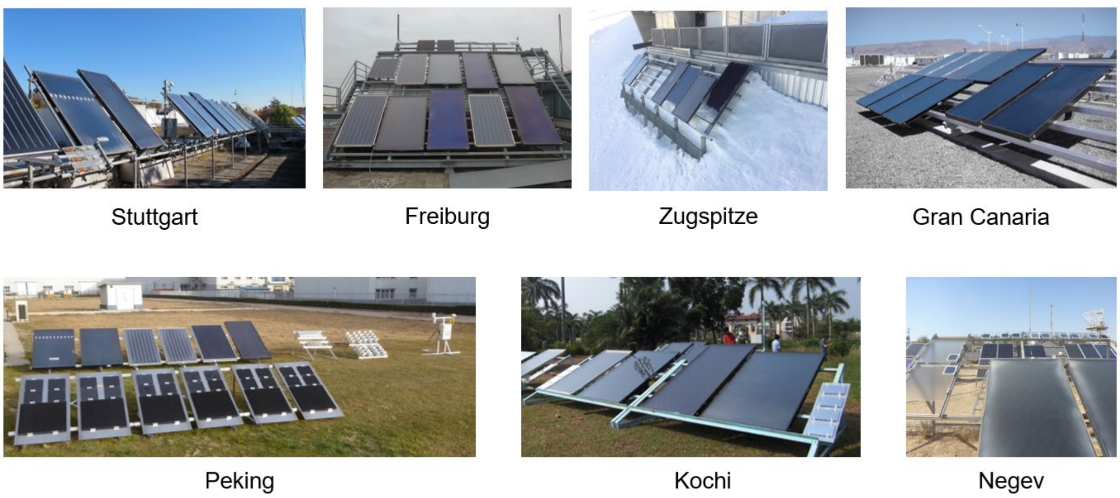

Fig. 1: Overview of the different exposure sites

The paper presents the performance degradation and degradation phenomena of the investigated collectors at the different locations. Furthermore, the revisions of the accelerated aging test procedures already defined in the

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SpeedColl project (Fischer, 2017) and their effect on the thermal performance of the solar collectors are presented and the service life of the solar collectors is estimated with the help of the results.

2. Performance degradation and degradation phenomena

All investigations and results presented in the following refer to the collectors of the 3 collector manufacturers involved in the project described in Table 1. These were exposed uncooled at the different locations for a period of 7 to 8 years.

Tab. 1: Brief description of the collector types investigated in the project

Collector	Description
Type I	Aluminium absorber, selective coating by means of Physical Vapour Deposition (PVD), copper absorber tubes, ultrasonically welded, aluminium casing, "floating" bearing of the glass cover with EPDM seal, solar glass, thermal insulation made of mineral wool (glass wool) on the rear wall and the side frame profiles.
Type II	Aluminium absorber, selective PVD coating, copper absorber tubes, laser-welded, aluminium casing, silicone bonding of frame and glass, solar glass, thermal insulation made of mineral wool (rock wool) on the rear wall.
Type III	Aluminium absorber, selective PVD coating, copper absorber tubes, laser-welded, aluminium casing and rear wall made of sheet steel, silicone bonding of frame and glass, solar glass with anti-reflective coating, thermal insulation made of melamine resin on rear wall and frame

After several years of exposure, the collectors were subjected to a performance test according to ISO 9806 and then opened. The main findings for the different collectors are summarised in Table 2.

Tab. 2: Damage of the different collectors

Collector	Damage
Type I	- Location-dependent dust and sand deposits on the absorber - Heavy corrosion on the collector frame and the absorber piping at the Gran Canaria site
Type II	- Location-dependent dust and sand deposits on the absorber - Heavy corrosion on the collector frame and the absorber at the Gran Canaria site - Contact glass absorber in the edge area - Fogging on the inside of the glass - Welding on collector pipes loosened
Type III	- Location-dependent dust and sand deposits on the absorber - Abrasion marks on absorber - Fogging on the inside of the glass - Welding on collector pipes loosened

Figure 2 to Figure 4 show examples of the performance curves and the difference to the new condition of the 3 collectors after 1 year, 3 years and 7.5 years of uncooled exposure at the Stuttgart site.

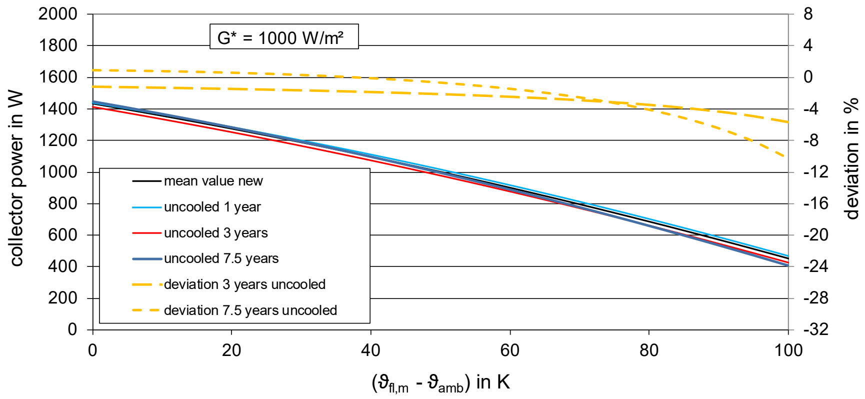

Fig. 1: Comparison of the power curves of collector type I in new condition after 1 year, 3 years, and 7.5 years of uncooled exposure at the Stuttgart site.

Collector type I shows a small performance degradation in the range of measurement uncertainty after 1 year, 3 years and 7.5 years of uncooled exposure at the Stuttgart site (see Figure 2).

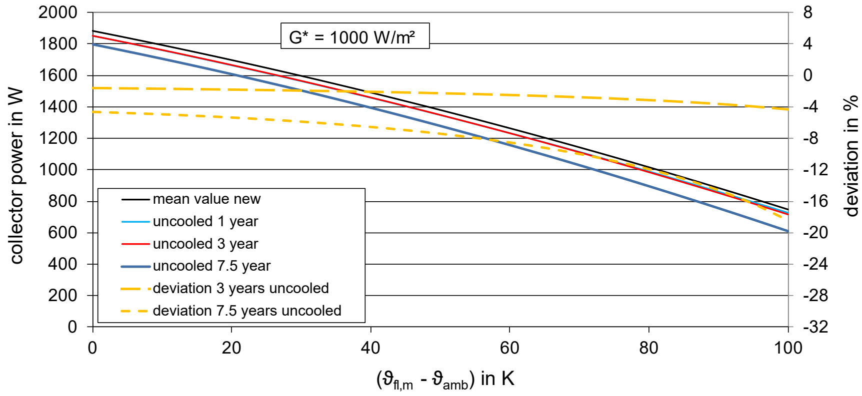

Fig. 3: Comparison of the power curves of collector type II in new condition after 1 year, 3 years, and 7.5 years of uncooled exposure at the Stuttgart site.

Collector type II shows a slight performance degradation within the measurement accuracy after 1 and 3 years of uncooled exposure at the Stuttgart site and a significant performance degradation after 7.5 years of uncooled exposure at the Stuttgart site (see Figure 3).

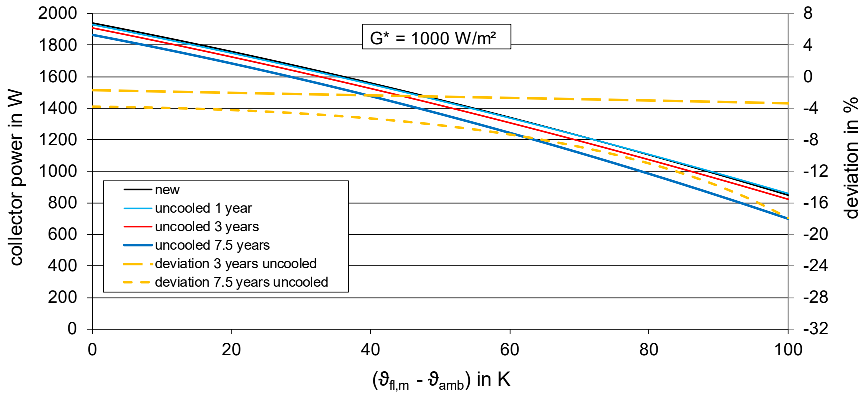

Fig. 4: Comparison of the power curves of collector type III in new condition after 1 year, 3 years, and 7.5 years of uncooled exposure at the Stuttgart site.

Collector type III shows no performance degradation after 1 year of uncooled exposure at the Stuttgart site, a slight one after 3 years (within the measurement accuracy) and a moderate one after 7.5 years (see Figure 4).

The power curves as shown above are suitable for an initial assessment of the performance degradation, but not for its quantification. A suitable measure for quantification is the change in energy savings in reference systems. To determine the influence of the collector performance degradation on the energy savings in a solar thermal system, system simulations were carried out with the simulation software TRNSYS using the reference system for domestic hot water heating (Bachmann et. al., 2018a) and reference combi system (Bachmann et. al., 2018b) defined in the IEA SHC TASK 54. The energy savings Q_{sav} achieved with the degraded collectors after the respective exposure in the corresponding system were determined.

Table 3 shows the ratio of the energy savings after exposure to the energy savings in new condition for the collectors in the combined system.

Tab. 1: Energy saving after exposure related to energy saving in new condition

	Typ I	**Typ II**	**Typ III**
Collector new	100.0 %	100%	100%
1 year uncooled (Stuttgart)	102.7 %	97.4 %	99.9 %
3 years uncooled (Stuttgart)	97.5 %	97.7 %	97.6 %
7.5 years uncooled (Stuttgart)	97.9 %	92.2 %	93.8 %

3 years cooled (Stuttgart)	100.5 %	98.1 %	98.9 %
7.5 years cooled (Stuttgart)	99.4 %	96.1 %	96.9 %
6.4 years (1.2 years cooled + 5.2 years uncooled) (Stuttgart)	102.7 %	-	92.0 %
5.4 years (1.2 years cooled + 4.2 years uncooled) (Stuttgart)	-	90.1 %	-
7.3 years uncooled (Freiburg)	93.0 %	89.4 %	90.8 %
3 years uncooled (Zugspitze)	94.7 %	93.7 %	97.8 %
8.1 years uncooled (Zugspitze)	94.1 %	83.9 %	-
2.5 years uncooled (Gran Canaria)	98.8 %	94.2 %	97.9 %
8.3 years uncooled (Gran Canaria)	-	84.8 %	95.1 %
3 years uncooled (Negev)	95.9 %	91.6 %	97.5 %
8.1 years uncooled (Negev)	-	85.7 %	90.2 %
2.5 years uncooled (Kochi)	100.1%	94.8 %	94.0 %
7.3 years uncooled (Kochi)	89.9 %	87.8 %	89.8 %

The results after 7.3 years of exposure in Kochi are not used in the rest of the paper due to the flooding that occurred at the Kochi site and the associated damage to the collectors.

The collector type I shows a low performance degradation at all locations. The maximum difference to the new condition is -7% of the energy saving. Values above 100% result from the measurement uncertainty in the measurement of the thermal performance. The collector type II shows a maximum difference in energy savings of -16 % at the Zugspitze site compared to the new condition. A moderate performance degradation of a maximum of -10 % of the energy saving compared to the new condition at the Negev site can be observed for collector type III. An overview of the damage patterns and their assessment based on exemplary measurements of the optical properties of the absorber layers from the collectors opened after exposure and the measurement of the thermal conductivity from the opened collectors are summarised in Table 4.

Tab. 4: Overview of the damage patterns of the different collectors

Damage	Type I	Type II	Type III
Dust and sand deposition on Absorber	yes	yes	yes
Salt deposition on absorber	yes	yes	yes
degradation optical properties of absorber	small	small	small
Welt seam detachment	No	small	small
Absorber deformation with contact to glass cover	No	small	small
Increase in thermal conductivity of insulation material	No	small	No
Fogging on glass cover	No	all over	partly
Loss of anti-reflective coating glass cover	not existent	not existent	not investigated

The assessment of the damage patterns listed in Table 4 leads to the following results:

1. Dust and salt deposits are present in all collector types and are more or less pronounced depending on the location and type. These lead to a performance degradation of 0 to approx. 2% related to the maximum collector performance.
2. The degradation of the optical properties of the absorber coating was determined by Fraunhofer ISE. It can be assumed that this can lead to a performance degradation of 0 to approx. 2% in relation to the maximum collector power. The performance degradation here depends, among other things, on the absorber temperature during exposure.
3. Weld seam detachment only occurs at collector type II and type III. However, the effect on the performance degradation is far below 1% in relation to the maximum collector performance.
4. Absorber deformation with contact to the glass cover in stagnation only occurs with collector type II and type III. However, the effect on the performance degradation is far below 1% in relation to the maximum collector performance.
5. An increase in the thermal conductivity of the thermal insulation can only be observed with collector type II (see IGTE measurements). However, the effect on the performance degradation is far less than 1% in relation to the power curve.

6. Fogging on the inside of the glass cover occurs over the entire surface of collector type II and over a large area of collector type III. The effect on the performance degradation is estimated at 2 to 4 % in relation to the maximum collector performance.
7. In case of collector type III, there may also be a loss or partial loss of the AR coating in addition to the reduction in transmission caused by the fogging, which would lead to a further reduction in transmission.

3. Accelerated aging tests

In the SpeedColl2 project, the accelerated aging tests developed in the previous SpeedColl project were revised and supplemented by the staff of IGTE and Fraunhofer ISE and the industrial partners. At the end of the project, the following service life tests were available, which are briefly explained below:

1. UV test
2. Internal thermal cycling test
3. External thermal cycling test
4. High temperature test
5. Condensation test
6. Salt spray test

3.1. UV test

The collector is placed in a climate chamber with a tilt angle of at least 60° and parallel to the light source. The light source is switched on and the climate chamber is set to 15 % ±5 % relative humidity. The temperature in the climatic chamber is then adjusted so that the surface temperature of the collector frame at the top of the collector reaches 80 °C ± 2 °C in an area that is not directly irradiated. When this temperature is reached, the test begins. During the test, ambient temperature, frame temperature and UV irradiance (280 nm - 400 nm) are measured and recorded. The test is finished when a UV irradiation of 280 kWh/m² (corresponding to approx. 5 years of exposure in Freiburg) is reached.

3.2. Internal thermal cycling test

During the internal thermal cycling test, the absorber of the collectors is subjected to thermal cycles of ± 75 K. During heating, the collector is operated with an inlet temperature of 95 °C until an outlet temperature of 90 °C is reached. During subsequent cooling, the collector is operated with an inlet temperature of 10 °C until an outlet temperature of 15 °C is reached. A total of 2000 cycles is carried out. This corresponds to the load that can be expected in real time operation within 25 years in a combi system. In addition, 4 thermal shocks are carried out according to ISO 9806. The number of 4 thermal shocks was determined on the basis of the assumption that this operating case can occur during the service life of a solar collector 1 time during commissioning and 1 time during each of the three service intervals during the service life, even though this should not occur if the collector is filled properly.

3.3 External thermal cycling test

The collector is placed in the climate chamber at ambient conditions (room temperature and appropriate relative humidity). The air in the climate chamber is cooled to a temperature that results in a temperature at the surface of the frame at the top of the collector of -40 °C ± 2 °C and kept at this temperature for 1 h. The climatic chamber is then adjusted to a temperature that results in a temperature on the surface of the frame at the top of the collector of +90 °C ± 2 °C and held for 1 h, see Figure 5. Throughout the test, the temperature and relative humidity inside the climatic chamber and the frame temperature at the top of the collector are measured and recorded. The test is completed when a total of 200 temperature cycles have been completed.

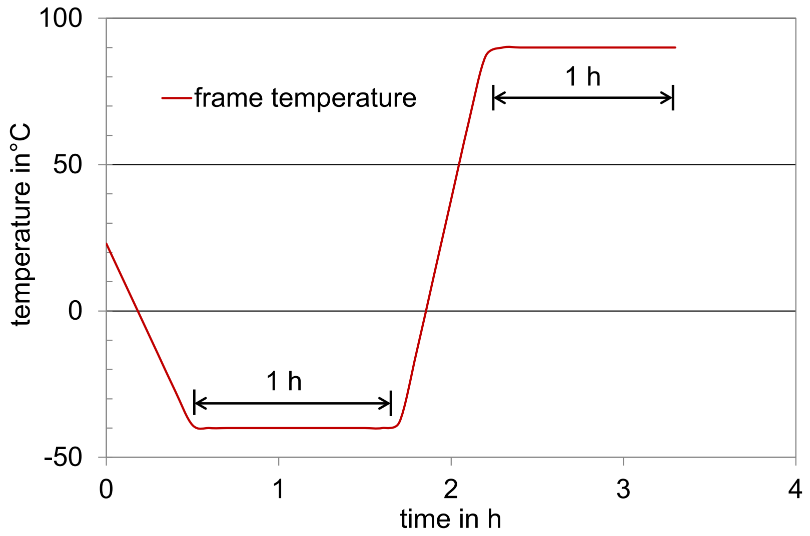

Fig. 5: Schematic test cycle of temperature cycle test

3.4 High temperature test

In the high-temperature test, the collector is exposed, unfilled and uncooled, to an irradiance of G = 1100 W/m^2 and an ambient temperature ϑ_{amb} = 40 °C for 8 hours. Alternatively, this operating condition can be achieved with a heat carrier flowing through the collector at the temperature resulting in the absorber temperature reached under the above mentioned operating conditions. After that the collector is exposed to an ambient temperature of 25 °C for 4 h without irradiation. The entire test consists of 15 cycles as described above. If necessary, the number of cycles can be increased.

3.5 Condensation test

The formation of condensation on the inside of the glass cover is a realistic scenario due to the cooling of the glass cover from the outside, e.g. by snow or radiation cooling. Condensation can be particularly harmful for solar glasses, especially for those with coatings (e.g. AR coating), and can lead to degradation. Furthermore, this test is intended to investigate whether the condensate drips onto the absorber and thus damages the selective layer of the absorber.

The collector to be tested is installed in a climate chamber at an angle of 30° to the horizontal. A condensate trap with thermal insulation above it is placed and fixed on the lower half of the collector.

During the test, the absorber of the collector is heated with an inlet temperature of 100°C. At the same time the climate chamber is operated at a temperature of 80°C and a relative humidity of 80%. In this way, the highest possible water loading of the air is generated for the greatest possible amount of condensate produced. Due to the difference between absorber and ambient temperature, a convection flow is forced inside the collector even without hemispherical irradiance. This ensures that there is an air exchange between the collector and the environment and that the humid air flows into the collector.

The condensate trap cools the transparent cover of the collector with a temperature of 50°C. Thus, a large amount of water in the air inside the collector will condense on the inside of the transparent cover.

3.6 Salt spry test

The salt spray test was developed on the basis of the main factors influencing the severity of the corrosive effect (presence of an oxygen-containing salt solution on the test specimen, temperature of the test specimen, temperature of the environment, relative humidity of the environment), following DIN EN 60068-2-52, severity level 3. The test procedure according to this standard is divided into three alternating phases: Salt spray phase, moisture phase and drying phase, which better reflects reality compared to continuous salt spray tests. In continuous salt spray tests, for example, a solid, constantly growing salt crust can form on the collector, which inhibits the oxygen supply to the collector and thus corrosion. The combination with humidity and drying phases both prevents the formation of a constantly growing salt crust on the collector and supports the formation of an electrolyte (salt solution containing oxygen) on the collector. The test conditions according to DIN EN 60068-2-52 are shown in Table 5.

Tab. 5: Test conditions according to DIN EN 60068-2-52

	Salt spray phase	Moisture phase	Drying phase
Ambient temperature	(35 ± 2) °C	(40 ± 2) °C	(23 ± 2) °C
Relative humidity	ca. 100 %	93 (+ 2 - 3) %	50 (± 5) %

Furthermore, the following specifications were made:

- The salt content during the salt spray phase is fixed at 3 (± 0.5) % (reduction by 2 % compared to DIN EN 60068-2-52).
- The pH value of the brine should be between 6.5 and 7.2 at 20 °C (analogous to DIN EN 60068-2-52)
- The precipitation during the salt spray cycle on 80 cm² should be 1-2 ml/h (analogue DIN EN 60068-2-52)

With the boundary conditions mentioned, the test cycle was determined as follows:

1. humidity phase (5 h), collector flow at 60 °C, test room temperature (40 ± 2) °C
2. salt spray (2 h), 60 °C flow through the collector, test room temperature (35 ± 2) °C
3. humidity phase (10 h), collector not flowed through, test room temperature (40 ± 2) °C
4. salt spray (2 h), collector not flowed through, test room temperature (35 ± 2) °C
5. humidity phase (5 h), collector not flowed through, test room temperature (40 ± 2) °C
6. drying phase 24 h, 60 °C flow through collector, test room temperature (23 ± 2) °C

The flow through the collector at 60 °C stimulates the exchange of air between the test chamber and the inside of the collector. This supports the entry of salt into the collector. The collectors are to be tilted 30° to the horizontal during the test.

The corrosion test chamber of the ITGE does not have a climate control system that allows the regulation of the relative humidity during the humidity and drying phases as well as the temperature regulation during the drying phase. The relative humidity is 100 % during the entire humidity phase. During the drying phase, ambient air is fed into the test chamber by a fan. Since the corrosion chamber at IGTE is located in the basement, a relatively constant ambient climate is ensured throughout the year, so that reproducible test conditions can still be expected. Figure 6 shows an example of the course of the relative humidity and the temperature inside the test chamber of the corrosion test chamber (test room temperature) during a test cycle in the corrosion test chamber.

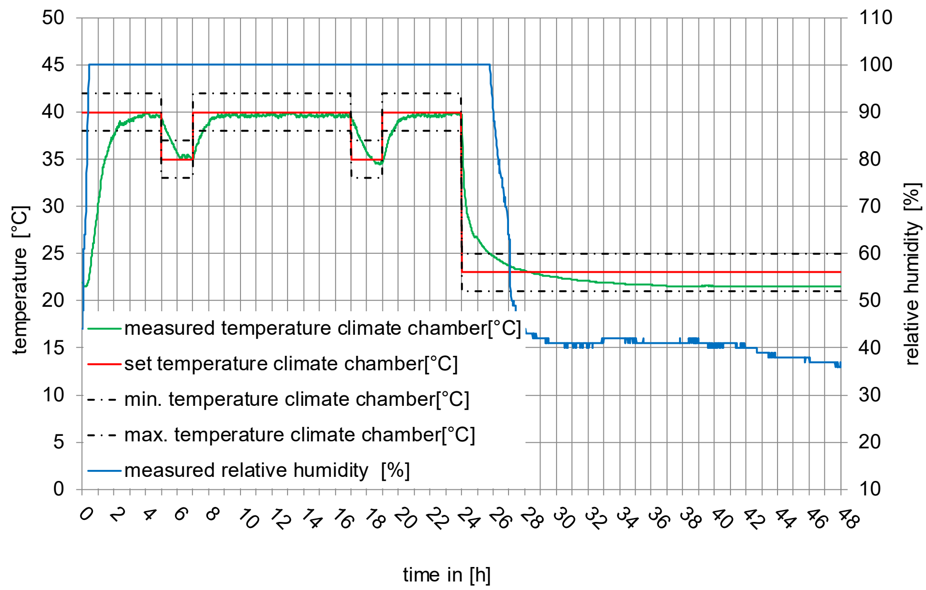

Fig 2: Test room conditions during a 48-hour test cycle in the corrosion test chamber

4. Thermal performance degradation after accelerated aging tests

Four of the accelerated aging tests described in section 3 were carried out on the collector type I, type II and type III in the following order:

- 1. UV test
- 2. internal temperature cycling
- 3. external temperature cycling
- 4. high temperature test

The results are shown in Figure 7 to Figure 9 in the form of power curves before and after the accelerated aging tests. After the accelerated aging tests, collector type I shows a very low performance degradation in the range of the measurement uncertainty (see Figure 7), collector type II a moderate one (see Figure 8) and collector type III a low performance degradation which, as with type I, is still in the range of the measurement uncertainty (see. Figure 9). Even though the performance degradation after the exemplary implementation is not as great as after the 7.5-year exposure, the collectors behave in a similar way to each other. This means that the developed accelerated aging tests are suitable for estimating the service life.

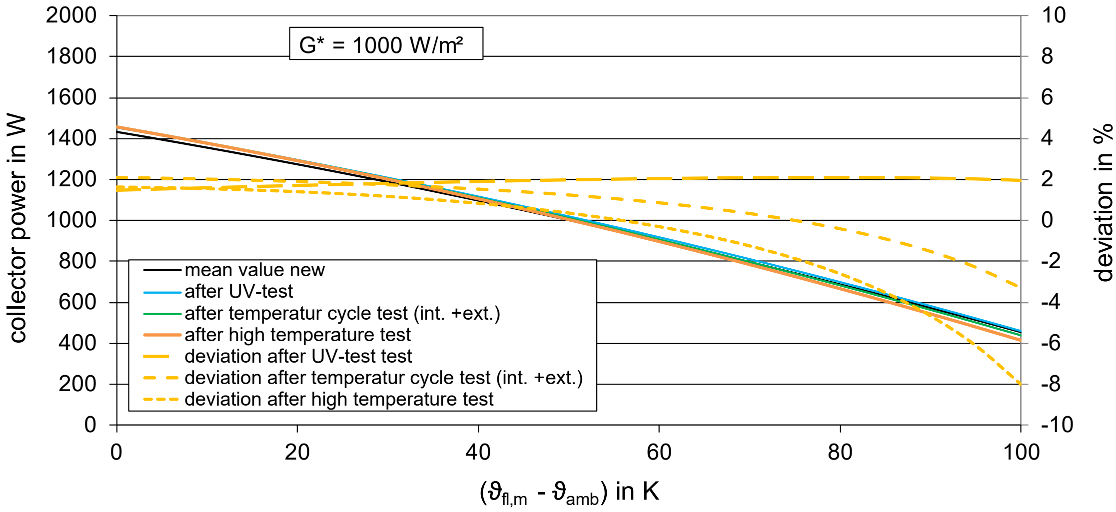

Fig 7: Comparison of the performance curves of collector type I in new condition, after the UV test, the internal and external thermal cycling test and the high-temperature test

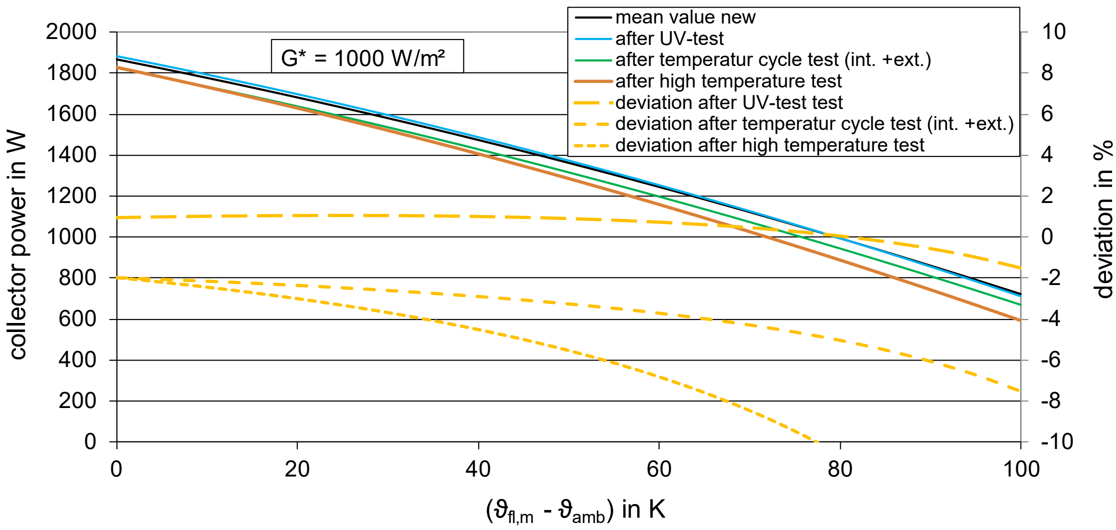

Fig 8: Comparison of the performance curves of collector type II in new condition, after the UV test, the internal and external thermal cycling test and the high-temperature test

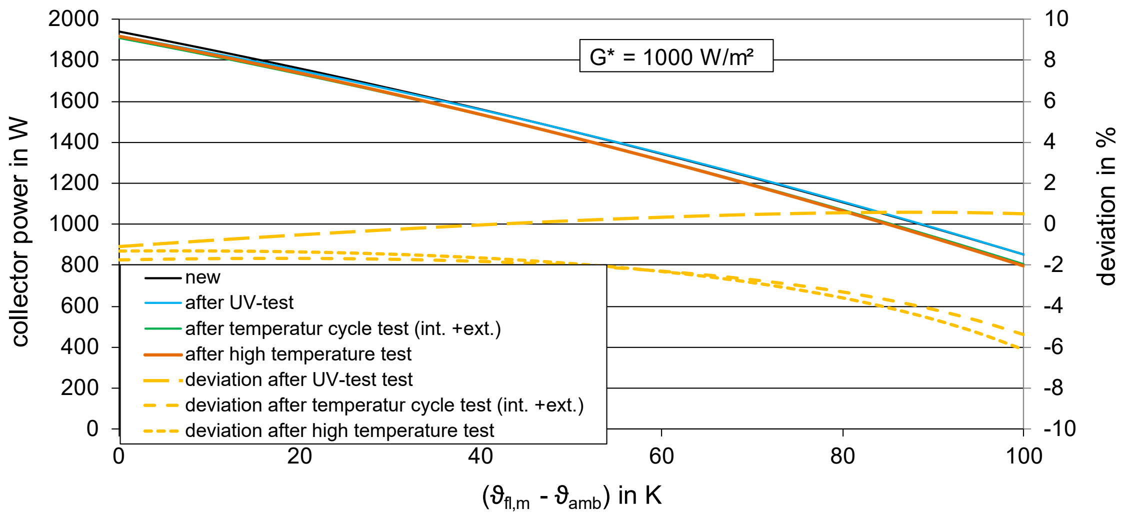

Fig 9: Comparison of the performance curves of collector type III in new condition, after the UV test, the internal and external thermal cycling test and the high-temperature test

Here, too, a system simulation was carried out for the reference combi system to quantify the change in energy savings. Table 6 shows the ratio of the energy savings after exposure to the energy savings in the new state for the collectors in the combined system.

Tab. 6: Energy savings after the exemplary service life tests in relation to the energy savings in new condition

	Type I	Type II	Type III
Collector new	100.0 %	100%	100%
After UV test	101.9 %	102.1 %	101.5 %
After internal temperature cycle test	99.9 %	98.3 %	101.0 %
After external temperature cycle test	99.8 %	97.6 %	98.5 %
After high temperature test	98.9 %	94.0 %	98.1 %

Both in the power curves shown and in the energy savings shown in the table above, a similar picture as after exposure to the extreme locations can be observed, albeit less pronounced.

The results presented in the following section give an indication of how many years of exposure and operation can be mapped with the accelerated aging tests carried out here.

5. Modelling of yield degradation and service life estimation

The load collectives and the absorber temperatures measured during exposure as well as the resulting reduction in energy savings in a typical combined system (see Table 3) were used to model the yield degradation.

The following influencing variables were determined to be significant for the performance degradation:

7. 1. the exposure duration t_{expo}
8. 2. the exposure time at an absorber temperature of 160 °C < $t_{160\text{-}200}$ < 200 °C
9. 3. the exposure duration at an absorber temperature of 200 °C > $t_{>200}$
10. 4. the exposure duration under salt load t_{Salt}
11. 5. the exposure duration under sand and/or dust load t_{Sand}

The degradation in the thermal performance was modelled as followed:

$$Q_{sav,t_{expo}=0} - Q_{sav,t_{expo}} = at_{expo} + bt_{160-200} + ct_{>200} + dt_{salz} + et_{sand} \quad \text{(eq. 1)}$$

For the Sede Boqer (Negev) site

$$t_{expo} = t_{sand} \quad \text{(eq. 2)}$$

was chosen and for the Gran Canaria site

$$t_{expo} = t_{salt} = t_{sand} \qquad \text{(eq. 3)}$$

was chosen.

The model applies to "clean" collectors, i.e. any soiling of the transparent cover is not taken into account. Table 7 shows the model parameters determined for collector type I, type II and type III according to equation (1).

Tab. 7: Parameters for modelling yield degradation

Parameter	Type I	Type II	Type III
a [1/h]	2.02E-05	6.00E-05	4.21E-05
b [1/h]	2.45E-03	2.42E-03	7.62E-04
c [1/h]	1.68E-03	1.42E-02	2.64E-03
d [1/h]	0	1.62E-04	0
e [1/h]	0	1.29E-05	0

No significant dependence on the salt and sand load could be identified for the type I and type III collectors. The reason for this is the relatively tight housing of collector type III. The salt and sand load of the entering ambient air is largely separated in the lateral edge insulation of the collector, so that only small amounts reach the absorber. For the collector type I the amount of data was not sufficient to determine any significance, as the collector from Sede Boqer was already brought back for investigation purposes after the end of the previous project and the thermal performance of the collector from Gran Canaria could not be carried out due to a leak in the absorber.

Figure 10 shows an example of the agreement between the measured and the model-calculated reduction in energy savings in the reference combined system for the measured values and the values calculated for collector type II using the parameters shown in Table 7. The accuracy of the model here, as well as for collectors type I and type III, is ±2% points.

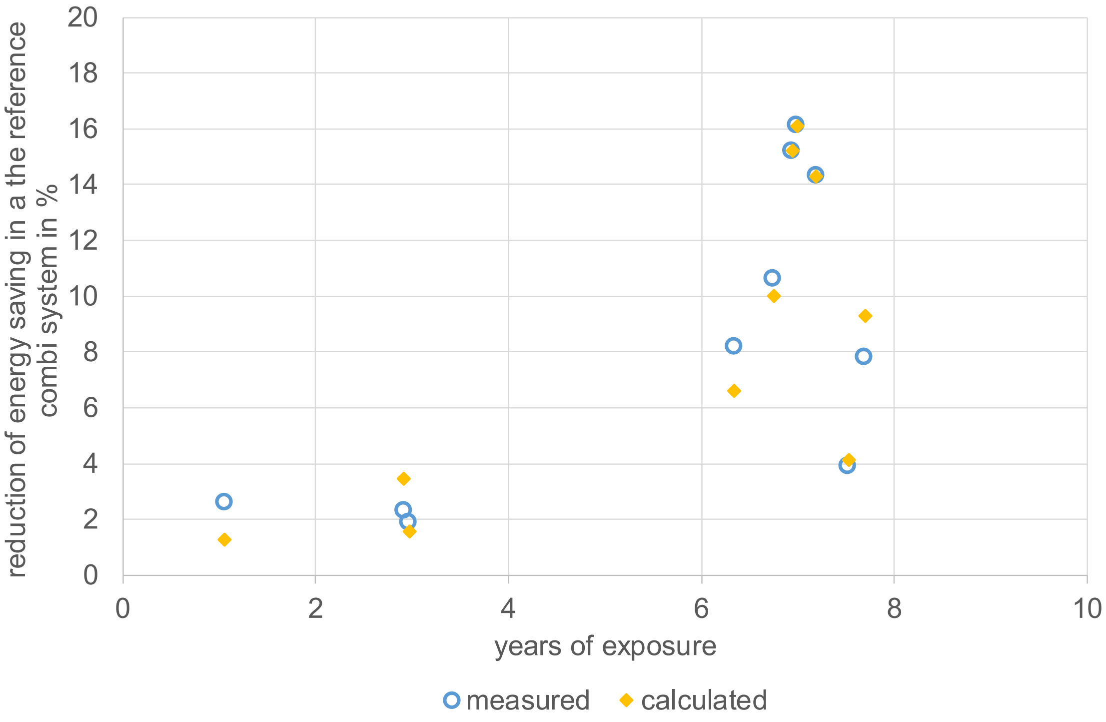

Fig. 3: Measured and calculated reduction in energy savings in the reference combi system for collector type II

Figure 11 shows the annual energy savings in relation to the energy savings in new condition in a typical combi system at the Würzburg site for an operating period of 30 years.

With the help of the yield degradation model, the service life can now be estimated depending on the user requirements. If, for example, a yield degradation of up to 20 % is accepted, this results in a service life of approx. 30 years for collector type II, and even significantly longer for type I and type III. However, if the yield degradation is only allowed to be 10 %, the service life for collector type II is 15 years, for collector type III 23 years and for collector type I still more than 30 years.

If the model according to equation (eq. 1) is applied to the results in Table 6, it results that the proposed test cycle corresponds to an exposure time of 4 years in Stuttgart or 9 years of operation in a typical combi system at the Würzburg site. With this knowledge, the length or number of repetitions of the proposed accelerated aging tests can be adapted to the requirements of the collector manufacturers.

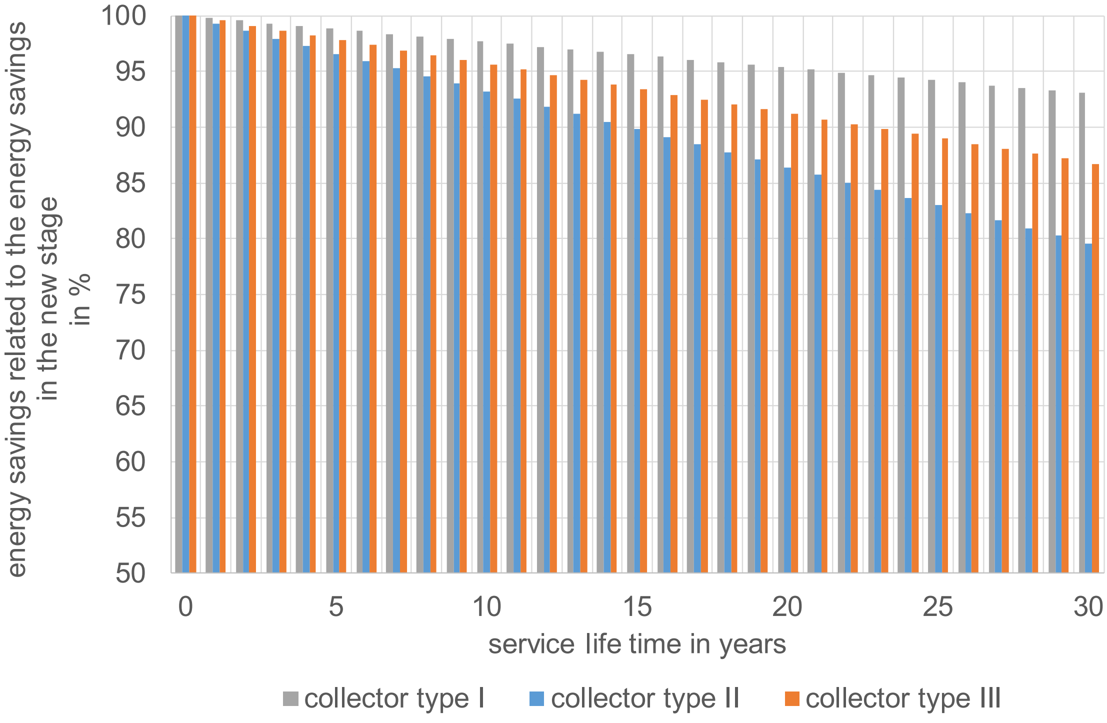

Fig 4: Annual energy savings related to the energy savings in new condition in a typical combined plant at the Würzburg site

6. Summary and outlook

In the SpeedColl and SpeedColl2 projects, a consortium consisting of the Institute of Building Energetics, Thermotechnology and Energy Storage at the University of Stuttgart (IGTE), Fraunhofer ISE and representatives from solar thermal industry examined the loads on solar thermal collectors in the period from 2011 to 2020. For this purpose, test specimens were exposed outdoors at various locations (Kochi (India), Sede Boker (Israel), Gran Canaria (Spain), Beijing (China), Zugspitze (Germany), Freiburg (Germany) and Stuttgart (Germany)). Based on the loads and degradation observed at the exposure sites, accelerated aging tests were developed and carried out on identical solar collectors to simulate the degradation that occurred at the exposure sites and thus estimate the service life of the solar collectors. After and during the multi-year exposure of 7 to 8 years, the solar collectors were subjected to a performance test according to ISO 9806 to determine the performance degradation caused by the loads. Based on these measurements and the loads measured at the exposure sites, a model for service life estimation of flat-plate collectors was developed.

The SpeedColl and SpeedColl2 projects have shown on the one hand that the collectors of German manufacturers are of high quality, but on the other hand they have also revealed weaknesses in individual designs. With the developed accelerated aging tests and the service life estimation, useful tools were created for the solar thermal industry to examine and estimate the quality and service life of their products and new developments. The developed accelerated aging tests can be incorporated into European or international standardisation if required.

7. Acknowledgments

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8. References

Bachmann, S., Fischer, S. et al. (2018a) Info Sheet A08: Reference System, Germany Solar Domestic Hot Water System for Single-Family House http://task54.iea-shc.org/Data/Sites/1/publications/A08-Info-Sheet--Ref-SF-SDHW-System--Germany.pdf

Bachmann, S., Fischer, S. et al. (2018b) Info Sheet A08: Reference System, Germany Solar Domestic Hot Water System for Single-Family House https://task54.iea-shc.org/Data/Sites/1/publications/A09-Info-Sheet--Ref-SF-Solar-Combisystem--Germany.pdf

Fischer, S., (2017), Test Procedure for Accelerating Aging of Solar Thermal Collectors, ISES Solar World Congress & SHC Conference, Abu Dhabi, 29.10. – 02.11.2017, ISBN 978-3-981 465 9-7-6