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ACCELERATED TC TEST IN COMPARISON WITH STANDARD TC TEST FOR PV MODULES WITH RIBBON, WIRE AND SHINGLE INTERCONNECTION

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ABSTRACT: Temperature changes in the field (day-night changes and seasons) can affect the performance of photovoltaic modules. Standard IEC 61215 temperature cycling (TC) tests emulate this ageing typically requiring 30 to 50 days for 200 thermal cycles (degradation < 5 % is the IEC pass criterion). A faster assessment of PV modules is desirable to rapidly evaluate new interconnection technologies and module concepts. We present an accelerated TC (aTC) test that ensures the IEC required temperatures of −40 °C and +85 °C to be reached within a PV module with 200 thermal cycles performed in around 9 days, which is up to 6 times faster than standard TC. We compare results of aTC and standard IEC TC for PV modules with different interconnection technologies (five busbars, wire interconnection, and shingle interconnection by electrically conductive adhesives). IV measurements show that the degradation of the PV modules treated with aTC is quantitatively similar to that of the PV modules treated with standard IEC TC. EL images do not show differences for both tests (IEC TC and aTC). We propose that our aTC test can be used in development and for material evaluation to accelerate development times.
Keywords: PV Module, Thermomechanical stress, Accelerated Temperature Cycling, Shingling, Multi Wire

1 INTRODUCTION

Photovoltaic (PV) modules in the field are exposed to temperature changes. Day and night, as well as seasonal changes determine module temperatures. Standard temperature cycling (TC) tests in laboratories already represent an accelerated ageing process with temperature cycles at least 4 times faster than the day and night temperature changes in the field. Nevertheless, the international electrotechnical commission (IEC) standard test procedure is time consuming with 3 to 6 h per cycle [1]. For 200 cycles 30 to 50 days are needed. To enable rapid prototyping of innovative materials, processes and module concepts, faster evaluation is advantageous [2].

In this work, we present an approach to test PV modules up to almost six times faster (full cycle around 1.1 h), with a ΔT of 148 °C to assure that the actual temperatures in the modules reach the required level of the IEC standard [1]. Extreme TC 30000 tests were performed by NASA with heating rates of 40 K min^{-1} and cooling rates of 20 K min^{-1}, respectively [3]. In that publication, however, soldering is compared with welding. Temperature shock tests for PV modules with heating ramps $\geq$ 1260 K min^{-1} and cooling ramps > 52 K min^{-1} were conducted by Kang *et al.* [4]. However, time-dependent processes such as creep behaviour of solder and electrically conductive adhesives (ECAs) are suppressed by the temperature shock tests. We therefore assume that different failure mechanisms apply to temperature shock tests and TC tests [4–6]. The advantage of aTC is that the failure modes in aTC tests are the same as in TC tests and temperature changes in the field due to the comparatively small difference in heating and cooling rates [5].

We compare the electrical properties of PV modules after accelerated TC (aTC, heating and cooling rate of 8 K min^{-1}) with those of similar PV modules after the standard IEC TC test (maximum heating and cooling rate of 1.67 K min^{-1}). We use standard PERC solar cells interconnected with 5 busbars (5 BB), with 12 wires (MBB), both infrared soldered and shingled solar cells interconnected with electrically conductive adhesives (ECA) using industrial stringing processes and standard cell interconnectors for photovoltaic modules. In this work, however, we do not compare the different interconnection technologies with each other, but the two methods of thermal cycle testing. Saving time is the major advantage of the aTC test procedure. We suppose that aTC causes comparable or stronger degradation of PV modules than TC and that similar failure modes occur [5]. Furthermore, we assume that steep temperature gradients in aTC will reduce the possibility for the solder to creep, which usually reduces thermomechanical stress in solder joints. The creep behaviour of solders is a decisive parameter, since it differs with temperature cycling speeds [6]. For that reason, we assume aTC to be a more severe test for standard PV modules. To track the temperature inside the modules, we use a test module with thermocouples.

2 EXPERIMENTAL

2.1 Sample preparation

To compare aTC with the standard TC test for PV modules we manufactured 2-cell modules with three different interconnection technologies: standard interconnection by five busbars (5 BB), multi busbar interconnection by 12 wires (MBB) and shingle interconnection (shingle). Each group consists of 24 2-cell modules (in the case of the shingle interconnection the modules feature 12 6th part shingle cells). We treated 12 modules of each group with aTC and 12 modules with standard TC and characterised them with IV measurements and EL imaging before and after climate chamber testing.

5 BB p-type PERC mono-facial cells, MBB n-type PERC bifacial cells, and p-type PERC-passivated precursors with selective emitter are used to manufacture the 5 BB and MBB 2-cell mini modules, as well as the shingled 2-cell equivalent modules, respectively.

For the manufactured 5 BB PV modules the solar cells are soldered with a teamtechnik industrial stringer (infrared soldering) with standard copper interconnector ribbons (0.9 mm x 0.22 mm) coated with tin lead solder (Sn60Pb40). As encapsulant ethylene-vinyl acetate (EVA, 460 µm), a 3 mm glass and standard white backsheet foil without water vapour diffusion barrier layer was used.

The MBB cells are interconnected with a conventional industrial multi wire stringer (infrared soldering) with standard solder (Sn60Pb40) and wire interconnectors (400 µm diameter). For these modules we used 600 µm thick EVA. The other module materials are the same as mentioned above.

We interconnect 12 shingle cells with ECA, based on epoxy resin, in the teamtechnik industrial stringer. The individual shingle cells overlap is ~1.7 mm. We build the 2-cell-equivalent modules with the same materials used for the 5 BB modules.

To track the temperature during the TC tests in the climate chamber, we prepared a special test module equipped with integrated thermocouples.

2.2 Thermal cycling tests

Figure 1 shows a time/temperature diagram of the fastest possible TC pattern according to IEC 61215 [1]. We performed the TC in an accredited climate chamber with an average cycle time of approximately 4:15 h in accordance with the IEC test standard.

Figure 1 also displays the set temperature-time profile of the aTC chamber. The ageing process starts at room temperature, followed by a cooling ramp (−8 K min^{-1}) and a dwell time of 19.5 min at −54 °C. The temperature then rises (8 K min^{-1}) to 94 °C and is held for 10.5 min before another cooling ramp starts. The cycle time is about 1:07 h. We use set temperatures deviating from standard temperatures required for IEC to compensate for the thermal inertia of the modules without increasing the cycle time significantly.

Because of the small size of the 2-cell PV modules, for both the TC and aTC tests no electric current is applied.

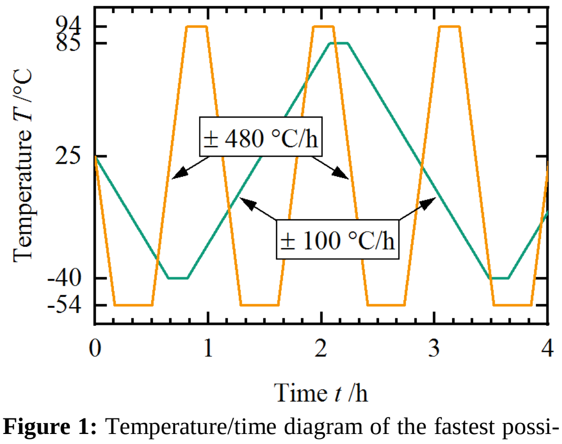

Figure 1: Temperature/time diagram of the fastest possible TC test of a PV module according to IEC 61215 [1] with minimum dwell times of 10 min (green line). Temperature/time diagram of the performed aTC tests with set times of 19.5 min (−54 °C) and 10.5 min (94 °C), respectively (orange line).

2.3 Measurement procedure

In order to ensure comparability of the pre- and post-ageing process for the power measurements, we illuminate the PV modules for 48 h prior to each IV measurement. During light soaking the PERC cells convert from an initial state, which is metastable upon illumination (light induced degradation, LID), to a degraded state which is stable under light irradiation [7]. This degradation of the samples is followed by dark storage and transport to the flasher. Subsequently, we conduct electroluminescence (EL) based upon the determined short-circuit currents (I_{SC}) of the modules by IV measurements of the modules at Fraunhofer ISE CalLab PV Modules.

3 RESULTS

3.1 Temperature profile

In figure 2 we plot the measured temperature profile inside the test module (black line) and the set temperature-time profile of the aTC chamber (orange line) for three temperature cycles. The results show that the measured temperature profile of the aTC is in agreement with the demanded temperatures inside the modules of −40 °C and +85 °C according to IEC 61215 [1]. However, the temperature is held only for about 6 min below −40 °C and above +85 °C, respectively.

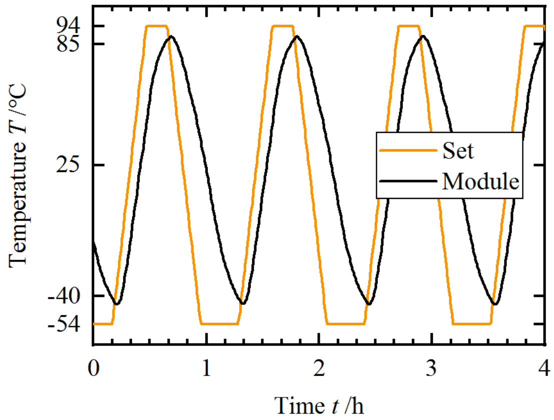

Figure 2: Temperature/time diagram of the set temperature in the aTC chamber (orange line) and the measured temperature inside the test module (black line).

3.2 IV measurements

Figures 3, 4 and 5 show the relative losses of short-circuit current (I_{sc}), open-circuit voltage (V_{oc}), fill factor (*FF*) and power output at maximum power point (P_{mpp}) after 50 and 200 thermal cycles for the 5 BB, MBB and shingle PV modules, respectively. The following relative measurement uncertainties are valid for all module types and every IV measurement: I_{sc}: 1.9 %, V_{oc}: 0.6 %, *FF*: 1.6 %, P_{mpp}: 2.1 %.

All PV modules pass the IEC criterion (degradation < 5 %) after 200 thermal cycles. On average, the degradation is less than or equal to 2.1 %. With the exception of one MBB module, which is close to the 5 % degradation limit after exposure to aTC 200, all modules show degradation less than 3.1 %.

The absolute differences of the mean values between TC and aTC after 50 and 200 thermal cycles for all modules are listed in Table I. After 200 thermal cycles, we find no significant differences between TC and aTC for all modules. The relative losses due to TC and aTC exposure are similar. However, for the 5 BB and MBB modules treated with aTC, we find a larger variation of *FF* and P_{mpp}.

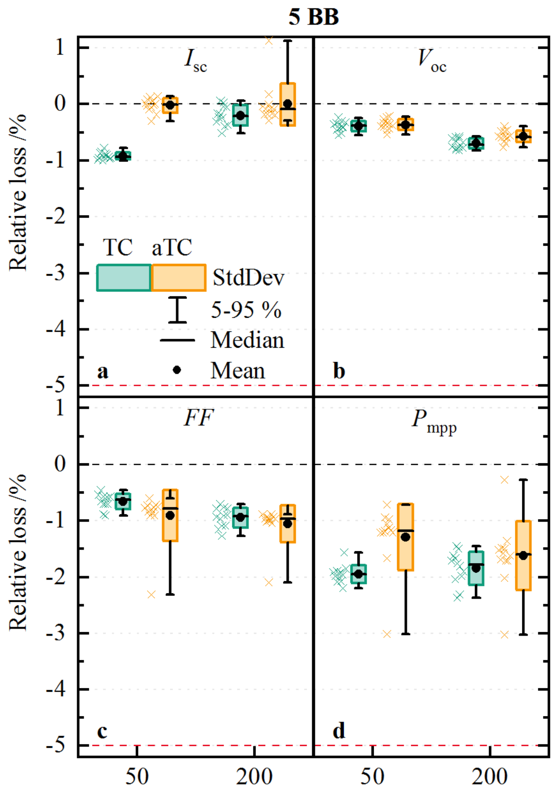

Figure 3: Relative losses of short-circuit current (a), open-circuit voltage (b), fill factor (c) and power output (d) at maximum power point of 5 BB mini modules after 50 and 200 thermal cycles (TC: green, aTC: orange).

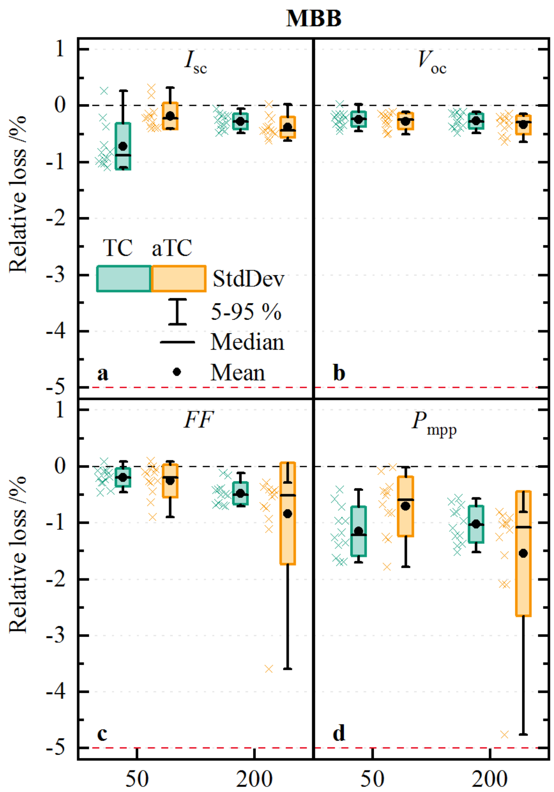

Figure 4: Relative losses of short-circuit current (a), open-circuit voltage (b), fill factor (c) and power output (d) at maximum power point of MBB mini modules after 50 and 200 thermal cycles (TC: green, aTC: orange).

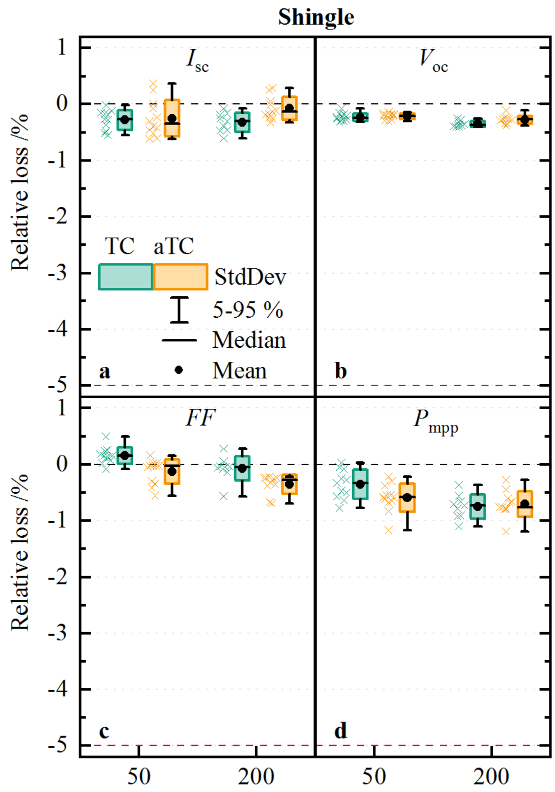

Figure 5: Relative losses of short-circuit current (a), open-circuit voltage (b), fill factor (c) and power output (d) at maximum power point of shingle mini modules after 50 and 200 thermal cycles (TC: green, aTC: orange).

Table I: Absolute differences of the mean values between TC and aTC.

	|TC – aTC|	I_{sc} /%	V_{oc} /%	FF /%	P_{mpp} /%
5 BB	50	0.9	0.0	0.2	0.7
	200	0.2	0.1	0.2	0.2
MBB	50	0.5	0.1	0.1	0.5
	200	0.1	0.0	0.3	0.5
Shingle	50	0.1	0.0	0.2	0.2
	200	0.2	0.0	0.3	0.0

3.3 EL imaging

Figures 6, 7 and 8 show typical EL images for the 5 BB, MBB and shingle PV modules in the initial state (a: TC, b: aTC) and after 50 thermal cycles (c: TC, d: aTC), respectively.

None of the EL images of the modules show severe initial defects. For all technologies the initial EL images of the TC modules and the aTC modules are almost identical. A negligible amount of initially defective fingers is visible. No damages like cell cracks are caused by the industrial stringing processes. After 50 thermal cycles, the EL images show no differences between modules treated with TC and modules exposed to aTC. Moreover, no severe degradation is visible. Therefore the EL images correspond to the IV measurements.

5 BB

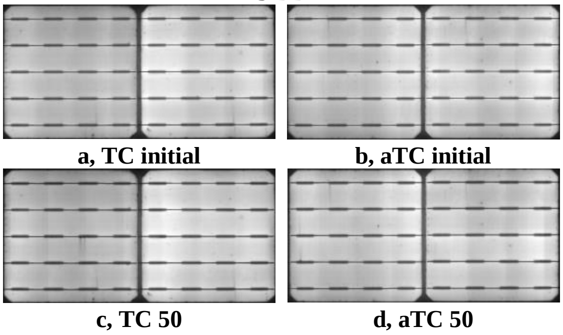

Figure 6: EL images of two representative 5 BB mini modules in initial state (a, TC and b, aTC), and after 50 thermal cycles (c, TC and d, aTC).

MBB

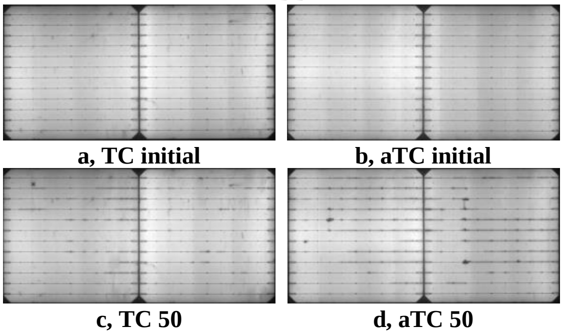

Figure 7: EL images of two representative MBB mini modules in initial state (a, TC and b, aTC), and after 50 thermal cycles (c, TC and d, aTC).

Shingle

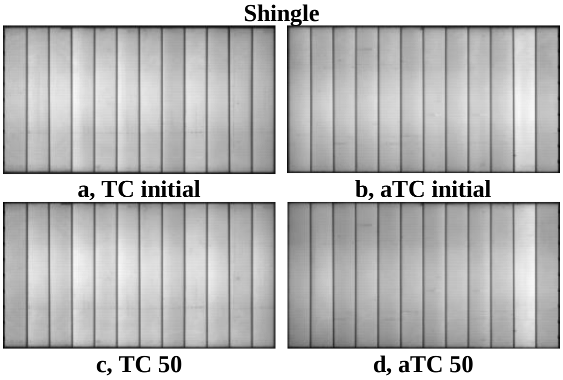

Figure 8: EL images of two representative shingle mini modules in initial state (a, TC and b, aTC), and after 50 thermal cycles (c, TC and d, aTC).

4 DISCUSSION

Our accelerated TC test features shorter dwell times compared to standard IEC TC (approximately 6 min versus ≥ 10 min). By means of the test module, we ensure that the modules reach the IEC target temperatures of −40 °C and +85 °C inside the laminate. Most important, our aTC heats and cools the PV modules at a rate of 8 K min^{-1} resulting in three to six times faster cycle time than the TC test according to IEC 61215 [1].

On the one hand, quicker temperature changes prevent the solder to creep, which presumably induces higher levels of thermomechanical stress [6]. On the other hand, the higher heating/cooling rates and shorter dwell times of our aTC test result in a mean degradation comparable to the slower heating/cooling rates and longer dwell times of standard TC. Our findings are in good agreement with [5], although we used even quicker thermal cycles.

The absolute differences of mean values between TC and aTC do not show any significant discrepancy within the relative measurement uncertainty for the performed 200 cycles. Since we find a larger mean variation for PV modules exposed to aTC with solar cells interconnected by soldering (5 BB and MBB), a larger sample size might be desirable for the accelerated test conditions.

The mean rel. P_{mpp} loss equals 0.7 % for shingle modules versus a mean rel. P_{mpp} loss of 1.7 % (5 BB) and mean rel. P_{mpp} loss of 1.3 % (MBB). Low degradation for shingle modules after 200 thermal cycles was also found by Ullmann *et al.* [8]. This indicates that ECAs can better compensate for different thermal expansion, which is in agreement with the results in [9]. However, it is difficult to make a well-defined statement about stress reduction derived from our results since different concepts are used (shingle interconnection versus 5 BB and MBB interconnection).

5 CONCLUSION

For all IV parameters, the determined data for TC samples and aTC samples do not show any significant differences between both test procedures.

The EL images correspond to IV measurements and do not show any differences between TC and aTC treated PV modules. However, prolonged temperature cycling is necessary to see degradation and analyse the failure modes.

The used aTC temperature/time profile is up to 6 times faster than the standard IEC TC test procedure and still about 3 times faster than the fastest possible IEC TC test. The target temperatures (+85 °C, −40 °C) are reached inside the modules.

Standard IEC TC and aTC degrade PV modules containing strings of different cell interconnection technologies in a similar way.

In a nutshell, our proposed aTC test needs 9.2 days for 200 cycles and is suitable to enable rapid prototyping of innovative interconnection technologies and novel module concepts. However, an extended exposition of the PV modules in TC and in aTC should be carried out to find the root cause for possible differences in degradation after enhanced thermal cycling beyond the test standard procedures.

6 ACKNOWLEDGEMENTS

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