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Evaluation of the Impact of Stagnation Temperatures in Different Prototypes of Low Concentration PVT Solar Panels

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Abstract

Photovoltaic thermal (PVT) solar panels produce both thermal and electric power from the some area. This paper concerns a PVT design where the series connected strings of cells are laminated using silicone to an aluminium receiver where the heat transfer fluid flows.

An evaluation of the impact of reaching high temperatures in the cell structural integrity and performance is presented. Eight small test receivers were made in which the following properties were varied: Size of the PV cells, type of silicone used to encapsulate the PV cells, existence of a strain relief between the cells, size of the gap between cells and type of cell soldering (line or point soldering).

These test receivers were placed in an oven for one hour, under eight different monitored temperatures. The temperature of the last round was set at 220°C which well exceeds the highest temperature the panel design can reach. Before and after each round in the oven, the following tests were conducted to the receivers: Electroluminescence (EL) test, IV-curve, diode function, and visual inspection.

The test results showed that the receivers made with the transparent silicone and strain relief between cells experienced less micro-cracks and lower degradation in maximum power. No prototype test receiver lost more than 30% of its initial power, despite the large cell breakage shown in some receivers. Prototype receivers with transparent (softer) silicone showed much far less cracks and power decrease when compared to red (harder) silicone receivers. As expected, larger cells are more prone to develop micro-cracks after exposure to thermal stress. Additionally, existing micro-cracks tend to grow in size into larger micro-cracks relatively fast with thermal stress. The EL imaging taken during our experiment leads us to observe that it seems far easier for existing cracks to expand than for new cracks to appear.

Keywords: *Stagnation Temperature, Electroluminescence test, IV-Curve, Concentration, PVT*

1. Introduction

Photovoltaic thermal (PVT) solar panels produce both thermal and electric power from the same area. Combining solar thermal and photovoltaic can be a way to increase the efficiency of the silicone cells by reducing the working temperature through active cooling (Giovinazzo et al. 2014).

Concentration allows a cost reduction by decreasing the receiver size in the panel. As per Giovinazzo et al. (2014), the biggest advantage of this type of collector design is to decrease material cost by reducing the amount of expensive components utilized (solar cell, receiver and/or selective surface).

Combining concentration with PVT (C-PVT) can also prove to be advantageous. However, concentrating does not bring only advantages. For non-concentrating collectors PVT, one disadvantage is

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the longitudinal shading caused by the frame or the absence of reflector on some solar incidence angles. This can have a very large impact on the electrical performance, if measures such as placing extra diodes are not taken (Gomes et al, 2013).

Stagnation temperature is reached when the heat losses of the panel are equal to the energy received from the sun. Another particularly important disadvantage of concentration is the increase of the stagnation temperature which can cause damage to the materials of the collector, in particular to the solar cells. This issue will be covered in detail in this paper.

A C-PVT collector was designed to produce 240W (electricity) and 1250W (thermal). An installation with 8 prototype C-PVT collectors has been made in a warm country and was found to produce only 1200 W (el). After one day, during which the stagnation temperature was reached, the production was found to have degraded significantly to 200W (el).

The most critical part in the manufacture of the PVT collector is the receiver, including all processes from the soldering of the cells to the choice of the materials (Khatri et al. 2011). Problems with the manufacturing process of the prototypes, in particular with the cell soldering, account for the difference between expected 1920W (el) and the initially obtained electrical output of 1200W. Such issues can easily be eliminated by process automation with an automatic tabbing stringer machine.

However, a more important issue that was discovered in this prototype C-PVT installation was the post-stagnation electrical power reduction to 200W. A number of hypotheses on the possible reasons for this decrease have been identified and a set of tests were designed to with the goal of gathering data to evaluate each hypothesis.

The Electroluminescence test (EL) is a powerful tool used to control the quality of the PV cell strings. Using this technique it is possible to identify defects that are not visible to the naked eye such as micro-cracks and black (or "dead") areas. These two defects are the principal cause of power losses in the cell strings, a fact which can be confirmed in the IV-Curve test (Chaturvedi et al. 2012).

2. Description of the collector and its components

Fig. 1 shows a schematic of the collector viewed from the top while fig. 2 shows a picture of the actual collector. The total size of the collector is 2.31 x 0.955 m. The length of the thermal receiver is 2.290 m and the height is 0.158 m (Bernardo et al. 2011).

The efficiency for direct (or "beam") light η_{direct} of the collector 70%, while the efficiency for diffuse light η_{diffuse} is 50,8% (Gomes et al. 2014). Furthermore, the linear loss coefficient a_1 is 4,484 W/(m^{2}K) and the secondary loss coefficient a_2 is 0,0034 W/(m^{2}K).

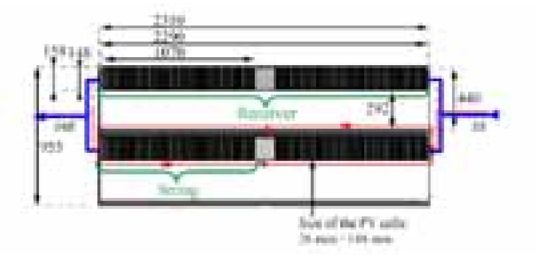

Fig. 1 - Top view of the PVT hybrid collector. The water connections are in blue and the electrical connections in red (Gomes et al. 2014)

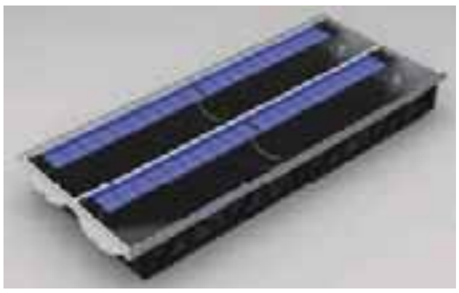

Fig. 2 - Solarus PVT hybrid collector

Reflector: The reflector geometry of the studied collector was initially developed by Vattenfall and the design is called Maximum Reflector Concentration (MaReCo) which belongs to a family of stationary reflectors patented by the Swedish company Solarus Sweden Sunpower AB. The reflector is composed of a compound parabolic and circular reflective material used to concentrate the solar radiation which is made of anodized aluminum with a total solar reflectance ρ_{total} of 95%.

Receiver: The receiver is made of a 2.29m alumunium extrusion with a maximum expansion of 8 milimeters. The cells and silicone are laminated on both sides of the receiver.

Cell encapsulation: Cell encapsulation is done with two layers of silicone. The bottom layer: between the receiver aluminium core and the cells. The top layer: between the cells and the air.

In the prototypes created for the tests, two types of silicone gels are used: A highly transparent and electrically insulating silicone is used in the top layer but it could also be used in the bottom layer. A reddish brown silicon that is equally electrically insulating but has better thermal conductivity can only be used in the bottom layer since it is not transparent and if used on the top layer would block the sunlight from reaching the cells. The red silicone is considerably stiffer than the transparent silicone and thus transmits more stress to the cells when the receiver experiences thermal expansion.

Silicone Solar Cell: There are several cell string designs but the standard consists of 2 strings of 38 PV cells connected in parallel for each receiver side. Both the front side and the back side of the receiver consist of two PV strings each. The measured prototypes have two different cell sizes: a) 28mm*148mm or b) 52mm*148mm. This way, total number of PV cells per collector can be 152 or 304 cells, depending on the prototype design.

Glass: The module contains a glazed protection which is made of low iron glass with a solar weighted transmittance τ_{glas} of 95% (Gomes et al. 2014).

3. Description of the stagnation temperature issue

Eight C-PVT collectors and six concentrating thermal (T) collectors were installed in a warm country as show in figure 3. The eight C-PVT collectors were connected to eight micro-inverters. Four thermal loops were connected to a central tank. Three loops contained two PVT and two T while one loop had only two PVT collectors.

Fig. 3 -Test installation at latitude 30^{0}

The water outlet was not connected in the first day which was a very sunny and warm summer day. This implies that the collector has reached stagnation temperature which is around 175 ^{o}C.

One hour after installation, the combined output of the eight PVT was measured and found to be only 1200 W (el) instead of the expected 1920W (el). It should also be noted that the eight PVT collectors may also have been exposed to sunlight without cooling, prior to the installation. In the morning of the following day, the electrical production of the installation was again measured and it had been greatly reduced to only 200W.

The first measured electrical output of 1200W is well below the theoretical value expected of 1920W. This decrease is clearly a manufacturing problem which the company that produced the prototypes is aware that it is caused by the manual hand soldering process and that the company will solve this matter with the purchase of an automatic tabbing stringer machine during Q3 of 2015.

However, a more important issue that was discovered in this prototype C-PVT installation was the electrical power reduction to 200W that the installation showed in the second day, after prolonged stagnation. Four hypotheses on the possible reasons for this large decrease have been identified and are described below:

- The diodes broke down due to the high temperature
- The thermal expansion of the copper cell ribbon has damaged the cells
- The thermal expansion of the aluminium receiver has damaged the cells
- Unsoldering of the copper ribbon from the cells caused by the stagnation

The thermal part of the C-PVT installation was not affected in any way by stagnation. No leaks were found as well as no reduction in thermal power output. In fact, a slight thermal output increase has been reported since the solar cells are not converting the solar irradiation into electricity.

The thermal part of the C-PVT installation was not affected in any way by stagnation. No leaks were found nor any reduction in thermal power output. In fact, a slight thermal output increase has been reported, and is understandable as the solar cells are no longer capturing a portion of the energy and converting it to electricity.

4. Method

The prototype receivers:

In order to discover the cause of the electrical performance reduction, eight prototype small receivers were manufactured at the company that made the prototypes C-PVT in the installation: Solarus Sunpower Sweden AB. Table 1 details the characteristics of each small receiver:

Table 1 - Characteristics of the eight small receivers

Receiver	Cell size	Cells number	Cell Gap	Soldering	Silicone layers	Tabbing Strip
Receiver 1	1/6	7	No	Line soldering	Red-Transparent	Straight
Receiver 2	1/6	6	No	Line soldering	Transparent-Transparent	Straight
Receiver 3	1/6	6	Yes	Line soldering	Red-Transparent	Strain relief
Receiver 4	1/6	6	Yes	Line soldering	Transparent-Transparent	Strain relief
Receiver 5	1/6	6	Yes	Two points soldering	Transparent-Transparent	Strain relief
Receiver 6	1/6	7	No	One point soldering	Transparent-Transparent	Straight
Receiver 7	1/3	4	Yes	Line soldering	Transparent-Transparent	Strain relief
Receiver 8	1/3	4	No	One point soldering	Transparent-Transparent	Straight

The 8 receivers were identical with the exception of 6 parameters that were varied: Cell size, cell gap, cell number, soldering type, type of silicon used, existence of the strain relief. Four parameters are further explained below:

- Two cell sizes were used: 1/3 (52*148mm) and 1/6 (28*148mm)
- The cell gap is the space between the cells. *"No"* means the small standard gap while *"Yes"* means a longer gap (approximately triple of the standard gap)
- The strain relief is simply a bump in a long copper busbar that is designed to cope with the thermal expansion and prevent cell damage.
- The strain relief is simply an exaggerated "s" shape bent in the tabbing strip between each cell, designed to absorb thermally-induced mechanical stress without passing it on to the cells.
- The silicone is applied in two layers. A bottom layer placed on the aluminium receiver before the

cells. And a top layer placed after the bottom layer has totally solidified and at the same time as the solar cells. Two types of silicone were used. A soft transparent silicone with a high transparence and high dielectric resistance and a harder red silicone with no transparence, similar dielectric properties and a lower heat resistance.

Test method:

The test consists in placing the receiver 8 times inside an oven for one hour each time with a gradual increase of the oven temperature. In the first round the receiver temperature will be raised from 0°C to 60°C and in the next rounds 80°C, 100°C, 130°C, 150°C, 180°C, 200°C, 220°C.

It is important to point out that the collectors stagnation temperature is 175°C. Nevertheless, the tests at 200°C and 220°C give interesting results in order to determine a safety margin.

After each thermal cycle, the following parameters are recorded:

- Electroluminescence (EL) Test: IR photograph of the cells on the receiver was made using a Digital Rebel XTi Black Canon Camera without an IR filter. The system features an image size of (3,888 x 2,592) in RAW format with 10 megapixels. The test was done in a completely dark chamber. Cells were in forward bias with a current close to 4A. This test allowed the team to spot microcracks which are not visible to the naked eye.
- IV Curve test in a solar simulator: Pmax, Imax, Vmp, Isc, Voc, FF
- Diode Function test
- Visual Inspection: note the condition of the cells, any discoloration, etc.

An important note is that the cells in the prototype receivers are soldered manually which means that some micro-cracks arise from prototype production issues that will not occur in automatic cell soldering production. For this and other reasons, a baseline scenario was also tested recording all the above shown parameters. Additionally, the cells in the prototype installation displayed in figure 3 are also manually soldered.

5. Results and Discussion

The first small receiver to be tested had very similar characteristics to the collectors of the installation shown in figure 3.

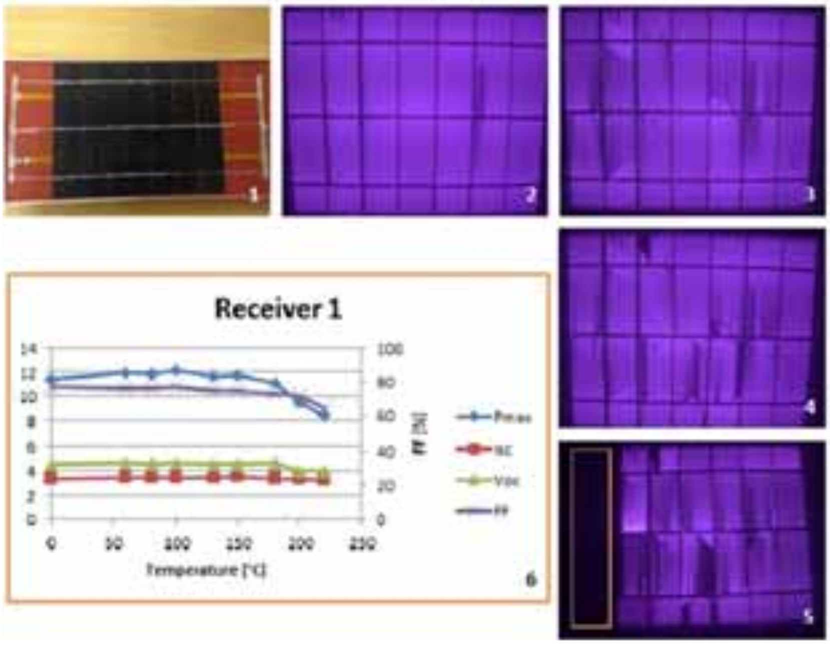

Fig. 4 – 1) Receiver 1; 2) Baseline; 3) Round 5 (150°C); 4) Round 6 (180°C); 5) Round 8 (220°C); 6) Parameters of the IV curve at different temperatures (Isc shown in the left Y axis).

As expected, after round 3 (exposure to 150°C), the EL test showed that the string has dark areas and a large number of micro-cracks which lead to a power decreases shown in figure 4 below. Raising the temperature in following heating rounds has significantly increased the amount of dark areas and micro-cracks. In the last round one cell became completely black caused by a short circuit between the top and bottom of the cell. The reason for the short circuit has not been determined but a likely explanation is that the solder on the top ribbon melted (or simply got contact) through a crack and reached the bottom ribbon.

The only difference between the first receiver and the second is the bottom silicone layer. In receiver 2, transparent silicone was used on both layers. From the 5 rounds of EL tests shown in figure 5, it is possible to see a large increase in microcracks after round 4 (180°C). Despite this, the IV curve basic parameters remain more or less constant throughout the 8 rounds with only a minor power decrease.

The number of micro-cracks in receiver 1 is higher than in receiver 2 for all temperatures, despite the baseline test (image 2) showing similar numbers.

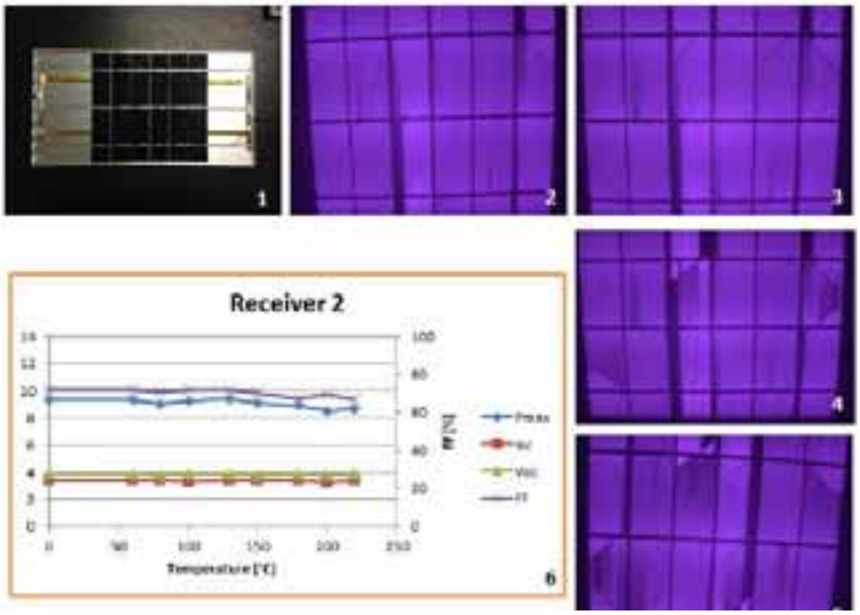

Fig. 5 – 1) Receiver 1; 2) Baseline; 3) Round 5 (150°C); 4) Round 6 (180°C); 5) Round 8 (220°C); 6) Parameters of the IV curve at different temperatures (Only Isc on the left axis).

The main goal of building receiver 3 and 4 was to test the impact of reducing the stress on the cell caused by the thermal expansion of the ribbon. This way, a strain relief bend was inserted before and after each cell. In order to isolate the impact of the different types of silicones two receivers were made: One with red silicone (receiver 3) and another with transparent silicone (receiver 4). The results from receiver 3 can be seen in Fig. 6 and from receiver 4 in Fig. 7.

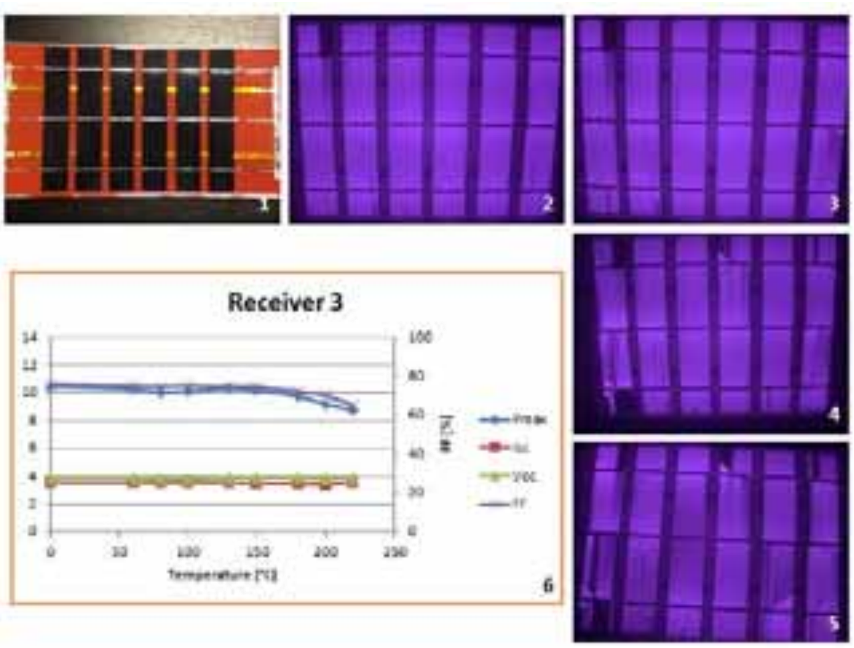

Fig. 6 – 1) Receiver 1; 2) Baseline; 3) Round 5 (150°C); 4) Round 6 (180°C); 5) Round 8 (220°C); 6) Parameters of the IV curve at different temperatures (Isc shown in the left Y axis).

The EL tests in Figure 6 show that in a receiver with red silicone, even with the strain relief between the cells, a large number of micro-cracks appear when exposed to higher temperature (180°C). Compared with receiver 1, receiver 3 exhibits a smaller power drop, albeit still displaying a significant power drop in the last 2 rounds.

In Fig. 7, the cells of receiver 4 have no significant damage along the 8 rounds, representing an improvement from the results obtained with receiver 2. However, receiver 4 showed one black cell in the last round likely caused by the same reason as in the receiver 1. The same black cell that appeared at round 7 (200°C) is also responsible for the sharp 15% drop. Excluding that effect, the power remains considerably constant.

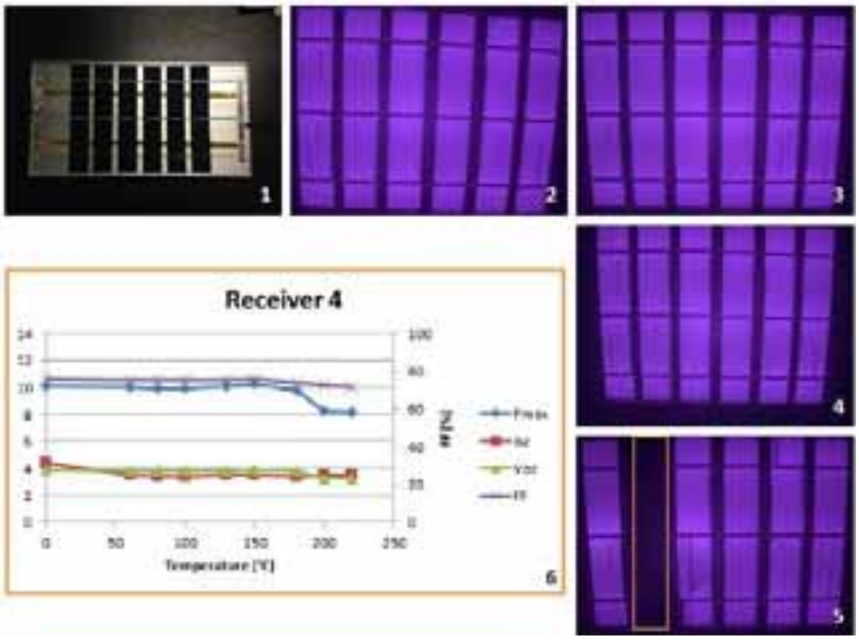

Fig. 7 – 1) Receiver 1; 2) Baseline; 3) Round 5 (150°C); 4) Round 6 (180°C); 5) Round 8 (220°C); 6) Parameters of the IV curve at different temperatures (Isc shown in the left Y axis).

Since our research group did not have, at the time of these tests, access to an expensive automatic cell soldering machine, it was also important that the group investigated the impact of different manual soldering techniques. This was accomplished with receivers 5 and 6 that have been made with point soldering instead of continuous soldering, like all previous receivers. Receiver 5 was done with two point soldering and strain relief, while receiver 6 had no strain relief and only one point soldering.

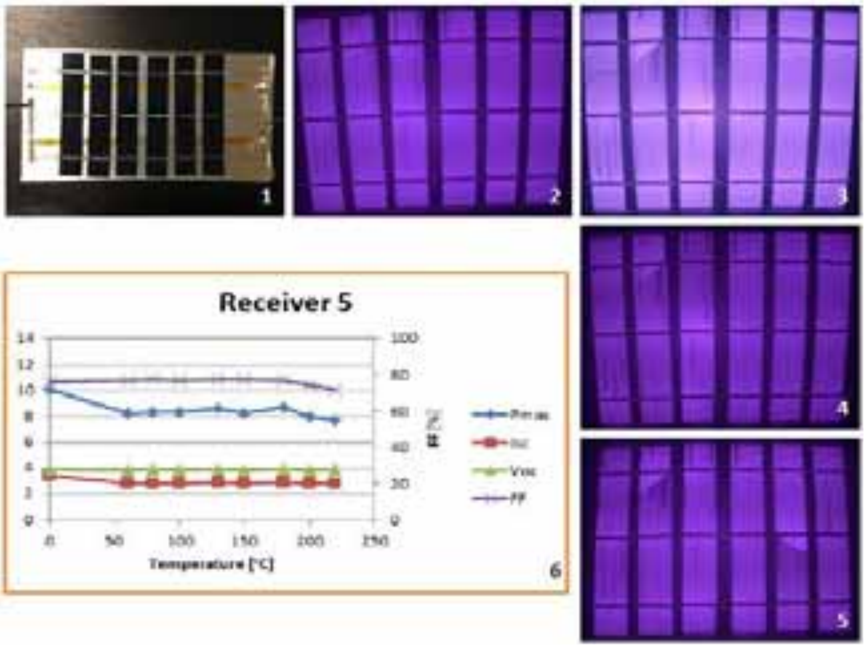

Fig. 8 – 1) Receiver 1; 2) Baseline; 3) Round 5 (150°C); 4) Round 6 (180°C); 5) Round 8 (220°C); 6) Parameters of the IV curve at different temperatures (Isc shown in the left Y axis).

In the graph of figure 8, it is visible that the Pmax of receiver 5 has one initial decrease at 50°C . This is due to the two broken cells shown in image three and it is likely to have been cause by our cell handling. If this effect is excluded, the Pmax remains relatively stable. It is interesting to note that only at 220°C one extra microcrack appears. The one point point soldering has much smaller electrical contact between the busbar and the cell than the line soldering but this shows no consequences in our measurements.

In figure 9, the Pmax of receiver 6 also remains fairly stable until one the cell becomes dark at 200°C (round 7) which seems to indicate that there are no large differences between one and two point soldering as well as with the existence of strain relief. One microcrack appears at 180°C and another appears 220°C.

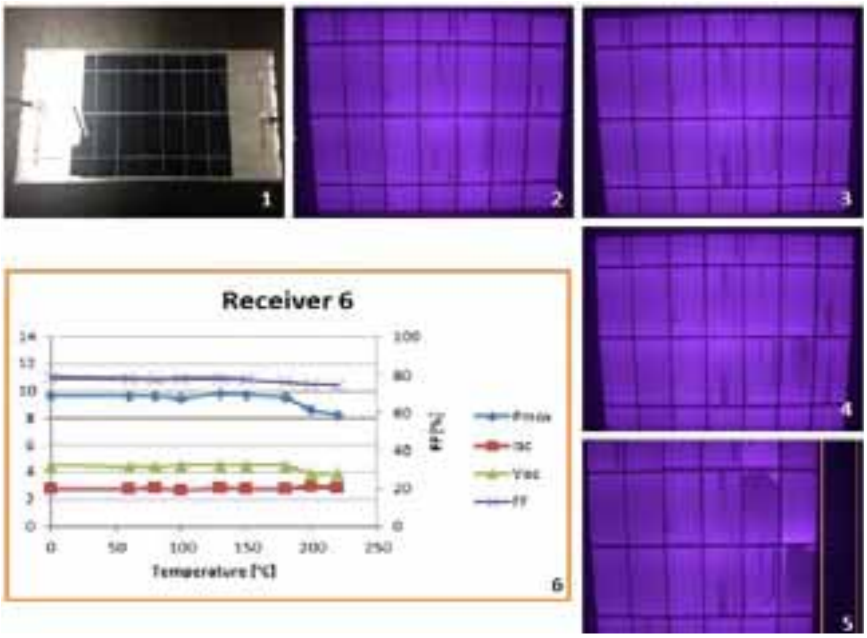

Fig. 9 - 1) Receiver 1; 2) Baseline; 3) Round 5 (150°C); 4) Round 6 (180°C); 5) Round 8 (220°C); 6) Parameters of the IV curve at different temperatures (Isc shown in the left Y axis).

Receivers 7 and 8 were made to evaluate the impact of temperature in larger cells (148mm*52mm). Receiver 7 was made with a much larger gap than usual between the cells, with line soldering and with strain relief between all cells while receiver 8 was made without strain relief, with point soldering and with a standard gap between cells.

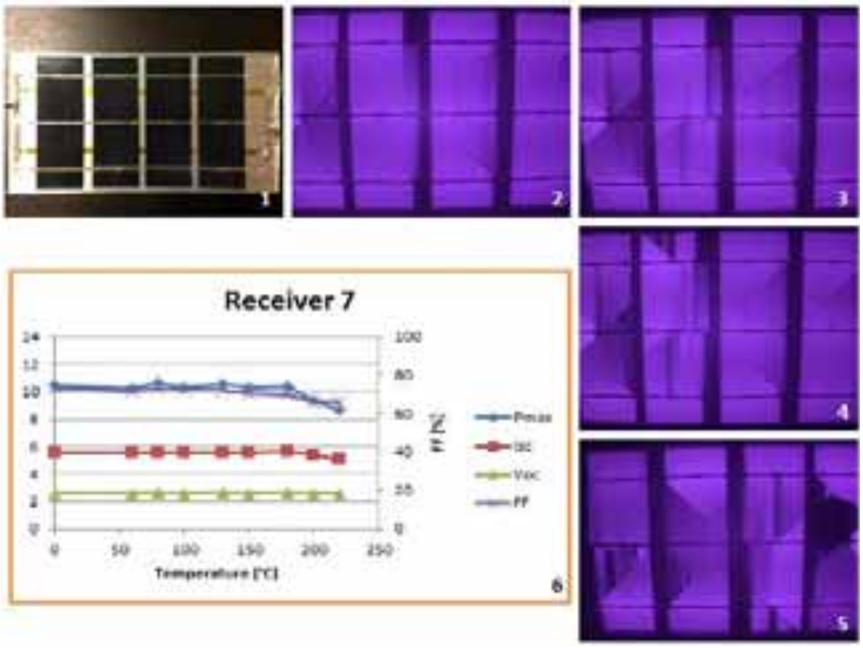

Fig. 10 - 1) Receiver 1; 2) Baseline; 3) Round 5 (150°C); 4) Round 6 (180°C); 5) Round 8 (220°C); 6) Parameters of the IV curve at different temperatures (Isc shown in the left Y axis)

Despite having more precautions against stagnation, receiver 7 shows more cell breakage then receiver 8 at any temperature. This seems to point that on large cells the effect of having large gaps with strain relief is less important than the type of soldering.

Strangely, the decrease in power is more pronounced in receiver 8 than in receiver 7. However, it must be noted that receiver 2 starts off from a much worst baseline scenario since it shows some microcracks from start. From all the testing accomplished, it also seems safe to state that existing microcracks expand at fast rate than new microcracks are created.

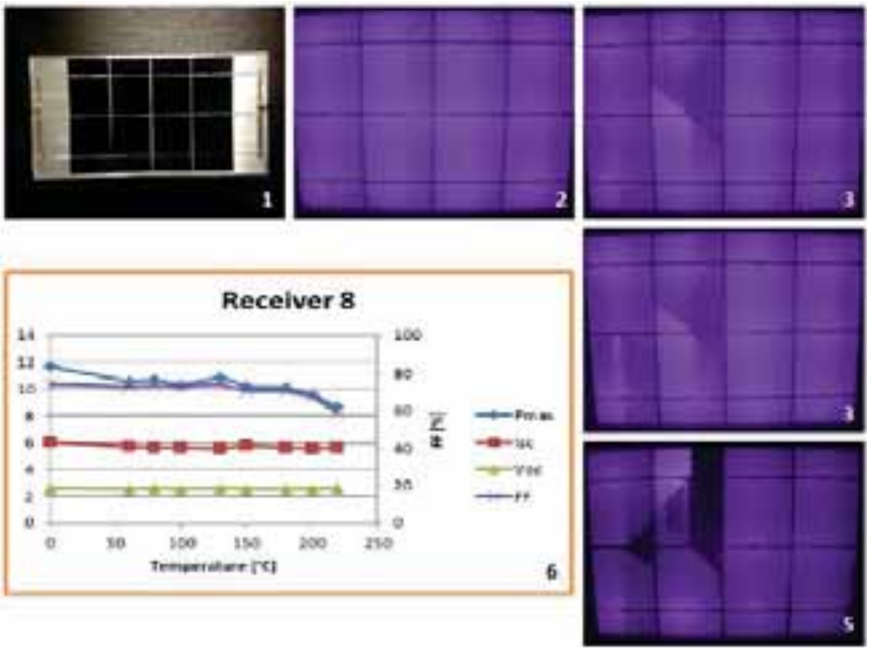

Fig. 11 - 1) Receiver 8; 2) Baseline; 3) Round 5 (150°C); 4) Round 6 (180°C); 5) Round 8 (220°C); 6) Parameters of the IV curve at different temperatures (Isc shown in the left Y axis)

Figure 12 and 13 compare the decrease in Pmax of the different receivers at different temperatures rounds. Receiver 2 shows the most steady Pmax across all temperatures Receiver 5 is also fairly stable is one excludes the handling problem on round 1. Receiver 1 shows an increase of power that is difficult to explain and is assumed to have been a human error. Overall, receivers with red silicone have the highest power decrease, if external factors are excluded. The existence of gaps seems to reduce the number of microcracks. No prototype test receiver losses more than 30% of its initial power, despite the large cell breakage shown in some receivers by the EL testing.

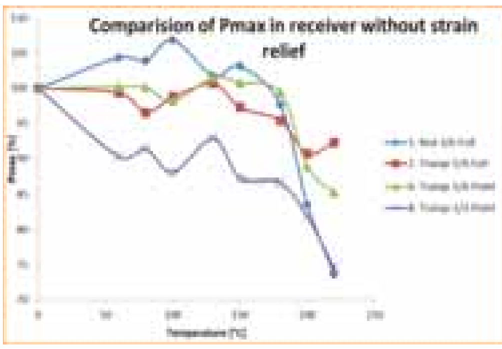

Fig. 13 - Comparison of Pmax decrease in receivers without strain relief

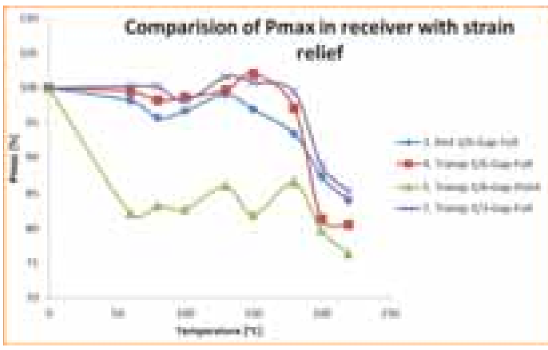

Fig. 12 - Comparison of Pmax decrease in receivers with strain relief

6. Conclusion

Eight different receivers have been built and were successfully tested to assess the impact of temperature variations in performance and cell structural integrity.

Two types of black areas in the cells were identified from the tests. They are namely irregularly shaped areas which are due to micro-cracks and regular rectangular areas which are due to broken finger contacts on the front of the cell. It was also noted that the majority of the micro-cracks were initiated at the soldering points, which is understood to be because of the different expansion coefficients.

From the previous figures, it is clear that receivers built with transparent silicone show far less cracks and power degradation after being exposed to the stagnation temperatures. This is understood to be due to two main reasons: 1) the transparent silicone is less rigid than the red silicone and thus further absorbs the mechanical stress of thermal expansion in the aluminium receiver; 2) the red silicone due to its lower viscosity is normally made in a thinner layer which further penalizes its ability to absorb mechanical stress.

No prototype test receiver lost more than 30% of its initial power, despite the large cell breakage shown in some receivers. After 8 rounds of testing, it was possible to conclude that the diodes were working perfectly at all temperatures, although the diode specifications stated a maximum junction temperature of only 200°C.

Larger cells are more prone to develop micro-cracks due to thermally induced stresses. From the tests that have been made, point soldering seems to lead to a reduction in the number of micro-cracks and black areas, especially in receivers with larger cells (148*52mm instead of 148*26mm). However, the impact of micro-cracks in the Pmax of receivers with point soldering is also larger because the smaller contact area between the ribbon and the cell.

From the electroluminescence images, the receiver presenting the lowest amount of micro cracks after round 8 (at 220°C) is receiver 5. This receiver has point soldering and strain relief between each cell. Receiver 4 and receiver 6 also exhibit low amounts of micro-cracks but both have a full black cell, possibly due to a contact between the top and bottom ribbon through the cell. Receiver 2 shows the most steady Pmax across all temperatures. Receiver 5 is also fairly stable if one excludes the handling problem on round 1.

Existing micro-cracks tend to grow in size into larger micro-cracks relatively fast. The EL imaging taken during our experiment leads us to conclude that it is far easier for existing cracks to expand than for new cracks to appear.

A limitation of this work was the absence of a fully automatic tabbing machine. Since this is expensive equipment, our team had to use manual soldering. However, by setting a baseline scenario for comparison, this limitation was addressed.

It is important to point out that the thickness of the bottom silicone layer is of the upmost importance in reducing the transference of thermally induced stress to the cells. The impact of the variations in the thickness of silicone in the thermal stress suffered by the cells has not evaluated in this paper and should be address in a future study.

7. References

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