Triple-Junction Concentrator Photovoltaic-Thermoelectric Hybrid Receivers: *Robustness, Validation and Preliminary Reliability Studies*

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1. Introduction

Multi-junction photovoltaic cells utilise the incident solar spectrum effectively with photon to cell efficiencies of up to 46% recently achieved for a wafer-bonded four-junction cell [1]. However even industry standard designs, such as monolithic lattice matched triple junction architectures, have high manufacturing costs. Optical concentration is an effective way of combining this technology with comparatively low-cost lenses to increase the incident light flux on the cell, achieving competitive parity cost per Watt with cell efficiencies over 50% [2], or in conditions with greater than 1500Wm^{-2} irradiance [3]. Thermoelectrics (TE) are solid state semiconductor devices that can either exploit a temperature differential to generate power (Bi_2Te_3 thermal to electrical conversion efficiency =~ 1% at 25^{o}C ΔT)[4] , or inversely use electrical power to act as a heat pump (typical Coefficient Of Performance of Bi_2Te_3 =~1 at 25^{o}C ΔT) [4]. One of the barriers for large-scale deployment of Concentrator Photovoltaic (CPV) technology for energy generation is its technology legacy. Silicon based panels have had many years of performance and lifetime data and investment risk is low. Recent publications show an evolving trend of hybrid solar devices being evaluated, including that of CPV-TE monolithic devices. Optimisation and simulation studies are prevalent [5-10], but experimental data is sparse especially for triple junction solar cells [11, 12]. Experimental characterisation and reliability testing of CPV-TE hybrids are investigated in this paper.

2. The Hybrid Receiver

A III:V CPV-TE monolithic CPV-TE hybrid receiver "proof-of-concept" design was manufactured at Cardiff University. The receiver consists of a bi-layer PCB structure, built on a 3mm copper substrate and incorporates an (8 x 6 x 1.6) mm encapsulated Bi_2Te_3 thermoelectric module. Bonded to this is a triple junction solar cell, wire bonded to the PCB for electrical connection. The cell and thermoelectrics are then further encapsulated by a silicone elastomer for dust and humidity protection. A photo is given in Figure 1.

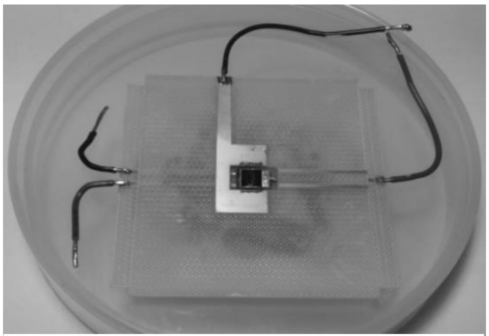

Figure 1. A Picture of "ALPHA"

To accurately evaluate device performance at 25^{o}C, current-voltage (I-V) characterisation scans under Standard Test Conditions (STC) were measured at Cardiff University. The receiver was then measured at Loughborough University's Centre for Renewable Energy Systems Technology (CREST) for cross-correlation analysis.

3. Experimental Methods

Three solar simulators were used for testing. Cardiff University's system, a LOT Oriel solar simulator, ABB rated according to ASTM E927-10. Bangor University has a plasma lamp simulator which achieves high incident flux for accelerated ageing and a Xenon lamp, ABB rated, for electrical I-V evaluation. A calibrated Kipp and Zonen Pyranometer, Silicon reference cell, and Spectroradiometer were used to characterise the solar simulator and confirm experimental performance comparable to the standard. A series of thermal images were taken during initial receiver I-V tests at Cardiff University to investigate thermal characteristics in the "ALPHA" receiver design (Figure 2).

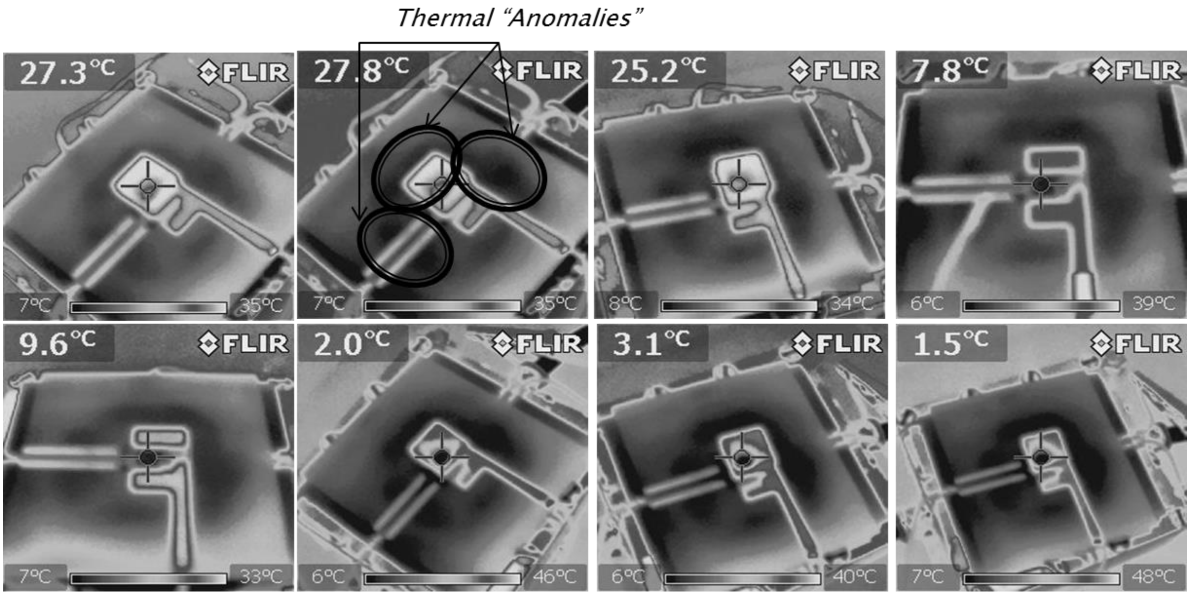

Figure 2. Thermal Images of ALPHA during Experimental Testing

4. Results

The data obtained from the STC receiver evaluation experiments at Cardiff and Loughborough CREST are shown in figure 3. The short circuit current and open circuit voltages obtained at Cardiff agreed to CREST data within 2% for I_{sc}, and the V_{oc} was identical to six decimal places, thereby substantiating the experimental methodology used at Cardiff. Experimental repeatability was also tested at Cardiff, and the I_{sc} was found to be within 1.1% for a complete takedown and setup (data shown in Figure 4).

Preliminary thermal simulations were undertaken using COMSOL to investigate and predict the thermal distributions of the PCB design under fixed incident light flux and bottom cold-side temperature as constraints. 10°C was chosen as experimentally representative to data obtained throughout water cooled receiver testing at Cardiff. Water-cooling and cell temperature control were crucial to the experimental setup when obtaining electrical characterisation STC data. Figure 5 shows the thermal distributions obtained from the preliminary COMSOL study, alongside a photograph of the ALPHA receiver post-accelerated ageing. Preliminary receiver accelerated ageing testing was undertaken on the ALPHA CPV-TE hybrid at Bangor University CLARET for 1200 hours. This data was used to evaluate current performance, and for estimation of future device long-term

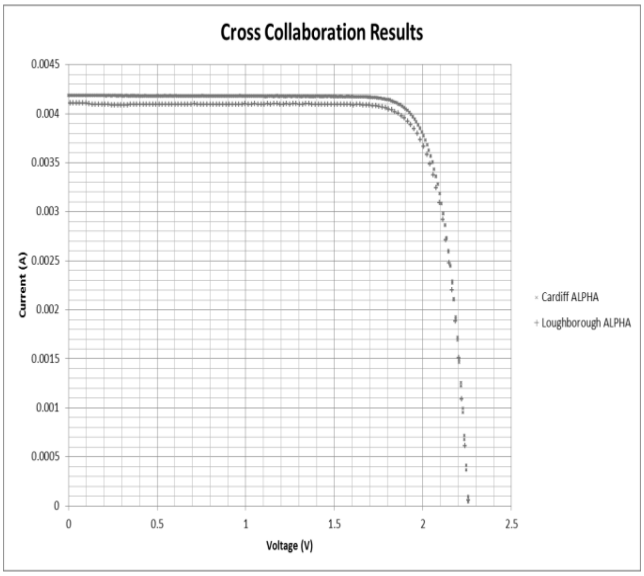

Figure 3. Cross correlation results Loughborough – Cardiff.

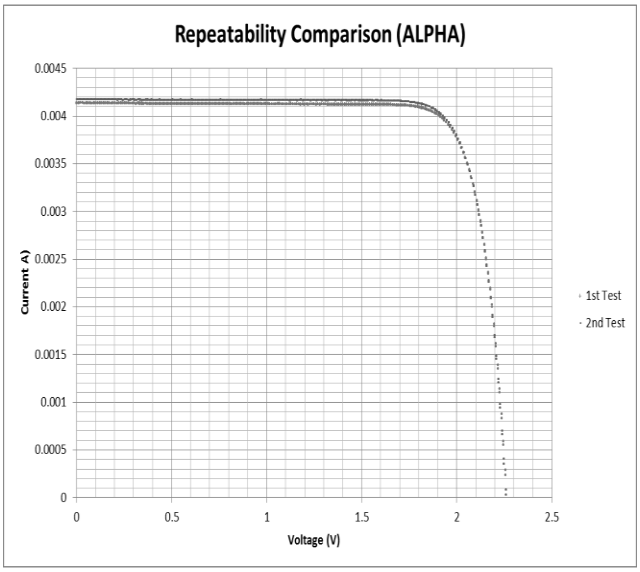

Figure 4. Repeatability Comparison (ALPHA) Cardiff.

performance and hence highlight possible premature failure areas to solve before progressing to large number / module testing. The testing involved a 600 hour study at 1 sun

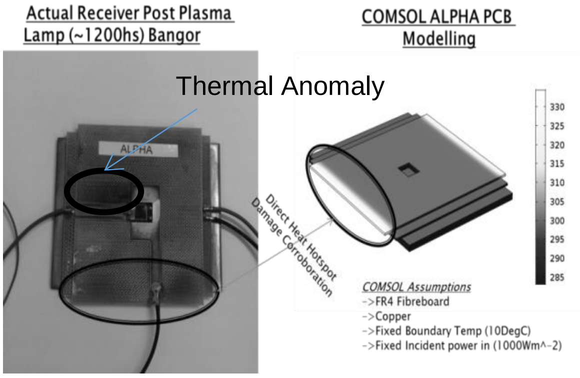

Figure 5. COMSOL and ALPHA (Post-Bangor)

and 2 sun light soaking, achieving elevated cell temperature measurements (thermal camera) of approximately 80^{o}C and 120^{o}C respectively.

5. Discussion

General heat degradation of the PCB fibreboard can be clearly seen by the discolouration in the comparison of the COMSOL model and the images of ALPHA post-reliability testing, shown in Figure 5. Included above (Figure 2) is a series of thermal images taken throughout the pre-ageing experimental testing of the ALPHA receiver at Cardiff. The areas of specific damage caused by the accelerated ageing process are also visible in the thermal images as a temperature inhomogeneity as compared to the rest of the board – a “thermal anomaly”.

Multiple temperatures were tested throughout this series of experiments, compensating for any temperature accuracy drifts of the camera exhibiting these distributions as spurious. Multiple orientations were photographed, thereby plausibly eliminating spectral or reflection errors that would also give anomalous dark spots on the images of Figure 2. Investigating this further, during manufacture, epoxy is used within the bi-layer PCB structure to ensure mechanical integrity. These thermal distributions occur if the epoxy layer is a non-uniformly applied – an effect previously thought negligible. This preliminary testing shows that a homogeneous adhesive application throughout the manufacture process would eliminate epoxy based hotspots from occurring, and hence eliminate a premature failure mode. Likewise, the PCB overhangs gave a secondary area of premature ageing for the PCB through an inadequate thermal contact to the copper substrate and hence heat flow path, as shown by the COMSOL simulation. With the exception of the aforementioned points, no other obvious degradation method was visible and the receiver exhibited good mechanical stability throughout testing.

From the long term performance data, the first 600 hour period of testing showed an overall degradation of approximately 2% power conversion efficiency, with the fill factor remaining comparable within experimental

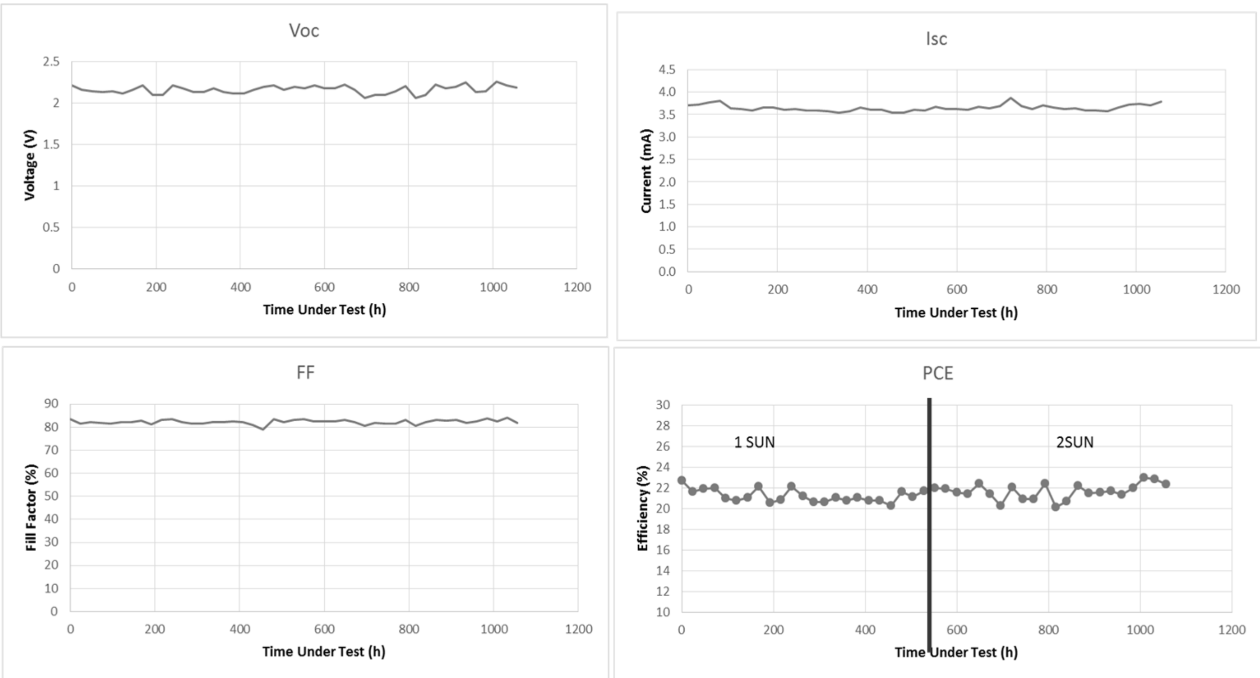

Figure 6. Reliability Testing Data of ALPHA from Bangor's CLARET

error. The 2 sun light soaking testing produced an elevated temperature of 120°C to further increase the thermal stress on the solar cell operating conditions. This temperature was obtained due to receiver surface-convection being exhibited as the predominant cooling mechanism in the ageing setup, as the receiver was placed on an insulated platform. During the successive 600hours testing the solar cell exhibited a power conversion efficiency degradation of a further 1%, once more showing promising long-term performance for these preliminary CPV-TE hybrids, regardless of the additional thermal resistance added by the thermoelectric being within the cooling heat flow path. Temperatures of 120°C are in excess of the rated operating temperature for all components involved in the hybrid's construction. However, the receivers gave good electrical characteristics after ageing tests. Future testing will focus greater on updated receiver design change evaluation, further device testing and thermal management with passive and active cooling methods for the hybrid CPV-TE receiver. It is clear that ALPHA remains stable under 1-2 sun testing conditions. Therefore to increase the degradation rate, higher irradiance levels, thermal cycling and humidity stressing is needed.

6. Conclusion

Pre-ageing, an experimentally observed repeatability within 1.1% and accuracy of measurement within 2% of an independent test centre was exhibited by the CPV-TE receiver. Preliminary accelerated lifetime and performance degradation testing was undertaken on a CPV-TE hybrid receiver for the first time. One sun showed 2% conversion efficiency degradation over 600 hours. Visible analysis highlights areas of PCB thermal degradation improvement and premature failure prevention. Two sun testing presented elevated temperatures up to 120°C, and an additional 1% degradation over a further 600 hours. This works shows great promise for the longevity possible with further developed CPV-TE hybrid solar receivers. Future work will investigate testing under higher concentration ratio and irradiance conditions. The thermal management of the receiver will be investigated further and optimised receiver configurations of the hybrid design will be manufactured and tested.

Acknowledgements

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