RELIABILITY ASSESSMENT OF A LINEAR PV-THERMAL MICROCONCENTRATOR RECEIVER BASED ON THE IEC 62108

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ABSTRACT

The Australian National University (ANU) in collaboration with Chromasun Inc., a US-based company, is developing a new hybrid CPV-Thermal (CPV-T) micro-concentrator (MCT) system that works at a concentration ratio of between 20 to 30X. The system design and reliability testing have been integrated as concurrent processes, enabling the early optimisation of the concentrator system receiver design. The key feature of this integrated design-test procedure is that carefully selected sets of simple tests can be conducted concurrently with the design of the concentrator module, without introducing extensive time delays in the receiver module design phase. Test results provide valuable information that significantly informs the design process and helps to avoid future failures.

1. INTRODUCTION

System and component reliability are widely recognised as critical aspects in the design and development of new electronic component and devices. The first qualification standard, IEC 62108 [1], has recently been approved for photovoltaic concentrator systems. This standard defines test procedures that a concentrator module must satisfy in order to guarantee long-term field performance. However, the solar concentrator space is filled with a multitude of different concepts and designs, with concentrator receivers, modules, and systems being composed of many different materials, structures, and combinations that encapsulate, electrically interconnect, and heat-sink the solar cells.

Many of these materials come from the power electronics industry, where their reliability and acceptability have been well-proven. Unfortunately, there is a general trend to extend the scope of application from the electronic to the concentrator arena and conclude that these materials from the power electronics industry are also reliable when used in concentrator PV (CPV) receivers. Although the components are certified reliable in their original field of application, they might fail when included in a solar photovoltaic concentrator module design. The specific failure modes are generally due to the changed operating environment, with the specific characteristics of the new device of lesser importance than the operation of the device under concentrated natural sunlight, elevated temperatures, and thermal shock [2].

The IEC 62108 standard specifies tests confined to the specific purpose of assessing the reliability of the complete concentrator receiver design. The specified tests are time-consuming, and the full test program occurs at the end of the development cycle. This is a critical consideration when planning the commercialization of any product, and even more important in the current rapidly developing CPV market. Carefully designed pre-qualification tests conducted during module design development can assist with detecting early failures or identifying potential failure modes, establishing confidence in the entire design process, and helping to improve the final module performance.

2. THE CHROMASUN-ANU MICRO CONCENTRATOR

At the Australian National University (ANU), a new hybrid PV-Thermal micro-concentrator (MCT) system working at a concentration ratio of 20 to 30X is being developed [3]. This system is very loosely based on the concept of the hybrid PV-Thermal CHAPS system [4], but it is adapted to the domestic and urban rooftop market. It uses a low-cost, ultra light-weight Fresnel mirror array as shown in see Figures 1 and 2), and incorporates modified mono-crystalline one-sun silicon solar cells.

The MCT system is a fully integrated heat and power solution, which will offer up to 75 percent combined heat and electrical power efficiency. The target performance of each module is to simultaneously produce 2kW of solar thermal energy and 500 Wp of electrical power. The MCT system incorporates single-axis tracking, and the system can be integrated into large buildings and domestic residences. Because of the low system profile, the MCT performance is not strongly dependent on elevation tilt angles or axial orientation.

Fig. 1: Detailed view of the CPV-T ANU-Chromasun MCT system installed alongside a conventional PV system on the same mounting support.

Fig. 2: A CPV-T ANU-Chromasun Micro-concentrator on a rooftop installation integrated with conventional PV panels at the Santa Clara University 2009 Solar Decathlon House.

The CPV-T receiver incorporates modified mono-crystalline, rear-contact, high efficiency silicon solar cells working at a concentration ratio between 20 to 30X. The solar cells are electrically mounted onto a commercial substrate that provides a thermal interface between the cell and the heat sink, and ensures electrical insulation [5], as shown in Figure 3. The assembly is encapsulated with clear silicone and thermally connected to the heat sink. Due to the integration of numerous materials with various physical characteristics, each independently subject to varying thermal stresses ranging from short intermittent heat-shocks from passing clouds to long daily thermal cycles, the concentrator receiver is the most complex element in a CPV or CPV-T system.

During the MCT design development, the possibility of assessing the reliability of the different components in order to improve the concentrator module design from its early stages was explored by establishing a procedure to test the reliability of materials, materials combinations, and progressive design iterations through all stages of the receiver design.

Arising from these considerations, an integrated process has been developed to assess the design and reliability of the concentrator receiver. This integrated process combines several different tests based on the IEC 62108 standard with adaptations designed to detect failures earlier in the design cycle. This process will effectively provide more time to enable the optimisation of material selection along with the development of the completed receiver design.

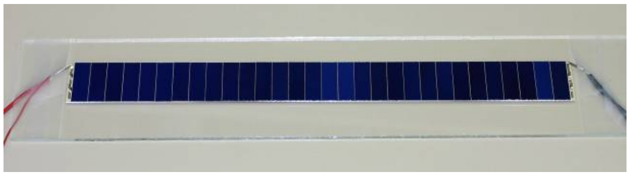

Fig. 3: A prototype assembly designed to test the combination of material performance along with the manufacturing and assembly process.

3. ASSESSING THE DESIGN OF THE CPV MODULE FROM A MATERIALS PERSPECTIVE (IEC 62108)

Concurrent with development of the MCT receiver design, the possibility of assessing the reliability of the different components was investigated in order to improve the design process and ultimately the overall receiver design. A procedure to test the component materials and design reliability throughout all stages of receiver design has been established. This procedure provides early evaluation of the performance and compatibility of isolated and combined receiver components and assemblies. This includes components ranging from the bare solar cells, thermally conductive and electrically insulated substrates, thermal adhesives, and even early accelerated lifetime tests of partial assemblies.

The performance of bare cells, bare cells soldered onto thermal substrates, assemblies of cells, substrates, and thermal adhesives are all being evaluated. Each of these groups is subjected to a different sequence of tests, including visual inspection, electrical insulation, electrical performance, thermal cycling tests, and damp heat tests.

Other tests based on the IEC 62108 standard have been also designed, including:

- Material tests of thermally conductive adhesives using thermal cycling tests, damp heat tests;
- Material performance and compatibility tests of the thermal substrate, both dielectric and thermal testing;
- Silicone dielectric strength (HiPot) tests; and
- Performance and compatibility tests of encapsulated receiver prototypes using thermal cycling tests.

For these new procedures, the development timing of the project, the cost of the tests, and the number of representative tests required have all been considered in order to reach a strategically optimised compromise. The key point here is to recognise that a carefully selected set of simple tests can be conducted concurrently with the design of the concentrator module, without introducing time delays on the module design. The test results provide valuable information that help to avoid future failures. The results of these early component and assembly tests, as well as their value in the assessment of the MCT receiver module design, are presented below.

3.1 Thermally Conductive Adhesive Tests

In the design of the MCT receiver, one of the important materials is the thermally conductive adhesive that provides a low thermal resistance interface between the main substrate and the heat sink. This material must possess favorable heat transfer properties as well as adequate mechanical properties, since it provides the bond-layer between the two components. In order to evaluate the thermal and mechanical performance of the selected range of materials, as well as to assess and rank the selection, a group of different thermally conductive adhesives was selected.

These adhesives were from different manufacturers, with differing thermal conductivities, mechanical properties, adhesion properties, and chemical constitution. Other aspects that were considered in the selection process include the toxicity of the materials, ease of integration into the manufacturing process, material availability, and material cost. Electrical insulation was not a requirement for this particular application since other elements of the receiver design provide for electrical insulation between the cells and the main mounting substrate to the heat-sink.

Thermal cycling tests and damp heat tests were conducted with test samples constructed using this group of adhesives as shown in Figures 4 and 5. The most significant outcome from these tests, conducted for durations lasting three times longer than those required by the official standard, was the identification of a small number of thermal adhesives with adequate long term thermal performance, along with sustained-mechanical adhesion. A large fraction of the materials sampled were rejected during the intermediate characterisation tests, due to poor adhesion, a significant drop in thermal conductivity, or some combination of the two effects.

3.2 Thermal Substrate Tests

To provide an interface between the cell and the heat sink with good thermal heat transfer and sufficient electrical insulation, a commercially available thermal substrate from the power electronics industry was selected. However, in order to ensure adequate electrical insulation of the cells, and to optimise the design of the electrical mounting pattern, variations of the Hi-pot or dielectric withstand tests were performed. These tests include two different types of the thermal substrate, along with different electrical mounting patterns.

With respect to the substrate type, dielectric breakdown tests were performed to determine the capability of the material electrical stand-off characteristic, and how this capability behaves outside the manufacturer’s specified limits. In testing this tolerance, it was found that the tolerance margin for lower insulation materials was very limited. However, upon upgrading to a higher insulation standard, a much greater tolerance margin was achieved.

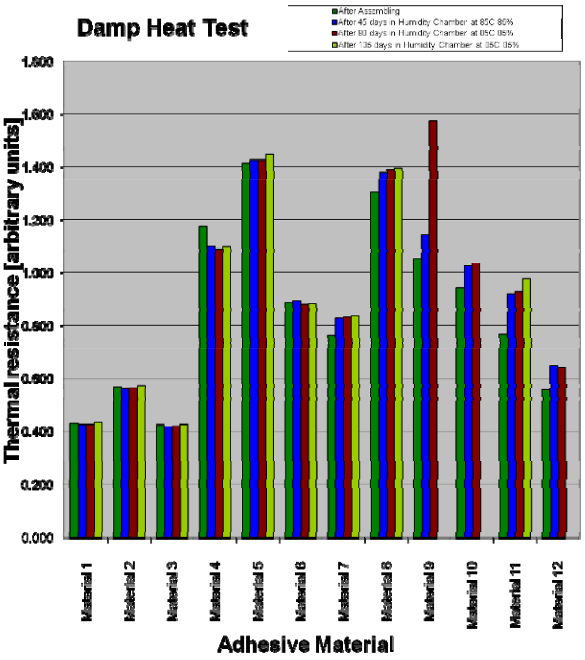

Fig. 4: Thermal resistance results from the damp heat test for the selected group of thermal adhesives.

In addition to over-stressing the insulation, reliability tests were used to detect material and workmanship defects. Most importantly, they detected areas where the spacing between current-carrying conductors and earth-ground connections were inadequate. This process can also be used to test and optimise the cell mounting electrical design pattern, ensuring connection reliability while also minimising the cost.

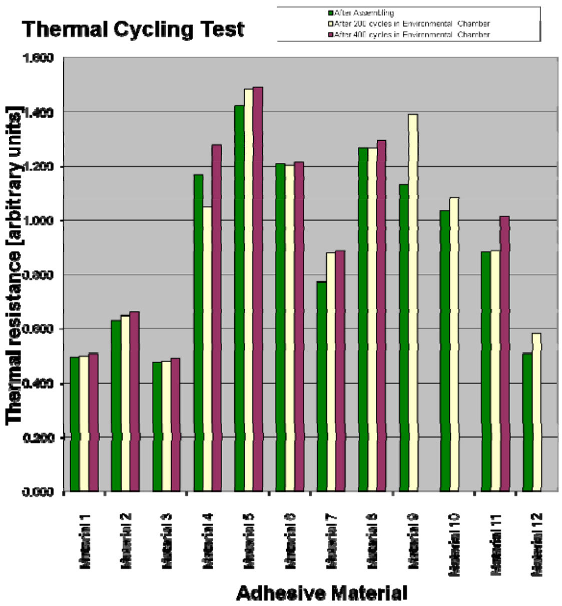

Fig. 5: Thermal resistance results from the thermal cycling test for the selected group of thermal adhesives.

3.3 Silicone Dielectric Strength Tests

A clear PMDS silicone was used to encapsulate the MCT receiver modules. In order to optimize the creepage distances between conductive elements in the modules, the dielectric strength of the encapsulant has been quantified. For these tests, samples with different gap distances between two electrical wires of 50, 150, 200 and 250 microns were built. The precisely spaced gaps were filled with clear silicone. The samples were then subjected to HIPOT tests at voltage levels up to 2000V_{dc}. At this voltage, all samples passed the test. When increasing the voltage to 2600 V_{dc}, the 50 micron sample exhibited breakdown, but the 150 micron gap sample, and the others with wider gaps, did not experience breakdown until 17 kVdc.

4. ASSESSING THE DESIGN OF THE CPV MODULE: INITIAL PROTOTYPES EVALUATION

During the MCT design development a number of small tests were conducted to provide feed-back on reliability and performance. A small selection of these tests will be described in order to illustrate the value of the process.

Prior to receiver encapsulation the sub-modules are very fragile and can easily be damaged. Although visual inspection and basic Voc tests conducted under one sun return normal results, testing of the 30-cell sub-modules under concentration revealed the possible presence of a number of faults that could not be detected by the previous test regime. The origin of these faults has not yet been identified, and it is unclear at this stage whether the problem lies with the design, the handling, with the manufacture process, or with the test process. Visual inspection after high concentration testing identified micro-cracks in a small percentage of the cells. It could even be possible that the cracks originate from the test procedure. Accordingly, a tool for measuring dark series resistance has been developed, and additional test steps have been introduced to the testing procedure in order to determine whether the procedures used for testing under concentration are responsible for causing the observed faults.

A second example relates to the encapsulation procedures. The separation layer between the rear surface of the cells and the mounting substrate is very thin. This poses a potential barrier to full and complete silicone encapsulation. Visual inspection of this space following a standard encapsulation procedure revealed an absence of silicone in the void. The expansion and contraction of this air space was suspected to be a contributing factor to early de-lamination failures under extended thermal cycling tests. Recently, a new encapsulation regime has been developed to overcome this problem. This process is described in some detail in a companion paper to this conference.

Visual inspection of test samples produced using this new process indicates that the silicone completely fills the space between cell and substrate. Thermal cycling testing of this new method of encapsulation is currently in progress.

A third example relates to the electrical inter-connection process and cell mounting methods on the thermal substrate. After prolonged thermal cycling, for a period exceeding six months which was several times that required by the standards, the integrity of some of the electrical interconnections appeared to be compromised. The possible failure modes have been identified, and design variations are under way. Possible solutions include alternative materials and a re-design of the electrical circuitry. It is likely that the solution implemented will comprise a combination of both solutions for additional robustness.

A selection of small prototypes have been manufactured at laboratory level in order to establish anticipated receiver performance at the sub-module level by examining the performance of the group cell level, the thermal substrate, and the silicone encapsulation behaviour. These initial prototypes were subjected to thermal cycling tests, which detected some performance issues in some of the samples, such as an increase in the electrical series resistance, as shown in Figure 6. This was identified as arising from a defective electrical connection process, rather than a materials issue. The early detection of failures has allowing a rapid improvement in receiver design, with respect to lifetime durability as well as efficiency and performance.

For example, the electrical interconnection materials are currently under study, with the view to optimising the mechanical properties of the interconnections, as well as to avoid the presence of residues or by-products that can affect the long-term performance of the rest of the module. This is an important consideration, particularly with respect to encapsulation contamination, which could result in the possible de-lamination of components due to compromised adhesion.

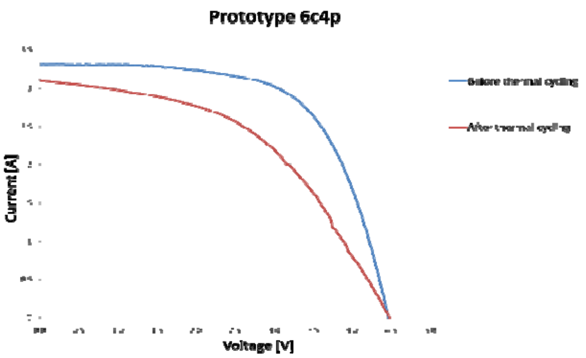

Fig. 6: I-V curves of one of the initial prototypes before and after the thermal cycling test, showing a significant increase in the series resistance of the sub-module.

Each CPV-T hybrid receiver consists of ten PV sub-modules similar to that shown in Figure 3, electrically inter-connected in series, with cooling water flowing along a channel to the rear of the cells. The sub-modules each contain 30 cells and four bypass diodes.

Prior to construction of the first full-sized receiver prototype, all the 30-cell sub-modules were tested individually under concentration using a test rig developed by Chromasun. The test rig is shown in Figure 7.

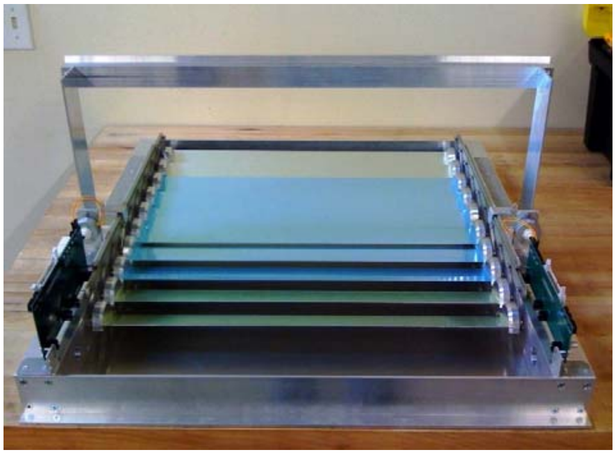

Fig. 7: The test rig developed by Chromasun using representative mirror sections and full tracking capability, used for testing and binning sub-module.

This testing allowed characterisation of the electrical performance, and enabled sub-modules to be binned according to their respective short circuit current. This provided the best match of modules for each full length receiver.

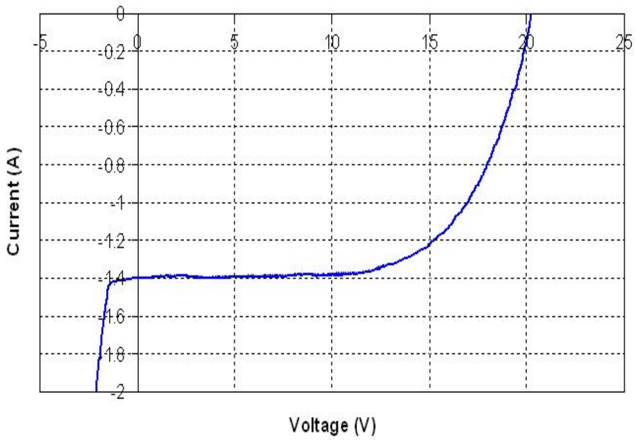

Fig. 8: A typical IV-curve of a 30cell sub-module operating at around 14 suns optical concentration.

A typical IV curve generated from one 30 cell sub-module operating at 14 suns is shown in Figure 8. Abnormalities in the shape of the curve can be used to detect the presence of faults such as cracked cells, faulty diodes, or high resistance electrical interconnections. Analysis of the faults detected from IV curves that were taken under concentration is performed through further visual and electrical tests. The results are fed back through the design and assembly process to improve performance and reliability.

This process will be iterated through prototype development and pilot manufacturing in the commercialisation process.

5. CONCLUSION

Early evaluation of the physical and mechanical properties of receiver components has been demonstrated to improve the receiver design process and the reliability of the end product. This methodology, as developed, has been applied to the Chromasun-ANU micro-concentrator receiver design. The main outcomes from this experience include the identification of an appropriate selected group of thermally conductive adhesives; the upgrading of the main thermal transfer and cell-mounting substrate between the cells and primary heat sink to a higher insulation standard due to very limited tolerance margins; and the early detection of performance issues in initial prototypes.

The early detection of these performance issues has provided the opportunity for more rapid and reliable design optimisation.

6. ACKNOWLEDGMENTS

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