The Design of a High Concentrator Photovoltaic Module (HCPV)

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Abstract
High concentration photovoltaics (HCPV) promise a more efficient, higher power output than traditional photovoltaic modules. This is achieved by concentrating sunlight onto a small 1 cm^2 concentrator triple junction (CTJ) InGaP/InGaAs/Ge cell by using precision optics. In order to achieve high performance, careful design decisions must be made in the development of a HCPV module. This paper investigated the design of a HCPV module (Module I), which was based on the Sandia III Baseline Fresnel module. The investigation concentrated on the optical design, thermal dissipation and electrical characterization of a CTJ cell. The best performance achieved was at 336 times operational concentration, which produced 10.3 W per cell, a cell and module efficiency of 38.4 % and 24.2 % respectively. The development of the second module (Module II) employed pre-monitoring criteria that characterized the CTJ cells and system components to eliminated faulty components from the system, observed in Module I. These criteria included visual inspection and one-sun Current-Voltage (I-V) characteristic curves. Optimized units in Module II showed no form of degradation in the I-V characteristics and detected defects. The units under thermal and optical stress showed a progressive degradation with operation in the field.

Keywords: Concentrator Photovolatics, Concentrated Triple Junction Cells, Efficiency, and Degradation.

1.   Introduction

High concentration photovoltaic (HCPV) systems offer a cost effective solution to the global power crisis faced by the world today. Using easily attainable, source able balance of system materials to concentrate sunlight, the standard commercial flat plate photovoltaic (PV) module silicon cells can be replaced with highly efficient, III-V multi-junction cells (MJC). The rest of the module will comprise of relatively cheap optical elements such as lenses and mirrors with the aim to collect, concentrate and evenly distribute the direct incident solar flux onto a small cell.

This paper addresses the design as well as the design considerations needed to manufacture an operational, field ready HCPV module. The first module (Module I) was be based on the Sandia III Baseline Fresnel module, which utilized a Fresnel lens as the primary concentrating optical element and a truncated reflective secondary.   These optical elements were used to concentrate light onto a concentrator triple junction (CTJ) InGaP/InGaAs/Ge cell. Performance parameters were measured, and the findings obtained from Module I were used as an evolutionary step to improve the design of the HCPV module. This was achieved with Module II. Module II was designed using separate units which were connectable to form the module. This design was beneficial as easy unit replacement was possible without the full decommissioning of the entire module. The optimal module units that were tested under optimal design conditions showed no form of degradation after 220 hours of operation under concentration, while degradation was seen in non-optimised units.

1.1.   Objectives

To determine the optimal design of a HCPV module by using standard and developed PV techniques to characterize the performance of a HCPV module.

2.   Proposed model or Conceptual method

Figure 1 illustrates the basic concept of a HCPV system. In the figure parallel light rays from the direct normal irradiance are incident onto the primary optical element where light is concentrated towards the secondary optical element. Concentrated sunlight interacts with the secondary and is further concentrated and distributed across the area of the receiver (MJC). This is the general process of HCPV modules to produce energy.
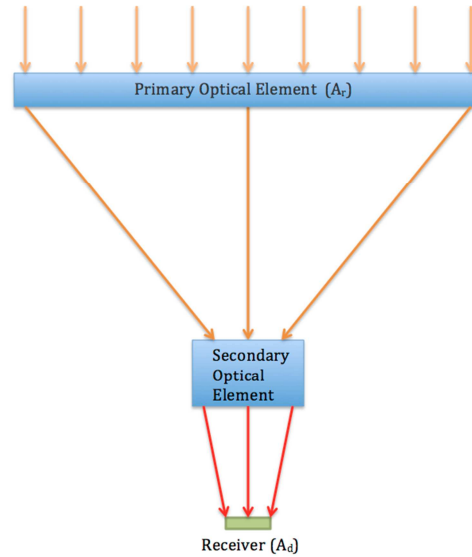

Figure 1: Illustration of the basic concepts of solar concentration for a HCPV module.

To understand the concept of defining the concentration factor, one needs to define and understand the operational concentration factor as it is used to define the HCPV system under operation.   The operational concentration factor (X_o) includes the combined effect of the photons interacting with the optical materials and the device, while factoring in the relative losses due to the interactions and physical construction of the module.   The X_o is thus the ratio of the measured irradiance of the module under concentration (Irx) to the irradiance at one-sun concentration (Ir1).

$$ \tag{1} $$

Since there is a linear relationship F between the short circuit current (Isc) and the irradiance, (F is dependent on device material and its fabrication), the irradiance can be replaced by the factor F and its respective Isc value [1].

$$ \tag{2} $$

The F factors cancel and the operational concentration value is given as

$$ \tag{3} $$

 Where Iscx and Isc1 are the measured short circuit current under concentration and at one-sun respectively. Equation 3 thus gives the operational concentration factor that takes into account all the interactions, misalignments and optical performance acting on the CTJ cell.

2.1.   HCPV Optical Systems

The most important part of the operation of HCPV systems is that of the optical configuration and the precision and quality of the optical elements.

To achieve maximum yield, the optical elements need to:
- be able to collect and concentrate sunlight,
- increase the acceptance angle of incident light onto the receiver to minimize back reflection, and
- distribute the solar spectrum and intensity uniformly across the device surface.

This is achieved by combining the use of primary and secondary optical elements, which are reflective or refractive in nature. The system can comprise of both primary and secondary optical elements being reflective or refractive and/or a combination of both in any configuration.

2.2.   Primary Optics
2.2.1. Fresnel Lens
A Fresnel lens is a light, thin, relatively flat alternative to the traditional glass lens that features the same properties as a curved glass lens used to concentrate incident sunlight. The decrease in lens thickness is achieved by creating concentric facets known as Fresnel zones which mimic the curvature of a spherical glass lens, identified in Figure 2(a) and Figure 2(b). The Fresnel lenses are made out of an acrylic, Poly (methyl methacrylate) (PMMA) and polycarbonate materials and are manufactured by compression molding. This allows for the manufacturing of single and parquet lenses in any shape or size. Figure 2(a) shows the flat lens structure, Figure 2(b) shows the size advantage due to facets and Figure 2(c) shows the optical losses due to interaction with the facet of the Fresnel lens are shown.
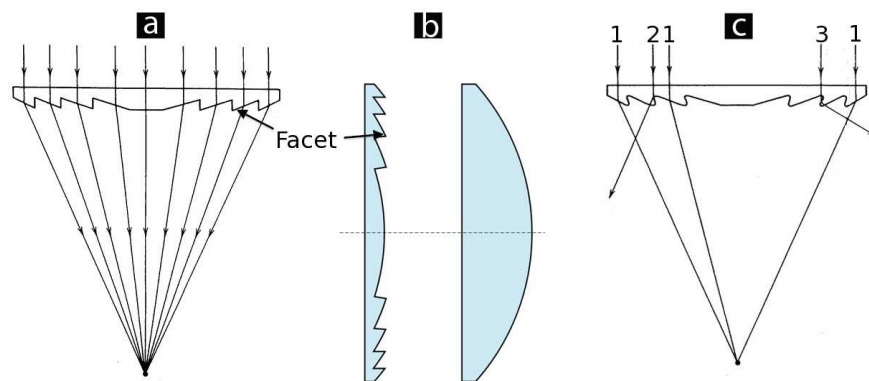

Figure 2: Illustrations showing the (a) structure, (b) size advantage and (c) optical losses of a Fresnel lens [7].

2.2.2.   Secondary Optics
The function of the secondary optical elements is to increase the concentration ratio, the acceptance angle from the primary optical element and to distribute the concentrated solar flux uniformly across the device's surface.

2.2.2.1. Reflective Secondary
Reflective secondaries utilise mirrors in the form of highly reflective aluminum sheeting with reflectance of 95 % to reflect the incident solar flux [2]. Figure 3 shows a schematic diagram of incident light rays reflecting off the reflectors surface towards the receiver's aperture.
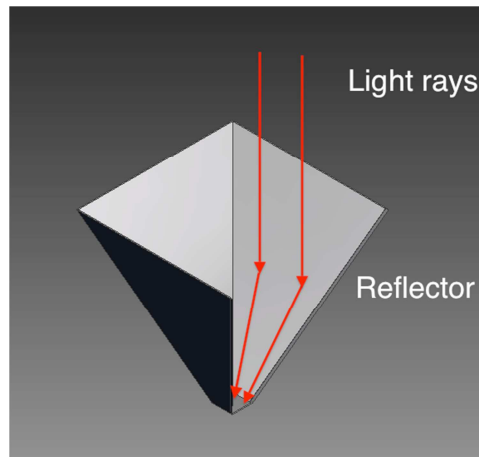
Figure 3: Schematic drawing of reflective secondary reflecting light rays towards the device aperture.

2.2.2.2. Refractive Secondary

Refractive secondaries utilise glass formed lenses that refract the light onto the cell's surface. The difference is that refractive optical elements have to make physical contact with the receiver in order to transfer the light energy in the cell, reducing any loss that would result from spillage from the sides of the interface. Figure 4 shows the schematic diagram of incident light rays being refracted by the glass secondary, through the glass optical medium to the receiver's aperture.
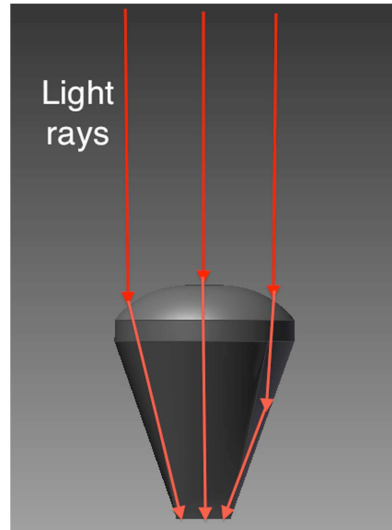

Figure 4: Schematic drawing of refractive secondary refracting light rays towards the device aperture.

2.3. Multi-Junction Cells

Multi-junction cells offer a better solution to the absorption of energy from a wider spectral range than that of conventional PV cells. The use of doped silicon as a semiconductor material only utilises a small fraction of the solar spectrum due to the defined band gap of the material. This is the limit of a single junction cell's performance. To increase the performance and power output of a cell, a device is created to allow for more absorption of the solar spectrum. This is achieved by

creating a device, which utilises multiple subcells connected in series. The subcells are made of different materials that have different absorption regions within the solar spectrum. This allows for a much larger portion of the solar spectrum to be absorbed, resulting in a higher performance [3, 4].

2.3.1. CTJ Cell

In this study InGaP/InGaAs/Ge concentrated triple junction cells (CTJ), lattice matched to the Ge substrate, were used. They are commercial cells produced by Emcore [1, 5]. In Figure 5 a schematic diagram of the CTJ cell used in the study is shown.
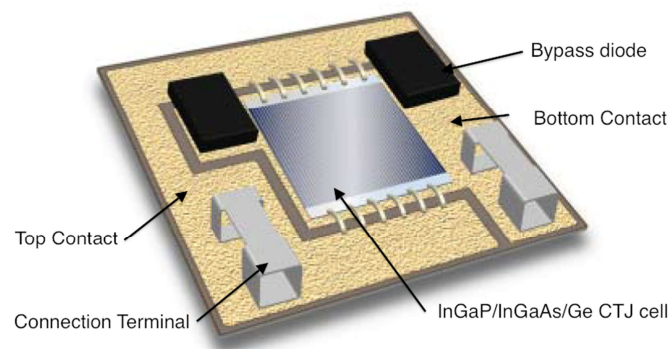

Figure 5: Schematic drawing of CTJ cell [5].

The structure of the CTJ cell consists of a 1 cm^2 triple-junction InGaP/InGaAs/Ge semiconductor material, two bypass diodes and connection terminals mounted on a 6.78 cm^2 gold and ceramic substrate [5]. The substrate acts as a thermal regulator and a platform for the electrical components. The semiconductor material is electrically and mechanically connected to the CTJ cell by the gold bottom contact and top contact by means of 12 gold ribbons. Bypass diodes across the bottom and top contacts allow for additional current to bypass the cell in the case of cell mismatch occurring in a HCPV module. The CTJ cells are electrically connected to the module by the connection terminals. In Table.1 the specification and performance of the CTJ at different concentrations are shown [6].

Table 1: Showing the effect of increased concentration on CTJ cell parameters.

	1X$_o$ concentration	503 X$_o$ Concentration	1182 X$_o$ Concentration
Efficiency	31.4%	39.0%	36.3%
Voc	2.605 V	3.193V	3.251 V
I$_{sc}$	13.85 mA	6.96 A	16.37 A
Power	31.4 mW	19.3 W	42.9 W

The main features seen in Table 1 shows a large increase in the Isc and power, a noticeable increase in Voc and variation in the efficiency of the CTJ cell when compared to 1 X$_o$.

3.   Research methodology

In this section, the design of the two HCPV modules will be explained as well as the investigative techniques used in charactering the designs.

The physical structure of the experimental HCPV module was based on the Sandia III Baseline Fresnel Module [4] because of its simplistic and compact design that uses a parquet Fresnel lens arrangement. The main structure of the experimental HCPV module was made from aluminum angle, which acts as the skeletal support structure. This structure supports a 2x4 Fresnel lens parquet array and 8 assembled CTJ cells with attached secondaries and heatsinks. Figure 6(a) shows a schematic diagram of the skeletal structure of the experimental HCPV module, and Figure 6(b) the shows the module developed mounted on a two-axis tracker.
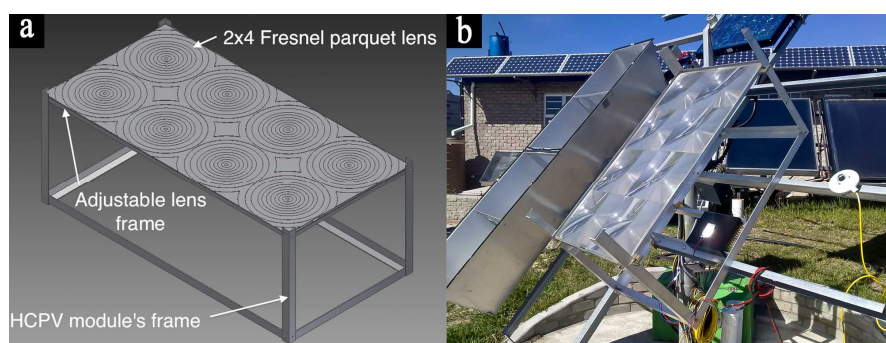

Figure 6: Illustrations of the design of Module I

The size of the parquet Fresnel lens dictates the dimensions (length and width) of the HCPV module's support and the lens frame. The height of the HCPV module's frame was lengthened to allow for the attached lens frame to be varied in height. This allowed for different concentration ratios for experimental use. Mounting clamps where used to attach the lens to the frame and to secure the lens frame to the main frame. These clamps also allowed for the adjustment of the lens frame for various concentration ratios. Once experiments with various concentration ratios were completed, the sides of the HCPV module frame were closed with 0.5 mm aluminum sheets. This allowed for weatherproofing of the HCPV module for long-term measurements.

3.1. Secondary Optical Design

Concentrating sunlight onto an area using a Fresnel lens without incorporating some form of secondary optical element will result in the formation of a non-uniform intensity illumination distribution across the CTJ's cell surface. This could result in the formation of hot spots, which can lead to low power production, cell damage and premature failure of the cell [2].

The secondary shape was chosen to be a truncated pyramid because of the square shape of the CTJ cell. The secondary was constructed out of 4 pieces of mirrored aluminum sheeting (Alanod 95 % [2]) that were triangular in shape with a straight base cut to 1 cm in length and connected at 90° to form the truncated pyramid shown in Figure 3. To determine the secondary's dimensions, the focal length of the Fresnel lens and the general shape of the reflective secondary must be considered. The dimensions for the reflective secondary were determined by ray- tracing and are shown in Figure 7.
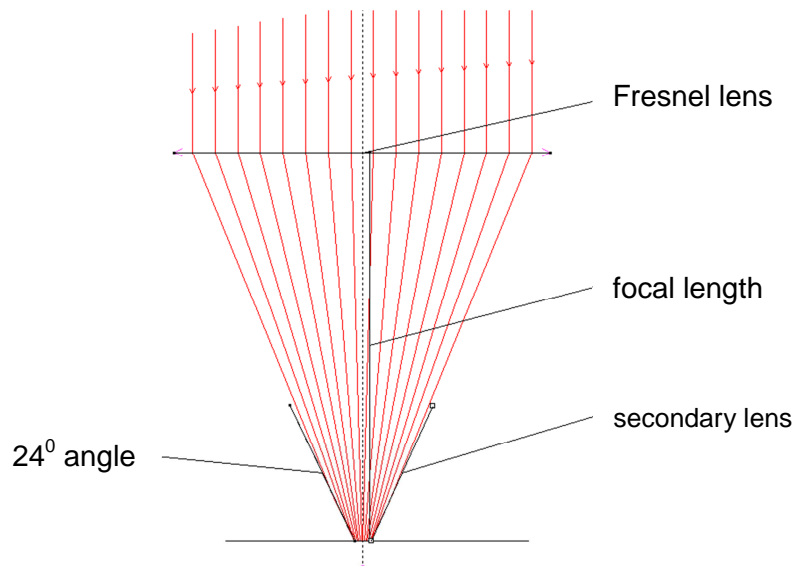
Figure 7: Ray-trace diagram used to determine the dimensions of the reflective secondary

Figure 7 shows parallel solar light rays entering the Fresnel lens and converging at 23° from the normal to the focal point. The focal length was determined to be at a point, 25 cm from the Fresnel lens, forming a circular high intensity spot smaller than the 1 cm^2 need by the CTJ cell. From the ray-trace diagram, a distance of 23.4 cm was found to be the optimal distance that allowed a 1 cm^2 area of the CTJ cell to be illuminated while showing minimal effect from lens aberration.

The experiments performed with this module included:
- the effect of the variation in concentration,
- the effect of insufficient thermal management for long term measurements, and
- the effect of optical misalignment.

3.2. Module Design of Improved HCPV Module

To eliminate the shortfalls observed in Module I, the experimental HCPV module was redesigned. The new design incorporated a unit design, which comprised of a unit that contained a Fresnel lens, refractive secondary, heatsink and CTJ cell. Figure 8 shows the schematic diagrams of the unit. The individual unit was designed to eliminate the need to disassemble the whole module in the case of a single cell failure. This allowed for easy replacement of a cell-secondary assembly into a module by the removal of the base plate. Additionally, the size of the module is not restricted to the number of Fresnel lenses in the parquet array. Hence the unit allows one to create any size module.

The unit comprised of a single PMMA Fresnel lens, which acts as the primary optical element. The use of a single lens eliminated lens warp and deformation, experienced by a parquet lens due to wind jarring and tracker movement. Additionally, this is an easier and cheaper way to replace a single lens than a parquet lens if damaged.
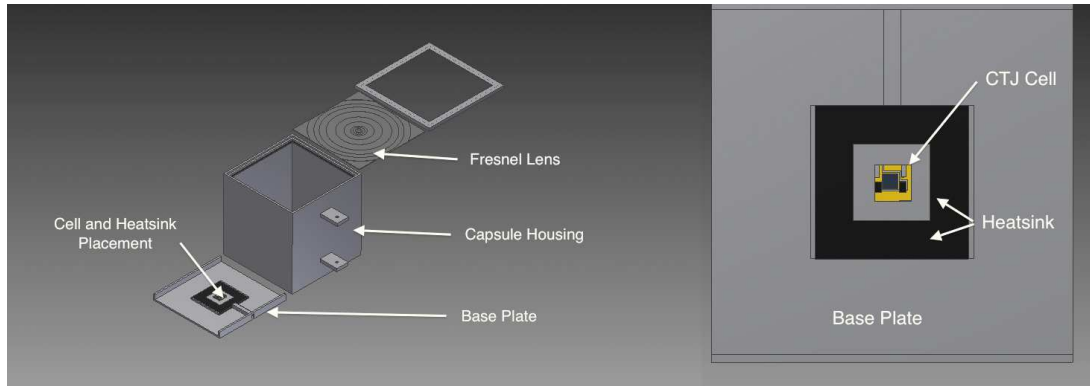
Figure 8: Schematic diagrams of HCPV module's cell unit.

The unit box shaped housing was made from 0.6 mm galvanized steel that was bent to form a box. The box offered isolation for the internal components of the HCPV module from environmental conditions. Also it acted as a rigid platform for the mounting of the Fresnel lens and base plate. The housing has fixtures on the side of the box to allow for mounting to the module frame. The base plate that is shown in Figure 8 (b) allowed for the attachment to the unit housing and as a platform for the attachment for a heatsink, the CTJ cell and refractive secondary.

3.3.   Refractive Secondary Design

The refractive secondary used in the new module was taken from a Sandria III-design module used in a previous study [8]. The top of the glass secondary is circular in shape with an optical aperture of 8.85 cm^2 that tappers down along the sides to form a square cell aperture area of 1 cm^2. The refractive secondary is optically coupled to the cell, eliminating soiling of the cell and reducing the amount of maintenance needed. Figure 9 shows the relative secondary design used in Module II.

Figure 9: (a) Schematic diagram and (b), (c) photograph of the refractive secondary.

3.4.   Assembled Module

In Figure 10 (a) the schematic diagram and in Figure 10(b) a photograph of the advanced HCPV module comprising of 8 units are shown, respectively.
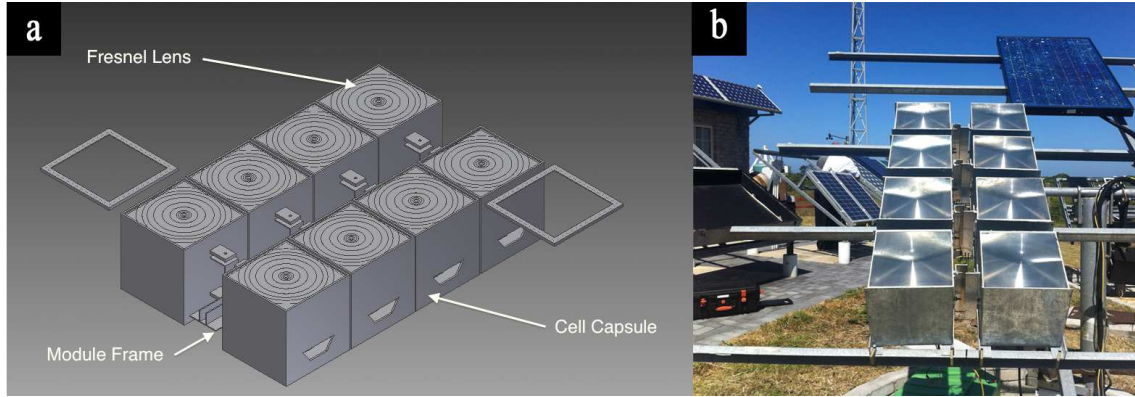
Figure 10: (a) Schematic diagram and (b) photograph of the improved HCPV module.

The experiments performed with this module included long term I-V measurements with different units operating under specific operational conditions.
These conditions include;
- optimal configuration of the optics and thermal management,
- optical misalignment of both the primary and secondary optics, and
- thermal stress due to the non-incorporation of a heatsink in the unit.

4.   Results
4.1. One Sun and Concentrated Sun Results
The results show the effect of solar concentration on the CTJ cell. In Figure 3.10 the one sun and 336 X I-V characteristics curve are for a CTJ cell are shown.
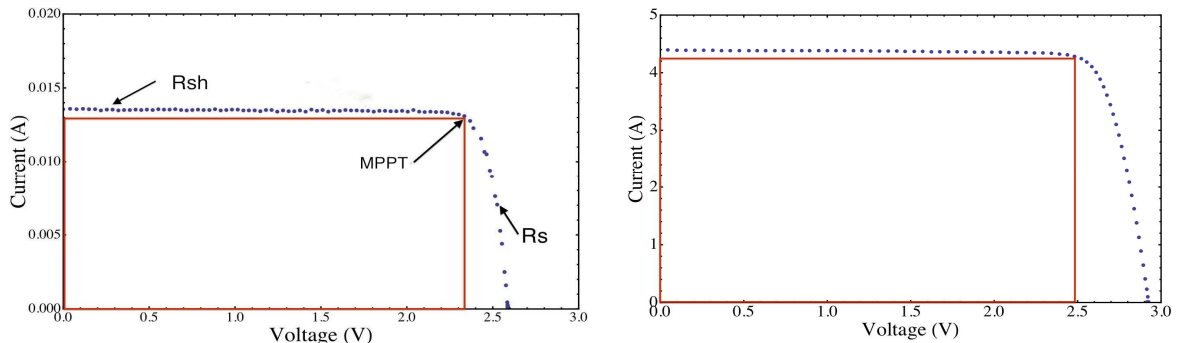

Figure 11: I-V Curve of a CTJ cell at 1 X_o and 336 X_o concentrations.

Under concentration as observed in Figure 11, the Isc is increased by a factor of $336X_o$ and the Voc is increased from 2.58 V to 2.92 V. The increase in Isc is due to the increase in incident irradiance. Since Isc is directly proportional to the irradiance, it will increase linearly with concentration. The increase observed in Voc is due to the logarithmic dependence on the increased Isc with increasing irradiance [2]. This also leads to a slight increase in the fill factor. The resulting increase in Isc and Voc will thus increase the power output to 10.29 W from 13mW, essentially 343 times greater than at one sun. Interestingly, an increase in efficiency from 33 % to 39 % was also seen, which can be attributed to the increase in Voc. Figure 12 shows the effect of concentration of CTJ cell's efficiency.
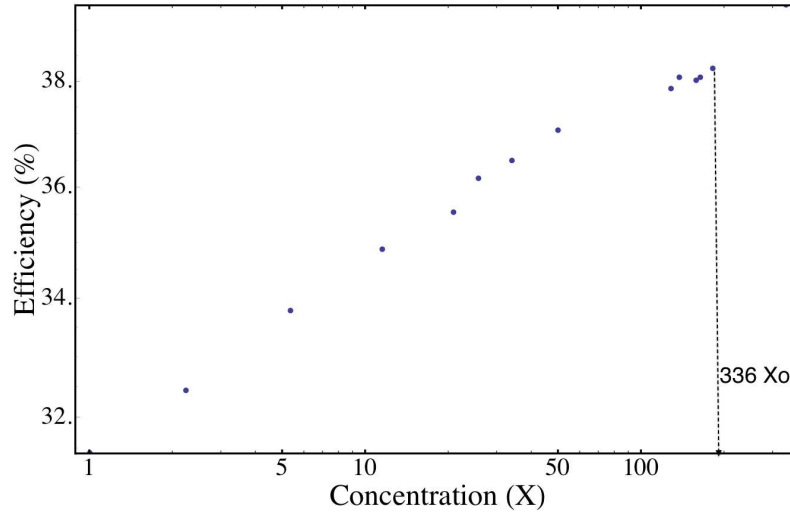
Figure 12: Efficiency as a function of concentration.

The efficiency of the CTJ cell can be seen to increase linearly with concentration in the region of concentration in the study. The increase in efficiency is due to the increase in both the Isc and Voc, with the latter playing the most important role.

4.2. Operation of Module I
4.2.1. Effect of insufficient thermal management for long-term measurements.

Figure 13 shows the initial I-V characteristics of the 4 cells in the Module I for a good and insufficient thermal management system before and after a 2-month operational period.
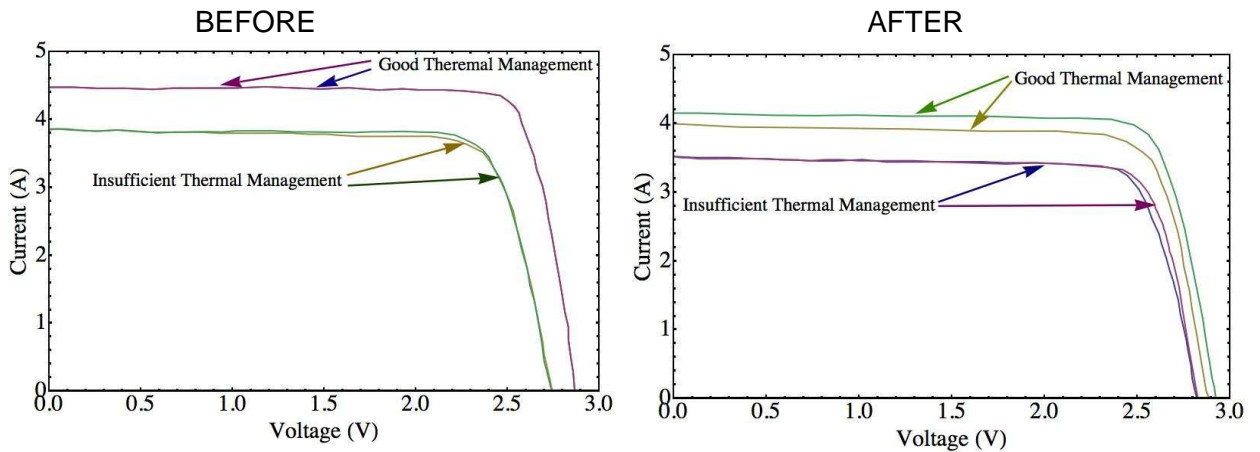

Figure 13: Graphs showing the effect of insufficient thermal management on the CTJ cell parameters after a period of 2 months operation.

The decrease in Isc and Voc seen in the pre-operational measurements are attributed to the effects of the difference in temperature (+- 40 °C) between the two test systems. There is a noticeable decrease in the performance of the CTJ cells with a decrease in all the Isc values. Table 2 summaries the difference in the parameters of the CTJ cell of the various modules after an operational period of 2 months.

Table 2: The difference in the parameters of the CTJ cells after 2 months of operation.

Parameter	Before	After	Before	After
	Good 1	*Good 2*	*Good 1*	*Good 2*
Current (A)	4.43	4.21	4.43	4.05
Voltage (V)	2.82	2.92	2.82	2.88
Power (W)	10.02	9.10	10.02	8.98
	Insufficient 1	*Insufficient 2*	*Insufficient 1*	*Insufficient 2*
Current (A)	3.84	3.55	3.84	3.55
Voltage (V)	2.73	2.83	2.73	2.83
Power (W)	8.12	7.53	8.12	7.53

The cells with insufficient thermal management showed a decrease in Isc of 0.22 A (1)and 0.38 A (2), respectively. The slight increase in Voc seen in the cells with good thermal management is due to increased irradiance. The currents of the cells with insufficient thermal management currents are both reduced by 0.29 A. The Voc of these cells is increased slightly due to increased irradiance. The decrease in the Isc is a combination of factors, namely;

- the decrease in optical performance, soiling of the Fresnel lens and dust deposits on the reflective secondary,
- the damage to the cells due to the optical configuration causing possible defects in the subcell that trap electrons. This further makes the subcell current limiting, and
- physical damage to the CTJ cell.
- Any combination of these factors can hamper / decrease the performance of the CTJ cell.

4.2.2. Optical Misalignment

Figure 14 shows the effect of misalignment on the power production from a CTJ cell.

Isc = 4.39 A
Voc = 2.92 V
Pmax = 10.69 W
Eff = 36.8 %

Isc = 3.83 A
Voc = 2.88 V
Pmax = 8.86 W
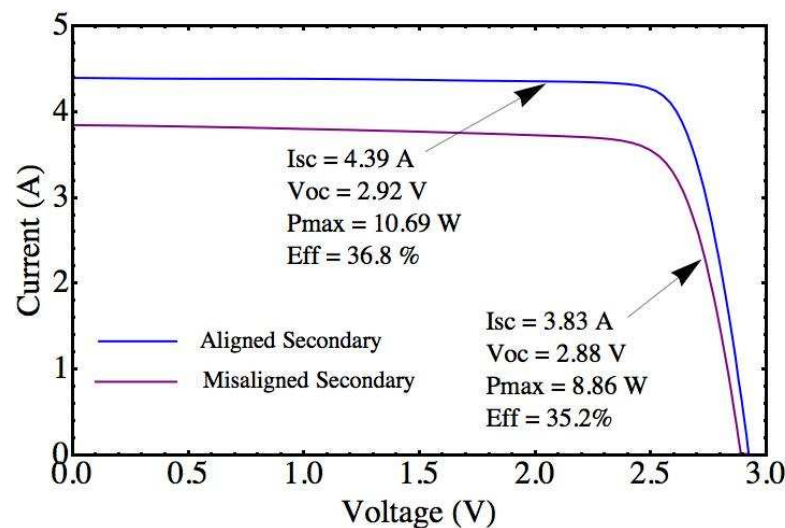Eff = 35.2%

Aligned Secondary
Misaligned Secondary

Figure 14: I-V characteristics of the effects of mis/aligned reflective secondary on CTJ cell.

The difference in the I-V curves results from a shift of the distribution from being

symmetrical to being less symmetrical across the cell. Although the maximum magnitude of the relative intensities is very similar, the photo-generated current produced is much less when the intensity distribution is less uniform. It appears that a less symmetrical distribution causes the shunt slope of the I-V curve to increase. Efficiencies of 36.8 % and 35.2 % were achieved for the aligned and misaligned secondary setup, respectively. The Voc under concentration increase from 2.6 V at one sun to 2.9 V at $336X_o$. This is due to the aforementioned logarithmic dependence of output voltage on the irradiance. The above result is made even more apparent when compared to that of a two-cell test module that was connected in series with bypass diodes. Figure 15 shows the I-V curves of the test module under the best conditions and with intentional misalignment of one reflective secondary. The effect of current bypassing the cell that produced the lowest short circuit current can be seen as a perturbation in the measured I-V curve.
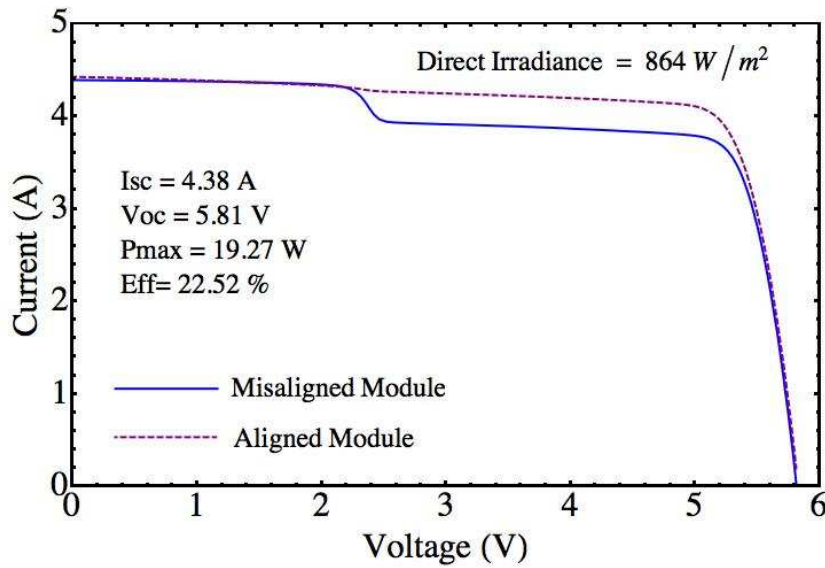

Figure 15: I-V characteristics of the effect of misalignment in a 2-cell HCPV module.

The current mismatch caused by a difference in the alignment of the secondary optics can be clearly seen in the resulting I-V curve. The mismatch caused a 2.23 W loss, a 13.2 % decrease in the power production relative to the best-aligned module with no misalignment or mismatch. This correlation between the optical alignment and performance of the cell due to the optics shows that proper optical alignment is important for the optimal functioning of a HCPV module.

4.3. Operation of MODULE II
Since the I-V curves were taken at different irradiance values and hence different concentrations, the I-V curves were normalize with respect to Isc and Voc. This is because both Isc and Voc are functions of concentration.

4.3.1. Optimal Cell Mode
In Figure 16 the normalized I-V characteristics at different sun hours show the effect of the optimized set up for a CTJ cell operating for the 2.5-month period. There is little variation seen in the I-V characteristics of the CTJ cell. As expected, good thermal dissipation and optical alignment has offset mechanisms that can cause a decrease in the performance of the CTJ cell.
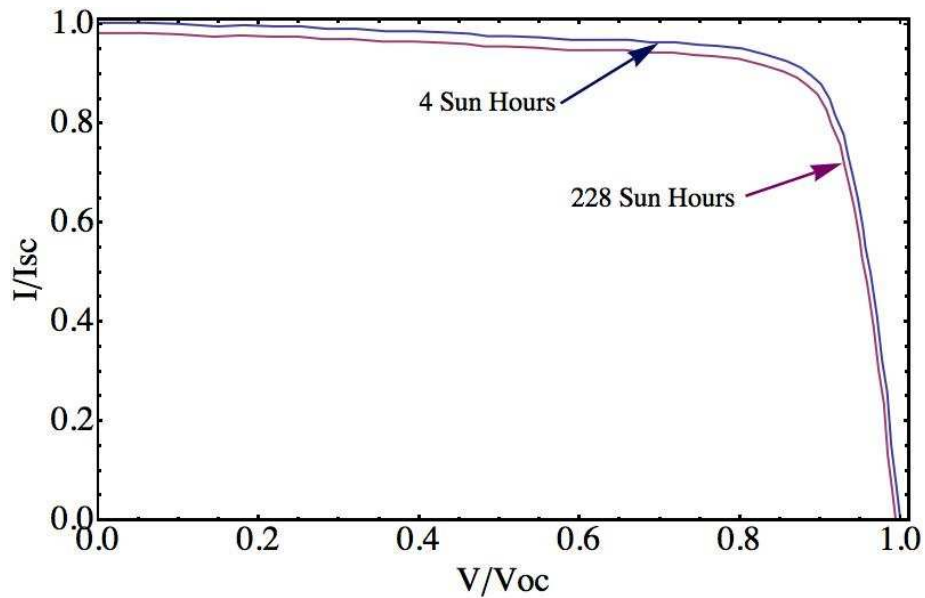
Figure 16: I-V characteristics for a CTJ cell at different sun hours for the optimal unit set up and showing little variation in I-V characteristics.

4.3.2. Optical Misalignment Mode

In Figure 17 the normalized I-V characteristics at different sun hours shows the effect of optical misalignment for a CTJ cell operating for a 2.5-month period. As time of operation increases, there is a noticeable change in the I-V characteristics with the "knee" or maximum power point shifting. This shift is attributed to a decrease in shunt resistance, possibly caused by induced defects in the CTJ cell resulting from the non-uniform intensity distribution. This decrease will reduce the power production of the CTJ cell with increased irradiance exposure.
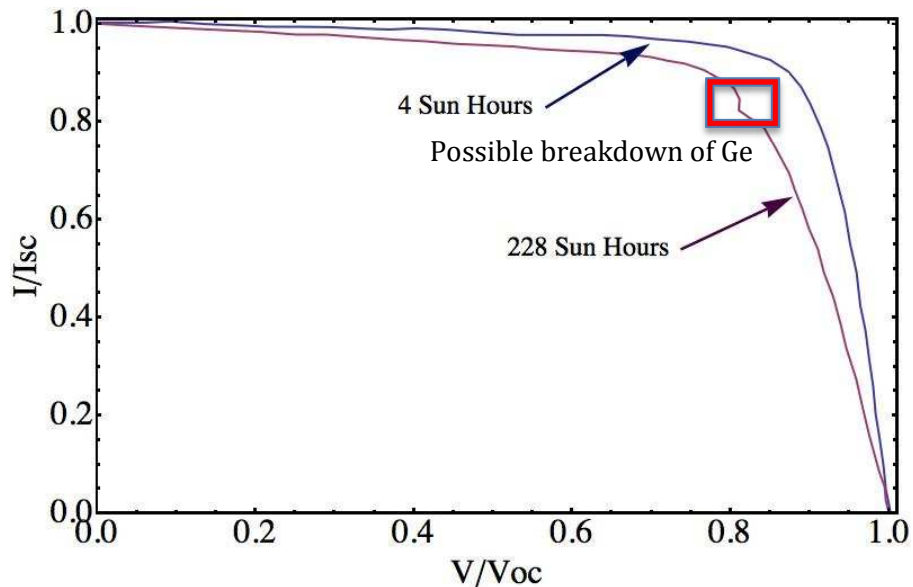

Fig.17. I-V characteristics for a CTJ cell at different sun hours for the optically misaligned unit set up.

4.3.3. Thermal Stress Mode

The cells operating without a heatsink showed an increased temperature of 50°C above ambient. The effect of the temperature can be seen in the I-V characterizes. In Figure 18 the normalized I-V characteristics for a CTJ cell show the effect of the thermally stressed unit set- up operating for the 2.5-month period. Operating the CTJ cells at temperatures 50°C above ambient will cause a decrease in performance with the increase in exposure time.
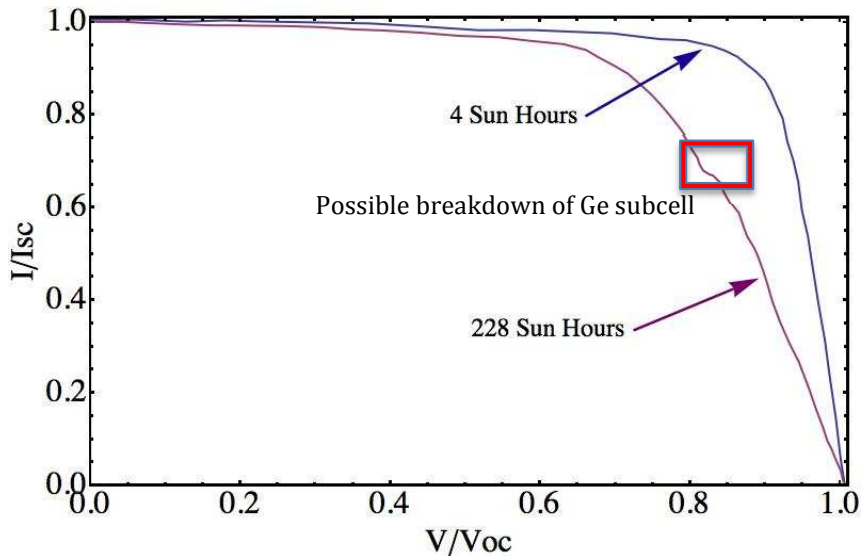

Figure 18: I-V characteristics for a CTJ cell at different sun hours for the thermally stressed unit set up.

The degradation in series resistance is due to prolonged exposure at high operational temperature of the CTJ cell [4]. This will result in a decrease in power with increased exposure time. It is also noted in both Figure 17 and Figure 18 that around the 0.83 mark on the x-axis, a small kink is seen (indicated by the red rectangle). This kink is possibly due to the breakdown of one of the subcells in the CTJ cell. Since the kink appears at a voltage of 2.42 V and the Ge has the smallest voltage of 0.2 V [3,5], it is proposed that it is the Ge subcell that is undergoing breakdown. If the breakdown occurred in any other subcell, the kink would be seen at a V < Vmax because both the other subcells have voltages greater than 1 V. The direct cause of the subcell breakdown is not certain. However, it can be deduced that a CTJ cell under some form of prolonged thermal and optical stresses may develop defects. It is proposed that these defects are induced from thermal stresses on the device as well as the thermal gradients within the CTJ cell created by optical misalignment. Optical misalignment, even with a sufficient heatsink will generate temperature gradient regions within and between the subcell layers. These temperature gradients will have a negative effect on the subcell and could cause breakdown of a subcell.

5.   Conclusion
In can be concluded that from the single cell measurements that the increase in concentration factor benefits the performance of a CTJ cell within this experiment. With an increase in irradiance concentration, an increase in Isc, Voc, power and efficiency is observed. It can be concluded from the results observed from Module I

and II, the best performance for a HCPV module must consist of good optical alignment and thermal management. This was confirmed by the I-V characteristics during the operational periods of the modules. This indicates that a system with good optical configuration and thermal dissipation will benefit the performance and longevity of a CTJ cell and hence a HCPV module. However, a CTJ cell under optical misalignment and thermal stress showed a progressive performance decrease (power loss) with prolonged operational exposure in both module systems. These were attributed to a decrease in shunt resistance of the optical misaligned cell and an increase in the series resistance of the thermally stress cell. The biggest decrease in operational performance was seen in the CTJ cells under thermal stress. Hence it can be proposed that thermal stress is the main factor in the degradation and failure of a CTJ cell.

In conclusion, to ensure the best design and to achieve the best performance from a HCPV module, it is recommended that:
- characterisation of the optics is preformed to identify faulty optical elements and misalignment before introducing them into an operational HCPV module.
- the incorporation of a good thermal management system that will dissipate heat away from the CTJ cell efficiently.

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