MEASUREMENT AND CHARACTERIZATION OF CONCENTRATOR SOLAR CELLS II

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Concentrator solar cells are continuing to get more consideration for use in power systems. This interest is because concentrator systems can have a net lower cost per watt in solar cell materials plus ongoing improvements in sun-tracking technology. Quantitatively measuring the efficiency of solar cells under concentration is difficult. Traditionally, the light concentration on solar cells has been determined by using a ratio of the measured solar cell's short circuit current to that at one sun, this assumes that current changes proportionally with light intensity. This works well with low to moderate (<20 suns) concentration levels on "well-behaved" linear cells but does not apply when cells respond superlinearly, current increases faster than intensity, or sublinearly, current increases more slowly than intensity. This paper continues work on using view factors to determine the concentration level and linearity of the solar cell with mathematical view factor analysis and experimental results [1].

INTRODUCTION

Solar cells are designed to convert photon energy directly into electrical energy. The amount of natural sunlight incident on a solar cell is considered the 1 sun power density. Higher than 1 sun power densities achieved using lens or reflectors are concentrated sunlight. The increase in power density or ratio of power density to the 1 sun power density is the concentration level. Efficiency measurement of concentrator solar cells has always been a difficult task due to the lack of equipment available to measure the light power intensity. Most laboratory measurements are done using a Large Area Pulse Solar Simulator (LAPSS) with data being taken in 1-2 milliseconds. Measuring the power density/flux under these conditions requires a very fast thermopile or pyroelectric device, if any exist. Consequently, determining the power density or light concentration ratio on a solar cell is the ratio of the measured short circuit current (I_{SC}) to the short circuit current at 1 sun. This process can be inaccurate for solar cells that do not behave linearly with power density.

One way to obtain power density/flux is by using radiative energy transfer equations and calculating the view factor between the source and the test sample. Energy radiating from a source incident on a surface at some fixed distance away can be characterized by the view factor between the source and the surface. Knowing the shape of the source and the incident surface and using numerical integration, the view factor can be calculated. The view factor has always been used in determining the efficiency of thermophotovoltaic energy conversion systems [2]. The view factor ratio between a location with a known power density and some other location can be used to determine the concentration (change in power density) by ratio of the view factors. When dealing with a point source, the view factor varies as $1/r^2$ where r is the distance between the source and the surface. The sun is modeled as a point source because of its distance from the earth, closer objects can't use this approximation.

THE VIEW FACTOR

The view factor is the fraction of the total energy emitted by one surface, the source, that is directly incident on another surface. As the source and surface move farther apart or off-axis from each other, the view factor becomes smaller. A point source with the incident surface forming a full hemisphere surrounding that source has a view factor of 1 because the total energy from the source is incident on the surface. Additionally, the view factor between a point source and the target surface decreases proportionally with the square of the distance between them. Calculating the view factor between two finite shaped surfaces requires numerical integration of both surfaces. The general form of the view factor calculation is defined by the following equation [3]:

$$\text{View Factor} \quad F_{AA'} = \frac{1}{\pi A'} \int dA \int \frac{\cos\theta \cos\theta'}{s^2} dA'$$

Where A and A' are the two surfaces, s is the distance between the two surfaces and ø are the respective angles between a point on surface A and a point on surface A' and vice versa. Generating and solving this equation for specific surface geometries is beyond the scope of this paper.

View Factor Solution for LAPSS

For the case described here, the source is the Spectrolab LAPSS100, and the incident surface is a planar solar cell. The source in the LAPSS is a Xenon arc lamp that generates a pair of 15 cm. arcs as shown in figure 1. To simplify the view factor calculation, the light source is modeled as a rectangle with a finite length and width, assumed to be uniform and isotropic. The LAPSS system contains two identical arc lamps which fire simultaneously. By placing the solar cell (incident surface) symmetrically centered between the two lamps only one view factor is calculated, and the resulting view factor for both lamps is simply twice that of the single lamp.

Using this model, a drawing of the test geometry is made as shown in figure 2. There are two identical sources, offset from the center line of the test solar cell. Because of the symmetry of the test setup, only one lamp needs to be used to calculate the view factor which is identical for the second lamp. These two view factors can be added to get the actual view factor. The lamp source is surface A_1 in the xy plane, the solar cell surface is A_2 in the $\xi\eta$ plane. The distance between the two planes is z and the distance between points the two surfaces is s with angles $\theta_{1,2}$ between them. Based on this model, discrete coordinates of the rectangular endpoints can be obtained for the view factor calculation. The actual view factor calculation is shown in appendix A, it is derived from two parallel and perpendicular rectangular finite surfaces.

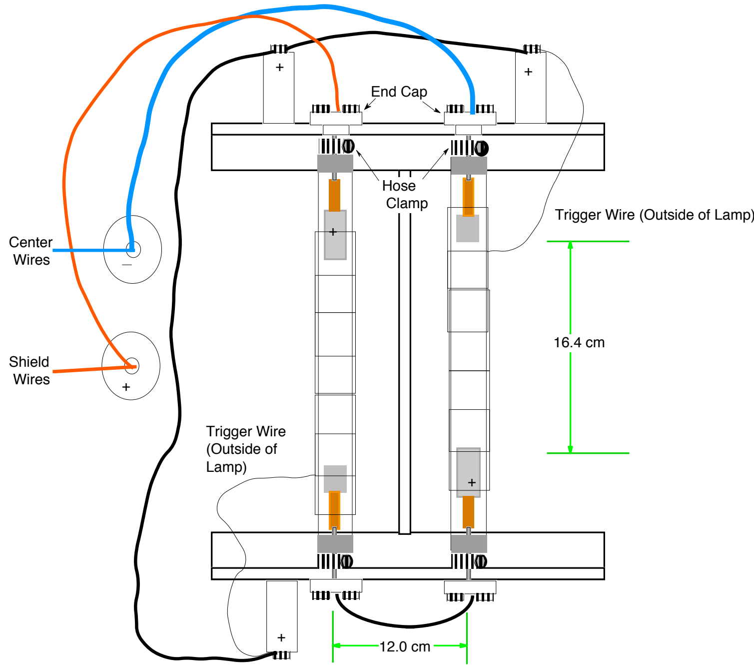

Figure 1 LAPSS lamp setup

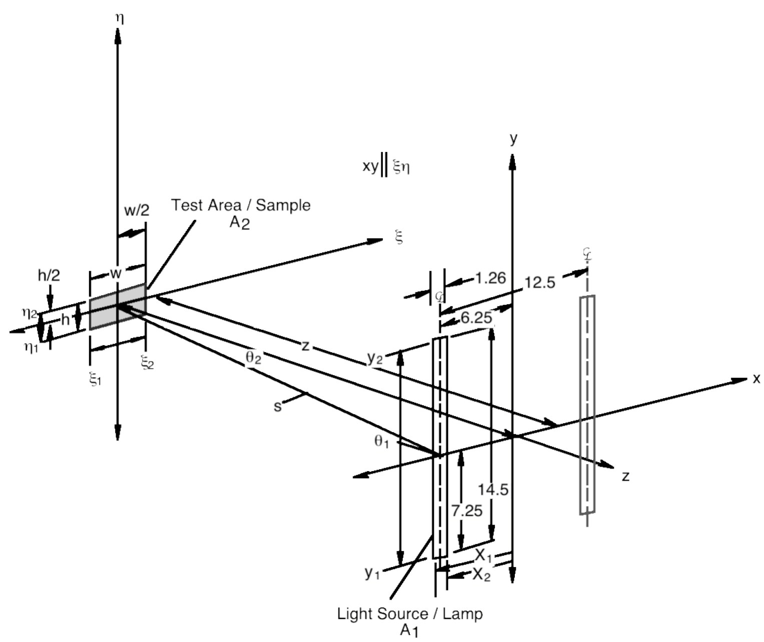

Figure 2 LAPSS test geometry

The viewfactor is calculated for a range of distances z from the source using the numerical summation from appendix A [4]. By plotting the ratio of the view factor at the farthest distance to shorter distances a graphical representation of this calculation is compared to a $1/r^2$ and shown in Figure 3. The concentration level of light on the solar cell is obtained by the following steps:

STEP 1: Measure the solar cell performance under a known or calibrated light source at 1 sun (this can be done in a solar simulator other than the LAPSS with a standard cell). Light level of the simulator is adjusted using a calibrated primary or secondary reference cell.

STEP 2: Set up a coordinate system for the cell and the LAPSS or concentrating light source, select a distance z between the two surfaces farthest away as a 1 sun starting point. The coordinate system is based on figure 2.

STEP 3: Using the coordinates in step 2 calculate a range of View Factors from z and shorter, ratio these view factors to the view factor at z to get the concentration level. A computer program can be written for this step.

STEP 4: Set up the solar cell at distance z from the light source(s), measure and adjust the light source to obtain the 1 sun numbers from Step 1.

STEP 5: Using the data from step 3, move the solar cell closer to the light source to various distances as denoted in Step 3, these measurements are at the calculated concentration levels.

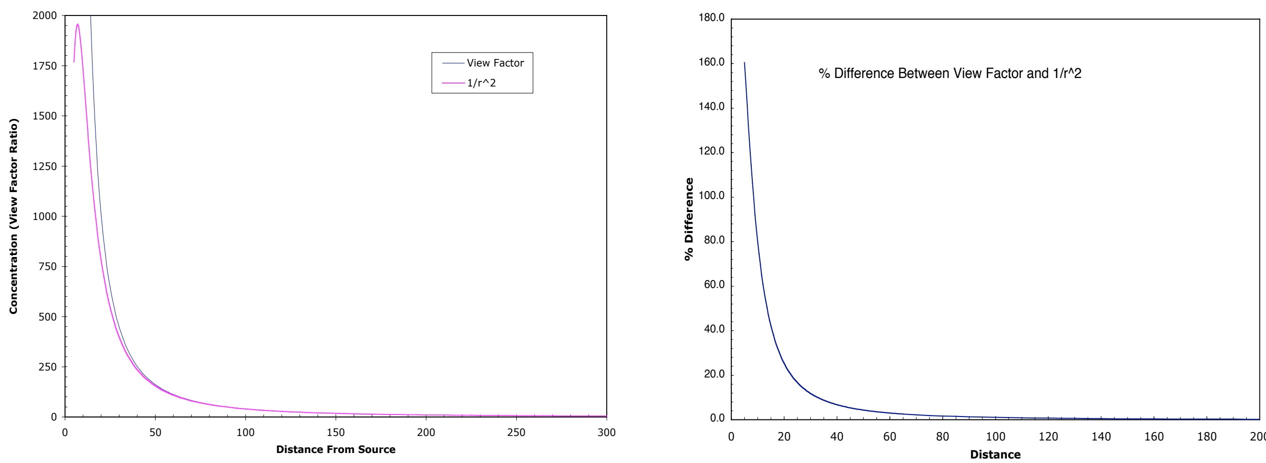

Figure 3. Concentration by View Factor Ratio

The data used in figure 3 was for a 2 x 2 cm. solar cell, the light source is the Spectrolab LAPSS and the 1 sun measurement was made at a distance of 635 cm. The view factor was calculated every 5 cm. going into the source.

THE ARC LAMP

The arc lamp is the most optimum single source solar simulator because of its close temperature match to the solar spectrum. The disadvantages are that the arc lamp's spectrum has many spikes due to the emission lines of the gas in the lamp. The Spectrolab LAPSS system was designed to minimize the spikes and maintain good uniformity at a 2 m x 2 m 1-sun plane within ±2%[5]. In order for the view factor calculation to be accurate, the light source is assumed to be uniform and isotropic. The uniformity of the lamp can be generated from knowledge of the plasma characteristics of the arc itself [6]. Arc lamps tend to be cooler near the electrodes but have relatively constant temperature across the arc. To minimize this temperature effect, the lamps were baffled 1 cm. above and below the electrodes. As can be seen in the photos, the arc completely fills the interior area of glass between the electrodes, this is a result of electrode design, and insures ionization of all of the gas, resulting in uniform light generation. The source is also isotropic, emitting light equally in all directions, however half of the lamp diameter is not used. Any reflective optics or lenses used on this lamp would enhance the light intensity but also complicate the view factor calculation.

High speed photographs of the lamp during a flash are shown in figure 4. As can be seen from these photographs, the arc fully saturates the glass housing and decays to a thin line. The solar cell performance is only obtained during the full light portion of the arc with the best uniformity. This full light section of the arc also has the flattest intensity and can last a few milliseconds. It is during these few milliseconds that the solar cell is characterized, a monitor cell is also used to adjust for slight intensity variations within the flash and between consecutive flashes. Typically, intensity between flashes of the arc lamp are controlled to be less than .25% which is needed for measuring the cell at different positions or concentration levels.

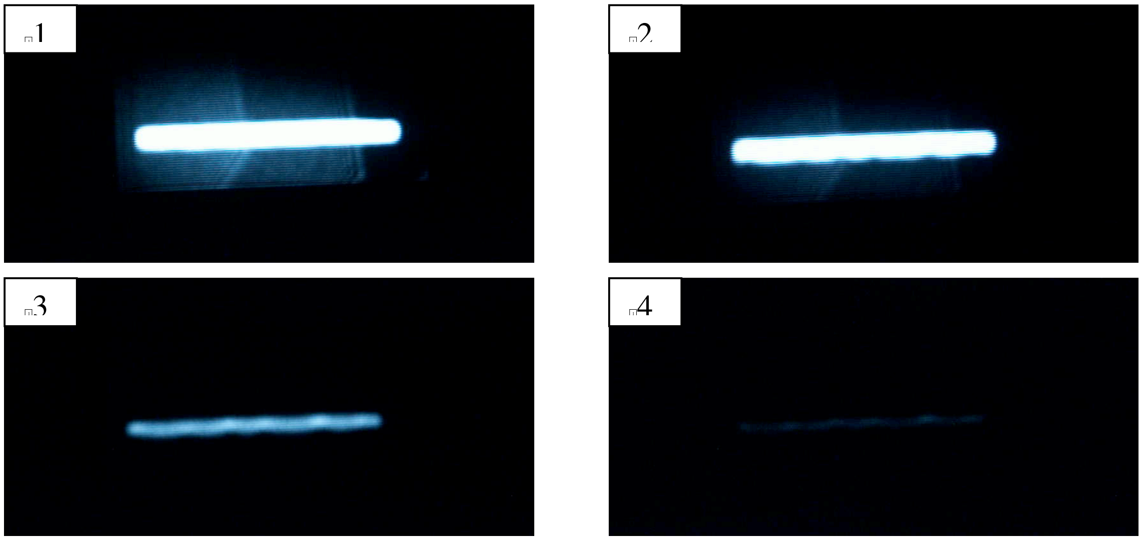

Figure 4 Arc Lamp Sequence (2000 frames/sec) frames 57,60, 61, & 62.

TEST

Several cells were measured at 1 Sun AM0 in a solar simulator using a calibrated reference cell. A LAPSS100 was used for a light source, assumed to be uniform and isotropic. The LAPSS light intensity was adjusted for 1 sun intensity at a fixed distance. Using the view factor ratio, the cells' current-voltage characteristics were measured at a variety of concentrations. Arc lamps exhibit uniformity in the center portion of the arc away from the electrodes which tend to be cooler. Therefore the lamps were baffled 1 cm. from either electrode. No additional optics were used with the lamps which would affect the view factor calculation. Based on the mathematical analysis defined in section 2, a test was set up. Four different solar cells were selected to cover a range of performance characteristics; Triple Junction InGaP/GaAs/Ge 1 cm. x 4 cm. from two different vendors. These cells were designed as space concentrator cells to operate at <20 suns. Each of these cells were characterized at 1 Sun AM0 using an appropriate reference standard.

All tests were performed at NASA Glenn Research Center. The Spectrolab LAPSS100 system performs IV curves on solar cells/arrays in 1-2 milliseconds. It has a 12-bit A/D measuring cell voltage, current, and monitor cell current simultaneously. IV curves consist of from 20 to 100 data points. The monitor cell was placed in a fixed position within the beam path, its location was selected to monitor flash intensity and not interfere with the test set up.

Test Setup

Before the test could be performed, several modifications had to be made to the existing LAPSS facility to minimize any measurement errors. The LAPSS data acquisition system was calibrated with special consideration for the scale range change accuracy. The lab was painted black with additional black cloth and drapes added to eliminate any stray light. A rail system was added on the centerline between the two lamps. A metric ruler was attached to the rail as an indicator of the distance from the lamps to the solar cell test plate. The solar cell test plate was suspended from the rail so that its center was aligned to the center of the lamps. These changes are shown in figures 5 and 6.

Test Procedure

The solar cell area was measured and its dimensions were used to calculate the view factor over a range of distances from the lamp. The lamps were fired 20 times with one minute wait intervals between flashes to warm up the electronics and lamps.

The solar cells were mounted to the test plate and set at a distance of 635 cm. Distances are estimated to be within 1 mm. Lamp intensity (pulse network voltage) on the LAPSS was adjusted until the solar cell I_{SC} matched the 1 sun AM0 measured previously. The monitor cell nominal current was recorded and used for a correction to normalize the intensity variation. This test was repeated 5 times with the monitor cell correction less than 0.25% for each of the IV curves to eliminate subtle variations due to lamp intensity and repeatability.

After the 1 sun measurement, the test plate was moved to the ~2 sun position and the tests were repeated 5 times as before. No adjustments were made beyond the original settings. The test plate was then moved in to a 5 sun position and the IV curves were measured. Testing was continued at other concentration levels. With this setup, a maximum ~62 suns is just outside the face of the lamp housing.

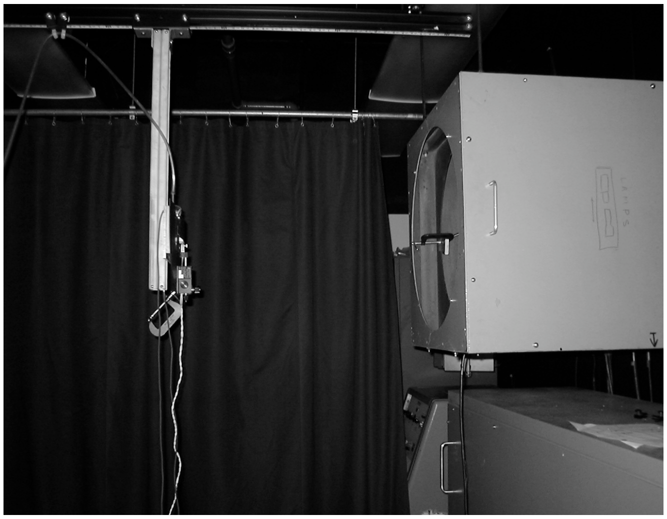

Figure 5. LAPSS test set up

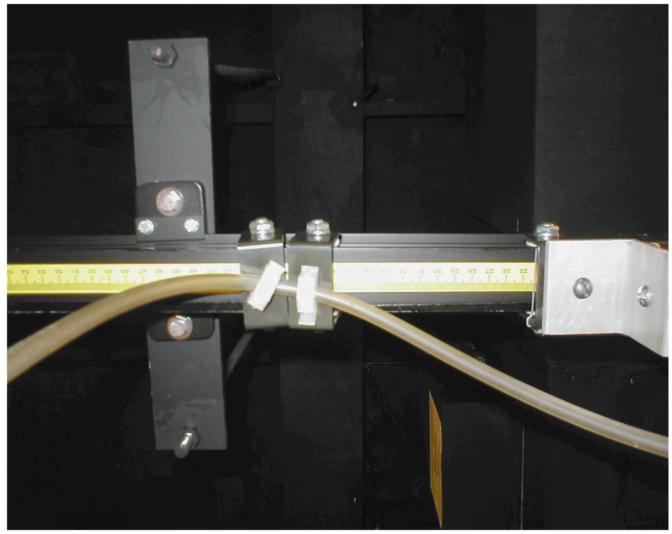

Figure 6. Test plate rail system

Test Results

The I_{SC} of a solar cell is used for setting the light intensity and calibration. The 5 sets of data points at each

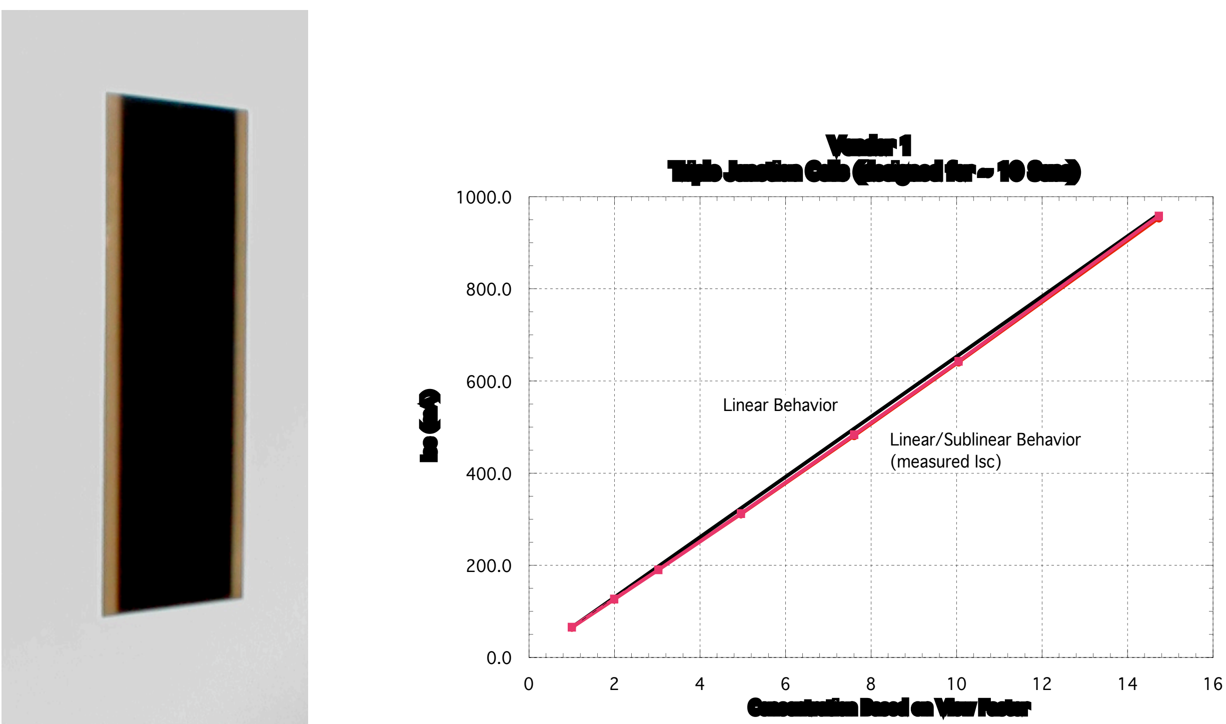

Figure 7 Vendor 1 Solar Cell Data

concentration level were averaged and then the I_{SC} is plotted as a function of the concentration level. The test results are shown in figures 7-8. A black line is added to the plot to depict a “linear” behavior of the I_{SC} as commonly used in concentrator measurements. None of the cells exhibited a true ‘linear“ response.

The cells plots shown depict either slightly superlinear or sublinear behavior with concentration. Other performance parameters such as Fill Factor, Maximum Power, and Open Circuit Voltage (V_{OC}) all increased as expected with increases in intensity. Details of the cell performance are not presented here as these test are primarily for proof-of-concept.

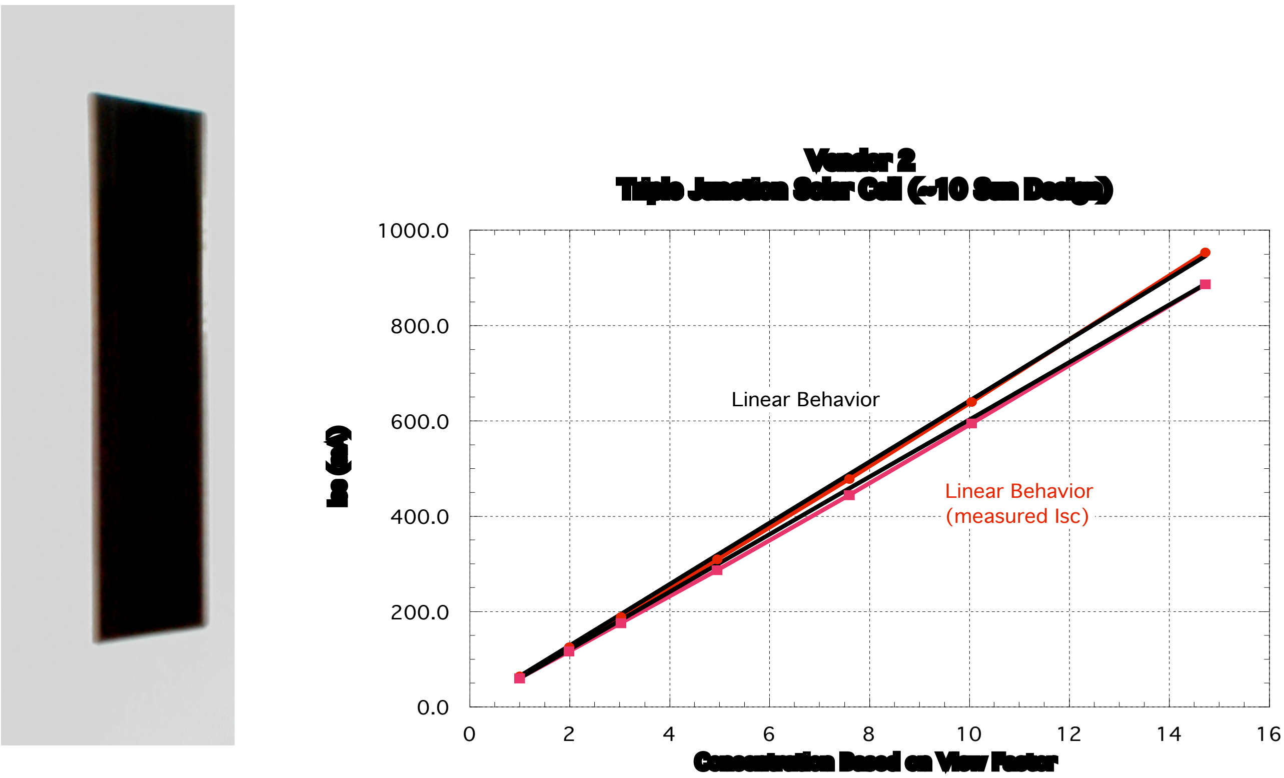

Figure 8 Vendor 2 Cell Data

CONCLUSION

This paper is the second publication of this method. It is intended to provide a simple means of calculating the view factor for a given source and sample and account for variations in light intensity at a given distance from the light source(s). The mathematical calculations include the derivation and integration required to solve for the view factor, its solution, and a way of applying that calculation to test systems. Knowledge of the light source is not required. Once the view factor calculation is applied, the value was used to determine the intensity at a given distance from the source. 4 solar cells were measured at a variety of intensities. The results show that this method is viable for measuring and calibrating concentrator cells. Solar cells have been tested to concentrations in excess of 500 suns.

These tests indicate that most solar cells do not exhibit a proportional 1:1 short circuit current behavior with intensity. Solar cells and arrays measured under concentration determined by the ratio of I_{SC} are suspect to the accuracy of the concentration level. Multi-junction cells with inherent current limiting due to spectral separation and current mismatch of junctions can exhibit even greater variation in linearity. This test eliminates the errors associated with determining the concentration by using mathematical analysis. Errors introduced with this method include assumptions about the uniformity and geometry of the source, and positioning of the test cells.

A need for this measurement technique has arisen from the fact that Vertical Multi-Junction (VMJ) Cells exhibit a superlinear behavior, having poor performance at 1 sun [7]. Other cells designed for high intensity also experience this non-linearity. There are also no known reliable standards for calibration of solar cells at high intensity, it is hard to assume that the current of a cell remains linear over many orders of magnitude in concentration especially when series resistance, minority carrier lifetimes, and recombination centers change with intensity.

Refinement of this method can be implemented for better accuracy at higher concentrations if so desired. The model of the arc lamp as a rectangular source could be changed to reflect the actual shape of the lamp, all depending on how far the modeler wants to go. Dimensional accuracy of the test plate could also be improved, high precision optical rails with fine positioning can help to avoid errors at high-intensity. Positioning errors tend to increase with higher concentration levels, at 60 suns a 1 cm. difference in position changes the intensity by nearly two suns.

It is the intention of this paper to provide a demonstration of a method to calibrate concentrator cells. NASA GRC facility is available for testing of cells/arrays with the limitations of the 50 Volts and 20 Amps.

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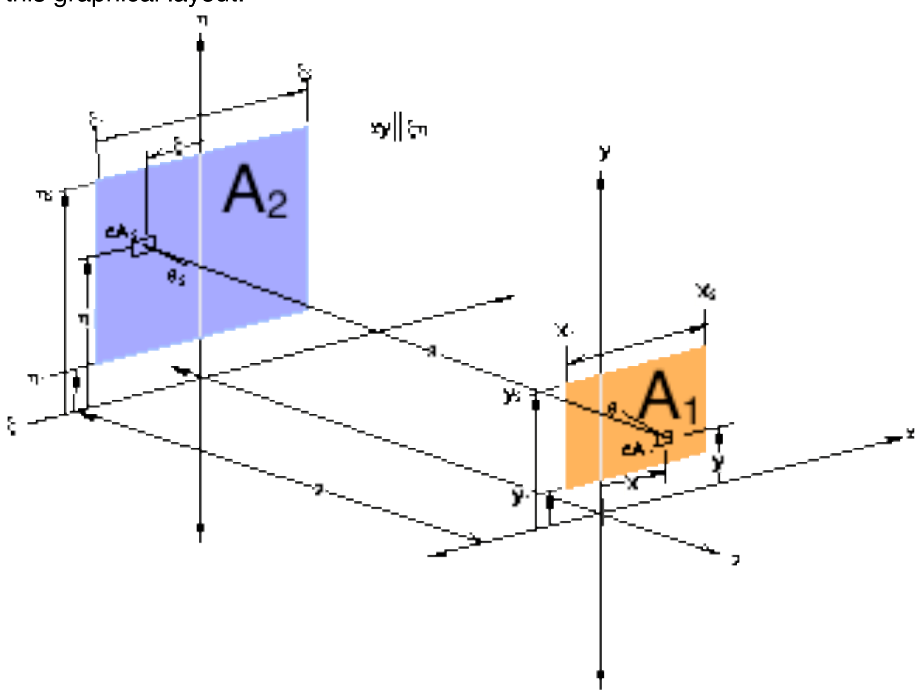
APPENDIX A : View Factor (Rectangle to Rectangle)

A view factor is defined as the fraction of area in the total field of view (180° hemisphere) of one surface as seen from another surface, its value is a maximum of 1. The general equation for the view factor between two finite areas is;

$$F_{1\rightarrow 2} = \frac{1}{A_1}\int_{A_2}\int_{A_1}\frac{\cos\theta_1 \cos\theta_2}{\pi s^2}\,dA_1 dA_2 \qquad 1$$

where F_{1-2} is the view factor from finite surface A_1 to finite surface A_2. Angles θ_1 and θ_2 are the angles between the two surfaces from a point dA_1 to dA_2 and vice versa.   Applying the general equation 1 to two surfaces which are parallel rectangles of different size and not coaxial (see figure 1), the following substitutions can be made from this graphical layout.



$$s^2 = z^2 + (x-\xi)^2 + (y-\eta)^2 \qquad \cos\theta_1 = \cos\theta_2 = z/s \qquad 2$$

by substituting the above, equation 1 can be re-written to the following integral based on the four corner coordinate terms (x, y) for the source rectangle A_1, and (ξ, η) for the rectangle A_2. The integral is in the following form:

$$G(x,y,\eta,\xi) = \frac{z^2}{\pi}\int_{\xi}\int_{\eta}\int_{y}\int_{x}\frac{x\square}{\left[z^2 + (x-\xi)^2 + (y-\eta)^2\right]^2}\,dx\,dy\,d\eta\,d\xi \qquad 3$$

and solving equation 3 using symbolic mathematics, the final solution becomes a series of summations based on the corner coordinates (x_1,y_1; x_1,y_2; x_2,y_1; x_2,y_2) for A_1 and (ξ_1, η_1; ξ_1, η_2; ξ_2, η_1; ξ_2, η_2) for A_2 of the parallel rectangles. The location of the axis for either coordinate system is random, as long as both rectangles are parallel to each other and their relative positions do not change. This solution is shown below;

$$F_{1\to 2} = \frac{1}{(x_2 - x_1)(y_2 - y_1)} \sum_{i=1}^{2} \sum_{j=1}^{2} \sum_{k=1}^{2} \sum_{l=1}^{2} (-1)^{(i+j+k+l)} G(x_i, y_j, \eta_k, \xi_l) \qquad 4$$

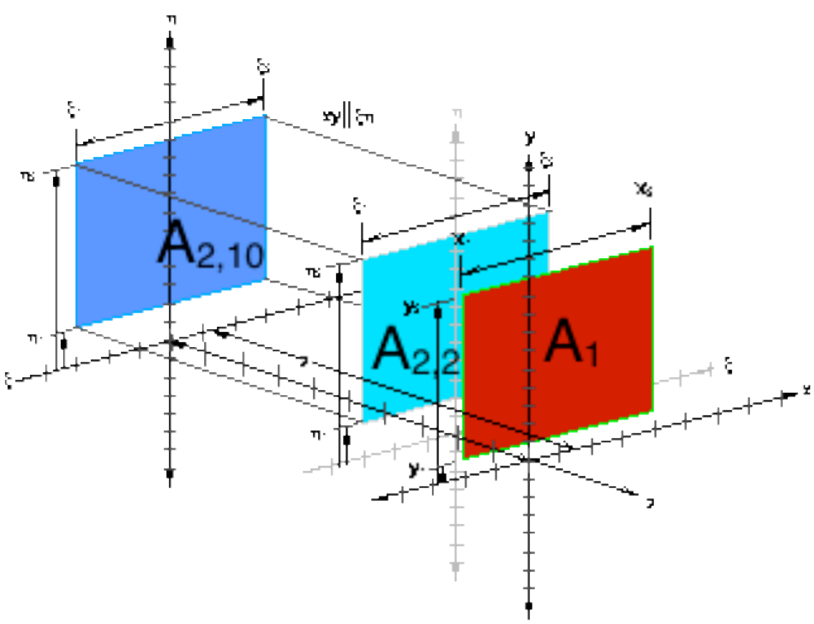
where

$$\text{G}(x,y,\eta,\xi) \text{ is : } G = \frac{1}{2\pi} \left\{ \begin{aligned} &(y_j - \eta_k)\left[(x_i - \xi_l)^2 + z^2\right]^{1/2} \tan^{-1}\left(\frac{y_j - \eta_k}{\left[(x_i - \xi_l)^2 + z^2\right]^{1/2}} \right) \\ &+ (x_i - \xi_l)\left[(y_j - \eta_k)^2 + z^2\right]^{1/2} \tan^{-1}\left(\frac{x_i - \xi_l}{\left[(y_j - \eta_k)^2 + z^2\right]^{1/2}} \right) \\ &- \frac{z^2}{2} \ln\left[(x_i - \xi_l)^2 + (y_j - \eta_k)^2 + z^2\right] \end{aligned} \right\} \qquad 5$$

A computer program can be written to calculate the view factor. Please note that double precision numbers should be used to avoid errors, large numbers are added and subtracted with small differences in the lower digits, single precision does not have the resolution to retain these small differences.

Example:

Rectangle A_1 has corners located at coordinates **(-2,1), (-2,10), (4,1), (4,10)**
Rectangle A_2 has corners located at coordinates **(-3,2), (-3,11), (3,2), (3,11)**
They are the same 6 x 9 size except offset by 1 unit in both axes.



Calculate the view factor if they are separated by 2 and 10 units, **z = 2, 10**

Plugging the coordinates into the view factor calculation equations 4 and 5 and performing the summation results in the view factors: **$F_{1\text{-}2}$ (z=2) = .54926 and $F_{1\text{-}2}$ (z=10) = .12407**