Development of Thermophotovoltaic Array Testing Capabilities

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Abstract. The present Jet Propulsion Laboratory (JPL) characterization test method for a single thermophotovoltaic (TPV) cell is to illuminate the cell with black body emission. However, this method is inadequate for the performance testing of a string or an army of cells. This is simply because the black body aperture is too small to supply sufficient illumination for much more than a single, small cell. Alternative light sources for TPV string or array testing would bc to use a large area gray body, a diffused high power laser, a high power lamp array, or the Large Area Pulsed Solar Simulator (LAPSS). These methods arc analyzed and compared. Conclusions are drawn concerning the needs and methods of TPV string and army testing. The large area gray body source was found to need more development toward larger sizes. The color temperature of this source is limited and a cooling system is required for the test devices. The diffused high power laser source was found to be expensive and power limited. This source would require a special optical system to achieve uniform illumination and atso requires a cooling system for the test devices. The high power lamp army source was found to need some development and it would require cooling systems for the lamps and the test devices. The LAPSS was found to be a feasible light source. It required very little development funds and did not heat the test article. In the near term, it was decided to use the LAPSS as the TPV light source. A preliminary technique using the LAPSS with an infrared bandpass filter was developed for high power, 8 watts per square centimeter, TPV testing purposes. Initial results indicate that this system is applicable to single cell, string and array testing of TPV cells because of its high emission power density and well matched emission spectrum. Tests and analyses were performed to establish test plane intensity and uniformity versus test device distance from the lamps. In addition, tests and analyses were performed to determine the spectral transmission characteristics of various infrared bandpass filter combinations. The LAPSS, with the infrared bandpass filter, is now operational at JPL for TPV cell, string and array testing.

INTRODUCTION

The present JPL test method for a single TPV cell is to illuminate the cell under black body emission at various known intensities. This is accomplished by positioning the cell at various distances from the black body aperture, which behaves somewhat like a point source [7, 8]. The intensities at the positions were measured with a broad spectrum laser power meter fitted with either a 0.1 cm^2 or a 1.0 cm2 watercooled aperture plate. These intensity measurements are used to correct any deviations from point source behavior.

However, this method for single cell testing is insufficient for testing a string or array of cells. A suitable size for a string of cells is about 10 cm x 1 cm and for an array, 10 cm x 10 cm, The string or array of cells cannot be uniformly illuminated at a sufficiently high intensity by the present black body source because the black body aperture is relatively small (1.27 cm diameter) in comparison to the size of the string or array. A source capable of illuminating an array of cells would have similar capabilities for a single cell. Therefore, several different illumination systems will be considered for their capabilities in array testing.

Possible candidate sources would be a large area gray body, diffused high power laser, a high power lamp array, or a configuration using filtered LAPSS emission. Gray body sources provide the advantage of having the same emission spectrum as the black body source, currently used for single cell testing. Lasers offer the advantage of simulating a perfectly selective emitter so peak cell efficiency could be attained if the wavelength of the laser is well matched to the cell bandgap. Lamp arrays are relatively simple and inexpensive compared to the previous two options. Filtered LAPSS emission would utilize existing JPL equipment and the development cost would be minimal. Each of these possibilities are examined in more detail below.

BLACK/GRAY BODY SOURCES

A black body source, with a large enough area to uniformly illuminate a 10 cm x 10 cm array, would need a circular aperture of 14.2 cm diameter. Black body sources [1] are not currently manufactured with such a large aperture because it is difficult to maintain uniform black body radiation at temperatures above 1000”C. An available black body capable of 1200°C typically has a maximum aperture of only 5 cm diameter. TPV cells illuminated with such a black body must be distant from the source for uniform emission, which greatly reduces emission intensity. This is a major drawback for black body sources because TPV cells typically require high power density in a particular wavelength region for efficient energy conversion. In addition, this 1200°C black body source is relatively expensive, costing approximately $15,000. These disadvantages eliminate large aperture black body sources for TPV string and array testing.

Large area planar gray body sources with an emissivity of approximately 0.9 are only produced for low temperature operation, due to material degradation constraints. A maximum temperature of 800°C can be achieved, but this is significantly below the current TPV testing needs. Furthermore, a planar gray body source with this temperature capability is only available with a 2.5 x 2.5 cm surface, which is too small to illuminate an array of cells. These disadvantages, in the near term, eliminate planar gray body sources for TPV string and array testing.

LASERS

High power lasers [2] were also considered for TPV array testing. The desired emission intensity to illuminate TPV cells is a minimum of 2 W/cm^2, therefore, a 200 W laser is necessary to illuminate a 100 cm^2 array. The wavelength of the laser must be about 80°/0-900/0 of the cell bandgap wavelength in order to be well matched to the cell bandgap. Most TPV cells will have a bandgap range of from .5 eV to .65 eV (2.48pm to 1.91pm).

Lasers that are bandgap matched include: Nd:YAG @ 1.06 μm and 1.32 μm, Er:Glass @ 1.54 μm, tunable Co:MgF2 from 1.75 μm to 2.5 μm, Tm: YAG @ 2.01 μm, and Ho: YAG @ 2.1 μm.

The Nd:Yag laser is the only high power laser among the group. It is produced as a continuous and pulsed laser. The 1.06μm and 1.32 μm continuous Nd:YAG laser has maximum power outputs of 400 W and 100 W, respectively, and is available from Lee Laser. Although these wavelengths are below the best bandgap match for many TPV cells, the cells will still respond sufficiently to these high power lasers.

The Er:Glass and $Co:MgF_2$ are both pulsed lasers with low average power. They have pulse energies of 650 mJ and 80 mJ for durations of 350 ns (1.86 MW peak) and 80 μs (1000 peak watts), respectively. The short pulse, 350 ns, is currently too fast for the electronics in the JPL LAPSS which requires 1.5 ms to take a full IV sweep and 15 μs for each data point [3]. Although the LAPSS data system is really not suited for pulsed laser-cell operation, it is probable that the LAPSS data system could be modified to be synchronous with the 80 μs laser pulse train.

The major disadvantages of lasers are the problems associated with the optics and the inherent non-uniformity of the beam intensity. The narrow beam must be diverged and recollimated onto the cell test area, which requires optics which could degrade with repeated use, especially with the high power Nd:YAG laser. Since the laser beam is inherently non-uniform, the TPV cells cannot be uniformly illuminated unless some sort of corrective means is used. Obtaining exact comparability of the laser power distribution and optical system characteristics between different laboratories would be difficult to achieve. Although at least one continuous laser is reasonably matched to some TPV cells, the difficulty with optics and non-uniform beam intensity make lasers an unlikely choice for TPV cell or array testing. Additionally, it is not known how well the various TPV cells will respond to the pulsed laser light. The described laser systems cost between $20,000 and $40,000.

LAMP ARRAYS

A simple alternative to using lasers, gray bodies or blackbodies [6] is to use a 30 cm x 30 cm array of high power, low temperature, tubular, tungsten lamps. The result would be a good approximation of gray body emission with color temperatures ranging from 700°C to 2200°C; this is well matched to TPV cell bandgaps. The intensity would be on the order of 2 W/cm^2 for the 900"C color temperature lamp with the cells placed close to the lamps.

These lamp arrays are produced by Research Incorporated of Minneapolis, Minnesota. They are tubular quartz, tungsten, infrared lamps arranged side by side in an array. Intensity uniformity is approximately +/- 10OA for an area ranging from 500 to 1000 cm2. Forced air and water cooling will be necessary to cool the lamps. Water cooling setup for the array of cells is necessary to maintain stable and moderate array temperatures. Although this plan may be feasible, the cooling requirements make it undesirable for a system which may need to handle a number of different configurations.

HIGH POWER INFRARED LAPSS EMISSION

A configuration with the JPL LAPSS system was analyzed for its potential in TPV array testing. It was believed that an infrared filter, placed in front of the LAPSS flash lamps would result in infrared light suitable for testing TPV cells. The analysis for this technique is detailed below and includes tests and discussion concerning emission uniformity, emission intensity, usage of infrared filters, emission characterization, and systems testing.

Emission Uniformity

In order to achieve high intensities in the infrared region, cells must be placed within 60 cm, or less, from the LAPSS flash lamps. At this distance, the emission uniformity is in question since the two lamps, which are 15.25 cm apart, no longer behave as a single point source. The individual contributions from each lamp, and the intensity variance along the lamp length may significantly affect emission uniformity. These characteristics must be verified in order to demonstrate this technique as a feasible method of TPV array testing.

Several tests were performed to show uniformity to be sufficient for string and array testing purposes. More detailed information and test results on LAPSS emission uniformity is provided in the Appendix. However, it is recommended that for greater intensity uniformity, cell strings should be arranged on the test plane in the horizontal direction, and arrays should be constructed in a rectangular configuration and arranged on the test plane horizontally, to take advantage of the non-symmetrical uniformity.

Emission Intensity

The intensity of the LAPSS was re-measured using three concentrator cells in an attempt to generate consistent high intensity measurements as shown in figures 1 and 2 The same method, described in the Appendix, of using the Voc/Intensity relationship was used. A linear curve fit of Isc versus intensity once again demonstrates that the point source equation for intensity is accurate up to 64 suns (8.75 W/cm^2), which is important in assuring accurate intensity values for the Voc/Intensity curve fits. The regression values for the curve fits are between 0.9998 and 0.9999 for Figure 1, and are between 0.9978 (ideal relation) and 0.9997 (non-ideal relation) for Figure 2. Data values for both the Isc and Voc are the average of three measurements taken at the same intensity.

Following the measurements made for Figures 1 and 2, the Voc of the cells was measured 17.8 cm from the flash lamps in an attempt to extrapolate for intensity at this location. Each result is the average of three measurements. Intensity extrapolations were made using both the ideal and the non-ideal

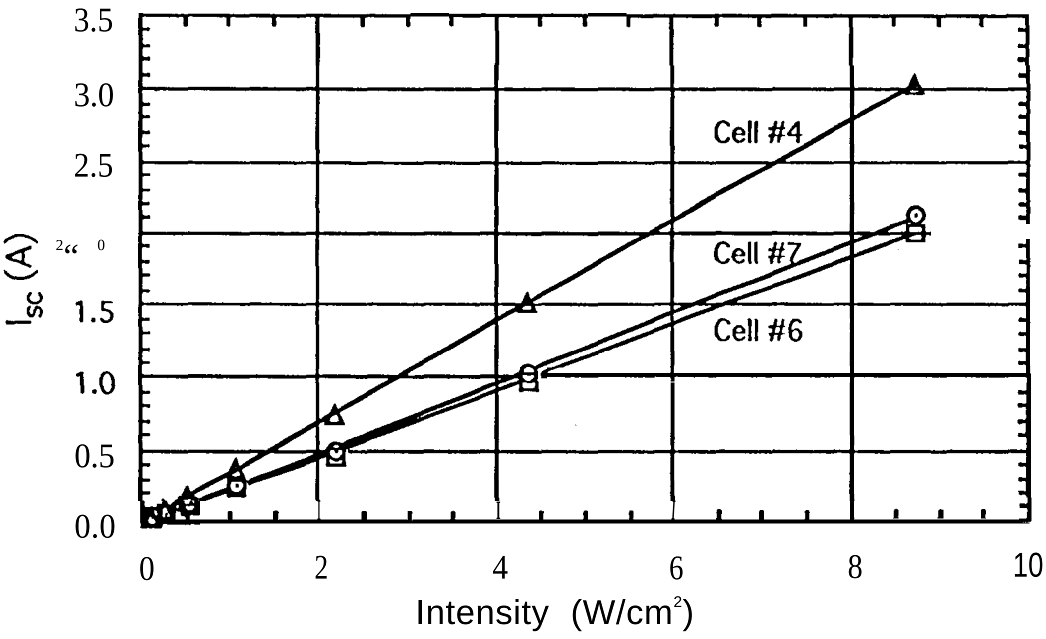

Fig. 1: Short circuit current versus point source intensity for silicon concentrator cells # 4, 6, and 7.

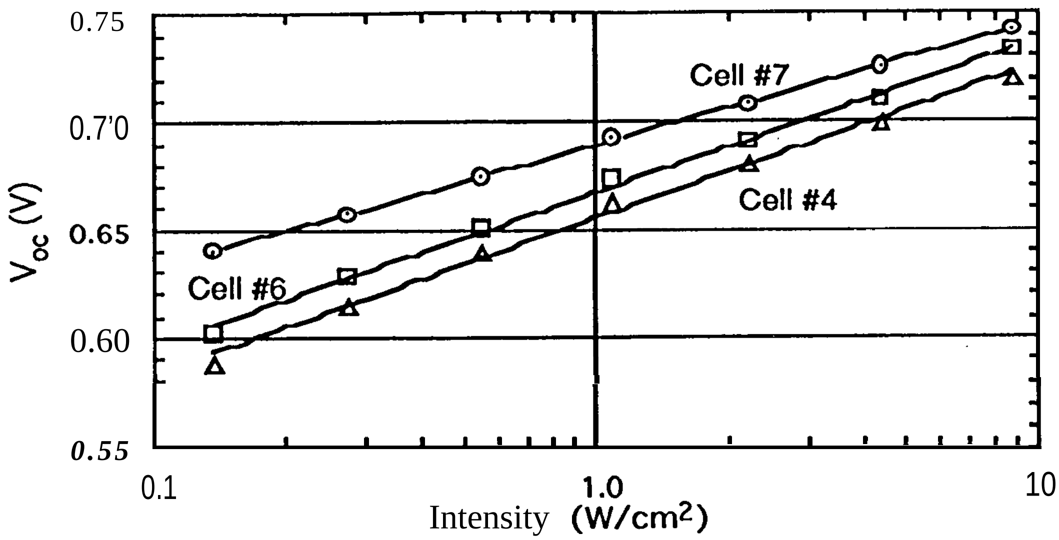

Fig. 2: Open circuit voltage versus point source intensity for Si concentrator cells # 4, 6, and 7

Cell Number	Voe (V)	Intensity Non-ideal (W/cm^2)	Intensity Ideal (W/cm^2)
4	0.7734	99	45
6	0.7990	130	75
7	0.7822	48	43

Table 1: Voc and intensity using the non-ideal and ideal relationships for concentrator cells #4, 6, 7, located 17.8 cm from the flash lamps.

Voc/Intensity curve fit equations derived from Figure 2 data and the results are shown in Table 1.

The values of maximum intensity, 17.8 em from the flash lamps, vary considerably between the three cells, indicating this method is not usable for measuring such a high intensity. This is due to different series resistance losses in the cells at extremely high intensities and that these concentrator cells were only designed to operate up to 100 suns. These results should, therefore, be disregarded.

Another method of measuring full intensity was performed. The laser power meter used for measuring black body intensity is used to measure LAPSS pulse energy. Power cannot be measured directly using this device because the LAPSS emission is a pulse, but pulse energy can be measured. Pulse energies are directly correlated to intensities because the LAPSS pulse energy profile and pulse duration are nearly constant, making the pulse energy directly proportional to intensity. The relationship of pulse energy to intensity must first be calibrated.

The intensity at the LAPSS 1 sun target plane was set to be 2% higher than AMO (0.1367 W/cm^2), as measured by the Si reference cell #SS1411, The calibrated intensity at the 1 sun plane is, therefore, 0.1394 W/cm^2. Furthermore, the Isc versus intensity graph (see Figure 1) shows that the point source intensity equation is extremely accurate for extrapolation to 64 suns. Thus, the calibration factor to convert LAPSS pulse energy to LAPSS intensity is determined by measuring the pulse energy and comparing the results to the accurate] y extrapolated intensities. The results are shown-in Table 2.

Distance from Lamps (cm)	Point Source Suns	Point Source Intensity (W/cm^2)	Pulse Energy (mJ)	Calibration Factor ($W/cm^2/mJ$)
1097.3	l x	0.1394	4	0.03485
775.9	2 x	0.2788	8	0.03485
548.6	4 x	0.5576	15.5	0.03597
388.0	8X	1.115	33.9	0.03289
274.3	16X	2.23	65	0.03431
194.0	32X	4.46	130.8	0.03410
137.2	64X	8.92	260.7	0.03422
106.7	128X	17.84	592	0.03014
100.6	N/A	N/A	645	N/A
70.1	N/A	N/A	1,260	N/A
39.6	N/A	N/A	3.320	N/A
17.8	N/A	N/A	12.820	N/A

Table 2: Results of AMO LAPSS (with GG395 Filter) pulse energy compared to intensities calculated from the point source equation.

The laser power meter does not accurately measure pulse energy below 30 mJ due to background light interference and the point source intensity extrapolations are accurate to only 64 suns Therefore, the most accurate calibration factors are from 8x to 64x suns, Averaging the calibration factor from the most accurate pulse energy readings yields a calibration factor of .0339 $W/(cm^2 mJ)$ which gives the following conversion:

$$\text{Intensity } (W/cm^2) = .0339\ W/(cm^2\ mJ) \times \text{Pulse Energy (mJ)}.$$

This equation is accurate at all intensities, as long as the laser power meter can accurately measure the pulse energy. Using this equation, full intensity (17.8 cm from the lamps) is 435 W/cm^2 (3 182 suns). This value is much larger than the intensities calculated from the Voc/Intensity relationships due to the excessive series resistance losses occurring at extremely high intensities which are generally unaccounted for by the equations derived at lower intensities. It is lower than the point source calculated value of 521 w/cm^2, which is not surprising since the source is not a point. The value of 435 W/cm^2 is, therefore, the most accurate measurement of the LAPSS intensity 17.8 cm from the lamps, with the Schott ultraviolet filter GG 395 in place. This method is a more direct means of measuring full intensity as compared to the Voc/Intensity relationships, and the laser power meter is especially designed to measure high energy pulses.

Spectral Match

The quantity of infrared radiation produced by the LAPSS flash lamps is now analyzed for its suitability for TPV cell testing. The emission spectrum of the lamps is modeled as a gray body with the peak emission occurring at 475 nm; this corresponds to a 6100 K gray body [3]. LAPSS emission is presently only characterized to 1.2 µm, therefore, the gray body model is used to approximate emission beyond 1.2 µm.

The bandgap of TPV cells will probably range from .65 to .5 eV (1.91 - 2.48 µm). Using the 6100 K gray body model, the percentages of illumination falling within a range of emission bands is calculated [4]. The emission bands are 0.5 µm or 1.0 µm wide, starting at a short wave length and stopping at selected cell bandgap wavelengths. The results are shown in Table 3.

At the highest LAPSS operating intensity, 435 W/cm2, the theoretical band emission intensities range from a high of 85.6 W/cm^2 for a 1.0 µm emission

cell Bandgap	.5 µm band emission % of total intensity	1.0 µm band emission % of total intensity
.4 eV. 3.1 urn	2.6 - 3.1 µm	2.1 - 3.1 µm
% of total intensity	1.1%	3.4%
.5 eV, 2.48 µm	1.98 - 2.48 µm	1.48 - 2.48 µm
% of total intensity	2.6%	8.9%
.6 eV. 2.07 urn	1.57-2.07 µm	1.07-2.07 µm
% of total intensity	5.2%	19.7%

Table 3: Estimate of LAPSS intensity for limited infrared emission bands.

band between 1.07 and 2.07 μm, and a low of 4.87 W/cm^2 for a .5 μm emission band between 2.6 and 3.1 p.m. Band emissions at longer wavelengths will require a wider bandpass because the power density will continue to fall off as wavelength is increased from the emission peak at 475 nm. These calculations show that the LAPSS is capable of producing high intensity infrared radiation in the response region of TPV cells if the proper filters are utilized to achieve the desired band emi ssi on.

Infrared Filters

In order for the LAPSS to be used as a source for illuminating TPV cells, the emission must be filtered to eliminate excessive quantities of high energy radiation. Ideally, the majority of the resulting emission must be slightly higher in energy than the cell bandgap (see Table 3). In order to achieve this, a pair of filters were placed together to achieve an infrared bandpass filter. The red/infrared filter is a Schott RG 645, and the blue/green filter is a Schott BG 38, which is transparent in the infrared, but red absorbing [5]. The transmission curve for the red/infrared filter is shown in Figure 3 and the transmission curve for the combined blue/green and red/infrared filters, resulting in an infrared bandpass filter is shown in Figure 4. LAPSS emission passes through the Schott BG 38 filter first.

A small spike occurs at 660 nm, as shown in Figure 4, because the transmittance of the filters slightly overlap at that wavelength. This spike can be eliminated by using a black glass, infrared filter, Schott RG 850, instead of the

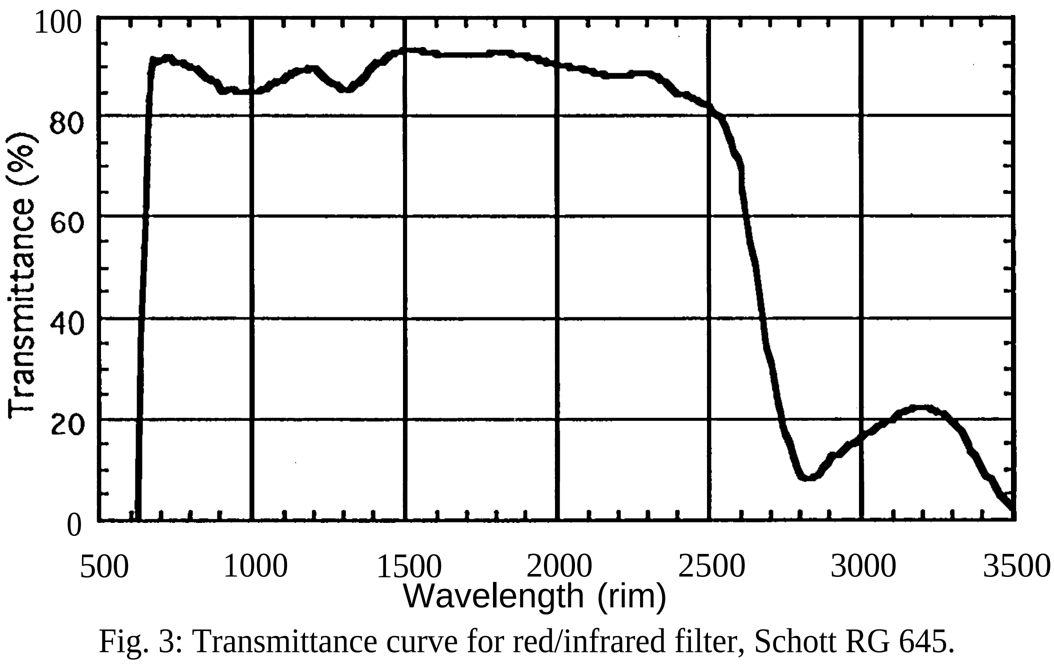

Fig. 3: Transmittance curve for red/infrared filter, Schott RG 645.

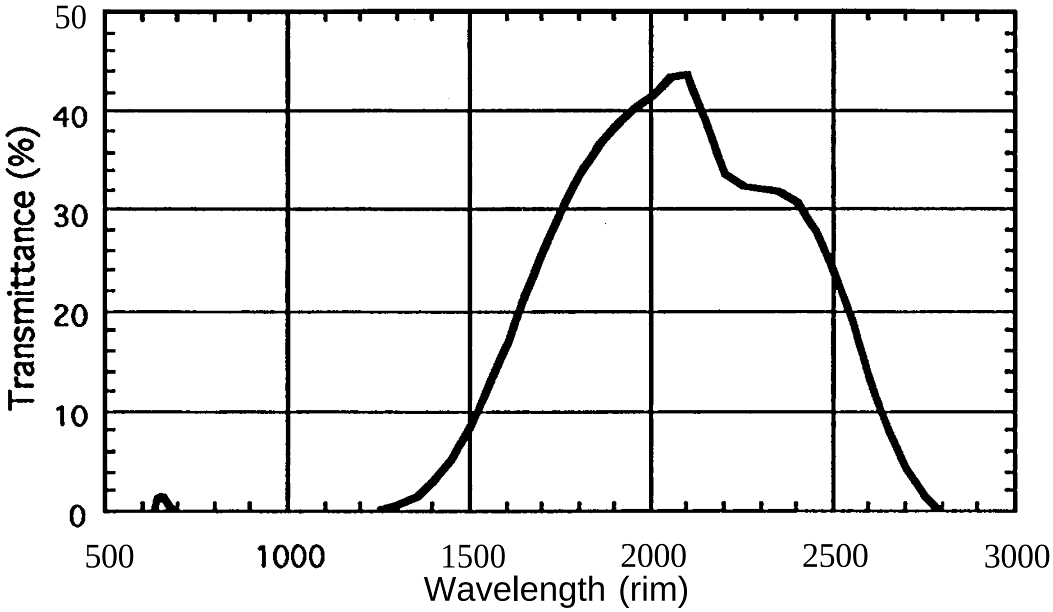

Fig. 4: Transmittance curve for the combined blue/green Schott BG 38 and the red/infrared, Schott RG 645 filters.

red/infrared filter, Schott RG645. The main transmittance peak would remain the same.

The overall transmittance is confirmed by using the laser power meter to measure the intensity with the infrared bandpass filter, at multiple locations from the lamps. Table 4 presents the results. An average of the bandpass transmittance values yields 1.87°/0 of normal LAPSS AMO illumination (with GG395). The transmittance at the 17.8 cm distance is questionable because the energy meter may have been slightly off position.

An alternative to using this filter combination for the bandpass filter is to

Distance from Bulbs (cm)	LAPSS AMO Pulse Energy (mJ)	LAPSS AMO (W/cm^2)	Bandpass Filter Pulse Energy (mJ)	Bandpass Intensity (W/cm^2)	Transmit-tance of Bandpass Filter (%)
106.7	592	20.07	11.05	0.375	1.867
100.6	645	21.87	12.04	0.408	1.867
70.1	1260	42.71	24.07	0.816	1.910
39.6	3320	112,55	62.1	2.105	1.870
17.8	12,820	434.60	238.0	8.068	1.856

Table *4:* Intensities of LAPSS using the infrared bandpass filter compared to the AMO GG395 filter use a Schott infrared filter (RG 1000). The transmittance of this filter is broader in the infrared region, so that TPV cells of greater bandgap can be tested.

Emission Characterization

The emission intensity from the LAPSS with the bandpass filter has been established as 8 W/cm^2, at a distance 17.8 cm from the LAPSS lamps. Multiplying the gray body LAPSS emission model with the bandpass transmittance curve, and normalizing the results for an intensity of 8 W/cm2 yields the spectral irradiance curve, as shown in Figure 5.

The emission spike at 660 nm is even more dominant than that depicted in the transmittance curve because the gray body LAPSS is more energetic at shorter wavelengths. However, the total energy of the spike is only about 4% of the total emission. The main emission peak occurs at 1800 nm, with the half power points at 1515 nm and 2215 nm.

Infrared LAPSS Testing

TPV cells were tested with the bandpass filtered LAPSS system to ensure that the setup is actually feasible. Two 1 cm2 InGaAs cells (6-1222-1 and 6-1222-2) from RTI/ASEC were tested with the infrared LAPSS emission at approximately 8 W/cm2, and the results compared with those from testing with

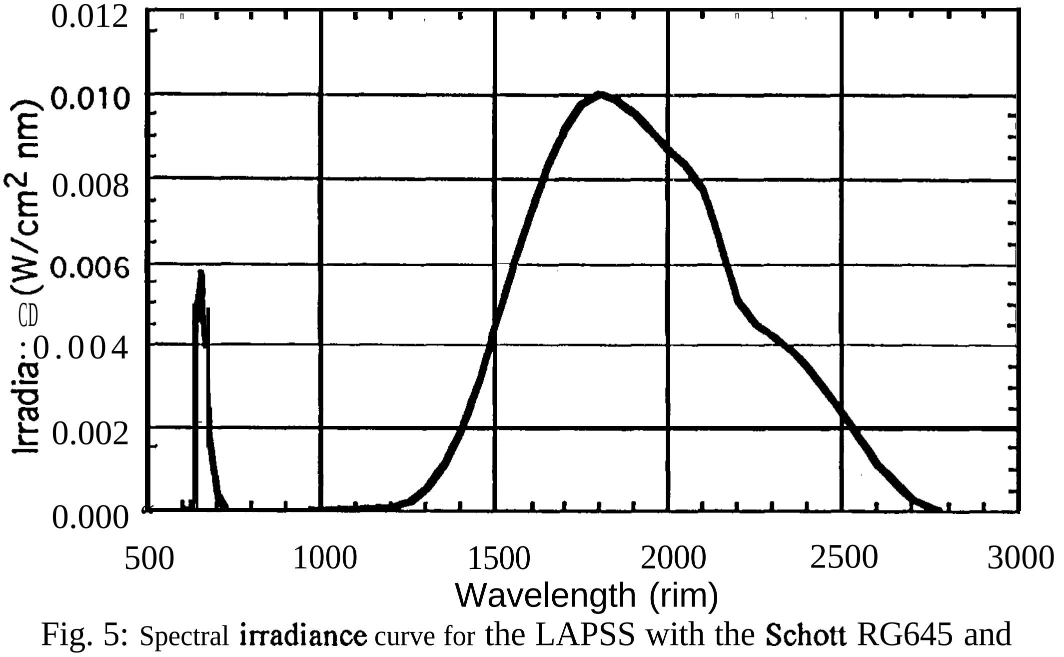

Fig. 5: Spectral irradiance curve for the LAPSS with the Schott RG645 and Schott BG38 combined as a bandpass filter.

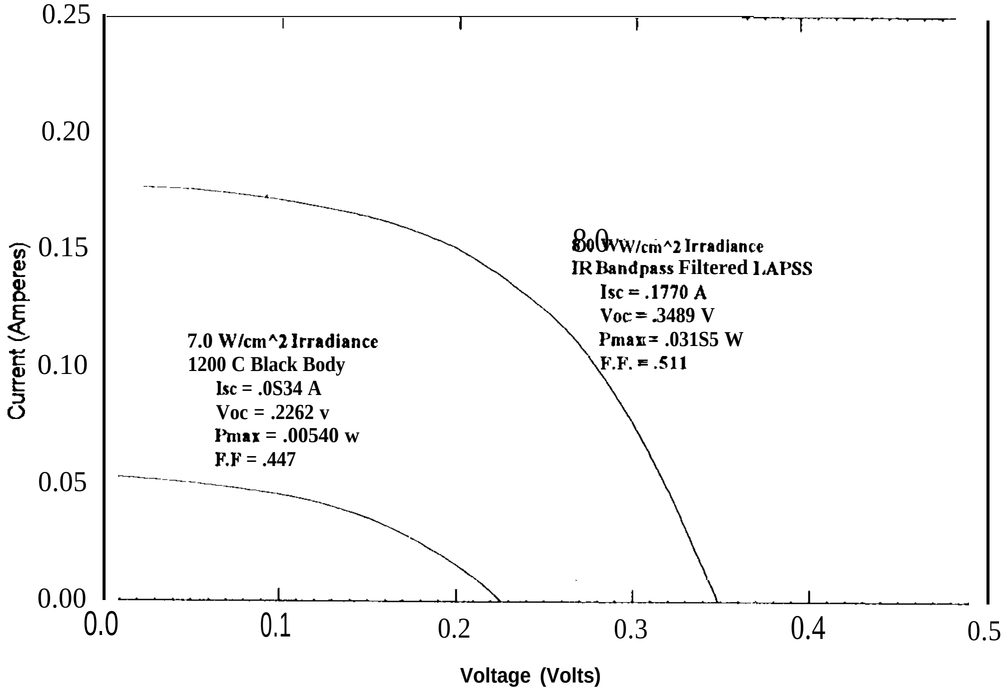

Fig. 6: Current-Voltage Characteristic at 28 C for InGaAs Cell #6-1 222-1, Area =1 cm^2

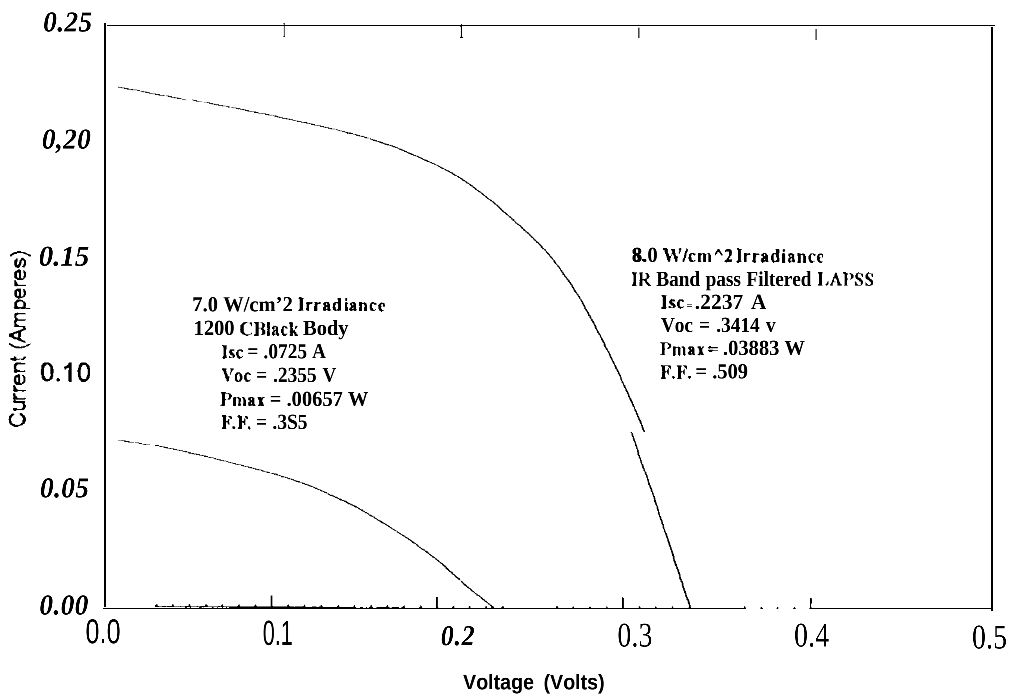

Fig. 7: Current-Voltage Characteristic at 28 C for InGaAs Ccl] #6- 1222-2. Area = 1 cm^2

the $1200^{o}C$ black body emission at approximate y 7 W/cm^2. Five separate runs were taken for each test to demonstrate the consistency in results. The upper intensity limit of 7 W/cm^2 for the black body prevented testing the cells at equivalent intensities. The results demonstrate that the narrow band infrared LAPSS emission is far better matched to the bandgap of the cells than is the broad-band black body emission. Performance could be improved if the cell bandgap was lower or if the filtered LAPSS emission peaked at a wavelength slightly higher than 1800 nm. Figures 6 and 7 show the results. The results of these tests indicates that using filtered LAPSS emission is a feasible method for testing TPV cells.

TPV cell 6-1222-2 was next tested at different locations across a 10.16 x 10.16 cm test plane, 17.8 cm from the bandpass filtered infrared LAPSS lamps (1.5 cm from the bandpass filter surface). The results are the average of two tests taken in forward and reverse order to minimize bias from temperature and raw LAPSS intensity variations. The results show that Isc of the cell changes -12.4% from the test plane center to the upper left corner (-5.08 + 5.08 cm location). This is equivalent to a variation of+/- 6.6% from the mean intensity. This Isc change is directly related to the LAPSS intensity uniformity.

This value is somewhat greater than the results from the emission uniformity tests (results shown in the Appendix). However, these results are the most accurate because they were obtained under actual test conditions and at maximum intensity with the infrared bandpass filter in position. Uniformity of intensity can be improved by placing the cell at a greater distance from the flash lamps, however, this will reduce emission intensity. The results are shown in Table 5.

The results also indicate that intensity uniformity is greater in the horizontal direction than in the vertical direction. Intensity changes an average of 4.1 % across a 10.16 cm horizontal traverse, and 8.8% across a 10.16 cm vertical traverse. This agrees well with previous uniformity tests. System testing has shown the bandpass filtered infrared LAPSS is a potential method for testing TPV cells and arrays requiring high power density in the infrared spectrum.

The high power infrared LAPSS system was developed with existing JPL equipment so that there was no material or equipment costs; the only cost for the system was research time.

Position (cm.)	**(-5.08, +5.08)**	**(0.0,+5.08)**	**(+5.08, + 5.08)**
Isc (mA)	**190.76**	**198.54**	**191.46**
Voc (V)	0.3155	0.3181	0.3157
Pmax (mW)	**25.14**	**26.67**	**25.36**
Ipmax (mA)	**126.75**	**129.99**	**124.91**
Vpmax (V)	**0.1984**	**0.2052**	**0.2032**
FF	**0.418**	**0.422**	**0.420**
Position (cm.)	**(-5.08,0.0)**	(0.0,0.0)	**(+5.08,0.0)**
Isc (mA)	**210.21**	**217.78**	**208.80**
Voc (V)	**0.3213**	**0.3228**	**0.3200**
Pmax (mW)	**28.64**	**30.03**	**28.46**
Ipmax (mA)	**136.95**	**144.49**	**136.95**
Vpmax (V)	**0.2077**	**0.2079**	**0.2077**
FF	**0.426**	**0.427**	**0.426**
Position (cm.)	**(-5.08,-5.08)**	**(0.0,-5.08)**	**(+5.08, -5.08)**
Isc (mA)	195.78	201.92	193.46
Voc (V)	0.3166	0.3182	0.3156
Pmax (mW)	**26.06**	**27.19**	**25.71**
Ipmax (mA)	127.92	133.28	124.96
Vpmax (V)	**0.2037**	**0.2040**	**0.2058**
FF	**0.420**	**0.423**	**0.421**

Table 5: TPV cell #6-1222-2 IV performance with bandpass filtered infrared LAPSS, 8 W/cm^2, 17.8 cm from the lamps.

RECOMMENDATIONS

Much of the emission testing for the infrared LAPSS was completed without a precise positioning system for exact cell and power meter placement from the flash lamps. This limits the accuracy of the results because test cells and the power meter cannot be repositioned with much precision. Great effort was taken to ensure precision positioning, but a long travel, linear positioning slide would bean improvement. In addition, slight changes in the distance to the lamps result in significant changes in intensity. This reinforces the need for a precise positioning system for TPV cell placement.

The present bandpass filter allows a small transmittance spike at 640 nm due to an overlap in the two filters. This can be eliminated by replacing the red/infrared filter with a black glass, infrared filter (RG 850). Also, for testing higher bandgap TPV cells, a single broad band infrared filter (RG 1000) could be substituted for the narrow band infrared filter. These two Schott Glass Technology filters would expand the capabilities of the infrared LAPSS for TPV cell and array testing; at a total filter cost of approximate y $300.

The emission characterization is an approximation calculated from a gray body emission model of the LAPSS multiplied by the bandpass transmittance curve and a 8 W/cm^2 correction factor. Actual LAPSS emission does not behave exactly as a gray body. Although it is unlikely that there are major deviations from this model, actual measurement of the spectral irradiance distribution would be desirable.

Although the present filtered infrared LAPSS irradiance characterization is sufficient for present testing purposes, it would be fruitful to completely characterize the LAPSS with and without filter(s) to three or four microns. This can probably be accomplished with loaned equipment and a good UV-VIS-IR grating monochromator.

CONCLUSIONS

A number of methods for high power TPV cell array testing were explored. These methods include using ideal black or gray body sources, high power lasers, lamp arrays, and filtered infrared LAPSS emission. Black or gray bodies provide the same emission as the present JPL single cell testing method. However, in order to illuminate a large area array, a black body with a large aperture area is necessary. Such a system is not presently available in the temperature range of interest; it would be costly to develop (if it is feasible), and a massive cell cooling setup would be necessary. Lasers offer the advantage of providing an extremely narrow band emission, so if the wavelength is well matched to the cell bandgap, peak efficiency could be achieved. However, only one high power laser with a wavelength appropriate for the bandgap of probable TPV cells was located. There is also considerable difficulty in diffusing and recollimating a laser beam so that it uniformly illuminates an array of cells. The difficulties with complicated optics and the high cost of lasers makes it an undesirable choice for array testing at this time. Lamp arrays provide a good approximation for gray body emission which could illuminate the necessary area at sufficient uniformity. However, massive cooling systems for the lamps and cell arrays are necessary, and lamp emission barely meets the 2 W/cm^2 minimum intensity requirement.

A system utilizing the present LAPSS system and an infrared bandpass filter was analyzed for large area TPV cell testing. The uniformity of LAPSS emission was tested and found to vary by a maximum of+/- 6.6% from the mean intensity over a 10.16 x 10.16 cm area directly behind the bandpass filter. The filtered LAPSS intensity at this location (17.8 cm from the flash bulbs, 1.5 cm from the bandpass filter surface) was measured to be about 8 W/cm^2. The emission was characterized by multiplying the transmittance curve of the filter with a gray body irradiance approximation of LAPSS emission. Thus, filtered infrared LAPSS emission is fairly uniform, possesses high intensity, and the emission is well matched for the probable TPV cell bandgap range. The system was tested and found to be a reliable method for TPV cell testing. The high power, infrared LAPSS is now operational at JPL for TPV single cell or array testing.

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APPENDIX

Emission Uniformity Tests

An indirect method of measuring light pulse intensity using the solar cell Voc/Intensity logarithmic relationship was first attempted. In addition, the solar cell Isc/Intensity relationship was measured. These tests were performed using a typical 2 x 2 cm, BSF, standard Silicon solar cell and the results are shown in Figures 8 and 9.

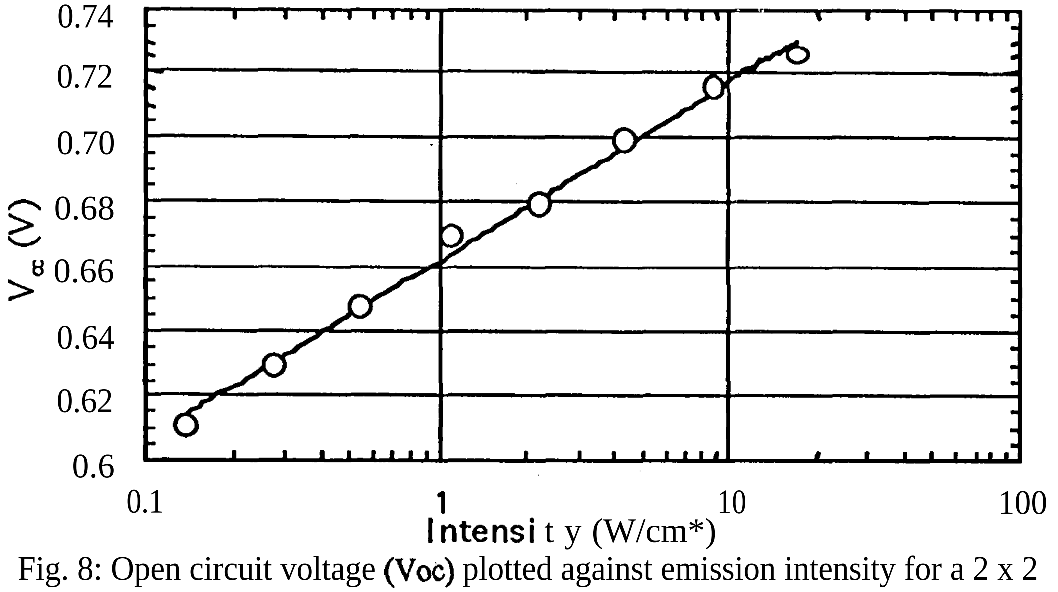

Fig. 8: Open circuit voltage (Voc) plotted against emission intensity for a 2 x 2 cm BSF Silicon solar cell.

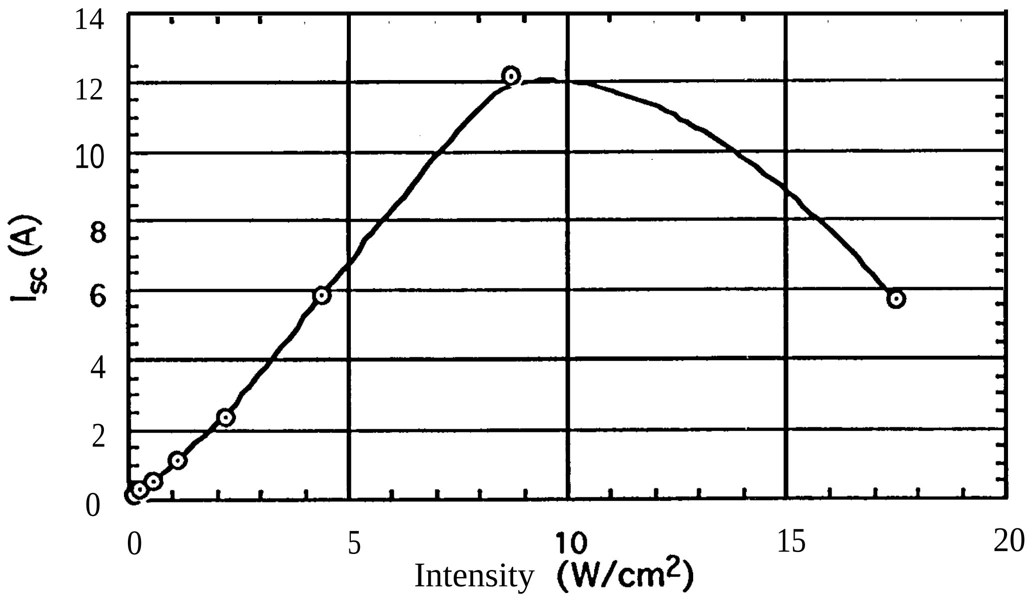

Fig. 9: Short circuit current (Isc) plotted against intensity for a 2 x 2 cm BSF Silicon solar cell.

Voc behaves logarithmically with intensity, where Voc = 0.662 + 0.055 log (Intensity) and the regression value for the curve fit is 0.9968, as shown in Figure 8. Intensity could be approximated with this relationship. The cell temperature was about 25°C, room temperature, and did not change appreciable y during the tests because the LAPSS is a pulsed light source.

Figure 9 demonstrates that although Isc is relatively linear with intensity for low intensities, it is nonlinear at higher intensities due to cell series resistance losses, which reduce cell Isc as the LAPSS intensity exceeds about 64 suns. The relationship is no longer linear preventing any intensity predictions. An ASEC concentrator cell was then tested for its Voc and Isc intensity relations. The Isc relationship remained nonlinear with intensity at higher intensities, but the series resistance losses were not as significant as they were with the 2 x 2 cm BSF Silicon solar cell.

Figure 10 shows Voc to be relatively logarithmic with intensity in an ideal relation where Voc = 0.501 + 0.062 log (Intensity), but there are series resistance losses at higher intensities, causing this relationship to become somewhat inaccurate. These losses are taken into account with a precise curve fit including intensity raised to a power factor in a non-ideal relation where Voc = 4.011.9 + 9.367 log (Intensity) -4011.5 (Intensity)”l. The regression value improves (0.9997 vs. .09943) with the non-ideal relationship. The ideal and non-ideal Voc/Intensity relationships are used later to evaluate emission uniformity.

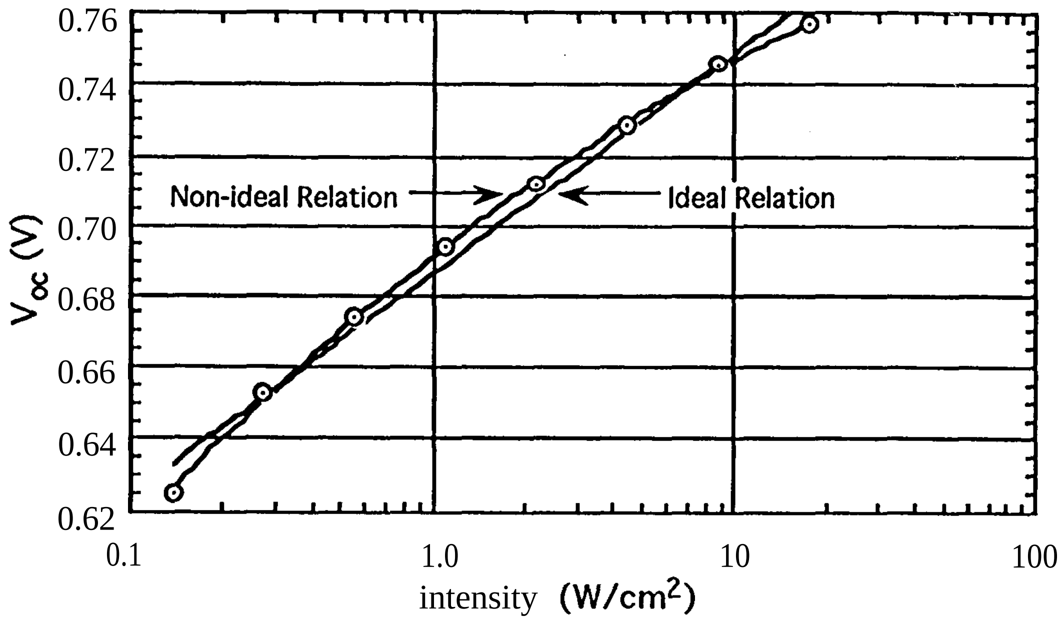

Fig. 10: Open circuit voltage plotted versus intensity for concentrator cell #7 from ASEC

In figures 8-10, the intensities are extrapolations which were calculated using a point source model. The lamp location is assumed to be a point source; and the 1 sun test plane has a calibrated intensity of 136.7 mW/cm^2 at a location of 10.973 m (36 feet) from the lamps. The approximate Intensity/Location relationship is:

$$\text{Intensity(mW/cm}^2\text{)} = (1.646 \times 104\ \text{mW-m}^2\text{/cm}^2) / \text{Distance}$$

An error results from this relationship at distances close to the lamps, because the point source approximation is only accurate to about 64 suns. The extrapolation errors, cell series resistance effects and cell temperature variations could possibly account for the non-ideal Voc/Intensity logarithmic relationship.

Intensity uniformity was now measured using the calibrated Voc/Intensity relationship from Figure 10. The same silicon concentrator cell #7 was now placed about 61 cm from the flash lamps. Voc tabulations are the average of t wo consecutive measurements taken at the same location. This test was performed for a planar (1 5.24 x 15.24 cm) area. Measurements were made every 1.27 an over a 15.24 cm horizontal traverse. This was completed for three rows. One row was centered with the lamps and the other two rows were 7.62 cm above and below the center. The results are shown in Table 6.

Horiz. Position (cm)	-7.62	-6.35	-5.08	-3.81	-2.54	-1.27	0.00
Vertical Position (cm)	**Open Circuit Voltage (V)**						
7.62	**0.7624**	**0.7627**	**0.7629**	**0,7629**	**0.7629**	**0.7629**	**0.7629**
0.00	0.7640	0.7640	0.7642	0.7642	0.7643	0.7644	0.7646
-7.62	0.7642	0.7638	0.7635	0.7636	0.7632	0.7628	0.7622

Horiz. Position (cm)	7.62	6.35	5.08	3.81	2.54	1.27	0.00
Vertical Position (cm)	**Open Circuit Voltage (V)**						
7.62	**0.7632**	**0.7633**	**0.7632**	**0.7632**	**0.7632**	**0.7634**	**0.7635**
0.00	0.7649	0.7649	0.7651	0.7646	0.7654	0.7659	0.7655
-7.62	0.7636	0,7636	0.7642	0.7641	0.7637	0.764	0.7637

Table 6: Open circuit voltage readings for a 15.24 x 15.24 cm plane located approximately 61 cm from the LAPSS flash lamps.

The test results suggest there is better uniformity horizontally than vertically, as indicated by the-smaller variation in Voc values. Voc varied from a high of .7659 V near the center, to a low of ,7624 at the top left, a change of -0.46%. This corresponds to intensities of 23.95 and 19.34 W/cm^2 respectively, using the non-ideal Voc/Intensity relationship, for a change of -1 9.2%. This also corresponds to intensities of 18.89 and 16.59 W/cm^2, using the ideal logarithmic Voc/Intensity relationship, for a change of -1 2.2%.

An inconsistency was found in the data where the Voc measurements are' repeated at the starting locations, (zero cm horizontal versus 7.62, 0, and -7.62 cm vertical) because the data was taken at different times. The sequence in which the data was taken seems to affect the result. This is possibly due to an increase in cell temperature after multiple flashes or variations in raw LAPSS intensity. Voc and intensity variance would, therefore, be less than this test indicates.

A more accurate test was made by performing the same test but measuring Voc at fewer locations to minimize possible cell heating or changes in raw LAPSS intensity, and then normalizing the data. Voc measurements were made for each row at the 7.62, 0 and -7.62 cm horizontal locations; the results are the average of two runs for each location. The Voc at the center location, (0,0), was measured immediately after each set of row readings for comparison with the other results. The results are shown in Table 7.

The effects of varying cell temperature or LAPSS intensity is compensated by assuming a constant Voc value at position (0,0) of .7621 V. The Voc values for each set of row readings are then corrected by the difference between the initial Voc readings and the follow-up measurements at the zero horizontal position. The results are shown in Table 8.

The corrected results show a significant improvement in uniformity in comparison to the uncorrected data and the initial test run. Corrected Voc readings varied from a high of .7623 at position (0.0, +7.62), to a low of .7603 at position (-7.62, 0.0). These correspond to intensities of 19.22 and 17.125 W/cm^2 using the non-ideal Voc/Intensity relationship, and 16.53 and 15.34 W/cm2 using the ideal logarithmic Voc/Intensity relationship. The -0.26 % change in Voc corresponds to an intensity change of -10.9’XO by the non-ideal relationship, and -7.2% by the ideal relationship. Again, results show that uniformity is

Horizontal Position (cm)	-7.62	0.0	7.62
Vertical Position (cm)	**Open Circuit Voltage (V)**		
7.62	0.7604	0.7603	0.7607
0.0 **after 7.62**		0.7620	
0.0	0.7622	0.7621	0.7623
0.0 after -7.62		0.7606	
-7.62	0.7594	0.7595	0.7595

Table 7: Open circuit voltage in a 15.24x 15.24 cm plane located approximately 61 cm from the LAPSS flash lamps with additional measurements at position (0,0) for comparison.

Horizontal Position (cm)	**-7.62**	**0.0**	**7.62**
Vertical Position (cm.)	**Open Circuit Voltage (V)**		
7.62	**0.7605**	**0.7604**	**0.7608**
0.0	**0.7622**	**0,7621**	**0.7623**
-7.62	0.7609	0.7610	0.7610

Table 8: Corrected open circuit voltage in a 15.24x 15.24 cm plane, 61 cm from the flash lamps.

Voc at Constant (0.0) X-Position			
Vertical Position (cm.)	Forward Order Voc (V)	Reverse Order Voc (V)	Average Voc (V)
7.62	0.7591	0.7586	0.75885
‘5.08	0.7594	0,7592	0.75930
2.54	0.7597	0.7598	0.75975
0.0	0,7598	0.7600	0.75990
-2.54	0.7596	0.7598	0.75970
-5.08	**0.7593**	**0.7596**	**0.75945**
-7.62	0.7588	0.7582	**0.75850**

Table 9: Open circuit voltage taken vertically in a 15.24x 15.24 cm plane, 61 cm from the flash lamps.

significantly better horizontally than vertically.

A more precise test for vertical Voc and intensity variance across the test plane was next conducted. Voc readings were made from position (0.0, +7.62) to (0.0, -7.62) in 2.54 cm intervals, and again, but in a reverse order, from (0.0, -7.62) to (0.0, +7.62). The results are for single measurements to minimize possible cell temperature or LAPSS intensity variations. The Voc readings for identical positions are averaged to cancel out these variances, The results are shown in Table 9.

The average Voc changed -O. 16%, in the vertical direction, which corresponds to a change in intensity of -7.2°/0. A summation of the change in intensity vertically (-7.2°/0) and horizontal y (-2.4°/0) yields -9.6°/0, the maximum intensity change Occurnng between the center and corner positi ens. This agrees well with the previous data resulting in a maximum intensity change of -1 0.9°A across the 15,24 x 15.24 cm area, 61 cm from the flash lamps.

Since the emission was fairly uniform at this distance, the same test was performed for a 10.16 x 10,16 cm test plane approximately 17.8 cm from the lamps. This is located directly in front of the LAPSS filter, where the highest intensity is achieved. A smaller test plane area was characterized because the LAPSS casing will not allow uniform illumination beyond this size at this location. The results, shown in Table 10, are single measurements to minimize variations due to changing cell temperature or intensity.

The average horizontal Voc ranged from a high of .7800 V to a low of .7795 V which corresponds to intensities of 66.75 and 63.9 W/cm2, changing -4.2%, by the non-ideal relationship, and 31.87 and 31.29 W/cm^2, changing -1 .7%, by the ideal relationship,

The average vertical Voc ranged from a high of .7798 to a low of .77925 V, which corresponds to intensities of 65.6 and 62.5 W/cm2, changing -4.7% by the

Voc at Constant (0.0) Y-Position			
Horizontal Position (cm)	Forward Order Voc (V)	Reverse Order Voc (V)	Average Voc (V)
5.08	0.7796	0.7795	0.77955
3.81	0.7798	0.7802	0.78000
2.54	0.7796	0.7801	0.77985
1.27	**0.7795**	**0.7800**	**0.77975**
0.00	**0.7793**	**0.7802**	**0.77975**
-1.27	**0.7788**	**0.7802**	**0.77950**
-2.54	0.7789	0.7804	0,77965
-3.81	0.7785	0.7806	0.77955
-5.08	0.7788	0.7805	0.77965

Voc at Constant (O.O) X-Position			
Vertical Position (cm)	**Forward Order** Voc (V)	Reverse **Order** **Voc (V)**	Average Voc (V)
5.08	0.7805	0.7785	0.77950
3.81	0.7804	0.7783	0,77935
2.54	0.7801	0.7784	0.77925
1.27	0.7803	0.7788	0.77955
0.00	0.7801	0.7793	0.77970
-1.27	0.7800	0.7796	0.77980
-2.54	0.7800	0.7794	0.77970
-3.81	0.7797	0.7797	0.77970
-5.08	0.7802	0.7794	0.77980

Table 10: Open circuit voltage in a 10. 16x 10.16 cm plane located 17.8 cm from the LAPSS flash lamps.

non-ideal relationship, and 31.64 and 31.0 W/cm^2, changing -2. 1°A by the ideal relationship.