REDUCED TEMPERATURE DEPENDENCE OF HIGH-CONCENTRATION PHOTOVOLTAIC SOLAR CELL OPEN-CIRCUIT VOLTAGE (Voc) AT HIGH CONCENTRATION LEVELS

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ABSTRACT

Thermal management has been an important issue for both one-sun flat-plate, and concentration system applications. It is well known that system output power, or efficiency, decreases with the increasing temperature of the cell incorporated within the system mainly due to a decrease in open-circuit voltage (Voc) as a function of increasing temperature. This paper reports the measurement results of temperature sensitivity for Voc of AMONIX's high-concentration photovoltaic (HCPV) cells at various temperatures (25^0 C — 65^0 C), and various concentration levels (one-sun up to 500 suns under AM1.5) and compares against typical one-sun flat-plate manufacturer's data. Even after taking into account the negative temperature dependence of the Fill Factor, the study shows that output power in concentration systems is less affected by temperature variations compared to one-sun flat-plate designs. The overall effect of this reduced temperature sensitivity for Voc of the HCPV cell on the power output at operating temperature is analyzed and compared against typical single and poly-crystalline silicon, front-junction, one-sun, flat-plate manufacturer's data. Experimental and analytical results show that typical flat-plate systems have a -0.4%/^{0}C (4000 PPM) decrease in power versus -0.25%/^{0}C (2500 PPM) for high-concentration systems.

INTRODUCTION

Thermal management has been an important issue in photovoltaic power generating systems for both one-sun and concentrated sun applications. Lowering the normal operating temperature of the system increases the power output for both applications. It is commonly believed that concentrator systems are fundamentally inferior, compared to one-sun designs, by having higher operating cell temperatures when they are installed and operated at similar sites under similar ambient conditions for wind and temperature. However, after careful review of AMONIX's Integrated High-Concentration Photovoltaic (IHCPV) system, which uses high resistivity high efficiency back-junction point-contact HCPV solar cells, it is clear that this simplistic concept is invalid.

The temperature dependence of the AMONIX HCPV cell for efficiency and open-circuit voltage have been investigated. In Figure 1, the first 20 kW (nominal) IHCPV system, installed at Arizona Public Service's Solar Test and Research (STAR) facility in Tempe, AZ is shown. The system contains approximately 4000 HCPV cells and produced >20 kW_{DC} under PVUSA operating conditions with an operating efficiency of 18.2% (20.3% under standard test conditions). In Table 1 the PVUSA report conditions and the standard report conditions are summarized [1]. Note the cell operating temperature would typically be ~55^0 C.

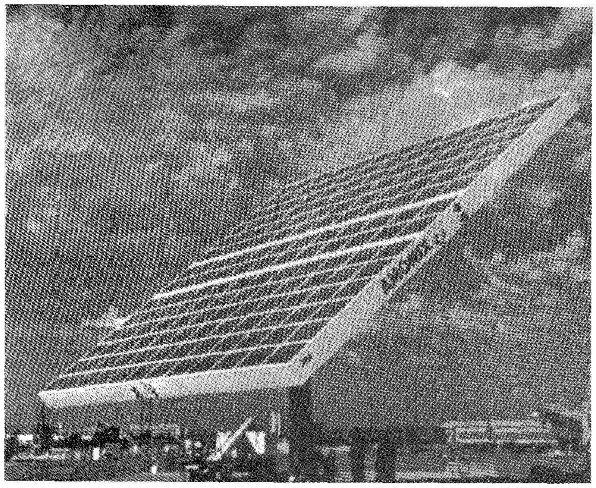

Figure 1: AMONIX 20 kW IHCPV System

TABLE 1
TEST CONDITIONS

PVUSA Test Conditions for Concentrators
850 W/m^2 direct normal irradiance, 20^0 C **ambient temperature**, and 1 m/s wind speed (at 10 meters above grade)

Standard Test Conditions
1000 W/m^2 direct normal irradiance, 25^0 C **cell temperature**, and 3 m/s wind speed (at 10 meters above grade)

It has been well known and consistently proven that a solar cell with a certain photovoltaic power conversion efficiency at one-sun would have a higher conversion efficiency if operated at higher concentration at the same temperature. The reason for this increase in efficiency is

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mainly due to the increase in open-circuit voltage (Voc) due to increased light generated current. For an ideal solar cell at 25^0 C this would result in an approximately 60 mV increase in open-circuit voltage per decade of concentration increase. A conventional low resistivity, front-junction P^+NN^+ solar cell with a one-sun efficiency of 17.3% and an open-circuit voltage of 630 mV at 28^0 C demonstrated approximately 20.3% efficiency with 745 mV at 100 suns, 28^0 C [2]. For this case, the increase in efficiency and operating voltage were approximately 17% and 18%, respectively.

It is apparent that, for 100 X concentrator systems, approximately 100 times the residual heat must be dissipated through the same cell area compared to one-sun applications in the example above. Therefore, in actual situations the temperature difference between the cell temperature and ambient temperature would be somewhat larger for concentrator systems compared to one-sun systems. However, high open-circuit voltage reduces the temperature sensitivity for the cell. Green et al. [3, 4, 5] have studied, and verified, this phenomena extensively over the last ten years using their best one-sun cells.

ANALYTICAL APPROACH

The electrical characteristics of a HCPV cell can be represented by an equivalent circuit as shown in Figure 2.

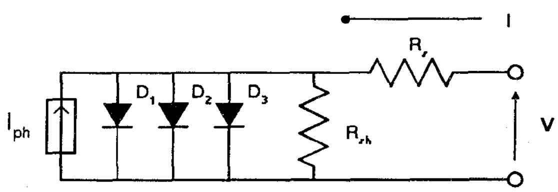

Figure 2: Schematic Diagram of Equivalent Circuit for HCPV Cell

Equivalent Circuit Description

In general, diode current characteristics are described by

$$I = I_o\left(e^{\frac{qV}{nkT}} - 1\right) \tag{1}$$

where n is called an ideality factor, k is Boltzman's Constant, q is the electric charge, and T is absolute temperature. Historically a solar cell's dark current characteristics in low injection conditions can often be represented by using two diodes, such as "D1" and "D2", with current transport characteristics of exp(qV/kT) and exp(qV/2kT) dependence on voltage, respectively [6]. The dark current component of diode "D2" is commonly attributed to depletion region recombination and surface recombination [7,8]. Diode "D3" is introduced to describe the electrical characteristics of the HCPV cell at high concentration operation where Auger recombination process is a dominant recombination due to the fact that minority carrier concentration approaches the majority carrier concentration under high injection conditions. Swanson et al calculated the contribution of each recombination mechanism at the maximum power point as a function of the incident power density for a high resistivity back-junction point-contact cell [9]. According to the simulation the recombination current contribution from Auger recombination process grows from zero percent contribution at one-sun level through 20% at 100 sun level, and 70% at 400 suns. In other words, the recombination current due to other causes than Auger recombination constitutes only 30% or less of the total recombination current for a high resistivity back-junction point-contact cell operating a concentrations higher than 400X.

The ideality (or diode quality) factor for a HCPV cell operating at high current density level where predominant recombination process is Auger recombination seems to be less than one and approaching 2/3 (see "EXPERIMENT and DISCUSSION" section). Similar behavior was predicted for a conventional front junction cell by Hall [10].

In Figure 2, the photocurrent is represented by a current generator, I_{ph}, and is opposite in direction to the forward bias currents of the diodes "D1", "D2" and "D3". Shunt resistance paths are represented by R_{sh}; they can be caused by leakage currents on surfaces or in junctions. The series resistance is represented by R_s and can arise from contact resistance, the resistance of the base region itself, and the diffused regions.

The equivalent circuit in Figure 2 becomes analytically manageable if the approximation that the series and shunt resistance effects are negligible and that dark current can be expressed as

$$I_{DARK} = I_{00}\left[\exp\left(\frac{qV}{n_0 kT}\right) - 1\right] \tag{2}$$

where n_0 is the ideality factor (junction quality factor or junction perfection factor) of the idealized diode which is dependent on the I_{ph} level. Then, the short circuit current and open circuit voltage are simply given by

$$I_{sc} = I_{ph} \tag{3}$$

$$V_{OC} = \frac{n_0 kT}{q}\ell n\left(\frac{I_{sc}}{I_{00}} + 1\right) \tag{4}$$

Since the power output is determined by ($I \bullet V$), the maximum power output for the idealized HCPV cell would be obtained by differentiating the product and setting the result to zero. Then, the power expression becomes

$$P = I_{00}V\left(e^{\frac{V}{n_0 V_T}} - 1\right) - I_{ph}V \tag{5}$$

where V_T, thermal voltage, is substituted for $\frac{kT}{q}$.

Setting $\frac{dP}{dV} = 0$ and using equations (3) and (4), maximum power point voltage and current, V_m and I_m, are obtained in implicit expressions

$$V_m = V_{oc} - n_o V_T \ell n\left(1 + \frac{V_m}{n_o V_T}\right) \quad (6)$$

$$I_m = (I_{sc} + I_{00})\left(\frac{-V_m / n_0 V_T}{1 + V_m / n_0 V_T}\right) \quad (7)$$

It is apparent from equation (6) that, for constant temperature and n_0 values, V_m is uniquely defined by V_{oc} only and so is I_m. If a ratio r is defined for V_m/V_{oc} (always less than one) and a dimensionless voltage v_{oc} is defined for V_{oc}/V_T, then equation (6) becomes

$$\frac{v_{oc}}{n_0}(1-r) = \ell n\left(1 + r\frac{v_{oc}}{n_0}\right) \quad (8)$$

For a special case of $n_0 = 1$, $r(=V_m/V_{oc})$ values corresponding to dimensionless v_{oc} values are plotted in Figure 3. The Fill Factor for the idealized HCPV cell, FF_0, can be obtained from

$$FF_0 = r\frac{I_m}{I_{sc}} \quad (9)$$

where the sign of I_m would be changed to positive knowing that the cell is generating power.

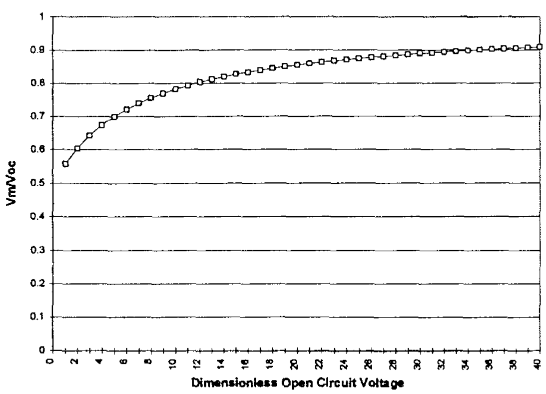

Figure 3: Calculated Values of r (=Vm/Voc) as a Function of Dimensionless Open Circuit Voltage

With proper rearrangement, an exact expression for FF_0 turns out to be

$$FF_0 = r\left(\frac{e^{v_{oc}/n_0}}{e^{v_{oc}/n_0} - 1}\right)\left(\frac{r v_{oc} / n_0}{1 + r v_{oc} / n_0}\right) \quad (10)$$

Equation (10) could be approximated, for a special case of $n_0 = 1$,

$$FF_0 \cong \frac{r^2 v_{oc}}{1 + r v_{oc}} \quad (11\text{-}1)$$

$$\cong \frac{v_{oc} + \ell n r - \ell n(v_{oc} + r)}{v_{oc} + r} \quad (11\text{-}2)$$

$$\cong \frac{v_{oc} - \ell n(v_{oc} + 0.72)}{v_{oc} + 1} \quad (11\text{-}3)$$

The equation (11-3) is an empirical expression independent of r as first introduced by Green [11].

Temperature Dependence Of V_{oc} and FF_0

Temperature sensitivity of V_{OC} can be obtained by differentiating V_{OC}, equation (4), with respect to temperature, T. The saturation current, I_{00}, in equation (4) can be expressed as

$$I_{00} = I_S T^{\left(3+\frac{\gamma}{2}\right)} \exp\left(-\frac{E_g(T)}{kT}\right) \quad (12)$$

where $E_g(T)$ is the bandgap energy at temperature T and the temperature dependence exponent $(3+\gamma/2)$ is from the third order dependence of intrinsic carrier concentration, n_i^2, and γ order dependence for the ratio between carrier diffusivity and lifetime (D/τ).

The temperature dependence of the term $T^{\left(3+\frac{\gamma}{2}\right)}$ is not important compared with the exponential term. The variation of bandgap with absolute temperature, T, is expressed as Thurmud [12]

$$E_g(T) = E_g(0) - \frac{\alpha T^2}{T + \beta} \quad (13)$$

where $E_g(0)$ is 1.170 eV, α is 4.73 X 10^{-4} eV/K, and β is 636 K.

Differentiation of equation (4) with respect to T and substitution of bandgap voltage, $V_g(T)$, for $E_g(T)/q$ results in

$$\frac{dV_{oc}}{dT} = -\left(\frac{V_g(T) - V_{oc} + \left(3 + \frac{\gamma}{2}\right)V_T}{T}\right) + V_T\left(\frac{1}{I_{sc}}\frac{dI_{sc}}{dT} + \frac{1}{V_T}\frac{dV_g(T)}{dT}\right) \quad (14)$$

The terms in the second parenthesis of equation (14) are essentially dependent on $dV_g(T)/dT$ which is on the order of less than 500 PPM at room temperature. Therefore, the temperature dependence of V_{oc} is approximated as

$$\frac{dV_{oc}}{dT} = -\frac{V_g(T) - V_{oc} + \left(3 + \frac{\Gamma}{2}\right)V_T}{T} \quad (15)$$

where Γ is redefined from γ to include the effects of temperature dependence of Isc and bandgap voltage.

The Fill Factor decreases with increasing temperature. The temperature dependence of FF_0 can be approximated assuming that parasitic resistances are not a strong function of temperature along with those assumptions used for the derivation of FF_0. For a special case when the ideality factor is one

$$\frac{1}{FF_0}\frac{dFF_0}{dT} \cong \frac{(1-FF_0)}{FF_0}\left[\frac{1}{V_{oc}}\frac{dV_{oc}}{dT} - \frac{1}{T}\right] \qquad (16)$$

In equation (16), the term $\frac{dV_{oc}}{dT}$ is a negative quantity.

EXPERIMENTS AND DISCUSSION

Experiments were performed using typical AMONIX HCPV cells to define the temperature sensitivity of V_{oc} at various temperatures and concentrations. A one-sun test was carried out using a standard cell (S/N AMNX 1805) at four different temperatures, namely, 25^0, 45^0, 65^0, and 85^0 C. For the temperature range tested, all cell parameters showed linear behavior as exemplified in Figure 4(a) and 4(b) for their efficiency and V_{oc}, respectively. As expected, I_{sc} sensitivity to temperature was below 500 PPM for the temperature range investigated.

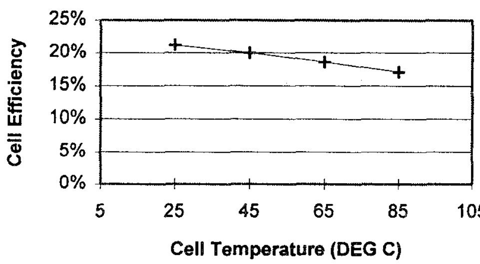

Figure 4 A: One-Sun Efficiency of AMNX 1805 as a Function of Temperature

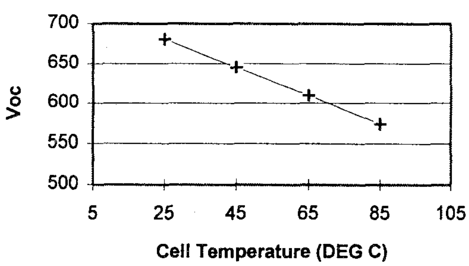

Figure 4 B: One-Sun Open Circuit Voltage of AMNX 1805 as a Function of Temperature

In Table 2, the temperature sensitivity results are summarized. For AMNX 1805 at one-sun, 25^0 C, the calculated values for $\frac{dV_{oc}}{dT}$ and $\frac{1}{FF_0}\frac{dFF_0}{dT}$ using equations (15) and (16) are 1.78 mV/^{0}C using Γ=0.8 and 1107 PPM/^{0}C using v_{oc}=26.52 respectively. In the 65^0 C case for AMNX 1805 at one-sun, calculated values using the same equations are: 1.79 mV/^{0}C and 1284 PPM/^{0}C. They compare favorably with measured values in these cases. The third and fourth columns are for AMNX 40 cell data under 250X concentration (25 W/cm^2 irradiance level).

TABLE 2
Temperature Sensitivity of AMONIX HCPV Cells for a Temperature Range of 25~65^0 C

		AMNX 1805 One-Sun		AMNX 40 250 SUNS	
Para-meter	Unit	25^0 C	65^0 C	25^0 C	65^0 C
V_{oc}	mV	681	610	812	756
$\frac{dV_{oc}}{dT}$	mV/DEG C	-1.76	1.79	-1.40	-1.35
$\frac{1}{V_{oc}}\frac{dV_{oc}}{dT}$	PPM/ DEG C	-2584	-2934	-1724	-1786
I_{sc}	A	4.57 X 10^{-2}	4.66 X 10^{-2}	5.96	6.01
$\frac{dI_{sc}}{dT}$	A/ DEG C	2.23 X 10^{-5}	1.85 X 10^{-5}	10 X 10^{-3}	15 X 10^{-3}
$\frac{1}{I_{sc}}\frac{dI_{sc}}{dT}$	PPM/ DEG C	488	405	168	250
FF	%	78.8	75.4	80.9	76.9
$\frac{dFF_0}{dT}$	%/ DEG C	-0.085	0.095	-0.055	-0.145
$\frac{1}{FF_0}\frac{dFF_0}{dT}$	PPM/ DEG C	-1079	1260	-680	-1886
η (EFF)	%	21.2	18.6	24.1	21.5
$\frac{d\eta}{dT}$	%/ DEG C	.0618	.0725	-0.055	-0.075
$\frac{1}{\eta}\frac{d\eta}{dT}$	PPM/ DEG C	2916	3898	2282	-3488

Figure 5 shows the characteristics of AMNX 1805 under concentration for its efficiency as a function of irradiance up to approximately 25 W/cm^2. The highest efficiency of 26.3% occurred near 100 suns at 25^0 C. At 23.3 W/cm^2 irradiance, the efficiency was 25.3% with a *Voc* of 823 mV and *Jsc* of 8.78 A/cm^2. If it is assumed that the recombination mechanism between 7 W/cm^2 and 9 W/cm^2 irradiance, also between 19 W/cm^2 and 23 W/cm^2, for each interval respectively, pseudo ideality factor, $n_{0,\text{pseudo}}$ values for the intervals can be calculated using

$$n_{0,\text{pseudo}} = \frac{V_{oc,H} - V_{oc,L}}{V_T\left(\ell n\, I_{sc,H} - \ell n\, I_{sc,L}\right)} \qquad (17)$$

where subscript *H* and *L* represent high and low irradiance data for the piecewise intervals. The $n_{0,\text{pseudo}}$ values calculated for 8 W/cm^2 and 21 W/cm^2 irradiance levels are 0.813 and 0.623, respectively, indicating that Auger recombination mechanism is replacing the dominating recombination mechanism at lower current levels.

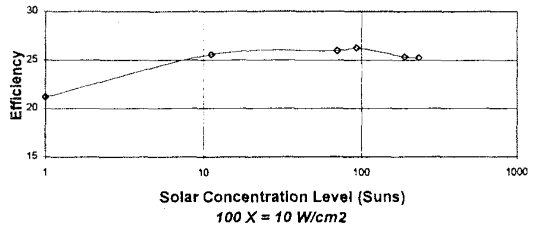

Figure 5: AMNX 1805 Efficiency Data

CONCLUSION

It is apparent from review of the AMNX 1805 data that concentrator applications of the same cell would produce power more efficiently. For a 250X concentrator application, the cell would be approximately 20% more efficient than one-sun applications. Due to the fact that concentrator systems operate at high V_m levels (also high V_{oc}), applying a typical V_{oc} temperature coefficient of -2.0~ -2.2 mV/^{0}C (both crystalline and polysilicon flat-plates), for predicting high concentrator performance severely underestimates the system potential. Instead, a value of -1.3~-1.5 mV/^{0}C should be applied for high-concentration applications.

Also, for silicon (poly and crystalline) flat-plate systems, a -0.4%/^{0}C (4000 PPM) power decrease around 25^{0}C is common [13]. However, for high-concentration cells, the power decrease would be only -0.25%/^{0}C (2500 PPM) around 25^0 C. This represents a significant shift for evaluating high-concentrator system performance.

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Mr. Warren McNaughton of Cornice Engineering provided considerble data and insight to this project [14].

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