TOWARDS COMMERCIALIZATION OF CONCENTRATOR MULTIJUNCTION PHOTOVOLTAIC MODULES

G. S. Kinsey, R. A. Sherif, P. Pien, P. Hebert, R. R. King, and D. Aldrich
Spectrolab, Inc., Sylmar, CA 91342

ABSTRACT

Concentrating photovoltaic (CPV) modules occupy the middle ground between conventional, flat-plate photovoltaics and concentrating solar power (CSP) technologies. CPV promises to deliver the best of both worlds: the highest efficiency of any photovoltaic system combined with the higher capacity factor and scale-up potential of dual-axis tracking systems characteristic of CSP power towers. Having demonstrated cell efficiencies over 40%, the CPV industry has now embarked on an aggressive program to demonstrate cost-effective, highly-reliable CPV modules in the field.

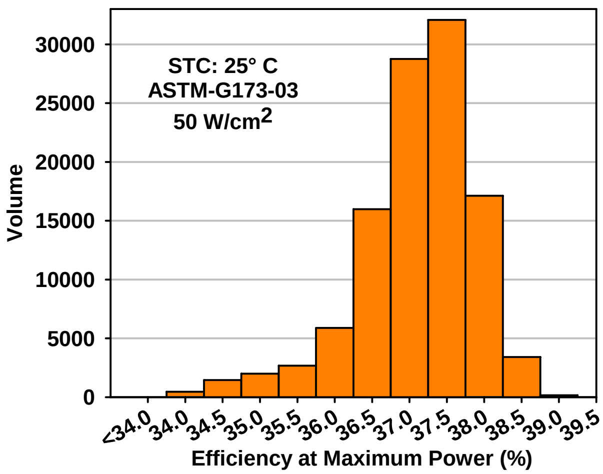

Fig. 1. Performance distribution of C1MJ.

PERFORMANCE

CPV modules have achieved module efficiencies above 28% using multijunction cells that tested in the 35% efficiency range [1],[2]. A 40% cell will allow for module efficiencies above 30% and solar-to-electric efficiencies above 25%. This compares favorably with, for example, a 13% solar-to-electric efficiency for CSP parabolic troughs [3]. Aided by the Department of Energy's Solar America Initiative, Spectrolab expects to have a 40% cell in high-volume (>100 MW/yr) production by 2010. The C1MJ ("Concentrator, 1st Generation Multijunction") introduced in 2007 had an average (mode) efficiency of 37.5% (Fig. 1). Prototype C2MJs, to be qualified in Q3 2008, are projected to have a mode efficiency of 38.5% (Fig. 2).

The measurement of cell performance under a single spectrum, such as AM1.5, is a heritage practice that is more suitable for single-junction cells than it is for multijunctions. The higher efficiency of multijunctions is accompanied by a greater sensitivity to changes in the spectral content. Current practice is to design multijunctions so that the top two subcells have matching current under an AM1.5 spectrum (there is excess current in the bottom subcell). When the spectrum changes, either the top or middle subcell will begin to limit the current of the three-subcell stack.

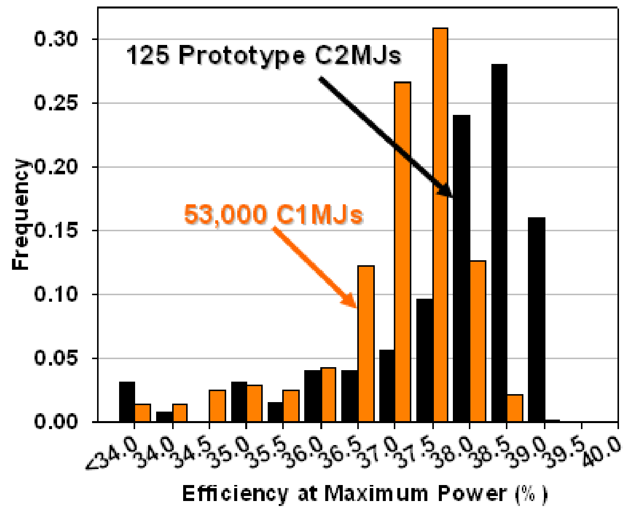

Fig. 2. Prototype C2MJs compared to C1MJs.

Understanding this transition will be critical in going beyond watt-peak power ratings to predicting the energy output (in kW-hr/yr) for modules containing multijunctions. Insight into cell performance under a range of spectral conditions can be gained by analyzing the multijunction quantum efficiency against atmospheric spectral content from the NREL SMARTS atmospheric model.

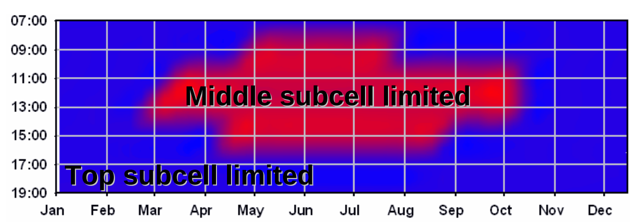

Fig. 3. Annual subcell limitations at the latitude of Phoenix, AZ.

As an example, Fig. 3 indicates subcell current limitations for a C1MJ cell at the latitude of Phoenix, AZ. Sample spectra were produced using the SMARTS model at twenty-four date intervals throughout the year and thirteen time intervals for each day. Comparison with respect to the quantum efficiency of the C1MJ cell provides an indication of which subcell is limiting the multijunction at any given time. As expected, the top subcell is limiting when there is a higher effective air mass.

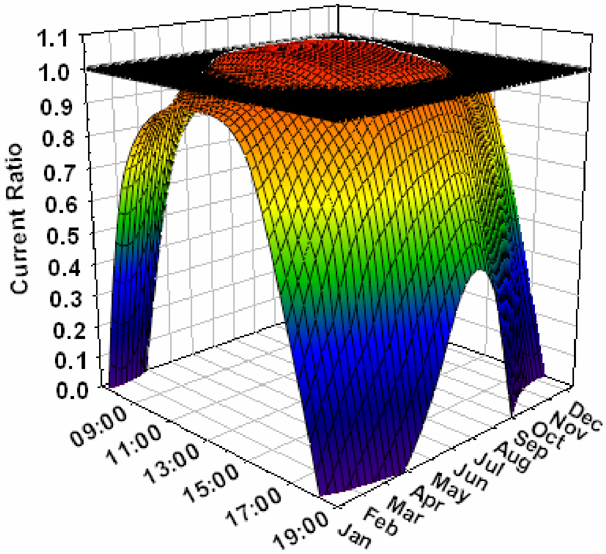

Fig. 4. The expected ratio of the top and middle subcell currents in Phoenix, AZ. The current-match condition for the top two subcells is indicated.

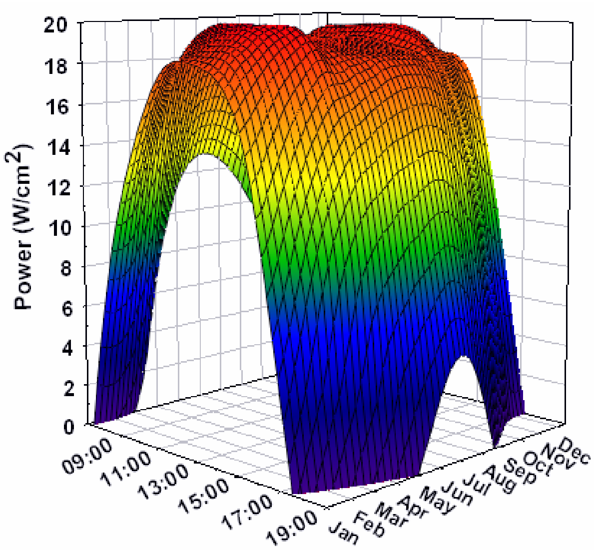

Fig. 5. C1MJ power output in Phoenix, AZ at 25° C. (Assumes clear skies.)

The multijunction cell can be expected to produce the maximum current when the ratio of the current produced by the two limiting subcells is unity. A contour plot of the current ratio (the "J-ratio") of the top and middle subcells is shown in Fig. 4. A horizontal plane is used to mark the current match condition. If the contributions of cell voltage and fill factor are incorporated, this analysis can be used to determine the annual power output of a multijunction cell (Fig. 5). Due to current mismatch conditions, the cell output does not peak in the summer, because the excess current generated in the top subcell is not matched by the middle subcell. Optimum performance occurs in the fall and spring, when the current ratio is closer to unity. The volume under the curve is the annual energy output, which integrates to 65 kW-hr/cm^2-yr. The structure of this contour provides insight into how future structures might be tailored to produce maximum energy in a given location. As data becomes available, these results will be compared against field performance data to confirm the validity of this approach.

RELIABILITY

The rigorous qualification of multijunction cells is a first step in demonstrating the reliability of CPV modules for 25-year operation. The space heritage of multijunction cells includes relevant environmental testing, but more testing is needed to confirm reliability for conditions specific to high-concentration module operation. The C1MJ cell was qualified in 2007 under a qualification schedule based on the IEEE 1513 standard (Table I). The C1MJ passed with margin the criteria required. The recently-released IEC 62108 module qualification standard will be used as the baseline for 2008 qualification of the C2MJ cell design. In addition, test-to-failure results, field data, and feedback from CPV system integrators will be used to expand the qualification in the years ahead in order to assure long-term operation in the field.

One potential vulnerability of multijunction cells that are soldered to a heat sink is the presence of solder voids. In [4], Sherif, *et al*. have shown that the quality of the solder joint between the back of the solar cell and the cell assembly is critical to the survival of the solar cell in a high-concentration environment. The presence of solder voids can lead to thermal runaway and an infant mortality failure of the cell. A specification for the acceptable quantity or size of solder voids has not yet been determined.

Table I. 2007 qualification schedule for C1MJ.

Test	Conditions	Result
Performance	I-V curve @ 25° C & 50 W/cm^2	CDO-080 Eff_{mp} = 37.2% CDO-100 Eff_{mp} = 37.0% CDO-225 Eff_{mp} = 36.5%
Temperature and Intensity	20°, 25°, 45°, 65°, 90° and 110° C under 36, 50, and 59 W/cm^2	$\frac{\partial V_{oc}}{\partial T} = -4.3 \frac{mV}{°C}$
Damp Heat	85% relative humidity at 85° C for 1000 hours	NP_{mp}=0.97
Temperature Cycle	500 cycles in air from -40° to 110° C 10-18 cycles/day	NP_{mp}=0.98
Humidity Freeze	Following temperature cycling exposure, 20 cycles of -40° C to 85° C with 85% RH	NP_{mp}=0.98

Another area of focus is the question of humidity resistance of the aluminum-bearing compound semiconductors. CPV system integrators are experimenting with a variety of polymers on the cell, both for bonding of optical elements and for environmental protection of the cell. Qualification of these materials for long-term operation will be an important milestone in demonstrating the viability of CPV systems in general.

COST

The economic justification for CPV systems arises from cost projections similar to that shown in Fig. 6. When reasonable assumptions are made for the various system costs [5], it is possible to compare the cost downside potential of both flat-plate silicon and multijunction CPV cells. Due to the leveraging effect of cell efficiency in multijunction cells under high concentration it is possible to project a system cost below that achievable by flat-plate silicon PV systems.

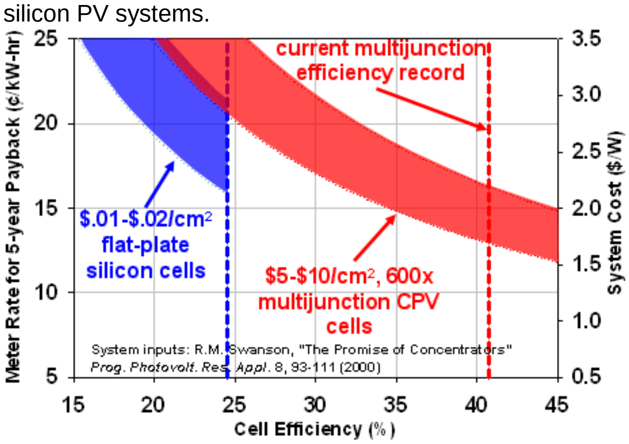

Fig. 6. Comparison of cost of CPV to flat-plate silicon systems. The multijunction cell is assumed to have greater potential for efficiency improvements.

In order to realize this potential, the entire manufacturing process, from crystal growth to cell test, is being overhauled to allow for high-volume, low-cost production of CPV cells. A transition from 100-mm to 150-mm wafers will reduce the per-cell processing costs by increasing the number of cells per wafer by over 2.5x. Back-end processes, currently a dominant cost factor, will be fully automated. Automated cell testers and welders are already in place; these tools will be ganged together in an automated assembly line.

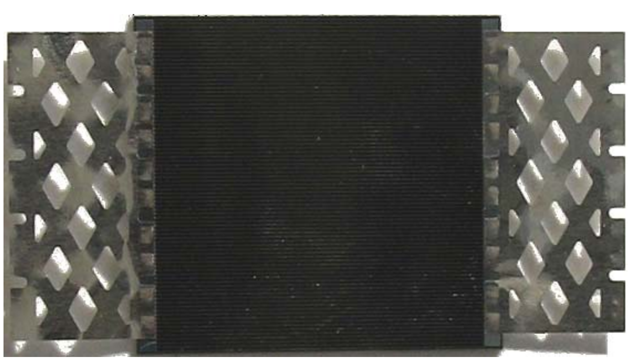

Fig. 7. The CDO-100-IC cell with leads (ICs) attached.

A typical cell produced today is the "CDO-100-IC," which is a cell with a 100-mm^2 aperture area and silver leads ("ICs") attached to facilitate robust module assembly (Fig. 7). The high-volume cost of this cell in 2007 was approximately $0.80/W. Cost reduction activities will reduce the cost to less than $0.35/W by 2010.

SUMMARY

As part of the Solar America Initiative, Spectrolab is embarked on a three-year program to increase multijunction cell efficiency to 40% in high-volume production, demonstrate reliability under operating conditions, and reduce the cost by over 50%. With multijunction CPV modules operating in the field in systems all over the world, CPV will then be poised to make a meaningful contribution to the world's energy supply.

---

[1] J. B. Lasich and P. J. Verlinden, 'Opportunities for Widespread Implementation of Concentrator Photovoltaic (CPV) Systems,' Proc. 4th Int'l. Conf. on Solar Concentrators, March 14, 2007.

[2] R. Gordon, A. Slade, V. Garboushian, 'A 30% (>250W) module using multi-junction solar cells and their one-year on-sun field performance,' Proc. SPIE Conf. Solar Energy & Its Applications, August 26-30, 2007.

[3] www.nrel.gov/csp/troughnet/pdfs/cable_frier_calexpr.pdf

[4] R. Sherif et al., 'The Performance and Robustness of GaInP/InGaAs/Ge Concentrator Solar Cells in High Concentration Terrestrial Modules,' Proceedings European Photovoltaic Solar Energy Conference, June 7-11, 2004.

[5] R. Swanson, 'The Promise of Concentrators,' Prog. Photovolt. Res. Appl., Vol. 8, 93-111, 2000.