

A SOLID 500 SUN COMPOUND CONCENTRATOR PV DESIGN

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ABSTRACT

SolFocus™ is developing two generations of photovoltaic concentrator systems, both based on reflective, Cassegrain – like architectures. Generation 1 is being readied for manufacturing, and is poised for roll out to test fields this year. Generation 2, a solid dielectric system, is under joint development by SolFocus and PARC, with prototype components under evaluation. The status of generation 1 is presented for background, and we discuss technical aspects of generation 2.

GENERATION 1 STATUS

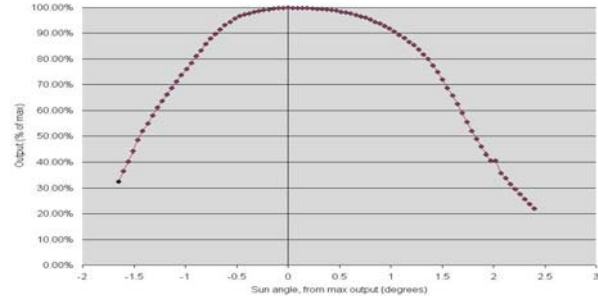
SolFocus has investigated small reflective concentrators as a path to dramatically reduce the cost of solar electricity. The first generation (Generation 1, or G1) product based on this research is being readied for manufacturing at this time, and is undergoing lifetime test.



Figure 1: Generation 1 panel.

Generation 1 is an array of reflective Cassegrain-like concentrators mounted in a compact, robust housing. A single panel produces 250 Watts peak, operates at 500 suns and employs Spectrolab 10mm² terrestrial triple-junction cells. Performance tests indicate that the system operates at approximately 90% of its designed output power, and at 85% of its designed acceptance angle.

The primary design hurdle was the accurate fabrication of the primary mirror. Its size was dictated by the target concentration and cell dimensions, and the most practical manufacturing method was to slump it from a thin sheet of glass in the manner of large truck or locomotive



headlights. After process development, this proved quite satisfactory, producing a specular surface and mainly monotonic errors in profile. In the graph below, the vertical axis is the contour error; the horizontal axis is the distance from center.

Figure 2: Output vs. sun tracking error – an indication of acceptance angle.

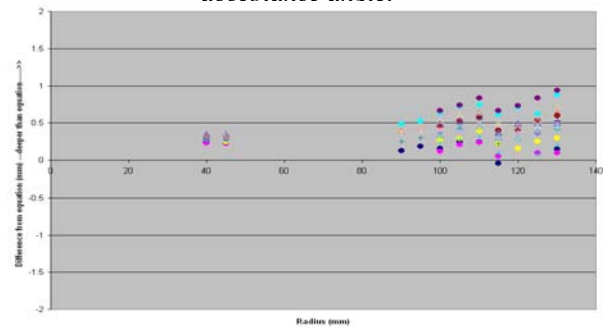


Figure 1: Contour errors, typical G1 primary mirror

The system lends itself well to manual or semi-automated production, and manufacturing has started with a minimum of capital equipment. It can be transferred to a totally automated manufacturing line as is, with no design changes.

Currently, G1 is undergoing reliability related design changes ahead of intense accelerated lifetime testing and a 2MW/p test field rollout.

GENERATION 2 SYSTEM

2nd GENERATION ENABLERS

Two significant technical advances allowed us to revisit certain design compromises made in G1, and SolFocus embarked on the development of a Generation 2 concentrator module in March 2005. An agreement made in November of that year added PARC to the team, and the joint venture is making rapid progress.

The first, triple-junction cells of 1mm², show promise in laboratory and field tests and their price per watt could drop significantly below that of 10mm² cells. These dimensions, though small, are well within the handling capacity of modern electronic assembly lines, and the cells can be sorted, binned, placed and soldered with minimal change to existing equipment. In addition, their small size increases their efficiency, due to lower series resistance and smaller top busbar losses. The smaller cells and proprietary dicing methodology increase wafer utilization, further reducing cost.

An array of concentrators built with these cells will have a more uniform thermal dissipation than G1's discrete 35 Watts per cell, and while the thermal flux in the cell's immediate vicinity will be similar, spreading it for removal is more easily accomplished.

Secondly, glass pressing at optical quality has been established for many years, though at smaller dimensions than required for our application. Demands from new headlight technology as well as the display industry have led to improvements in both quality and size. Several companies can now meet our requirements. A single, pressed sheet of glass that comprises all the optics of a concentrator array will have two significant advantages.

Primarily, it greatly simplifies the overall structure. All optical elements are produced in a single fabrication operation, aligned to the tolerances of the tool and the single process. The "tile" of small concentrator arrays can be easily mated to a receiver subassembly consisting of the cell and thermal management system.

Then there is the increase in concentration for a given optical design that comes from running in a solid dielectric. This can be transformed into a larger acceptance angle by reducing the power of the optics to, in our case, 500 suns. Lower power optics, in general, have higher tolerance to manufacturing variances.

Our analysis concluded that cells of 1mm² illuminated at 500 suns would require an optical system just inside the capabilities of the glass pressing process. In addition, it would produce an optical system with an average glass thickness of approximately 5mm, about the size of a standard window pane. Since the glass is the prime driver in the system's weight, the whole structure would be approximately the same weight as an equivalent sheet of glass.

The G2 photovoltaic module was designed to the following targets:

Characteristic	Value	Notes
Concentration (suns)	500	
Optical efficiency	81%	
Acceptance angle	+/- 1 ^o	For 10% power loss
Overall conversion efficiency	26%	Depending upon cell efficiency
Tile dimensions	280 x 430 x 12mm	A 'tile' is the basic assembly, several integrated into a module
Tile output	30W	1kW/m ² AMI 1.5
Module output	240W	eight tiles

G2 is an array of small reflective concentrator elements in a single housing, not unlike G1, but with the following key differences:

- The optical elements are fabricated in a single glass pressing.
- The optical path is completely within a dielectric
- Optics are of a non-imaging design
- Optical design is approximately 1/10 that of G1, and the cell is 1mm vs. 1cm²

There were four main analytic pathways through the design: Optics, Thermals, Mechanics, and Manufacturing.

Optics

A basic optical design was arrived at that met the above parameters, using an inexpensive, pressable glass. The optic design was then subjected to a Monte Carlo analysis, the variables being the process quality guaranteed by our glass vendor, assembly variations, and tracking errors. The results follow:

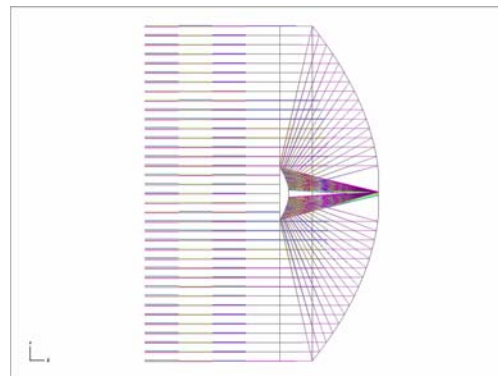


Figure 5: Cross section initial G2 optics

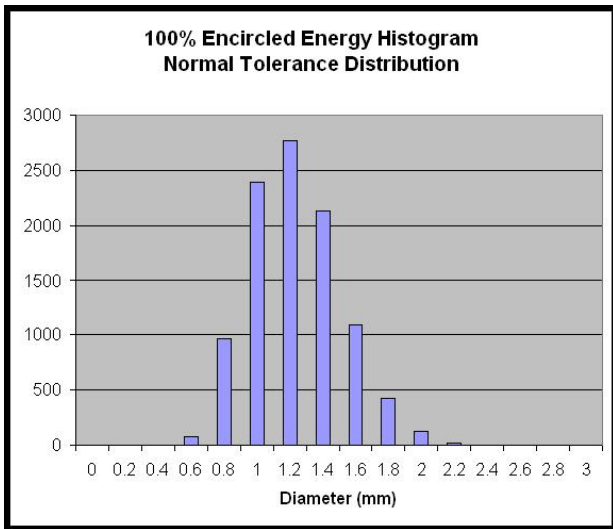
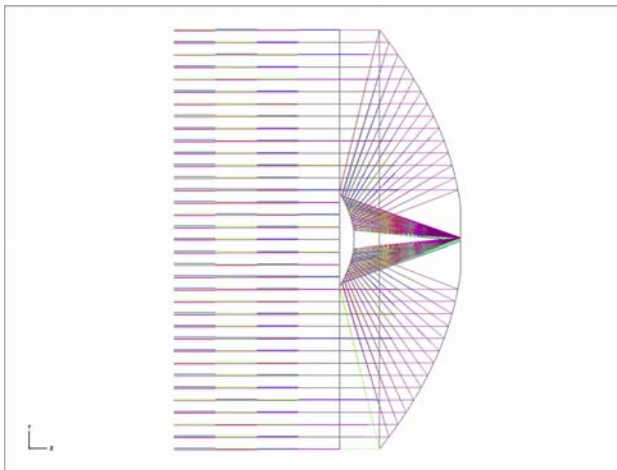


Figure 6: Worst case energy capture, initial G2 optics.

Figure 6 indicates that we would lose significant energy on average. Only 50% of the energy was guaranteed to lie within the bounds of the 1mm cell. While we had added a margin to the vendor's process variation numbers, we decided to redesign the optics.

This took the form of increasing the size of the secondary mirror. This decreased the rate of curvature of this mirror, which would cause smaller deviation to rays that were not "on course" from the primary, due to primary mirror contour errors. The results from the second Monte Carlo



analysis are below:

Figure 7: G2 redesign, larger secondary

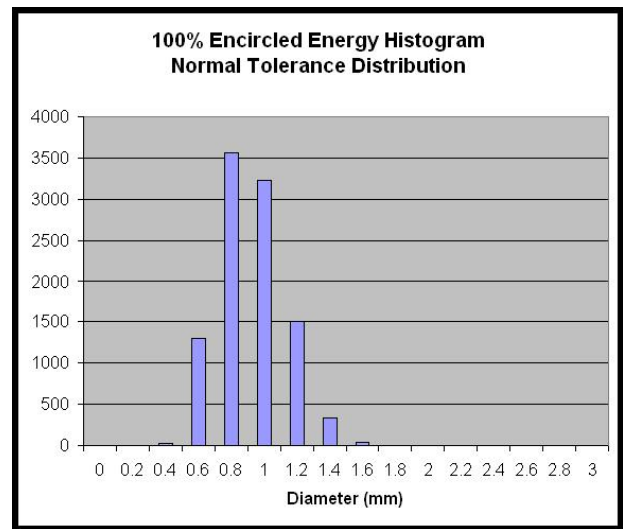


Figure 8: Redesign, worst case energy capture.

With the redesigned system, 90% of the energy is captured within 1mm.

Thermal Management

The first calculations showed that a heat spreading system made from copper could be very thin — in the same order as the 2oz copper planes used in printed circuit boards. This opened the possibility of using a formable surface to spread the heat for removal.

Further FEA analysis showed that there was sufficient surface area on the optical structure that the heat could be removed through the front of the system and radiated, not unlike a flat panel. This is a significant improvement, partly brought about by the small size of the cells.

Accordingly, a conformal heat spreader was designed that spread the waste energy from the cell, over the back side surface of the primary mirror. Final FEA analysis results are below.

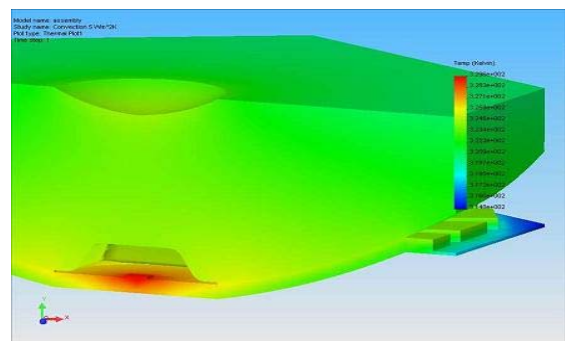


Figure 9: Temperature profile, one cell

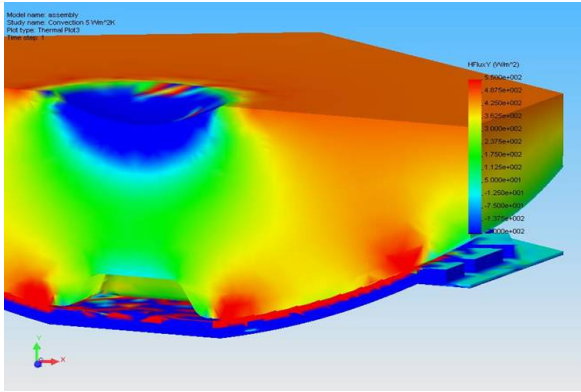
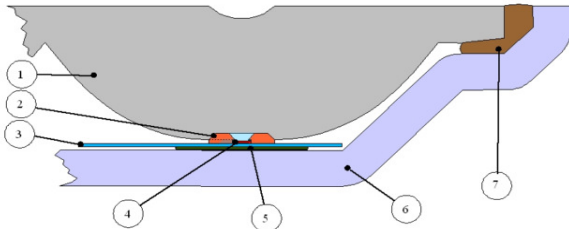


Figure 10: Thermal flux, one cell

Using the above design, the cell will not rise more than approximately 25°C above ambient. With our operating limit set to a maximum of 55°C, the cells will always operate at a highly reliable temperature.

Mechanics

The Mechanics of the system are still evolving. One



approach is outlined below.

The cross section of G2 above shows one concentrator unit, at the edge of the module. The components are:

1. **Solid glass optical assembly**, formed by glass pressing. Mirrors are fabricated by silver sputtering the curved surfaces.
2. **Cell mount**. It aligns and optically couples the cell to the optics, and assists with heat spreading.
3. **Printed wiring substrate**. Aggregates the power output from all the concentrator elements.
4. **Triple-junction cell**.
5. **Thermal transfer layer**. Completes the thermal path from the cell to heat spreader.
6. **Encapsulate**. Tedlar®, used to seal flat PV panels.
7. **Seal**

Manufacturing

The most obvious issue with this approach is that there are vast numbers of cells to be assembled to make significant amounts of power. Generation 2 cannot be built in any volume by hand, or in a semi-automated fashion. It must be introduced to a fully automated, high speed process from first rollout.

While this scale of manufacturing is somewhat daunting, it is not out of line with that of the high volume electronics industry today, and SolFocus is engaging with the companies that have the appropriate experience. These partners will be involved in the design at an early stage, to guarantee the smooth transition from prototype to production.

One of the design goals is that Generation 2 can be assembled on a minimally modified electronics pick and place line, where there is access to vision systems, 6-axis robots and high speed material handling methods. Meeting this goal will ensure a rapid rollout of the system, once reliability has been established.

Costs

Several cost models have been produced, the latest having good agreement to others in the industry.

Module costs over volumes only are summarized in the chart below. These costs do not include trackers or other balance of system items, so they can be compared to the cost of flat panels.

