

NEW ARCHITECTURE FOR UTILITY-SCALE ELECTRICITY FROM CONCENTRATOR PHOTOVOLTAICS

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ABSTRACT

The paper describes a new system architecture optimized for utility-scale generation with concentrating photovoltaic cells (CPV) at fossil fuel price. We report on-sun tests of the architecture and development at the University of Arizona of the manufacturing processes adapted for high volume production. The new system takes advantage of triple-junction cells to convert concentrated sunlight into electricity. These commercially available cells have twice the conversion efficiency of silicon panels (40%) and one-tenth the cost per watt, when used at 1000x concentration. Telescope technology is adapted to deliver concentrated light to the cells at minimum cost. The architecture combines three novel elements: large (3.1 m x 3.1 m square) dish reflectors made as back-silvered glass monoliths; 2.5 kW receivers at each dish focus, each one incorporating a spherical field lens to deliver uniform illumination to multiple cells; and a lightweight steel spaceframe structure to hold multiple dish/receiver units in coalignment and oriented to the sun.

Development of the process for replicating single-piece reflector dishes is well advanced at the Steward Observatory Mirror Lab. End-to-end system tests have been completed with single cells. A lightweight steel spaceframe to hold and track eight dish/receiver units to generate 20 kW has been completed. A single 2.5 kW receiver is presently under construction, and is expected to be operated in an end-to-end on-sun test with a monolithic dish before the end of 2010. The University of Arizona has granted an exclusive license to REhnu, LLC to commercialize this technology.

keywords: utility-scale solar electricity, energy telescope, triple-junction cells, glass reflector dish, spaceframe structure

1. INTRODUCTION

As of 2009, the total solar electricity generating capacity in the U.S. amounted to roughly 2 GW. About 2/3 of this is from flat silicon PV panels, and 1/3 is provided by electric utility systems using glass reflecting concentrators to focus sunlight for conversion to electricity by steam turbines. The installed costs in both cases are around \$5/watt, high enough to be uneconomic without government subsidy. The cost of solar electricity must be brought down to around \$1/watt if it is to compete directly with the energy cost of fossil fuel generated electricity.

By combining the best aspects of PV and focusing systems we have devised a system for which \$1/W is a realistic goal. The basic problem with making solar electricity is that of dilution. Solar energy is free, abundant and carbon-free, but it is widely spread out. Because it takes ten square miles of today's photovoltaic panels to harvest the energy supplied by one coal-fired power station, costs are high. But once sunlight energy is concentrated by focusing optics, it can be inexpensively converted with high efficiency.

The most efficient of any devices made for converting solar energy into electricity are triple-junction concentrator PV cells. They make the conversion directly, with efficiency currently exceeding 40% and rising. When used at 1000x concentration their cost, per unit of energy produced, is ten times less than flat PV panels. They are thus ready to make solar electricity at fossil fuel prices, provided that the equipment to concentrate the light and point at the sun can be reproduced in huge quantities at very low cost, about \$10 per square foot of sunlight collected.

To date, high concentration PV systems incorporating triple-junction cells have captured little significant market share because of expensive concentrating and tracking systems. One cost driver has been the constraint on the concentrating system of maintaining uniform illumination across each cell, and between cells, as needed for efficient series chain

connection cell outputs. Another is the added need to remove heat from the small cells, which would otherwise be quickly damaged under concentrated sunlight. There is also the added cost of pointing the concentrator/cell units at the sun, requiring a two-axis tracker that will be both accurate and survive the highest winds experienced in 20 years of operation.

In present systems, the constraints above are typically met by using many identical, small optical concentrating systems, each one illuminating a single cell. This satisfies the need for uniform illumination from cell to cell, and also results in the individual cells being widely spaced, leaving room for aluminum or copper heat sinks behind and much bigger than each cell, enabling the cells to be cooled passively. The aperture of the individual concentrating optics compatible with this standard architecture is constrained by the need to hold cell temperature rise within reasonable limits when heat removal is by conduction only. For a cell of dimension ℓ operating at concentration C with incident radiation flux I , the input power $IC\ell^2$ may be equated with the heat conduction, approximately equal to $k\Delta T/\ell$ where k is the thermal conductivity and ΔT the temperature difference across length ℓ . Solving for ΔT , we find $\Delta T \sim IC\ell^3/k$, i.e. it is strongly dependent on cell size. Typically cells of 1 cm² square are used at a concentration of 500x, so as to hold the cell temperature to within a few tens of °C above ambient. (The loss of conversion efficiency for triple-junction cells is 4% per 10°C rise). Primary apertures for 1 cm² cells at 500x concentration are ~0.25 m across. Typical concentrators take the form of Fresnel lenses or small Cassegrain reflectors. Variants with cells as small as 1 mm are used in some passively cooled systems, allowing for much higher concentrations consistent with moderate rise in cell temperature. Concentrator/cell/heat sink units are typically made up into modules which function much like flat PV panels: their input is natural sunlight and the waste heat is carried away by natural convection from the back surface formed from the heat sinks.

While simple to implement and operate, such architecture with small concentrators and passive cooling has inherent features that may limit economies of scale for materials, assembly, transportation and field deployment. The architecture requires the manufacture of many small optical and mechanical elements. In the assembly factory, the small cells are placed into module structures whose size is determined by the 500 times larger primary optics. The result is hundreds of small parts that must be accurately aligned within large structures, increasing manufacturing cost. CPV modules are also bulkier than the flat panels they replace, driving up also transportation costs. Another disadvantage is that passive cooling with heat sinks requires large quantities of aluminum, typically 50–100 kg/kW for cooling 1 cm² cells. This translates to an energy payback time of a couple of years for just the aluminum, as well as higher costs. Smaller cells require less aluminum, but a larger number of smaller concentrators. Another disadvantage is that in most systems the modules are typically dead weight in the two-axis tracking structure.

2. NEW CONCENTRATING OPTICAL DESIGN

Our new architecture exploits the efficiency of triple-junction cells by operating them in optomechanical concentrating systems that can be built and installed in very high volume at very low cost. This requires use of the lowest cost materials, steel and glass, configured in the most efficient mechanical structures, manufactured in ways that take best advantage of already well-established methods of mass production. To develop this architecture, we have drawn on the heritage of design and manufacture of astronomical telescopes, going back as far as the first reflecting telescope, made by Newton in 1668. He used a 2.5 cm-diameter disc of polished speculum metal to focus light, rather than a glass lens, as in Galileo's telescope. He also incorporated another advance that we will find valuable. The eyepiece of Newton's telescope is a small convex lens which forms an image of the primary mirror. At this image, which is normally positioned on the pupil of the observer's eye, the illumination is uniform for stars taken over a significant field of view.

In the following 350 years, astronomers have learned how to make much bigger reflectors. The Steward Observatory Mirror Lab, where we are based, makes the world's largest telescope mirrors in the form of round glass discs 8.4 m in diameter. In use, the mirrors are held in an optimized steel tracking structure that points them at the stars with pinpoint accuracy. The faint light of distant galaxies at the focus is converted into electrical current by a semiconductor, just as sunlight is converted into electricity in a photovoltaic solar generator. In the following, we show how the design principles used to optimize telescopes can be applied to solving the problem of low cost solar concentration.

In the new architecture, solar radiation is focused by a single large reflector onto a small receiver incorporating many triple-junction cells. The optical design takes a novel approach to ensuring that all the cells receive equal illumination, independent of pointing errors. Figures 1 and 2 illustrate this approach.

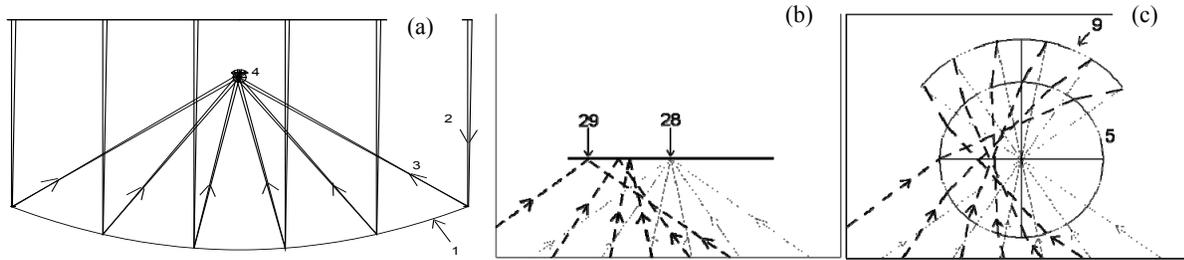


Figure 1. Optical design of large dish-based concentrator. a) paraboloidal primary mirror b) rays at focus for distant source on-axis (28) and off-axis (29) c) rays after inclusion of a ball field lens centered at the focus. Both off-axis and on-axis rays are uniformly distributed across the same concave surface (9).

Figure 1a is an overview showing the large primary mirror and receiver, drawn to scale. (In the prototype to be described below, the primary mirror is a 3.1 m x 3.1 m square paraboloid with 2 m focal length.) Figure 1b is a detail of the paraboloidal focus, showing the very high concentration of light entering along the axis (solid rays, 28) and strongly aberrated for small mispointing error (dashed rays, 29). In the new design, a spherical field lens is placed at the focus, forming a curved image of the primary reflector (9). The light is smoothly distributed across this image, remaining unaffected by small pointing errors. Figure 1c illustrates how the on- and off-axis rays shown in Figure 1b, after refraction by the ball, are now brought to the same points on the curved image surface.

Optically, the reimaging of the primary mirror by the ball lens is very similar to the reimaging of Newton’s primary mirror onto the pupil of the observer’s eye, and the wide field of view of the telescope translates into a high tolerance to mispointing for the solar concentrator.

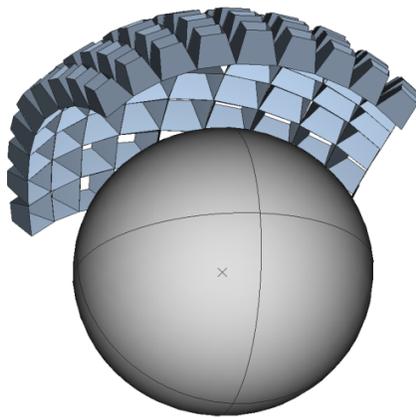


Figure 2. Optical funnels at the concave image surface bring light to an array of separated square photovoltaic cells.

The second aspect of the new optical design is shown in Figure 2. An array of light-reflecting funnels is arranged with their entrances tiling the concave image of the primary reflector. The triple-junction cells are located at the funnel exits. The funnels are shaped so their entrances meet in knife-edges, so no light is lost between gaps, while their exits are separated, leaving room between the cells for electrical connections. The funnels are sized so that all collect the same optical flux. Their exits, where the cells are located, are square and all the same size, to match a standard square cell. The compact configuration including the ball lens, funnels, and cells we call the receiver, and the complete system an “energy telescope”.

3. STRUCTURAL AND MANUFACTURING STRATEGY

The optical design outlined above cleanly separates the two very different sizes of a concentrating photovoltaic system: the large optical apertures needed to harvest dilute sunlight, and the much smaller receivers needed to house the clustered cells operating in highly concentrated light. This separation opens the path to highly efficient manufacture. The large elements, including the structure that supports the reflectors and receivers and points them at the sun, along with the primary reflectors themselves, will be optimized for mass production on a large scale. The small receiver is separately optimized for mass production on a much smaller and completely different production line. The large and small elements will be separately transported to the solar farm, and come together only in the final on-site assembly.

3.1 Mass production of large dish reflectors

The primary reflectors are made of back-silvered reflectors of low-iron glass. This is the type of reflector used in nearly all concentrating thermal systems, where they have proven in the field to maintain high reflectance and excellent longevity. For example, cylindrically bent reflectors of 4 mm thick, back-silvered glass have been in operation in the 350 MW SEGS trough thermal systems in California for almost 20 years, with reflectivity maintained at 94% by regular washing and brushing of the glass. The rate of loss of panels from hail, microbursts, etc. has been only 0.3% per year.

We envisage that in very high volume the dishes will be manufactured at lowest cost when the shaping and silvering processes are incorporated into a dedicated float glass factory. These factories produce float glass continuously in a standard 3.3 m wide strip. For 4 mm thickness, the strip emerges from the production line at a speed of 0.33 m/sec, i.e. 1 m²/sec. We envision that in a modified factory, the hot glass, after hardening, will enter a shaping unit, which will be built in to the production line ahead of the annealing and cooling section. The 3.1 m square dishes will be shaped from 3.3 m squares of hot glass cut every 11 seconds.

Once annealed and cooled, the pristine glass dishes will be immediately silvered. Float glass is already silvered in the mass production of low-e glass for architectural use—each low-e coating incorporates two or more layers of silver around 10 nm thick, deposited in vacuum as part of a multilayer coating with dielectrics. High reflectivity coatings require 50-100 nm of silver. In-line coating processes will be adapted to the rate of one every 11 seconds by using 10 coating lines in parallel. One factory will produce enough silvered reflectors to build 6 GW/year of generating capacity, assuming an overall conversion efficiency of 25% and a flux of 1 kW/m² at direct normal incidence, and that the geometric collecting area of each reflector is 9.4 m² (3.1 m square with 2% central obscuration). We envisage that the reflectors, which weigh 100 kg each, will be stacked 200 at a time for shipment in 20 ton loads from the factory directly to the solar farm site.

3.2 Receiver and active cooling system

Triple-junction cells maintain very high efficiency when operated at concentrations of 1000x and more. We baseline operation at 1000x, when the total cell area required for conversion of energy from a 10 m² primary reflector is ~100 cm². The sunlight is concentrated by the funnels by a factor 2.5, a factor chosen to provide uniform illumination across each cell. Thus the primary image formed by the ball lens must have area ~ 250 cm², in a square about 15 cm on a side. The lens itself of fused silica is 12 cm in diameter. The entire receiver, rated at around 2.5 kW, is thus about the size of a soccer ball. Manufacture and transportation of such compact receivers is optimized quite differently from modules of conventional CPV, which for the same power would need to have the same area as our primary mirror, 10 m².

Each receiver generates twice as much heat as electrical power (around 5 kW if the cells are 33% efficient), which must be removed from the small volume. In our concept, this heat is removed by active cooling with liquid coolant recirculated through a fan-cooled radiator, as in an automobile. While this is more complex than the passive cooling of conventional CPV, because heat is transported by flowing water rather than conduction, the required mass of aluminum is minimized, amounting to around 10 kg/kW in the finned radiator tubes of the active system. The additional 1-2% of the electrical power used by pumps and fans for active cooling is more than offset by the higher output of cells cooled more efficiently than for passive conduction cooling.

3.3 Design of the supporting and tracking structure

Our choice of reflectors that are square and large, 3.1 m on a side, was made not only because it respects the production width of float glass, and is thus likely to lead to the lowest production cost per unit area, but also because such square reflectors lend themselves to a very efficient supporting structure, namely a spaceframe made with square cells. The 3-dimensional form of the spaceframe provides the highest stiffness for given mass, and also naturally provides stiff nodes to support both the reflectors and the receivers above.

In our structural design, shown in Figure 3, the spaceframe takes the form of two offset rows of cubes, linked by angled edge struts that complete a prism structure of hexagonal cross section. The internal structure formed by the struts has three planes intersecting at an extremely stiff central axis passing through the center of gravity. The elevation bearings are located at nodes along this axis, and the elevation drive arc is held from adjacent perimeter nodes of the spaceframe. The two-axis mount is completed by an azimuth truss and drive wheel that turns about a fixed pedestal.

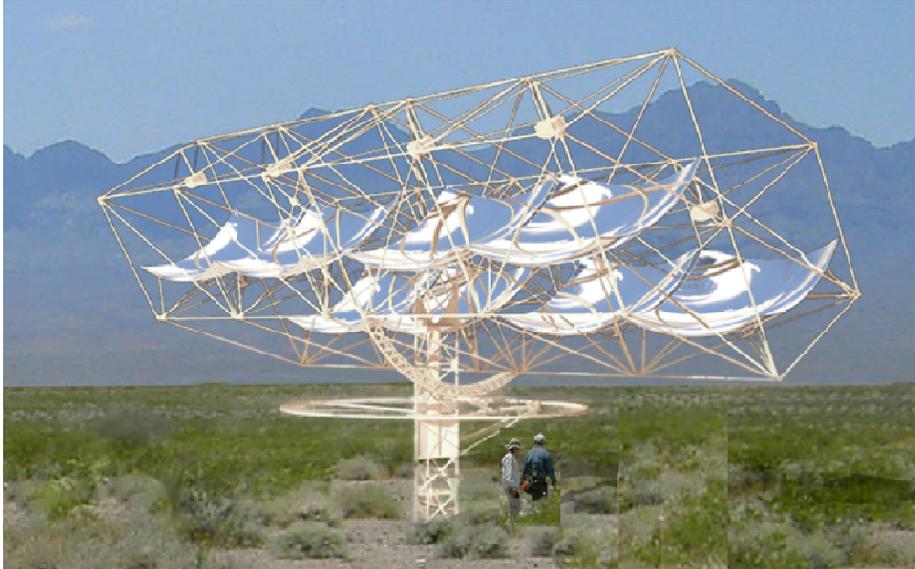


Figure 3. Artist's rendition of a generator built according to the new architecture, with eight large square dish reflectors and associated receivers above supported by a lightweight steel spaceframe.

spaceframes weighing three tons will be driven out into position in the solar farm, to be picked up by a waiting crane and set onto the pedestal and azimuth bearing, already in the ground.

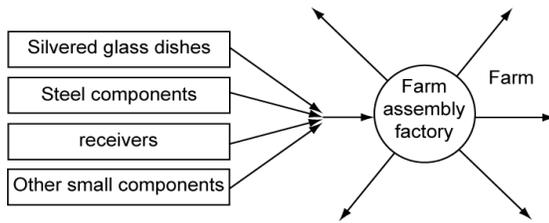


Figure 4. Schematic for assembly at the solar farm

The assembly and installation will be highly mechanized in the case of large installations. Thus a 1 GW farm comprising 50,000 20 kW units can be built in 2 years, given an installation rate of 3 units per hour, 24/7.

3.4 Assembly and deployment

The large and small scale components will be delivered separately in containers to an assembly factory located at the center of the large solar farm under construction (Figure 4). The large components include the silvered glass dishes, the steel struts of the large spaceframe, and the pedestal trusses. The small components include the receivers, cooling radiator assemblies, and inverters. In the assembly factory the spaceframe structures will be made from the struts, and the reflectors and receivers installed. The loaded

4. MANUFACTURING DEVELOPMENT AND TESTS RESULTS

Of all the components required for this disruptive new architecture, only the triple-junction concentrator cells are available through the current CPV supply chain. The other major elements are new and are being designed for rapid and low cost manufacture. The designs and manufacturing methods are being developed and tested at the Steward Observatory Mirror Lab. In the following, we report on progress in the methods for shaping large, deep dishes, making the concave receivers, and constructing the spaceframe trackers. We also report on already completed end-to-end tests, in which a segment of the full-sized reflector is imaged on to a single triple-junction cell, with a secondary reflector to provide the full 1000x concentration.

4.1 Large Reflector manufacture

The Steward Observatory Mirror Lab is developing a new deep-dish shaping process suitable for later incorporation into a float glass factory, as described above. The bending procedures in common use for CPV and CSP to shape large flat sheet of glass into cylindrical or mildly dished glass segments are not suitable for shaping large sheets into the deep, two-dimensional curve we need, thus a new process is being developed. We first performed tests on a smaller scale,



Figure 5. 2.5 m in diameter solar reflector prototype, with segments shaped from 4 mm thick float glass.

with meter-sized segments of paraboloids shaped on full-body molds and used to assemble paraboloids. Figure 5 shows a 2.5 m diameter reflector of 1.5 m focal length made from segments shaped and silvered at the lab. Another segmented reflector of 3 m diameter was also made and used in tests described below.

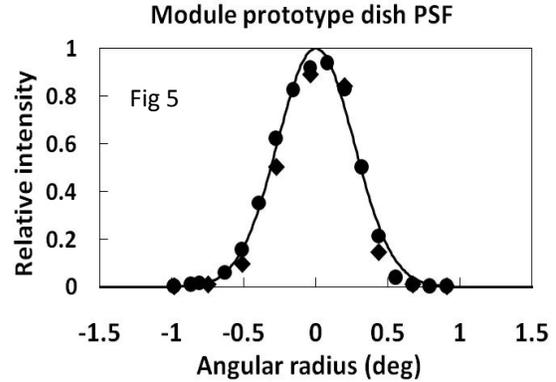


Figure 6. PSF of an image of the moon formed by a segmented 3 m diameter solar dish.

4.1.1 Energy concentration by a 3 m diameter, annular segmented reflector.

The point spread function of an annular, segmented 3 m dish of 1.5 m focal length was measured directly with a photometer at the paraboloid focus (using the moon for convenience). The data in Figure 6 show the full width at half maximum 0.7° FWHM, with 99% of the reflected energy in 1.65° (40 mm) diameter. A focus of this quality gives high tolerance to wind buffeting and flexure, as shown in Figure 11 below. The optical quality of the monolithic primary, replicated by a similar method, is expected to be superior, due to improvements in the molding procedure.

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4.1.2 Manufacture of a single-piece 3.1 m square dish



Figure 7. Shaped, uncoated dish 3.1 m square made at the University of Arizona Mirror Lab.

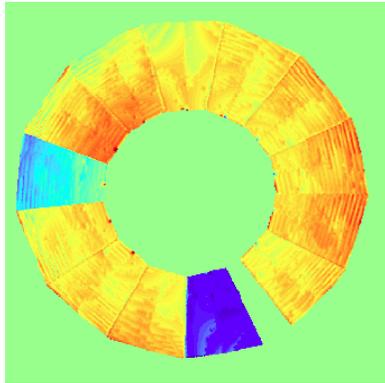


Figure 8. Slope errors in the 3 m paraboloidal segmented solar dish measured by the SCOTS test. The surface slopes represented are 20 mrad. p-v.

SCOTS test (Peng et al. 2010). Figure 8 shows the surface slope map of the 3 m segmented annular mirror whose energy concentration was shown above in Figure 6. The detailed surface map shows misalignment of two of the segments.

4.2 Receiver manufacture

A receiver designed to yield 2.5 kW DC from the focused light of the 3.1 m square reflectors is now being manufactured at the Mirror Lab. It uses triple-junction cells from Spectrolab. A continuous curved copper shell with flat facets on the concave side is used to mount the flat cells. Copper wires routed around the cells carry the photovoltaic currents. Some wires run to the edges of the cell array, passing between the gaps between the reflecting funnels. Processes to replicate the complex copper shells and the funnel reflectors have been developed at the Mirror Lab, and are being used in the manufacture the first full receiver (Figure 9).

Heat from the cells is conducted through the copper shell to the concave face, where it is carried away by liquid coolant. For the

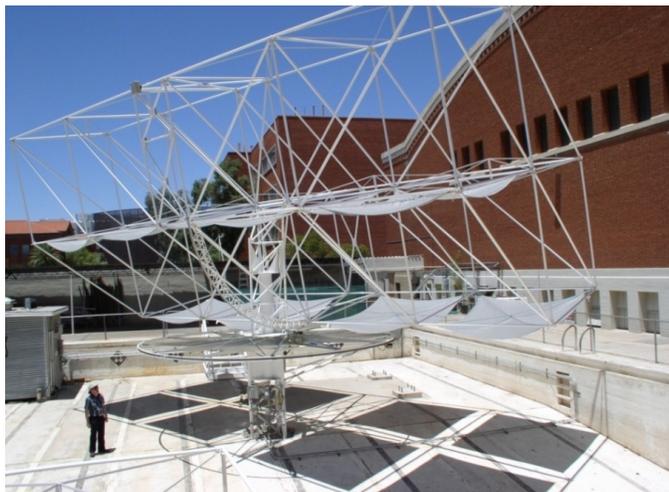


Figure 10. Prototype tracker designed to hold eight reflectors and receivers.

Our effort is now focused on the process to shape 3.1 m reflectors in one piece. Figure 7, above, shows a 3.1 m square glass dish, shaped from a flat float glass sheet in a customized furnace at the Steward Observatory Mirror Lab, at the University of Arizona. This piece was freely formed by heating and softening. The four corners were held in the furnace by hinged supports which prevent wrinkling by forcing the glass to stretch as it sags. Currently, a large, full body mold is being manufactured, and will be placed in the furnace under the present support frame, so the sagged and stretched glass will touch the mold and take on the precise paraboloidal shape, as demonstrated in the segment formation.

The full-sized reflectors will be optically tested from their center of curvature by a new method developed at the University of Arizona specifically for solar dishes. Test methods developed previously for large precision astronomical mirrors are intolerant of large slope errors and cannot be used for solar mirrors. The new test provides both very high spatial resolution over the full dish surface, and is tolerant to surface slope errors of many arc minutes. The new method is called Software Configurable Optical Test System, or the

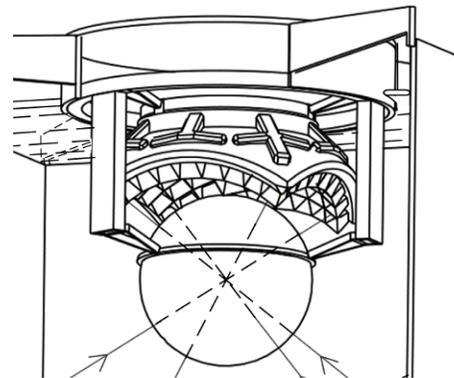


Figure 9. Receiver configuration with ball lens and secondary reflectors.

present prototype, the coolant pumped across the back of the cells is circulated through a finned radiator, using technology already mass produced in huge volume for cooling automobile engines. The parasitic power used for the pump and fan in the present system is 50W, 2% of the receiver power output. This loss will be reduced to 1% by using custom designs optimized for mass production.

4.3 Spaceframe tracker

Figure 10 shows a prototype spaceframe tracker awaiting installation of mirrors and receivers at the Steward Observatory Solar Lab

on the University of Arizona campus. Square tarps have been installed in place of the mirrors, and the pointing stability in wind is being tested. The regular shadow pattern of the tarps shows that the structure is oriented to the sun.

The total mass of steel in this completed unit, including the foundation post and mirror support frames (not shown), is 1940 kg. The total mass of the completed generator, including reflectors, receivers and radiators will be 3250 kg. Given the 20 kW output, the specific masses are 100 kg/kW for steel and 160 kg/kW total. The foundation is set in broken rock; no concrete is used anywhere in the system.

4.4 End-to-end tests at the sub-system level

Since there is a one-to-one correspondence between each cell and the section of the dish reflector surface imaged onto that cell, a realistic end-to-end test of performance can be made using a prototype made as a section of the full scale optical system. In our test, sunlight reflected from a 0.5 x 0.5 m segment of a 3 m, f/0.5 primary mirror was imaged by a 100 mm diameter ball lens onto the entrance of a single secondary reflector. The secondary reflector output falls on a 15 mm square Spectrolab triple-junction cell at 980x geometric concentration. The test cell was mounted on a BeO substrate with high thermal conductivity, and actively cooled with the same thermal coupling as the multicell receiver under construction.

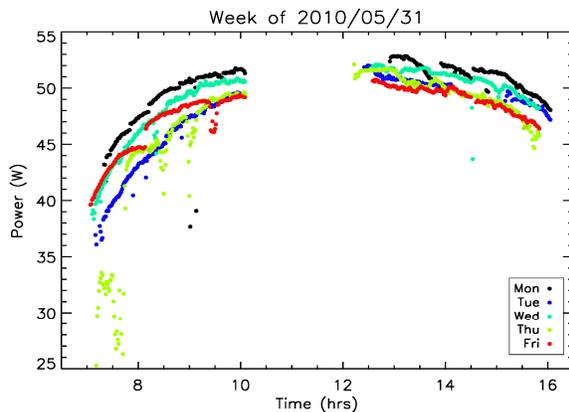


Figure 11. Power from a single 15 mm triple-junction cell at 980 x concentration in an end-to-end test

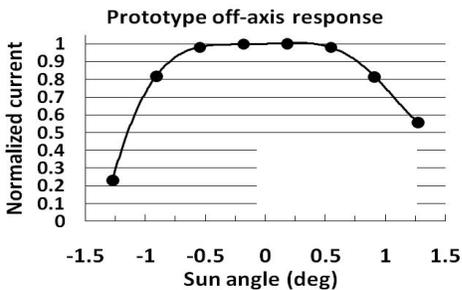


Figure 12. Current as a function of off-axis pointing angle for single cell prototype

The power from the single 15 mm cell peaks typically above 50 W, as shown in Figure 11, and the end-to-end peak efficiency is 25%. The Spectrolab triple-junction cell, not optimized for 1000x, is rated at 33% efficiency at the 60°C operating temperature. Improvement of overall efficiency to close to 30% is expected by use of better optimized cells and improved optical coatings for the reflectors and ball lens. The active cooling system works well, resulting in a cell temperature (derived from the I-V curve) of less than 20°C above ambient air temperature.

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The sensitivity of the system to mispointing is shown in the measurements of Figure 12, giving the current into a fixed load as a function of measured pointing angle. The current remains at more than 90% of its peak for mispointing angle up to 0.75°, verifying that the imaging concentrator has high tolerance to mispointing, even at 1000x concentration.

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