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# PERFORMANCE TESTING AND QUALIFICATION OF SANDIA'S THIRD BASELINE PHOTOVOLTAIC CONCENTRATOR MODULE

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## ABSTRACT

Sandia designed, built, and tested prototypes of a new photovoltaic concentrator module, the Sandia Baseline Module 3 (SBM3). The SBM3 is intended to be a high-efficiency module that can be readily adapted for commercial production. It consists of a 2 by 12 parquet of lenses arranged with 24 cells in an aluminum housing. The geometric concentration ratio is 185. The cells were made at the University of New South Wales and employ prismatic covers designed by ENTECH. The module features a new concept in cell assemblies in that the cells are soldered directly to a copper heat spreader, eliminating the expensive ceramic wafer and heat sink that have been used in previous designs. Electrical isolation was accomplished by anodizing and electrophoretically coating the aluminum housing. Lessons learned during construction and testing of the SBM3 are presented, along with the outdoor performance characteristics of prototype modules and results from qualification testing.

## INTRODUCTION

Many advances in photovoltaic (PV) concentrator module technology have occurred over the last several years. New concentrator cells have been developed at the University of New South Wales and Stanford. ENTECH adapted their highly-successful prismatic cover design, which they use on their low-concentration line-focus modules, for use in higher-concentration point-focus modules. Improvements in soldering technology at Sandia allow cells to be soldered directly to copper. New methods for electrically isolating the circuits promote good heat transfer and eliminate the need for heat sinks. In addition, a number of projects are currently underway to reduce the cost of optical components.

For these advances to result in decreased cost and increased reliability of photovoltaics, they must be incorporated into the design and production of commercial modules. To accelerate this process, Sandia designed a new photovoltaic concentrator module, the Sandia Baseline Module 3 (SBM3) (Figure 1). The SBM3 combines advances in cells, cell assemblies, and electrical isolation techniques to produce a module that can be readily adapted for commercial production. We made the design available to manufacturers interested in commercially producing the SBM3 or similar designs. Alpha Solarco adopted the basic design and is currently producing modules, and several other companies, including SKI, are also adapting the design for commercial production.

At the 20th IEEE Photovoltaic Specialists Conference (PVSC) the basic design was described and a rough cost analysis presented [1]. This paper presents the results from performance characterization and qualification, along with the lessons learned during construction and testing of prototype modules.

## DESIGN SUMMARY

The overall objectives of the SBM3 project were to combine recent technology advances into a design that could be adapted for commercial production and to transfer the technology to the PV industry. We decided to use an existing lens because of the long lead-times associated with designing and obtaining a new lens. Although the SBM3 is not optimized for cost or performance because of our limited lens selection, it successfully demonstrates the advances in module

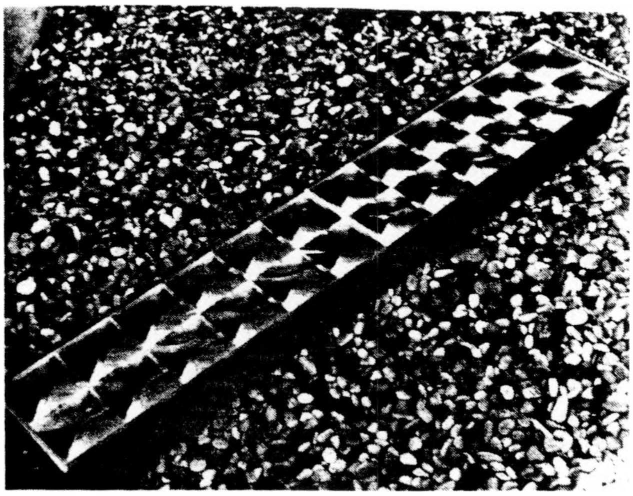

Figure 1. Sandia Baseline Module 3.

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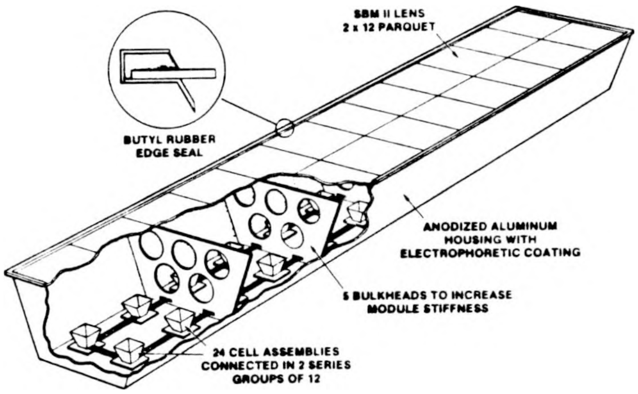


Figure 2. Artist's Conception of SBM3.

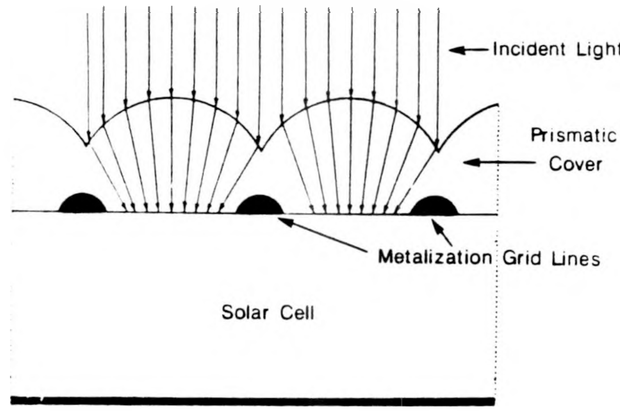


Figure 3. Prismatic Cover Refracts Light Away from Gridlines.

technology. The basic design can be easily adjusted for new lenses to optimize the cost and performance.

Figure 2 shows the basic components of the SBM3. It consists of 24 square lenses (17 cm on a side) and 24 square cells (12.5 mm on a side, active area), giving a geometric concentration ratio of 185. The housing is made of specially coated anodized aluminum (1-mm thick) and measures approximately 37-cm wide by 207-cm long by 21-cm deep. The module features a new concept in cell assemblies in that the cells are soldered directly to copper heat spreaders, eliminating the expensive ceramic wafer that has been used in the past. The heat spreaders act both as the bottom cell contacts and as a means to transfer heat away from the cells. The heat spreaders are attached directly to the housing with a thermally conductive adhesive. The lens parquet is positioned in a channel in the housing and sealed with an ultraviolet-stabilized butyl rubber. The module efficiency goal was 20% with an output of 140 W at standard peak conditions.

The housings employ a technique that has not been used before in photovoltaic modules. The aluminum housings are first anodized and then electrophoretically (EP) coated with a high-temperature acrylic, leaving a thin (50 $\mu$m) electrically isolating layer capable of withstanding 3000 volts [2]. No additional electrical insulation between the electrically-live heat spreader and the housing is required, thereby enhancing heat transfer and, in combination with the copper heat spreader, eliminating the need for a separate (expensive) heat sink.

The optical system uses the point-focus Fresnel lens developed for the Sandia Baseline Module 2. A reflective secondary optical element is installed on each cell assembly to improve the uniformity of the flux profile and provide tolerance to tracking errors. The secondaries are cut from polished anodized aluminum, bent into shape, and attached to the upper cell interconnects with an adhesive. They have a reflectivity of about 82%.

The cells were designed and made at the University of New South Wales (UNSW) and incorporate some of the recent advances in concentrator cell technology, such as light-trapping microgrooves, surface passivation, double-layer anti-reflective coating, and a thin low-resistivity base. ENTECH designed a prismatic cover for the cells, allowing us to increase the metallization grid coverage on the front surface of the cells to 15% from the 6% that is optimum for bare cells, thereby reducing series-resistance losses in the cells and at the same time capturing light that would otherwise be reflected off the grid lines (Figure 3). The projected efficiency for the cells with prismatic covers was about 24%; we achieved 24.3% on one of the first cell assemblies to have a prismatic cover applied and achieved 25% on subsequent cell assemblies [3].

We also experimented with another type of cell, designed and made at Stanford University. These cells are based on an extension of the point-contact cell technology developed at Stanford, but with contacts on both the front and back side of the cells to facilitate conventional cell mounting. They have a thin high-resistivity base, use inverted pyramids for light-trapping, and have grid lines located on ridges so that most light striking the grid lines is reflected onto the cells. They do not require prismatic covers. These cells were not incorporated into any module prototypes because of difficulties in soldering them. However, once the cell metallization is perfected they would certainly be a viable option.

The cell assembly design for the SBM3, shown in Figure 4, was described at the 20th IEEE PVSC [4]. Basically, it consists of a concentrator cell soldered to a copper heat spreader, which also acts as the bottom cell contact. The top cell contact is also copper and supports the aluminum secondary reflector. We achieved a record PV module efficiency of 20% with SBM3 cell assemblies [5]. They represent the first successful use of solar cells soldered directly to copper.

## TEST RESULTS

Many experiments have been or are being conducted in the course of this project, including extensive indoor testing of cells and cell assemblies, outdoor lens-cell tests, lens-sealant tests, cell metallization and adhesive evaluations,

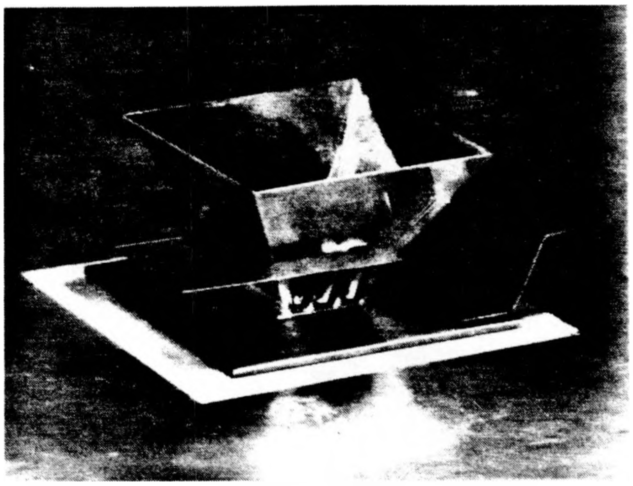

Figure 4. Cell Assembly for SBM3.

and high-voltage breakdown tests of electrophoretic coatings, as well as performance characterization of modules and qualification of cell assemblies and modules. Many of the experiments are applicable to PV concentrator module technology in general, not just the SBM3. Some of them are documented in an earlier report [1]; only those conducted since will be included in this paper.

Design Testing

Prismatic Covers. During lens-cell testing we discovered a problem with the prismatic covers. Although indoor flash testing showed cell assembly efficiencies exceeding 25%, the efficiencies were much lower under a lens. Subsequent evaluation identified the problem to be prismatic covers that were too thick. If the covers are too thick, they have acceptance angles that are too narrow to accommodate all the incident light from a lens. It turned out that the existing process used to mold the prismatic covers and glue them to the cells could not be modified to produce thinner covers. Sandia and ENTECH then developed a process to mold the covers directly to the cells. The new process, while extremely time-consuming at the prototype level, has great potential for automating the application of prismatic covers to cells, improving their performance and decreasing their cost.

Considerable development work remains, however, as the yield of acceptable prismatic covers at the prototype level was only about 50%. There are still a number of issues that remain unresolved, such as surface quality, deformation, and dust attraction.

Electrophoretic Coatings. Electrophoretic coatings have been used for many years for corrosion protection of items such as automobile wheels, but have only recently been developed for high-voltage-isolation applications. Initially we had difficulty obtaining coatings that had consistently good (above 2200 V) standoff, but as we refined the process and incorporated some quality control measures (such as filtering the EP solution before application and applying the coating in two or more layers) we were able to obtain coatings that had no breakdowns below 2200 V.

Under contract to Sandia, Russ Sugimura, Gordon Mon, L. Wen, and Ron Ross of JPL conducted corona-inception tests on samples of anodized aluminum that had been EP coated [6]. Their test results parallel Sandia's experience in EP coating large module housings.

Early JPL results on small (2-in by 2-in) samples were inconsistent. While some tests showed good voltage standoff capabilities in the 2500 to 3000 V range, there appeared to be flaws in the coatings, causing breakdown at unacceptably low voltages in some locations on the samples. More recent tests on a new 12-in by 12-in sample have shown good results. Thirty different points on the sample were tested. Corona inception (defined as the voltage at which a 5-pC discharge is detected) began at 2500 V or higher, and breakdown occurred no lower than 3000 V for all points.

Some hi-pot failures did occur, however, on a module subjected to the qualification tests, so some further refinement of the EP coating process is still required. The failures were probably due once again to quality issues, rather than the technology itself.

Performance Characterization

Experimental Module. As stated above, we chose to use an already existing lens to reduce lead time on the SBM3 project, thus forgoing optimization of the lens. The lens that we used did not have the optical efficiency necessary to achieve a 20% module efficiency with the UNSW cells. So, in addition to building SBM3 prototypes, we assembled an experimental module with 12 SBM3 cell assemblies and higher-quality lenses to demonstrate 20% efficiency [5].

Four-Cell Module. Before testing full-size (24-cell) modules, we assembled and tested outdoors a four-cell "mini-module." The purpose of this module was to verify the overall module design and uncover any unforeseen problems before building full-size modules. The mini-module had the same cell assemblies as the SBM3 and similar optics, the only differences being that the lens was coated with magnesium fluoride and the secondary reflectors were coated with silver to reduce reflection losses. The results are given in Figures 5 and 6. The efficiency of this module was about 19% at a direct normal insolation (DNI) of 800 $W/m^2$ and 25°C cell temperature. Extrapolating the data to 1000 $W/m^2$, the efficiency is around 18%. At $\pm 1°$ off-track, the output is 90% of on-track; at $\pm .5°$ off-track it is 95%.

Full-Size Module #1. After testing the four-cell mini-module, we assembled and tested the first full-size (24-cell) SBM3 prototype. The purpose of this module was to provide a prototype for qualification testing and to give us some practice in assembling a module before we used our best-performing cell assemblies. The cell assemblies used in this module, while functional, were essentially rejects (based on indoor flash testing) and were not matched for current. They had an average indoor efficiency of about 22% at a concentration of 125 suns; a few were much lower. The efficiency of this module as a function of DNI is given in Figure 7.

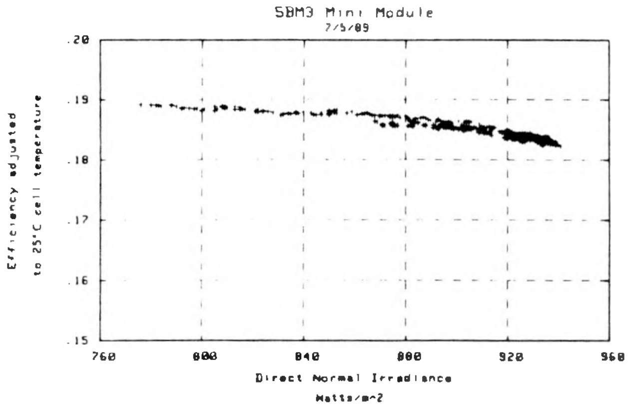


Figure 5. Efficiency vs. DNI for Four-Cell SBM3.

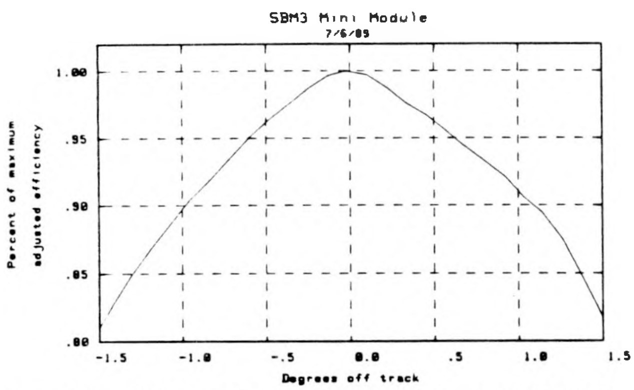


Figure 6. Off-track performance of Four-Cell SBM3.

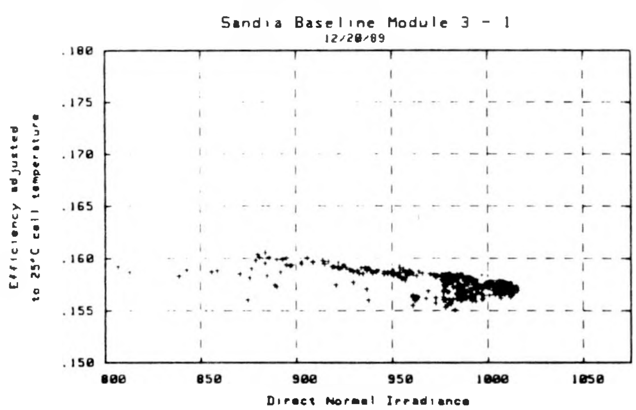


Figure 7. Efficiency vs. DNI for Module #1.

Twelve-Cell Module. Before testing the second full-size module, we tested a half-module containing 12 cell assemblies. These 12 cell assemblies were the same ones used in the 20%-efficient experimental module; the main purpose of this test was to provide a comparison between the two modules. The results are shown in Figure 8.

Data for this module was obtained only for DNI levels around 1000 W/m², and any extrapolations to 800 W/m² would not be meaningful. At 1000 W/m², the efficiency (adjusted to 25°C cell temperature) is about 17%. This compares to the extrapolated efficiency of 18% for the four-cell module and 20%-

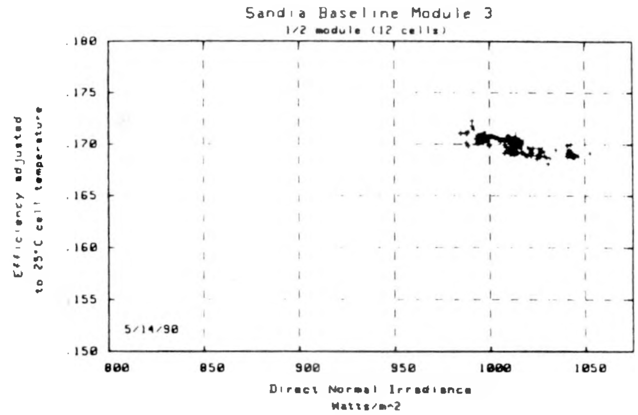


Figure 8. Efficiency vs. DNI for 12-Cell SBM3.

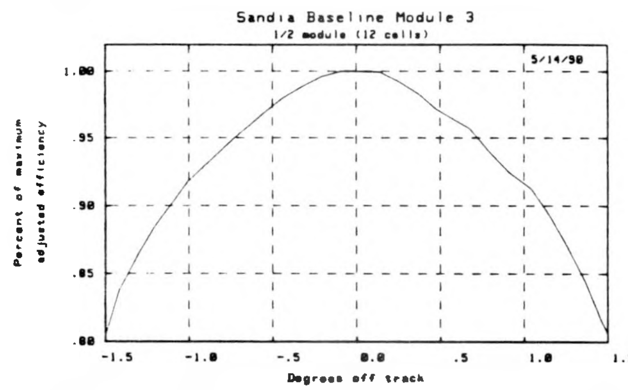


Figure 9. Off-track performance of 12-Cell SBM3.

efficiency of the experimental module with the same cells (at 1000 W/m²).

We also conducted an off-track test on this module; the results are shown in Figure 9. This module performed slightly better than the four-cell module on this test.

Full-Size Module #2. Figures 10 and 11 give preliminary efficiency and off-track data for the second full-size module. The efficiency results were somewhat disappointing given that we used the best available cell assemblies, including the 12 from the 20% experimental module. The cell-assembly efficiencies averaged about 24% (as measured by indoor flash testing at 125 suns) and were matched for current in lens-cell tests. The module efficiency at 1000 W/m² was about 16.7%, and the data imply (by extrapolation) that the efficiency would be about 17% at 800 W/m². Considering that the first full-size module had an efficiency of 16% with much lower-efficiency cells that were not matched for current, we would expect a much better result. We are conducting additional tests on this module to determine the reasons for its low performance. Possible explanations include soiled or degraded optics, prismatic cover deficiencies, or a bad cell.

Cell Operating Temperatures. Cell operating temperatures are an important consideration in both flat-plate and concentrator modules because cell efficiency generally decreases with increasing

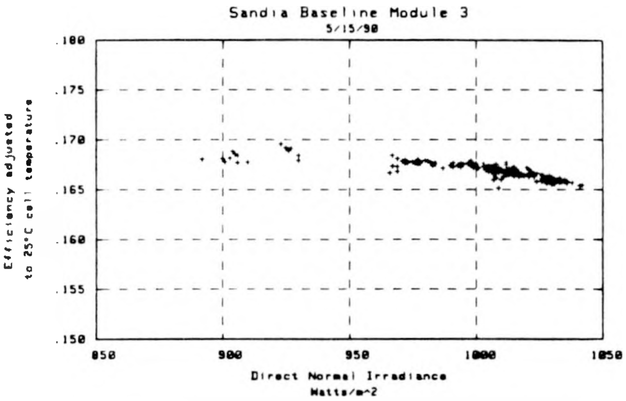


Figure 10. Efficiency vs. DNI for Module #2.

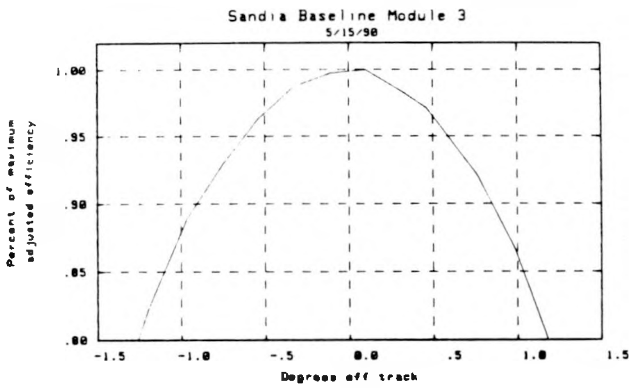


Figure 11. Off-Track Performance of Module #2.

temperature. The SBM3 design was optimized for energy cost, trading off cell temperature (and therefore efficiency) against the cost of additional heat removal capability. Two different adhesives were used to mount the cell assemblies in the two full-size modules. Module #1 used a liquid, thermally loaded, silicon RTV, which probably resulted in fewer voids (air bubbles) than the acrylic sheets used in Module #2. Module #1 operated about 10°C cooler than Module #2 (the average cell temperature was calculated from the open-circuit voltages and corrected for differences in ambient temperature). In both cases the cell operating temperatures were slightly higher than 65°C, the design temperature calculated in the computer design analysis. This indicates that the copper heat spreaders should possibly be made larger or, more likely, that more attention should be given to the adhesive layer between the cell assemblies and the module housing.

### Qualification Testing

The full-size SBM3 prototypes are currently being subjected to the standard Sandia qualification tests for concentrator modules [7]. Module #1 has been subjected to all the tests except rain and hail testing; it is currently undergoing the post-humidity freeze-cycling characterization (the lens itself passed the hail test in a previous module). Module #2 is currently undergoing pre-test characterization.

Module #1 has suffered two failures during qualification so far. Although it passed the initial hi-pot tests, it failed the one that is required within one hour of humidity/freeze cycling (when the module is wet inside). The failure occurred at 750 V. After the module was allowed to dry out for a few days, the test was repeated, and failure occurred a second time at 1250 V. The failure is probably due to quality control in applying the EP coating, although it is conceivable that the EP coating degraded during thermal- and/or humidity/freeze cycling. The failures demonstrate that some more development is probably needed to commercially produce high-quality EP coatings on PV module housings.

The other failure of Module #1 occurred in the lens seal. This seal design previously passed the qualification tests with no failures. The failure was apparently due to a defective batch of butyl rubber combined with careless application, illustrating once again the importance of quality control.

SBM3 cell assemblies passed the separate series of tests required for cell assemblies; they survived more than 1000 thermal cycles although the tests currently require only 250.

## CONCLUSIONS

The major goals of this project have now been met: commercially producible, high-efficiency modules incorporating recent technology advances have been designed, built, and tested. The technology has been transferred to and adopted by industry. The test results were mostly favorable; the few test failures can be corrected with minimal further development of the processes, and we expect to continue to see improvements in efficiency as the technology evolves.

## ACKNOWLEDGEMENTS

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