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Reflective Optics CPV Panels Enabling Large Scale, Reliable Generation of Solar Energy Cost Competitive with Fossil Fuels

15 November 2007 – 30 June 2009

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SolFocus, Inc.
Mountain View, California

Subcontract Report
NREL/SR-520-47310
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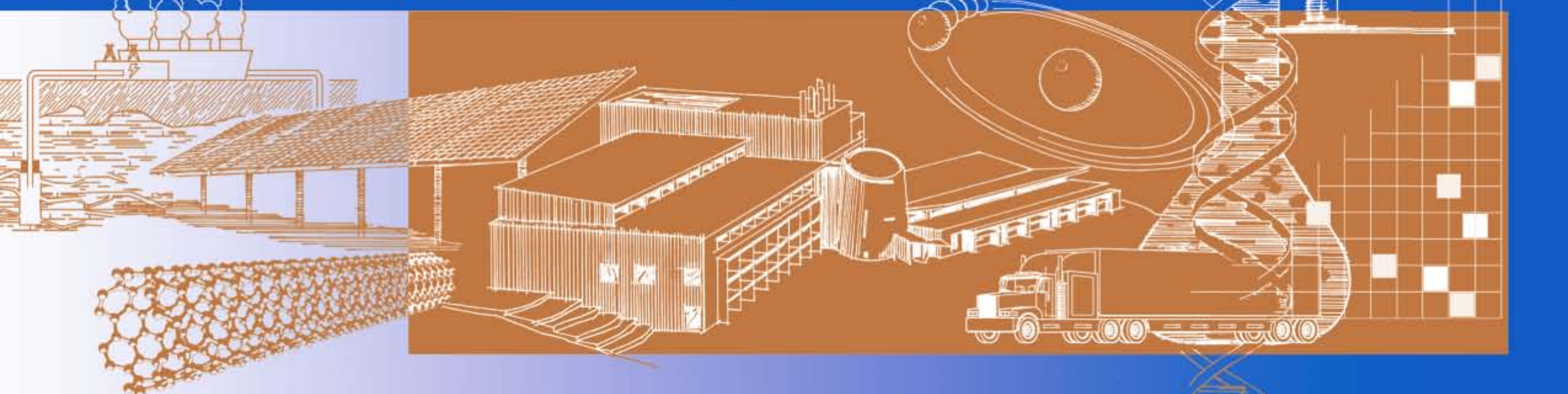

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S. Horne, M. McDonald, N. Hartsoch, and K. Desy
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Mountain View, California

NREL Technical Monitor: Brian Keyes
Prepared under Subcontract No. NAT-7-77015-09

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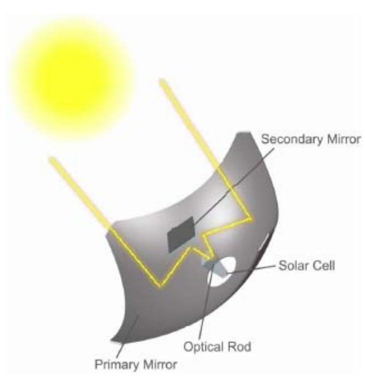
Introduction

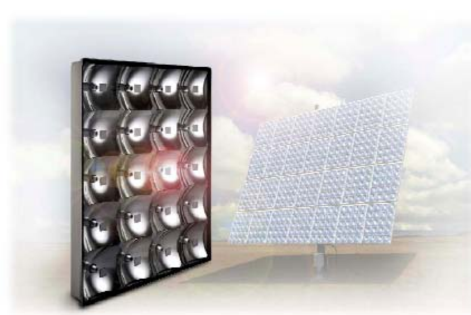
The objective of this 18 month subcontract was the improvement of reflective optics CPV panels to enable the large-scale, reliable production of solar electricity to meet SAI-established LCOE targets, and ultimately provide a path to solar power at parity with or better than the cost of energy generated utilizing fossil fuels. To this end, SolFocus has completed this subcontract with great success as evidenced by the end results of a CPV panel with conversion efficiencies greater than the targeted 22% and manufacturing capabilities with a run rate capacity far exceeding the milestone benchmark >3MW.

Phase I of the subcontract focused on improving the panel efficiency, reliability, and overall module performance. Phase II of the subcontract focused on the development of processes and equipment for high volume, low-cost manufacturing through automated fabrication of optics and panels to improve the speed of manufacture and quality control. This summary report accompanies the final presentation for Subcontract NAT-7-77015-09 presented at the National Renewable Energy Laboratory in Golden Colorado on June 29, 2009.

Contract Start Date:	November 15, 2007
Phase I End Date:	August 15, 2008
Phase II End Date:	June 30, 2009
Presenter's Name and Title:	Steve Horne, Chief Technical Officer, Principal Investigator Nancy Hartsoch, Vice President Marketing Mark McDonald, Senior Optical Scientist Kelly Desy, Manager Government Relations & Public Policy
Technical Monitor:	Brian Keyes, NREL

	NREL	SolFocus	% Cost Share
Phase I	$1,322,150.00	$1,081,760.00	45%
Phase II	$919,582.00	$752,385.00	45%
Total	$2,241,732.00	$1,834,145.00	$4,075,877.00





Shown to left: SolFocus SF-1100 optical system utilizing primary and secondary mirrors and optical rod are combined with high-efficiency multi-junction PV cells to form a power unit. Twenty power units are integrated into a panel, and then 28 panels are integrated on a dual axis tracker for field deployment.

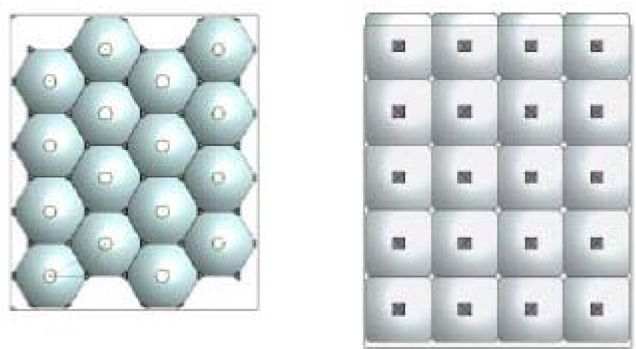
Phase I

The first objective of Phase I was the development of an efficient and reliable module design with better than 1% annual degradation. Work commenced in six different areas to accomplish this objective including: developing higher efficiency optics, enhancing reflectivity and durability of the mirror coatings, developing anti-reflection coatings, increasing the durability of the optics, improving the sealing of the module enclosure, and III-V PV Cell performance monitoring/test development.

Task 1 - Improve Efficiency and Reliability of Module Design

Overview

The overall objective of this task was to minimize the wasted space in a concentrator panel and to maximize the efficiency of the optical path to the multi-junction PV cell. The first subtask was to develop higher efficiency optics. To accomplish this, SolFocus redesigned the shape of the primary mirror from a hexagon to a square and enhanced the reflectivity of the optics through improved Silvering techniques. By working with vendors, the durability of these coatings was improved until satisfactory longevity was shown for both primary and secondary mirrors. Lastly, anti-reflection coatings on the transmissive elements further improved efficiency. Fabrication was to be completed at SolFocus Glassworks facility in Mesa, Arizona. The two silvering technologies evaluated were sputtered first surface silver and liquid applied protected second surface silver. Due to the market-ready availability of the first surface coating, this is the coating that was selected; however, the flexibility to switch to a potentially less costly second surface method is available once this technology has advanced. Further HAST research and testing in the area of optics durability indicated that the glass and the coatings are sufficiently robust to maintain the integrity of the optic.



Optical architecture redesign from hexagonal to quadrangle shaped optics

Sealing was another module-level enhancement included in this subcontract, which would improve overall module performance and field life durability. Breathing and sealing measures that allow the module to maintain a clean and moisture controlled environment were tested in both lab and field tests in various extreme climates such as tropical, maritime, desert, and moderate/mixed weather environs. An improved sealing technology that could pump out excess moisture was implemented.

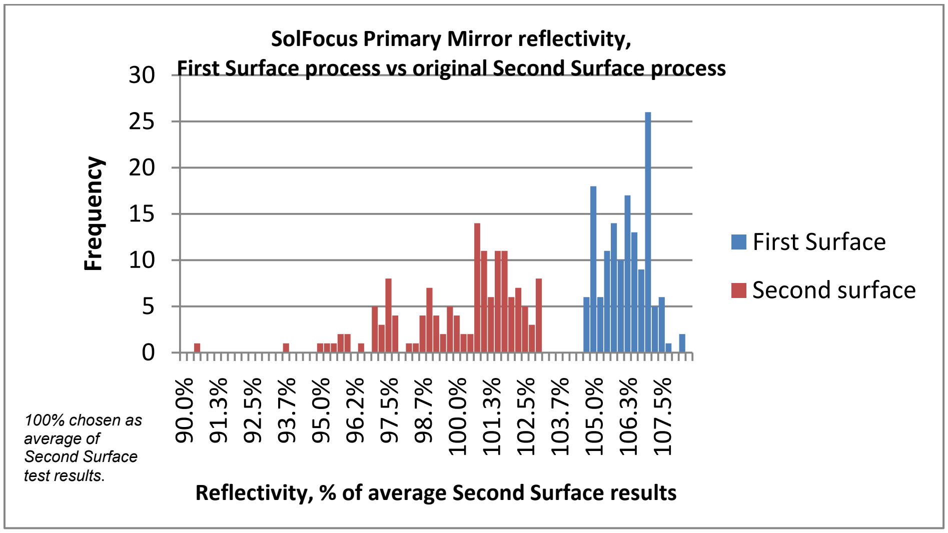
The final subtask of the first task was to model the multi-junction cell performance and project the variation in cell performance as a function of various environmental factors and to develop test methodologies to be able to predict field life and performance. SolFocus gathered test data and modeled Dark and Lit IV curves and HiPot testing at the cell level to determine leakage, fill factor and peak performance. To enable this, a cell flash tester was developed, which continues to be used for testing cell and receiver performance.

Subtask 1.1 - Develop Higher Efficiency Optics

A variety of rough optical shapes and designs were evaluated through a series of simulation tests and lab tests. A square mirror was determined an optimal fit in the rectangle module and glass processing allowed for the efficient manufacture of a square aperture. The secondary mirror shape was also altered to a square design, which when combined with the square aperture of the secondary mirror, minimized shadowing. A report of the evaluation was submitted to NREL on March 15, 2008.

Subtask 1.2 - Enhancing Reflectivity and Increasing Durability of Mirror Coating Process & Subtask 1.3 - Development of Anti-reflection Coatings

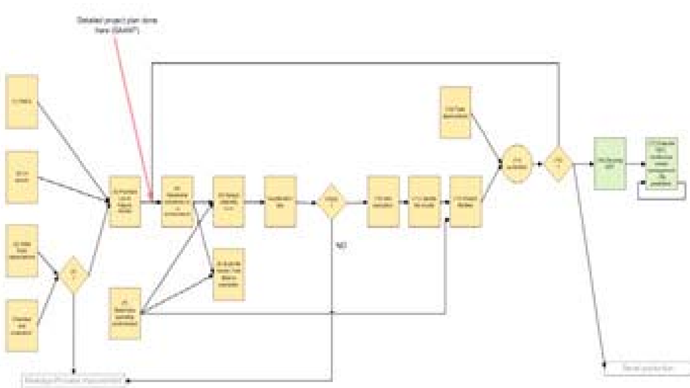
These two subtasks are being reported together as they were done simultaneously. The engineering team worked with various vendors and fabricators of mirror coatings to evaluate samples for enhanced, durable reflectivity of the primary mirror collector. SolFocus engineers analyzed various mirror coatings looking for a coating that would provide highly efficient, specular reflectance across the solar spectrum, and maintain durability. A report outlining the analysis and conclusions of this selection process was submitted as part of deliverable 3.1.2 and a primary optic with the selected coating was delivered to NREL in April 2008. SolFocus decided that the best course of action was to use a sputtered, protected first surface Silver due to its high reflectivity, durability, and market readiness. The first surface primary mirror with enhanced reflectivity coatings yielded approximately 6% higher relative reflectivity and simulations using the anti-reflective coating indicated 80% potential optical efficiency with an acceptance angle of +/- 1 degree. Fabrication of these primary mirrors, incorporating the improved coating, is being done in-house at our Glassworks facility in Mesa, Arizona.

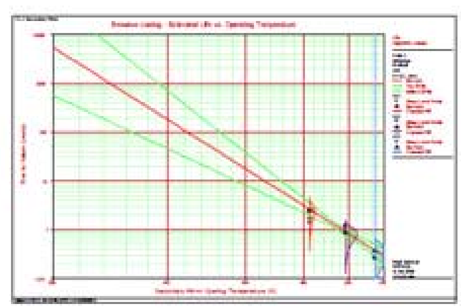


Test results, first surface vs. second surface reflectivity

Subtask 1.4 - Increase Durability of Optics

In addition to enhancing reflectivity, the reflector substrates were also analyzed for durability and reliability. Research and testing in the area of optics durability indicated that the glass and first surface coatings are sufficiently robust to maintain the optics' integrity. Various reflecting material substrates were tested and glass consistently yielded the best results. A specific issue of localized degradation and damage arose when systems were operated for prolonged periods of time off-axis. A Tiger Team dedicated to the issue found that the best remedy for this issue was a combination of preventative measures at the system level and improved thermal management on the mirror itself.





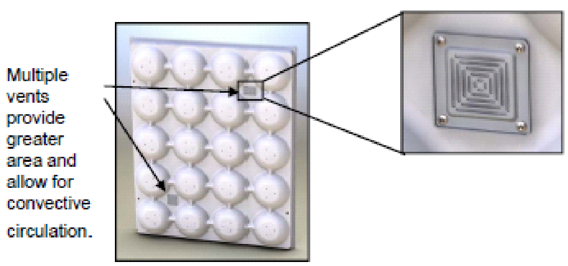
Left: Summary flowchart used by SolFocus to estimate component and module lifetime. Right: Graph showing secondary mirror lifetime extrapolation. Under normal operating conditions; graph indicates and average 33 year lifetime

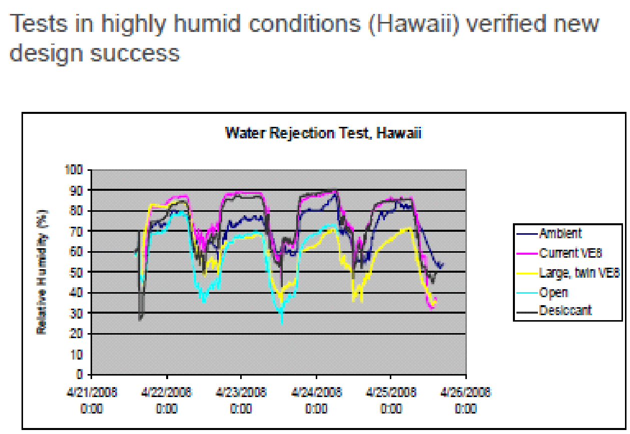
A second issue arose with the integrity of the adhesive of the secondary mirror to the front glass. Excess energy was absorbed due to the dark coloring of the adhesive; a switch to a white colored adhesive with increased reflectivity eliminated this issue.


Left: Secondary mirror with dark adhesive. Right: Secondary mirror using adhesive with increased reflectivity.

Subtask 1.5 - Improved Sealing of Module Enclosure

The initial module sealing technology used in the first generation of this product was ineffective and allowed moisture to accumulate inside the module. Different breathing and moisture control measures were tested in the lab and field testing in different geographies measured the impact of varying external climactic factors inherent to targeted geographic location. A redesigned vent that pumps moisture out of the module was implemented into this generation of the module.





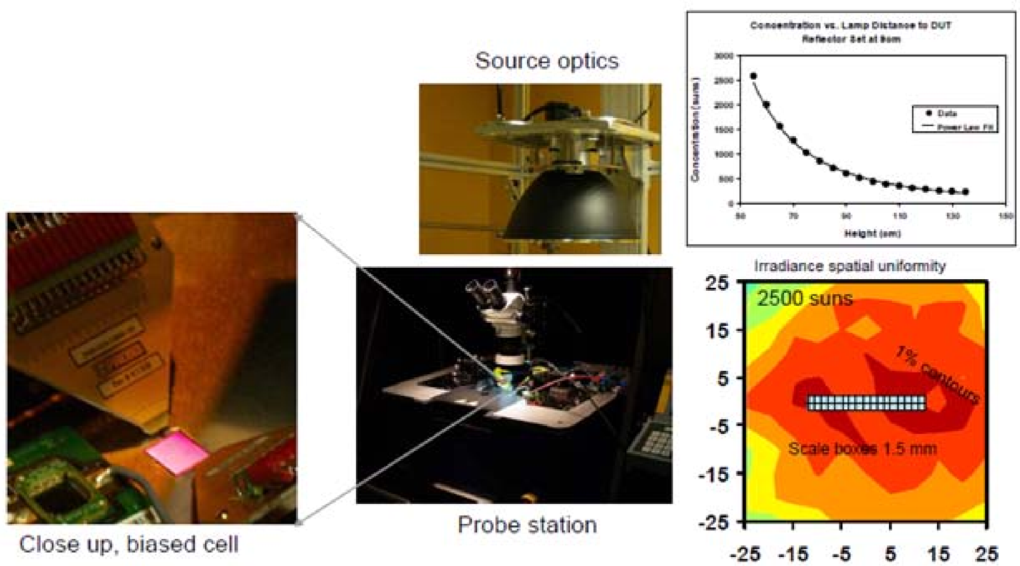
Left: Image of new venting system design.   Right: Test results of various venting schemes.

Subtask 1.6 - Group III-V PV Cell Performance Monitoring and Test Development

The objective of this task was to determine multi-junction cell performance in order to project the variation in cell performance as a function of different environmental factors. SolFocus developed test methodology approaches and tested both modules and cells using flash testers. A full report detailing these methodologies and preliminary results with regards to modeling of a Dark and Lit IV curves, HiPot testing, and determination of leakage were outlined in deliverable 3.1.4 submitted in April 2008.

The III-V PV cell performance, reliability, and flux were tested in house at SolFocus facilities and at NREL. III-V cell performance, Dark IV leakage and HiPot were measured at the cellular level by a multi-sun flash tester and the performance of the III-V cell as part of the receiver and module were tested by a module flash tester. A Dark IV test method was developed to test the cell sub assembly by biasing the cell sub-assembly, to heat and with current ramp to 5 amps. Through this we developed the following factory qualification parameters:

Fail at the factory:
Fail low >10 mA at 2.2V
Fail high >3.8V at 5A



Cell and wafer testing apparatus and test output.

Task 2 - Reliability Validation

Overview

The objective of this task was to determine the likely failure modes and test protocols for the thermal path, mirrors, and panel. Subtasks under this task included: analyzing mirror coatings and identifying appropriate testing and validation protocols for the reliability of coatings; analyzing fully assembled panels and identifying appropriate testing and validation protocols that need to be completed to demonstrate target reliability for panels; and analyzing thermal paths to validate existing testing and modeling methods to verify that cell/heat transfer surface interface meets reliability metrics. Failure Mode Effects Analysis (FMEA) was performed at both the component and panel levels, critical failure modes were identified, validation/test protocols were created, and modeling methods outlining the analyses for each of the above areas were submitted to NREL. Testing is ongoing and has been crucial in directing the industrialization effort.

Subtask 2.1 - FMEA Analysis of Thermal Path, Mirror and Panels (UTRC)

Work in this area commenced earlier than outlined in the SOW, as SolFocus felt that testing protocols and reliability targets for these components was critical in the path towards IEC certification. SolFocus engineers utilized a Design Failure Mode Effects Analysis (dFMEA) to find design risks and prioritize mitigation. dFMEA metrics and rankings were applied to all optical coatings, all optical substrates, the backpan, the receiver, adhesive system, thermal paths, tracker mechanics, and the tracker control system.

Task 3 - Development of Processes and Equipment for High Volume, Low-Cost Manufacturing

Overview

The objective of this task was to automate the fabrication process for the primary optics (mirrors) in order to improve speed of manufacture and quality control, resulting in achievement of specifications for smoothness and improved cost targets. The SolFocus Glassworks facility in Mesa, Arizona is evidence of the completion of this task. To achieve targets for this task, Mesa Glassworks expanded capability to include Lehr ovens, batch slump ovens, water jet cutting, a rotary oven, and semi-automated silvering procedures. Production capacity increased from a 2MW capacity in 2008 to a 34MW capacity by April 2009. This manufacturing expansion is expected to produce 15MW of primary reflectors in 2009 and more than double that capacity in 2010. Primary mirror fabrication costs are critical to reducing LCOE of SolFocus CPV systems.

Subtask 3.1 - Mirror Fabrication

Work toward this subtask also commenced ahead of schedule. Batch slump ovens were put into operation with optimized process parameters. A batch coating machine was developed by our manufacturing partner and implemented at Glassworks. By moving primary mirror fabrication in-house, SolFocus was able to achieve a higher level of quality and run consistency of the primary optics compared to the original vendor. The SolFocus Glassworks facility came online in mid-year 2008 with a theoretical production capacity of 2MW; 45,000 primary mirrors were produced in 2008. In March of

2009, Glassworks expanded and increased its automated production capabilities; this expansion has a production capacity of 34MW and is estimated to produce 1.2 million mirrors this year.

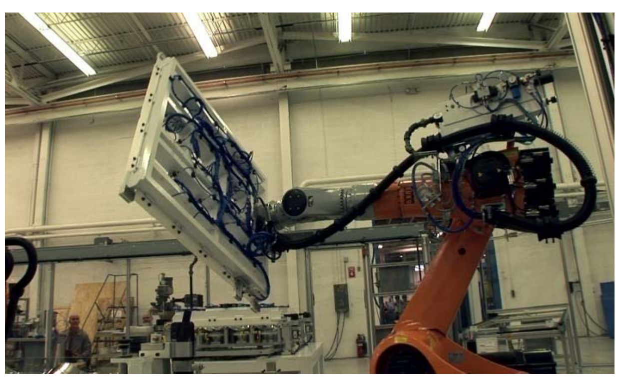
Left: Rotary batch oven. Right: Rotary coating applicator.

Subtask 3.2 - III-V PV Cell Manufacturing Capacity and Cost Reductions

SolFocus engineering team actively engaged with III-V PV cell manufacturers in order to assure quality and supply of cells to meet CPV module design requirements for functionality. SolFocus decided the most cost-effective approach would be to source III-V cells from manufacturers and not bring this capability in-house. This is an ongoing process and the collaborative work in this area continues, but SolFocus has contracted to source all the cells necessary to meet its contracts in 2009 and 2010.

Subtask 3.3 - Module Assembly

This task incorporated all of the tasks and subtasks outlined in Phase I and was the last step before moving into the work outlined in Phase II. SolFocus completed significant work with manufacturing automation partner Meikle to design the necessary alignment tooling and manufacturing processes to achieve consistent quality and accuracy of high volume manufacturing. This process began in late 2007 and came to fruition in April 2009 with a pilot run of a fully automated panel assembly line in Rochester, NY.



The Kuka robotic arm is the key to the automated Meikle panel assembly line.

Stage Gate Review

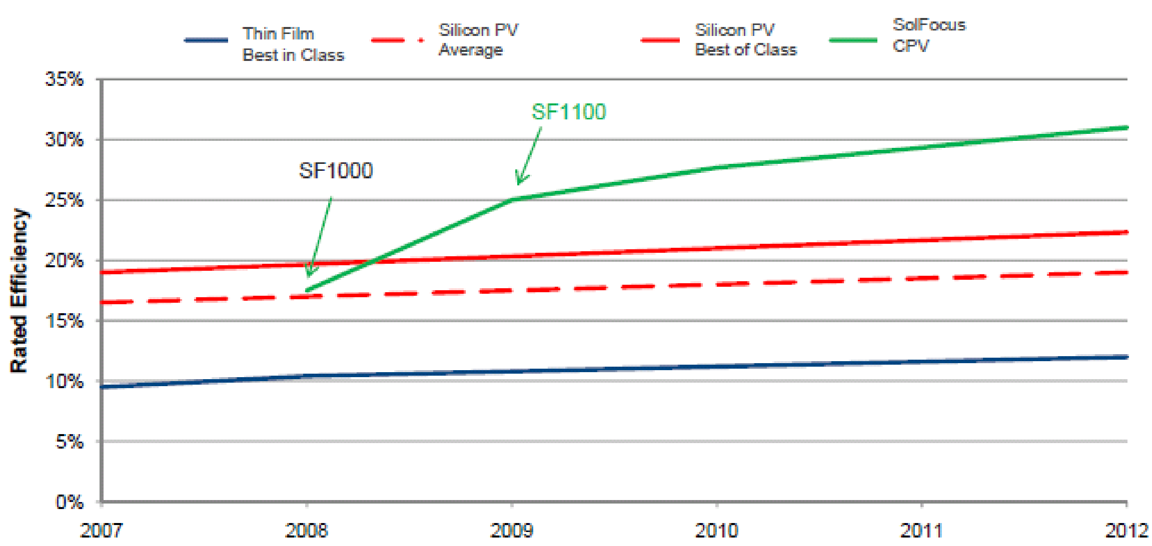
A final Stage Gate report was delivered to NREL on July 16, 2008 detailing the measured performance of the module delivered to NREL on July 9, 2008. The improvements to the performance and efficiency of the CPV panel resulted in a CPV panel that met and exceeded the metrics listed below.

The target metrics at the Stage Gate at the end of Phase I:

Optical efficiency: 74%
Power unit efficiency: 25%
Module efficiency: 18%
Acceptance angle: +/- 0.75 degree
Cell temperature 55°C over ambient
Module degradation of 1% - 2% per K

Measured outputs at the Stage Gate:

Optical efficiency: EQE and high solar resource range 400 to 1350 nm, exceeds 74%
Power unit efficiency: 27.0%
Module efficiency: 25.3%
Acceptance angle: >1 degree
Cell temperature: 50.8°C to 53.9°C
Module degradation: 1.2% per K



End product efficiency comparison of SolFocus CPV with other best in class PV technologies

Phase II

The Second Phase had two objectives. The first objective of Phase II was focused on the complete in-depth reliability validation on the CPV module, which included Highly Accelerated Life Test (HALT), a correlation of HALT results with field test results, and group III-V PV cell accelerated life testing. The second objective of Phase II was focused on ramping up overall manufacturing processes and equipment in order to transition from prototype manufacturing to high volume manufacturing. The expected results by the end of the grant project were to have a run rate of greater than 3MW with module manufacturing cost <$5/Watt. A third party validation of module manufacturing costs was performed by Navigant Consulting, and based on their analysis, SolFocus exceeded the goal of <$5/Watt manufacturing costs. The manufacturing accomplishments are described in detail below.

Task 4 – Reliability Validation

Overview

Passing IEC test specifications is critical in achieving market penetration and acceptance in the United States and other countries. SolFocus completed all of the tests related to IEC 62108 internally and is only awaiting the final outdoor test results (a six-month process due late July 2009) prior to obtaining certification from TUV to IEC 62108. In June 2009, SolFocus became the first CPV company to receive certification to IEC 62108, which they achieved on the first generation SF1000 product. All lessons learned from that effort were applied to the SF1100 system, and testing has gone very smoothly on the new product. SolFocus has also received listing on the SF1100 panel on the California Energy Commission (CEC) approved list qualified equipment for California Solar Initiative (CSI) rebates governed by the California Public Utilities Commission. This listing requires certification by TUV to safety standards. SolFocus is also the only CPV company to be listed on the CEC's approved equipment list.

The implementation of an extensive Highly Accelerated Stress Testing (HAST) program that included temperature/humidity cycling, high flux (including UV) exposure and vibration stress testing was completed under this subcontract. HAST stress tests are critical in establishing module failure modes and degradation rates of both the overall module and at the component level. Component HAST tests included testing for mirror reliability and thermal path degradation. Module HAST testing included rigorous module environmental testing. The correlation of the HAST program with field data indicated field failures, degradation rates, and ultimately, the lifetime of the module and its components. A linear extrapolation of power degradation from environmental stress test measured 8% degradation at 10 years => 25 years life.

Reliability testing continues at SolFocus, and has become a part of the control loop in the manufacturing process. As is normal for reliability work, field and HAST learnings improve accuracy estimates of the lifetime of the equipment.

Subtask 4.1 - IEC Qualification

Passing IEC qualification is critical in achieving market penetration and acceptance in the United States and other countries. Prior to submitting the SF1100 product to PTL for IEC 62108 testing, SolFocus performed its own internal testing in the critical areas, and based on results of this internal testing, we were confident in the products' ability to pass IEC certification. Due to complications recognized by the testing lab, the final certification for the SF1100 was delayed, but is expected by the end of July 2009 once outdoor exposure tests are complete. Further complications are not anticipated, nor is non-passage, as internal qualification tests in all sequences indicate a successful passage. Furthermore, the previous generation of module (SF1000) was awarded IEC certification, making it the first CPV panel on the market to receive IEC certification.

\- Zweitschrift (Copy) -

Certificate

TÜVRheinland

Certificate no. T 72091357 01

License Holder:
SolFocus Inc.
510 Logue Ave.
Mountain View CA 94043
USA

Manufacturing Plant:
SolFocus Inc.
510 Logue Ave.
Mountain View CA 94043
USA

Test report no.: USA-MRH 30872555 003 Client Reference: Mark Spencer
Tested to: IEC 62108:2007

Certified Product: Concentrator Photovoltaic Panel License Fee - Units

Model Designation: SF-1000P 7

Rated Voltage: DC 1000V
Rated Current: 6.0A
Rated Power: 215W ± 5%

Special Remarks: To be installed in accordance with the National Electrical Code (NEC) 2005; Article 690: Photovoltaic Power Systems.
The system is considered for industrial applications.
Replaces Certificate T72082546.

Appendix: 1 Inh. = 790621 / Deb. = 790621 / Fert. = 790621 7

Licensed Test mark: IEC 62108

Signatures
Stephan Schmitt, President
Dipl.-Ing. M. Raap, QA Certification Officer

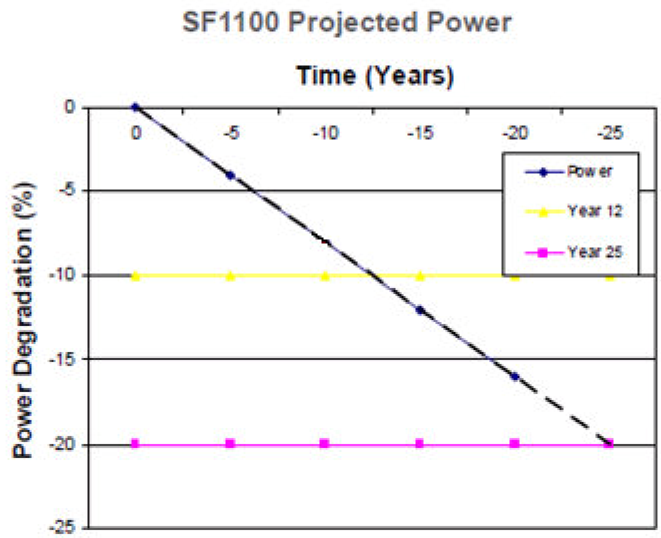
Date of Issue (day/mo/yr) 09/06/2009

Copy of IEC 62108 certificate for the SF1000 product, dated June 2009.

Subtask 4.2 - Highly Accelerated Stress Test (HAST) & Subtask 4.3 - Correlation of HALT with Field Test Results using Analytical Model

The objective of this task was to implement an extensive HAST program; including temperature/ humidity cycling, high flux (including UV) exposure and vibration stress testing. These stress tests are critical in establishing module failure modes and degradation rates of the overall module as well as at the component level. Component HAST tests included testing for mirror reliability and thermal path degradation; module HAST testing included rigorous module environmental testing to assure a 25-year life of the module and components. A complete report outlining each of the component HAST tests was delivered to NREL in November 2008.

The correlation of the HAST program with field data indicated field failures, degradation rates, and ultimately, lifetime of the module and components. We collected field data related to HAST tests in Arizona, which gave us an indication of degradation, output, reliability, and failure modes. It is important to note that the SolFocus field data was collected in a geography with very high annualized DNI (7-7.3); an environment which is typical of areas well-suited for CPV and that stress the robustness of the product. In summary, a linear extrapolation of power degradation from environmental stress tests measured 8% degradation at 10 years on a panel with a 25 year life, thus beating targeted objectives under this subcontract.



Module lifetime power prediction as of June 2009.

Task 5 – Manufacturing Readiness

Overview

The objective of this task was to have a seamless transition from pilot-run manufacturing to high-volume manufacturing. This task included subtasks for assuring that all parts of the supply chain were in place and able to meet manufacturing demand, as well as assure that all equipment, facilities, and processes were placed to allow rapid ramp from pilot run to volume production.

This past year, SolFocus has been heavily focused on manufacturing readiness. SolFocus underwent negotiations with our supply chain partners for module components, resulting in secured material supply business contracts. We are confident that our supply chain partners have alleviated bottlenecks and will have the resources available for panel manufacturing at volume and cost targets indicated for 2009-2010. Furthermore, a quality control program for suppliers was developed and is in place for both the Glassworks facility and for component supplier partners at their facilities.

Additional steps were taken to assure high volume manufacturing and quality control, which included actively engaging with III-V PV cell manufacturers in order to assure quality and supply of cells to meet CPV module design requirements for functionality and developing the necessary alignment tooling for an automated assembly line.

As mentioned earlier in this report, the SolFocus Glassworks facility in Arizona expanded and is fully operational, with an expected production this year of 15MW of primary reflectors and more than doubling that quantity in 2010. The Glassworks facility has the capabilities to produce a small volume (5MW) of SF1100 panels via its semi-automated prototype line, but could be quickly expanded given US demand increases.

Meikle Automation was contracted for the development of automation for the manufacturing process to enable SolFocus to expand capacity to 100MW by mid-2010. The pilot automation line for volume panel assembly was implemented at Meikle's Rochester, New York facility. The pilot run of this line tripled our SF1100 panel population in one week's time. This automated assembly line is being replicated by our manufacturing partners, and is projected to have a 50MW production capacity by year end 2009 and a 100MW capacity in mid 2010.

Subtask 5.1 - Supply Chain

In the second half of 2008, SolFocus was heavily focused on manufacturing readiness. SolFocus' manufacturing and supply chain plan of record was set by December 2008 and was moved into the execution phase by January 2009. Our supply chain partners underwent materials negotiations for module components and material supply business contracts were awarded by year-end 2008. A quality control program for suppliers has been developed and is in place for both the Glassworks facility and for component supplier partners at their facilities. As well, SolFocus Glassworks facility initiated an internal program schedule for ISO certification.

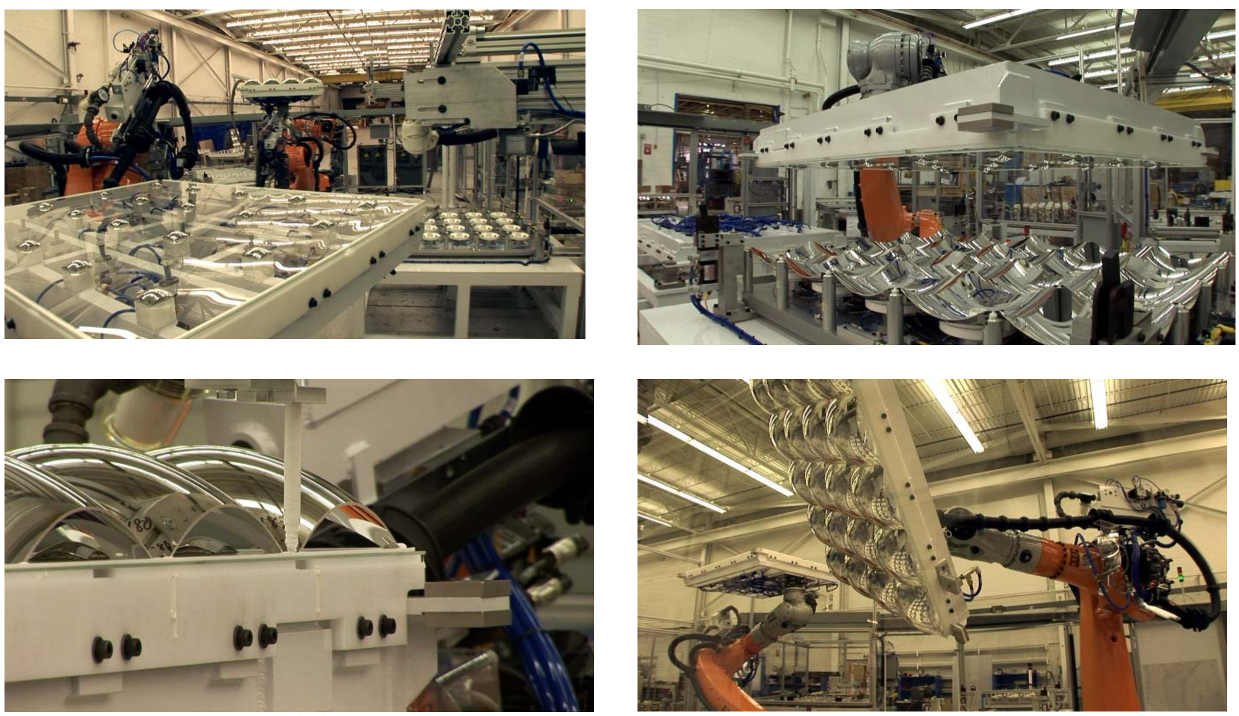
A cost throughput analysis was reported to NREL in November 2008 and was based on negotiated materials contracts, which showed SolFocus beating its aggressive cost targets for the SF1100 panels. Navigant consulting provided a third party validation of the throughput analysis and reported that SolFocus BOM costs were under $5/Watt, the target for this subcontract.

Subtask 5.2 - Factory/Assembly

As mentioned above, the SolFocus Glassworks facility in Arizona expanded in March 2009 and was fully operational by April. This manufacturing expansion is expected to produce 15MW of primary reflectors in 2009 and more than doubling capacity in 2010. The Glassworks facility will also have the capabilities to produce a small volume of SF-1100 panels via its prototype line.

The pilot automation line for volume panel assembly was developed and tested in New York with SolFocus' automation manufacturing partner, Miekle. This pilot line had >3MW capacity and more than tripled the SF1100 panel population in one week of operation during the test run in April, proving that SolFocus is on a path to high volume manufacturing.

By the end of 2008, SolFocus and its manufacturing partners had produced approximately 1MW of SF1000 product to meet supply contracts and engineering R&D testing needs. By the end of 2009, SolFocus and its manufacturing partners are projected to build 15MW of SF1100 panels and have a 50MW manufacturing capacity which can be quickly scaled up to 100MW or beyond to meet demand. An additional benefit of the automated assembly was the increase in assembly precision, which is leading to an increase in panel acceptance angle and consequently, lower installation costs.



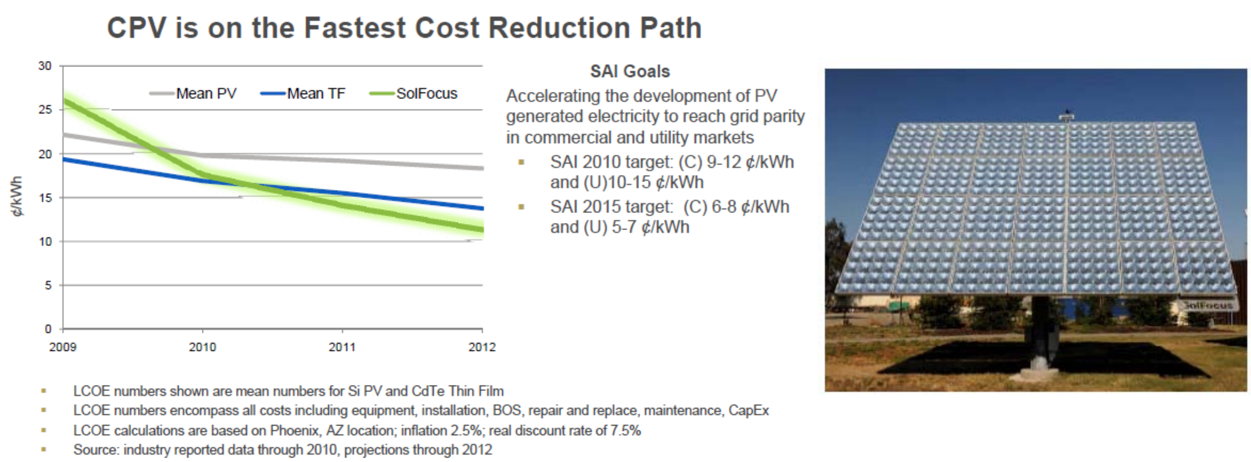
Meikle high volume automated assembly line. Top left: secondary mirrors on sheet glass. Top right: Primary mirror attachment to front glass. Bottom left: Adhesive application to primary mirrors. Bottom right: Kuka robots moving panels to next step of process.

Summary

SolFocus has executed according to plan and has met or exceeded the targets laid out in the original statement of work set 18 months ago. This subcontract was instrumental in the commercialization of the SolFocus concentrator photovoltaic module and helped put it on an aggressive cost reduction curve resulting in LCOE numbers that beat SAI goals, as well as having the fastest cost reduction curve compared to other PV technologies.

In summary, the key metrics of the program have been achieved:

Panel efficiency of 25+% (22% was program goal)
Module cost of <$5/Watt (target exceeded)
On path to meet SAI cost targets
>3MW manufacturing/production capacity



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14. ABSTRACT *(Maximum 200 Words)*
The goal of SolFocus' 18-month subcontract was to improve reflective optics concentrator photovoltaic (CPV) panels: (1) to enable the large-scale, reliable production of solar electricity to meet Solar America Initiative-established levelized cost fo energy targets, and (2) to ultimately provide a path to solar power at parity with or better than the cost of energy generated using fossil fuels. To this end, SolFocus completed this subcontract with great success, as evidenced by the end results of a CPV panel with conversion efficiencies greater than the targeted 22% and manufacturing capabilities with a run-rate capacity far exceeding the milestone benchmark of more than 3 megawatts.

15. SUBJECT TERMS
PV; CPV; concentrator photovoltaics; reflective optics; large-scale; generation; solar cells; cost; conversion efficiencies; manufacturing; fossil fuel; LCOE

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