Final Report for PV Incubator Subcontract No. NAT-0-99013-01

June 14, 2010 — March 2, 2012

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Durham, North Carolina

NREL Technical Monitor: Kaitlyn VanSant

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Subcontract Report
NREL/SR-5200-54690
April 2012

Contract No. DE-AC36-08GO28308

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

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Summary

The goal of the subcontract is to scale up Semprius' novel micro-cell based modules to an annualized rate of 500 kW of receivers and 10 kW of modules, in support of the DOE 2020 SunShot Initiative goals. The statement of work (SOW) was broken up into two Phases. Phase I was directed towards process development efforts towards addressing fundamental manufacturing metrics such as yield, die per wafer, automation and throughput. Phase II objectives are to scale to an annualized production rate of 500 kW of receivers and 10 kW of modules, while improving cell efficiency, module efficiency and transfer yield.

Semprius has met all the technical milestones and deliverables for the contract. All subtasks were completed earlier than expected and the results exceeded the technical targets. In particular, 3J cell efficiency of 41.2% exceeded the target of 38%, module efficiency of 28.3% exceeded the target of 28% and transfer yield of 96.4% exceeds the target of 95%, with all tasks completed well ahead of schedule. Also, devices fabricated from 1st use GaAs substrates and substrates with two re-uses have been shown to be identical.

The progress of each task is summarized in Table 1.

Semprius has secured funding from energy giant, Siemens. Siemens will take Semprius' HCPV technology to market. A 5-35 MW plant in Henderson, NC is now under construction and will be operational in 3Q2012. Semprius' module efficiency now exceeds 32%. Semprius has additional RD&D systems in the planning stage with partners to seed the market, ramping up to larger installations in late 2012.

Table 1: Phase I Progress Summary

Task Activity	Milestone/Deliverable	Due Date	Status
Task 1 - Epitaxial wafer scale up			
Subtask 1.1 Cell optimization	Deliverable: Three cell-on-interposers (COI) with 2J cells that exhibit an average efficiency of at least 30% at 800X concentration, 25°C and spectrum ASTM G173-03	12/15/10	Completed 7/07/10
Subtask 1.2 Multiple epitaxial growth vendor qualification	Milestone: Demonstrate at least three epi runs from two foundries with an average efficiency of 27% at 800X, 25°C and spectrum ASTM G173.	12/15/10	Completed 12/13/10
Subtask 1.3 Demonstrate substrate re-use	Milestone: Comparison of device performance from epi wafers with one re-use to the performance of devices from 1st use substrates.	2/15/11	Completed 9/13/10
Task 2 - Cell fabrication, cell release, and transfer printing scale up			
Subtask 2.1 Cell pick-up yield improvement	Milestone: Demonstrate pick up yield of >90% for one COI lot.	12/15/10	Completed 9/13/10
Subtask 2.2 Transfer yield improvement	Deliverable: Deliver one 100 mm COI wafer with >90% transfer yield. Provide a representative yield report for one COI lot.	12/15/10	Completed 7/08/10
Subtask 2.3 Transfer printing scale-up	Milestone: Demonstrate transfer printing on 2nd generation tool by running three COI lots on the second generation tool with an average transfer yield of 90% for 100 mm wafers.	12/15/10	Completed 12/13/10
Task 3 - Interposer wafer scale up			
Subtask 3.1 Wafer scale-up to 150 mm	Deliverable: Deliver one 150 mm fabricated interposer wafer with >750 interposer die.	2/15/11	Completed 11/23/10
Subtask 3.2 Transfer print process scale up to 150 mm	Milestone: Demonstrate a transfer yield of at least 85% on a 150 mm interposer wafer.	2/15/11	Completed 12/13/10
Task 4 - Module scale up			
Subtask 4.1 Module efficiency improvement	Deliverable: Deliver one module with an on-sun module aperture efficiency of 22% at the ASTM 2527 test conditions.	9/14/10	Completed 7/08/10
Subtask 4.2 Module assembly process scale up	Milestone: Documentation of a scalable module assembly process used to produce > 25 modules with module aperture efficiency of >20%.	2/15/11	Completed 9/13/10
Task 5 – Perform thermal cycling			
Subtask 5.1 Perform thermal cycling	Milestone: 1. Deliver 10 receivers to NREL by month 6 for thermal cycling (-40 to 110C, 500 cycles, Isc = 30 mA). 2. Deliver the Subcontractor's receiver thermal cycling report documenting receiver performance for 10 receivers before and after thermal cycling (-40 to 85C, 1000 cycles, Isc = 30 mA).	12/15/10 2/15/11	Submitted 10/15/10 Completed 1/24/11

Table 2: Phase II Progress Summary

Task Activity	Milestone/Deliverable	Due Date	Status
Task 6 - Epitaxial wafer scale up			
Subtask 6.1 Cell optimization	Deliverable: Three COIs with 3J cells that exhibit an average efficiency of at least 38% at 800X concentration, 25°C and spectrum ASTM G173-03	9/15/11	Completed 4/29/11
Subtask 6.2 Epitaxial wafer scale up	Milestone: Documentation on capacity calculations and foundry quotations that demonstrate that at least two foundries are capable of delivering epi wafers that meet the Subcontractor's performance criteria at volumes that enable an annualized receiver production rate of 500kW. (4th Quarterly Report)	6/15/11	Completed 6/15/11
Subtask 6.3 Demonstrate substrate re-use	Milestone: Comparison of the performance of devices from epi wafers with two re-uses to the performance of devices from virgin substrates. (Final Technical Progress Report)	12/15/11	Completed 6/15/11
Task 7 - Cell fabrication, cell release, and transfer printing scale up			
Subtask 7.1 Printed array size scale up	Milestone: Report on the maximum print array size and the results of the stamp size optimization process. (4th Quarterly Report)	6/15/11	Completed 6/15/11
Subtask 7.2 Transfer yield Improvement	Deliverable: Deliver one 150 mm COI wafer with >95% transfer yield. A representative yield report for one COI lot shall be provided. (5th quarterly report)	9/15/11	Completed 4/1/11
Subtask 7.3 Cell fabrication, cell release and transfer printing scale up	Milestone: Documentation of wafer fab capacity calculations, demonstrating capability of an annualized receiver production rate of 500 kW (Final Technical Progress Report)	12/15/11	Completed 11/18/11
Task 8 - Receiver pilot line scale up			
Subtask 8.1 Receiver pilot line scale up	Deliverable: Deliver a technical report with detailed calculations demonstrating a process capable of producing a receiver capacity of 500 kW per year. The capacity may be verified by NREL personnel.	12/15/11	Completed 10/11/11
Task 9 - Module pilot line scale up			
Subtask 9.1 Module efficiency improvement	Deliverable: Deliver one module with an on-sun module aperture efficiency of 28% at the ASTM 2527 test conditions.	6/15/2011	Completed 5/23/2011
Subtask 9.2 Module assembly scale up	Deliverable: Deliver a technical report documenting capacity calculations that support capability of meeting a 10 kW per year module production rate.	12/15/11	Completed 10/3/11
Subtask 9.3 RD&D system data	Milestone: Documentation of performance and energy yield of RD&D data from installations with 2J and 3J modules on sun (assuming permission from the owners of the RD&D systems) (Final Technical Progress Report)	12/15/11	Completed 11/20/11
Subtask 9.4 Cost model	Milestone: Updated cost model information to be provided in a meeting with NREL/DOE.	12/15/11	To be presented
Task 10 – Reliability			
Subtask 10.1 Damp heat aging of encapsulated 3J cells	Milestone: Documentation of the results of damp heat testing of encapsulated 3J cells (Final Technical Progress Report)	12/15/11	Completed 11/20/11
Subtask 10.2 Accelerated aging of sealed modules	Milestone: Documentation of the outcome of the accelerated aging tests of the sealed modules (Final Technical Progress Report)	12/15/11	Completed 11/20/11

Task 1 – Epitaxial wafer scale up

Subtask 1.1 – Cell optimization: Completed

The deliverable for this subtask was three cell-on-interposers (COI) with 2J cells that exhibit an average efficiency of at least 30% at 800X concentration, 25°C and spectrum ASTM G173-03. This subtask has been completed and NREL (Concentrator cell test report, July 28, 2010) reported an average efficiency of 31.5% at 800X concentration. A report on this subtask is presented in Appendix A. Semprius has now shifted its developmental efforts to focus on releasable 3J cells.

Subtask 1.2 – Multiple epitaxial growth vendor qualification: Completed

The milestone for this subtask was to demonstrate at least 3 epi runs each from two foundries with an average efficiency of 27% at 800X concentration, 25°C and spectrum ASTM G173-03D+C. This milestone has been completed, and the subcontractor has qualified two epitaxy foundries for growth of dual junction InGaP/GaAs cells with an average efficiency of 30.3% at 800X concentration. A report for this subtask is presented in Appendix B.

Subtask 1.3 – Demonstrate substrate re-use: Completed

The milestone for this subtask was a comparison of the performance of devices from epi wafers with one re-use to the performance of devices from 1st use substrates. This milestone has been completed and is reported in Appendix C. There is virtually no difference in the devices fabricated from 1st use substrates and substrates with one re-use.

Task 2 – Cell fabrication, cell release, and transfer printing scale up

Subtask 2.1 – Cell pick-up yield improvement: Completed

The milestone for this subtask was the demonstration of a pick yield of >90% for one 100 mm cell-on-interposer lot. This milestone has been completed and is reported in Appendix D. The pick yield for Lot 27 was 99.6%. In addition, the average pick yield for nine lots was 98.4%.

Subtask 2.2 – Transfer yield improvement: Completed

The deliverable for this subtask was the demonstration of a transfer yield of >90% on a 100 mm COI wafer, and a representative yield report for one COI lot. This subtask has been completed and is reported in Appendix E. The transfer yield of the deliverable was 95.6%. In addition, the average transfer yield of nine lots was 95.0%.

Subtask 2.3 – Transfer printing scale-up: Completed

The milestone for this subtask was to run three cell-on-interposer (COI) lots on second generation (production) printing tools with an average transfer yield of 90% for 100 mm wafers. This milestone was completed and is reported in Appendix F. The average transfer yield of the three lots was 96.5%.

Task 3 – Interposer wafer scale up

Subtask 3.1 – Wafer scale-up to 150 mm: Completed
The deliverable for this subtask was a 150 mm interposer wafer with more than 750 interposer die. This subtask was completed and one 150 mm interposer wafer with 1024 die was delivered to NREL. A report on this subtask is presented in Appendix G.

Subtask 3.2 – Transfer print process scale up to 150 mm: Completed
The milestone for this subtask was a demonstration of a 150 mm printed ceramic wafer with a transfer yield of >85%. This subtask was completed and is reported in Appendix H. An average transfer yield of 99% was achieved on 6 wafers, using a 1st generation tool and an average of 92.9% was achieved on 2 wafers, using a 2nd generation tool.

Task 4 – Module scale up

Subtask 4.1 – Module efficiency improvement: Completed
The deliverable for this subtask was one module with an on-sun module aperture efficiency of 22% at the ASTM 2527 test conditions. This subtask has been completed and NREL (Report, July 6, 2010) reported a module aperture efficiency of 23.1±1% at PTC. The module submitted for this deliverable has an optical aperture of 0.1170 m^2 and a geometric concentration ratio of 1000X. Each module consists of an array of 18x18 receivers (324 total), fabricated from 650µx650µ transfer-printed cells. Semprius has now shifted its developmental focus to fabricate a cost optimized module with improved efficiency.

Subtask 4.2 – Module assembly process scale up: Completed
The milestone for this subtask was documentation of a scalable module assembly process used to produce >25 modules with module aperture efficiency of >20%. This subtask has been completed and is reported in Appendix I. More than 50 modules have been fabricated in a production-like process. The modules manufactured in this project have been used to install a 1 kW Research, Development and Demonstration (RD&D) system at Tucson Electric Power in Tucson, AZ.

Task 5 – Perform thermal cycling

Subtask 5.1 – Perform thermal cycling: Completed
The milestone for this task was simultaneous thermal cycling of 10 receivers at NREL and at Semprius per IEC 62108, Section 10.6. Semprius completed the thermal cycling of 10 receivers at its facility, and the results are reported in Appendix J. None of the receivers show any statistically significant change in performance after thermal cycling. Semprius provided thermal cycling sample with 10 solar receivers to NREL in the 4th month of the subcontract and the status of this test is presented in Appendix J.

Task 6 – Epitaxial wafer scale up

Subtask 6.1 – Cell optimization: Completed

The deliverable for this subtask was three cell-on-interposers (COI) with 3-junction cells that exhibit an average efficiency of at least 38% at 800X concentration, 25°C and spectrum ASTM G173-03. This subtask has been completed and NREL (Concentrator cell test report, May 25, 2011) reported an average efficiency of 41.2% at 800X concentration. The efficiency of one of the cells is presented in Appendix K.

Subtask 6.2 – Epitaxial wafer scale up: Completed

The milestone for this subtask is documentation of capacity calculations and foundry quotations that demonstrate that at least two foundries are capable of delivering epi wafers that meet the Subcontractor's performance criteria at volumes that enable an annualized receiver production rate of 500kW. This subtask has been completed.

The capacity calculation matrix is presented in Appendix L. Using the assumptions from the SOW (8640 hours of operation per year and 85% tool utilization) and current yield and module rating, the run rate of epitaxial wafers required to meet a capacity of 500 kW is calculated to be 1291 wafers per year. The yield and module rating assumptions will be updated when more data is available. The subcontractor has qualified two epitaxial wafer suppliers to provide 3-junction printable cells. The first one will provide the primary path towards commercialization. They can provide > 2000 wafers per year (capacity letter presented in Appendix M), which exceeds the number of wafers required for a 500 kW pilot line. The second epitaxial wafer supplier can also supply >2000 wafers per year (capacity letter presented in Appendix N).

Subtask 6.3 – Demonstrate substrate re-use: Completed

The milestone for this subtask is a comparison of the performance of devices from epi wafers with two re-uses to the performance of devices from virgin substrates. This milestone has been completed and is reported in Appendix O. There is virtually no difference in the devices fabricated from 1st use substrates, 2nd use substrates and 3rd use substrates.

Task 7 – Cell fabrication, cell release, and transfer printing scale up

Subtask 7.1 – Printed array size scale up: Completed

The milestone for this subtask is to report the maximum print array size and the results of the stamp size optimization process. This report is presented in Appendix P.

Subtask 7.2 – Transfer yield Improvement: Completed

The deliverable for this subtask was the demonstration of a transfer yield of >95% on a 150 mm COI wafer, and a representative yield report for one COI lot. This subtask has been completed and is reported in Appendix Q. The transfer yield of the deliverable was 96.4%. In addition, the average transfer yield of 29 wafers in 5 COI lots was 96.9%.

Subtask 7.3 – Cell fabrication, cell release and transfer printing scale up: Completed

The milestone for this subtask was documentation of wafer fab capacity calculations, demonstrating capability of an annualized receiver production rate of 500 kW. Appendix L presents the calculations that will form the basis for this subtask. A COI wafer per hour rate of 0.9 wafers per hour in each of the process steps is required to meet this deliverable. Appendix R presents the data collection form that will be used to collect throughput data on each of the process steps. This report has been submitted.

Task 8 – Receiver pilot line scale up

Subtask 8.1 – Receiver pilot line scale up: Completed

The deliverable for this subtask is a technical report with detailed calculations demonstrating a process capable of producing a receiver capacity of 500 kW per year. Appendix L presents the calculations that will form the basis for this subtask. A COI wafer per hour rate of 0.9 wafers per hour in each of the process steps is required to meet this deliverable. The wafer run rate for each of the process steps will be determined. Appendix R presents the data collection form that will be used to collect throughput data on each of the process steps. This report has been submitted.

Task 9 – Module pilot line scale up

Subtask 9.1 – Module efficiency improvement: Completed

The deliverable for this subtask was one module with an on-sun module aperture efficiency of >28% at the ASTM 2527 test conditions. This subtask has been completed. This module was tested at NREL and its aperture efficiency was determined to be 28.3±1.7%, as presented in Appendix I. The Alpha modules have an optical aperture of 0.264 m^2 and a geometric concentration ratio of >1100X. Each module consists of an array of 30x22 receivers (660 total), fabricated from μ-transfer-printed cells.

Subtask 9.2 – Module assembly scale up: Completed

The deliverable for this subtask is a technical report with detailed calculations demonstrating a process capable of producing a module capacity of 10 kW per year. Appendix L presents the calculations that will form the basis for this subtask. A module per hour rate of 0.02 in each of the process steps is required to meet this deliverable. Appendix R presents the data collection form that will be used to collect throughput data on each of the process steps.

Subtask 9.3 – RD&D system data: Completed

Appendix T presents performance data from RD&D-1, installed at Tucson Electric Power. The modules in this system were 2-junction engineering prototype modules. The performance data from a recent 3-junction based 2.8 kW system is also presented.

Subtask 9.4 – Cost model: Completed

The updated cost model was presented in confidence to NREL/DOE in a web conference, as previously discussed.

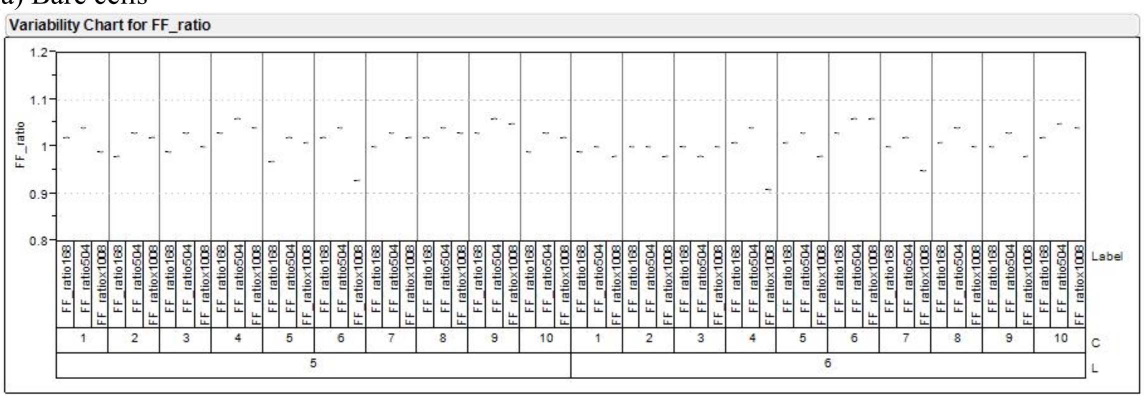
Task 10 – Reliability

Subtask 10.1 – Damp heat aging of encapsulated 3J cells – Completed

The milestone for this task is damp heat exposure of Semprius' latest triple-junction (3J) solar cells and to assess the impact of adding encapsulation. These 3J cells are different from prior parts because they have a different bottom cell and a new antireflection coating stack. Forty 3J cell on interposer (COI) parts were soldered to a backplane substrate. Half of the parts were encapsulated while the balance remained uncoated as bare cells. High concentration light current-voltage (IV) and dark IV sweeps were measured before and after 1000 hrs of damp heat (85C at 85% relative humidity).

The devices under test completed 1000hrs of damp heat exposure in the 1st week of November. The light IV curves were measured using a Xenon CW light source at ~250X concentration with a Keithley 2601A source-meter. The fill factor from light IV testing was used as the metric for evaluation, and the FF_ratio (FF measured after accelerated aging relative to the value at time equal to zero) is reported after different periods of damp heat exposure. As shown in Figure 1, the FF ratio did not significantly degrade after damp heat exposure for either the bare or passivated cells, however it could be argued that the encapsulated parts are slightly more consistent in their response with no significant outliers.

(a) Bare cells



(b) Cell with encapsulation

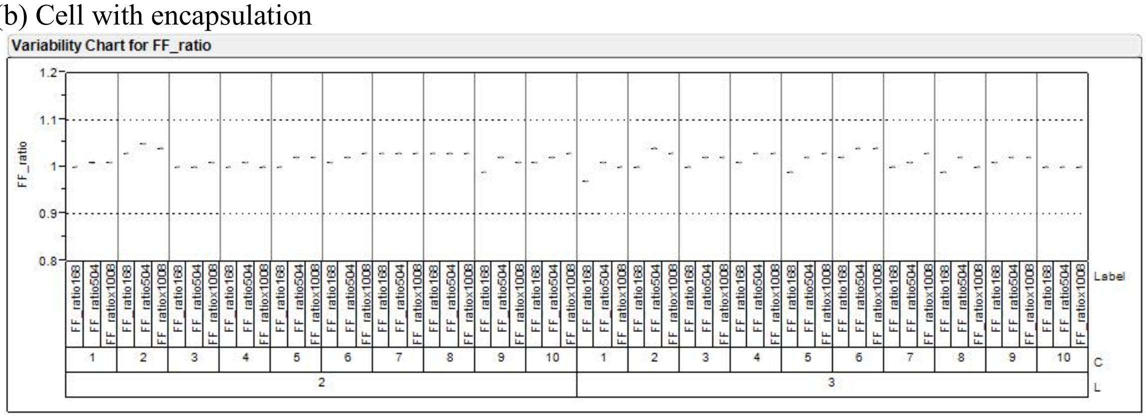
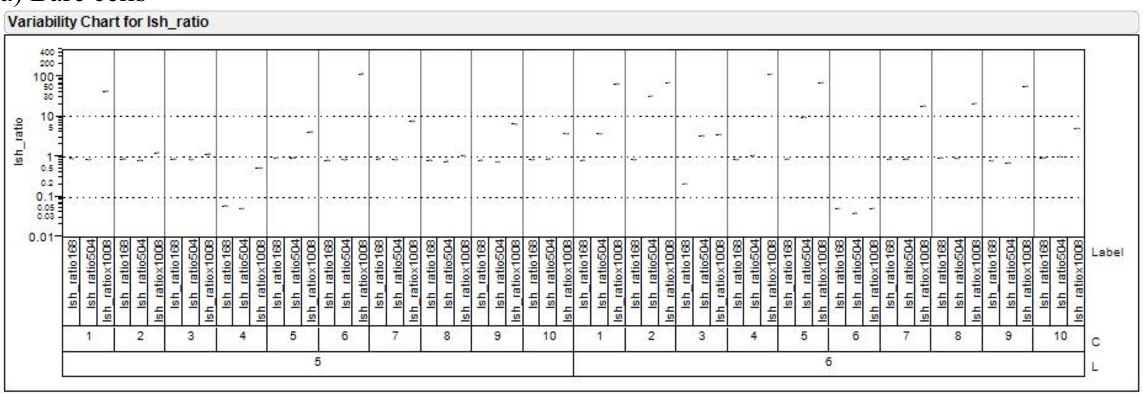


Figure 1. Relative ratio of FF before and after damp heat exposure for 100, 504, and 1008 hours for (a) bare cells, and (b) cells with encapsulation.

The dark IV (DIV) measurements were made using a Keithley 2601A. The performance metric chosen to evaluate DIV performance is the shunt resistance. The easiest measurement to report is the shunt current, Ish, measured at 2V bias (Voc is more than 3.4V). For good 3J solar cells, Ish is typically around 2uA at 2V (1 M-Ohm shunt resistance), and our manufacturing specification is no more than 100uA shunt current at 2V. Figure 2 shows the ratio of Ish after accelerated aging relative to the value at time equals to zero. Ten of the twenty bare cells showed at least a 10X increase in Ish, and six of the twenty showed more than a 50X increase in Ish and would fail our manufacturing specification. Only one of twenty encapsulated cells showed more than a 10X increase in Ish but would still pass our manufacturing specification. Upon closer inspection (see Figure 3), the encapsulated cell with lower performance had a bubble in the encapsulant that did not provide as much protection from the damp heat.

(a) Bare cells



(b) Cell with encapsulation

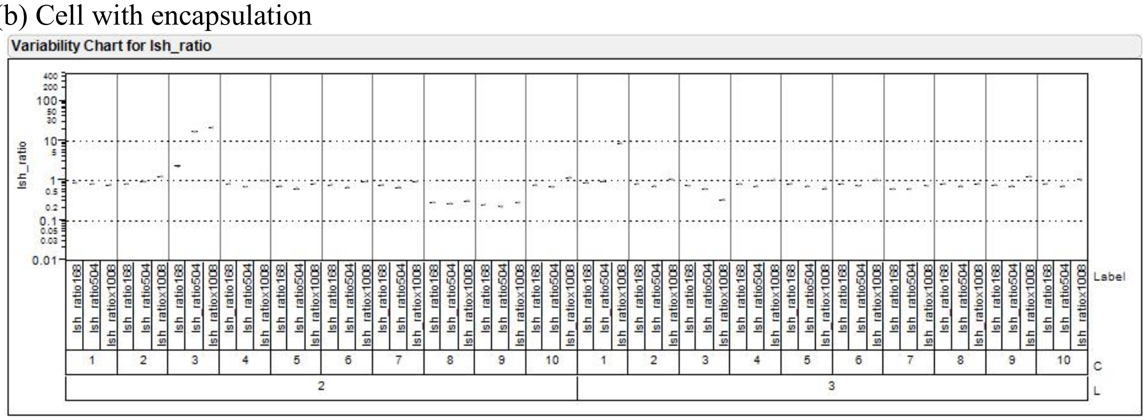


Figure 2. Relative ratio of the shunt current Ish (current at 2V bias) before and after damp heat exposure for 100, 504, and 1008 hours for (a) bare cells, and (b) cells with encapsulation.

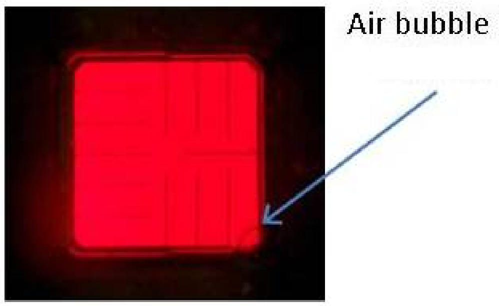


Figure 3. The only encapsulated solar cell that showed an increase in shunt current after 1008 hours of damp heat. Notice the air bubble in the encapsulant that did not provide as much protection from damp heat exposure. The cell appears red because it has been forward biased to approximately 100mA.

Subtask 10.2 – Accelerated aging of sealed modules - Completed

The milestone for this task is accelerated aging of a sealed module with subsequent IEC 62108 mechanical integrity tests. The module tested includes a silicone-on-glass primary lens, powder-coated steel enclosure, lens attach adhesive, junction box attached with potting, breather vent attached with a pressure-sensitive adhesive, and aluminum rails attached to the module with a structural adhesive. The module was subjected to 20 humidity freeze cycles based upon the IEC 62108 section 10.8 (85C option) at NREL.

Before and after the humidity freeze exposure, the modules passed all of the mechanical testing without any obvious signs of degradation. The mechanical testing was performed at Semprius. The robustness of termination (IEC 62108 section 10.12) was passed at 40 lbs in multiple loading conditions as shown in Figure 4. The testing was repeated after humidity freeze and all of the same loading conditions passed at 40 lbs.

(a) (b)

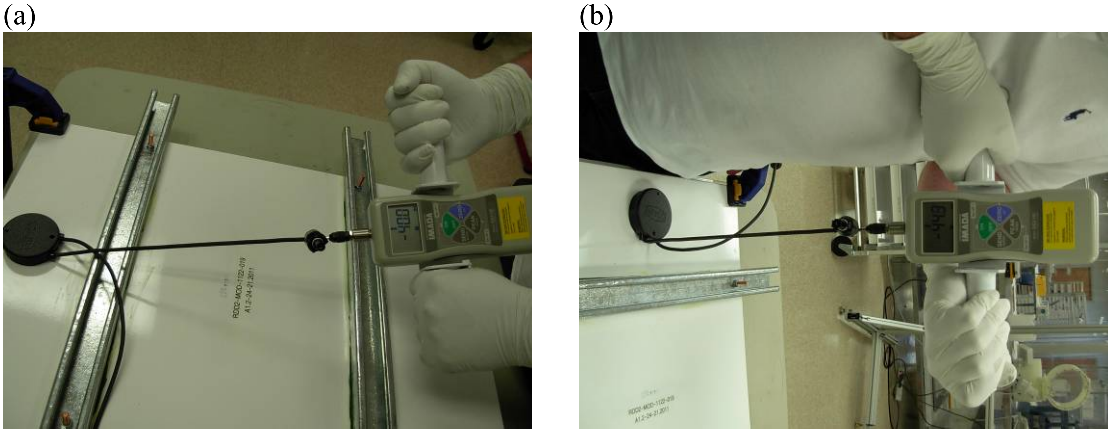


Figure 4. Robustness of termination testing to 40 lbs in (a) tension on the wire and shear on the jbox, and (b) tension on the wire and peel of the jbox. These test were passed both before (shown above) and after humidity freeze.

The mechanical loading (IEC 62108 section 10.13) of the module passed at 2400 Pa (0.35 psi) both before and after humidity freeze exposure. Continuity of the module was monitored every 20 seconds for 1 hour under top and bottom loading (see Figure 5) and repeated three times without any signs of failure. In addition, there were no visual indications of damage such as cracking, disbonding, or fracture. After the mechanical load test, the water spray test (IEC 62108 section 10.10) was performed (1hr in each of four orientations) and there were no signs of water penetration into the module.

(a) (b) (c)

Figure 5. Mechanical loading setup for the (a) top of the module, (b) backside of the module, and (c) after covering with a tarp and four 35-lb bags of sand.

Appendix A

The 2J cell efficiency of three cell-on-interposers (COI) was determined at NREL at 800X concentration, 25◦C and spectrum ASTM G173-03. The average cell efficiency was 31.5%. Figure 3 presents the efficiency versus concentration plots of one of the cells.

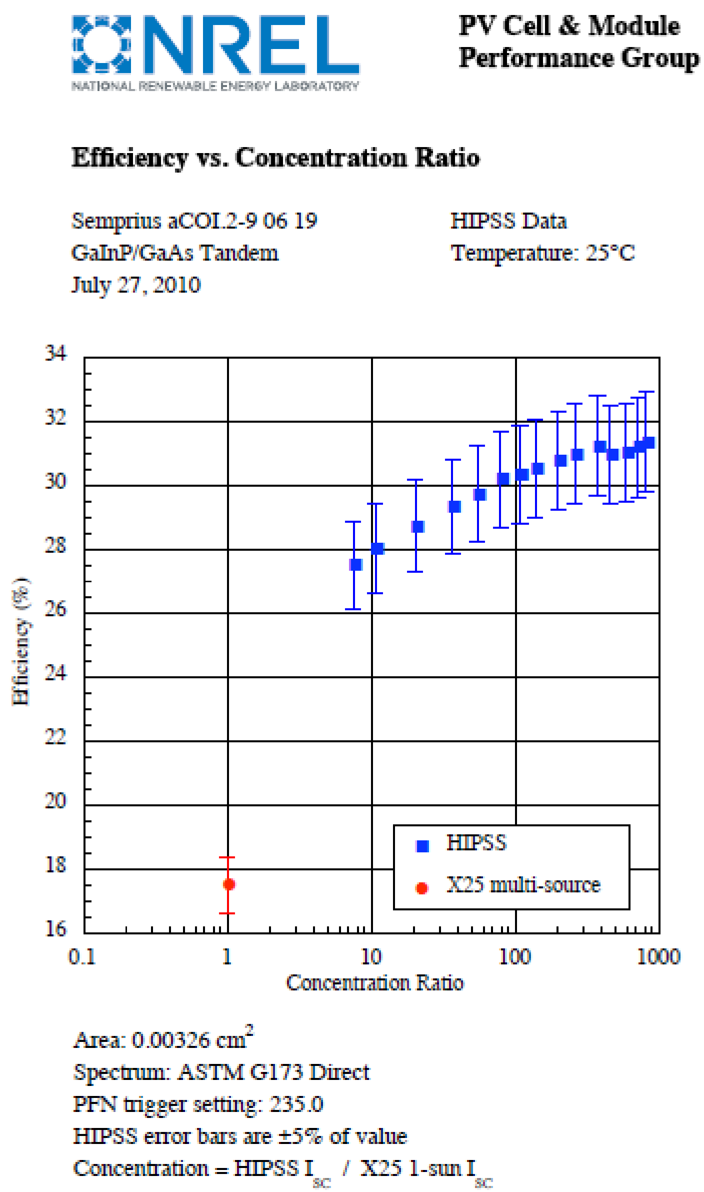


Figure 3: Representative efficiency versus concentration ratio plots for one of the cell-on-interposers.

Appendix B

Vendor A (growth run # 8559) and Vendor B (growth run SMPR01-1-5) provided dual-junction InGaP/GaAs solar cell material which was run together in Semprius fabrication run 2J.23. Figure 4 presents the quantum efficiency for solar cells produced by the two vendors. The plots show very similar spectral responses of solar cells produced by each vendor with the top InGaP cell response overlapping very well below 500nm suggesting that the top cell window layer, top cell emitter and top cell base are well matched. The top cell performance between 500-700nm is well matched and implies good matching of the InGaAlP back-side field and the InGaP base material ordering and quality. The GaAs middle cell response exhibited a slight difference in the magnitude of the quantum efficiency which is attributed to measurement variation.

Concentration measurements at multiple sites per wafer have been performed on three runs from Vendor A and three runs from Vendor B. Concentration measurements were performed using the unfiltered spectrum of a xenon arc lamp. The average efficiency of each of the runs exceeded the target of 27%. The results are presented in Table 3.

Table 3: Summary of Epi vendor qualification

Vendor	Run	Status	Efficiency *
Vendor A	8261	Completed	31.5%
Vendor A	8094	Completed	32.0%
Vendor A	8559	Completed	28.4%
Vendor B	3583	Completed	30.2%
Vendor B	3585	Completed	30.1%
Vendor B	2708	Completed	29.4%

*Efficiency is at 800X concentration and is the average of five samples

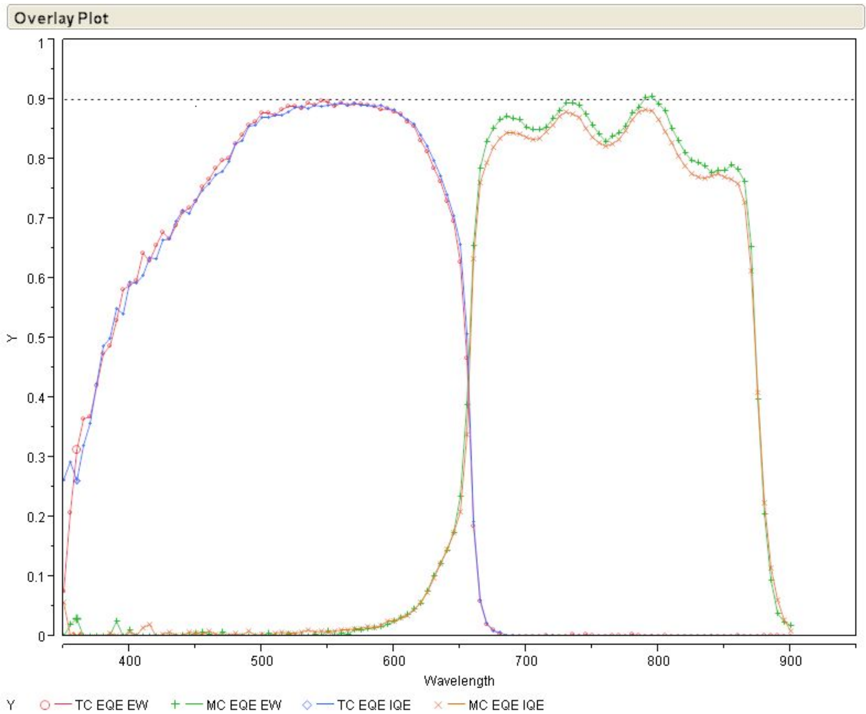


Figure 4: Quantum efficiency of solar cells from Vendor A and Vendor B in the same process run

Appendix C

One of the subcontractor's value propositions is the re-use of GaAs substrate multiple times, thereby reducing the cost of the substrate per Watt in high volume production. The milestone for this subtask is a comparison of the performance of devices from epi wafers with one re-use to the performance of devices from 1st use substrates.

The subcontractor reclaimed spent gallium arsenide wafers by chemical mechanical polishing and sent the reclaimed wafers for epitaxial growth. Epitaxy growth run # 8559 produced a dual-junction InGaP/GaAs solar cell stack on both first-use (i.e. virgin) substrates and second-use (i.e. reclaimed) substrates. The contractor fabricated solar cells from the epi-materials from run # 8559 on both first-use and second-use substrates. Figure 5 presents the quantum efficiency for solar cells produced on a first-use substrate and a second-use substrate. The measurements show very similar spectral responses of solar cells produced on each substrate type. Integrated against the AM1.5D spectrum, solar cells from each substrate type are limited by the current in the top InGaP cell. The integrated current in the top cell on the second-use and the first-use substrate are within the measurement error.

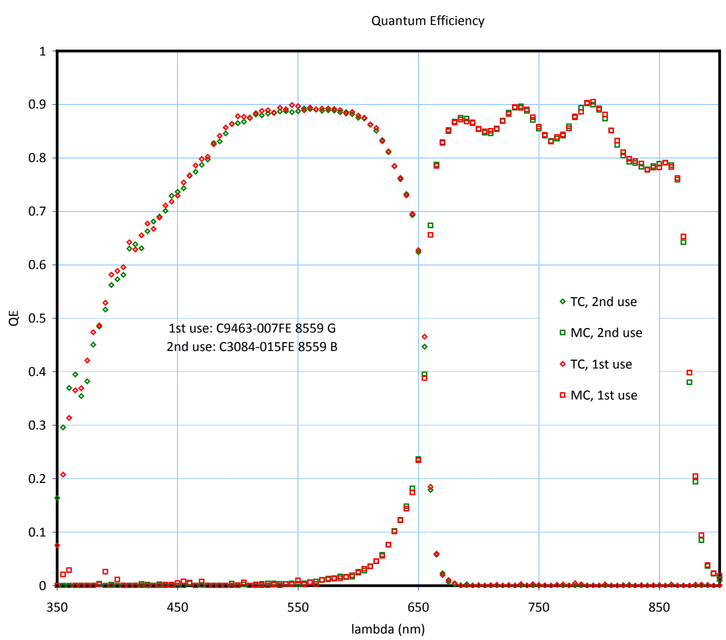


Figure 5: Quantum efficiency of solar cells on first-use and second-use substrates.

Figure 6 presents the results of concentration measurements of solar cells on first-use and second-use substrates, using the unfiltered spectrum of a xenon arc lamp. The results are equivalent, and within the measurement error.

The subcontractor performed micro-transfer printing and receiver fabrication using solar cells from first-use and second-use substrates. Modules were fabricated with these receivers. Figure 7 presents the performance of two modules, one built with cells grown on 1st use substrates and the other built with cells grown on 2nd use substrates. The operating characteristics of the two modules are nearly identical.

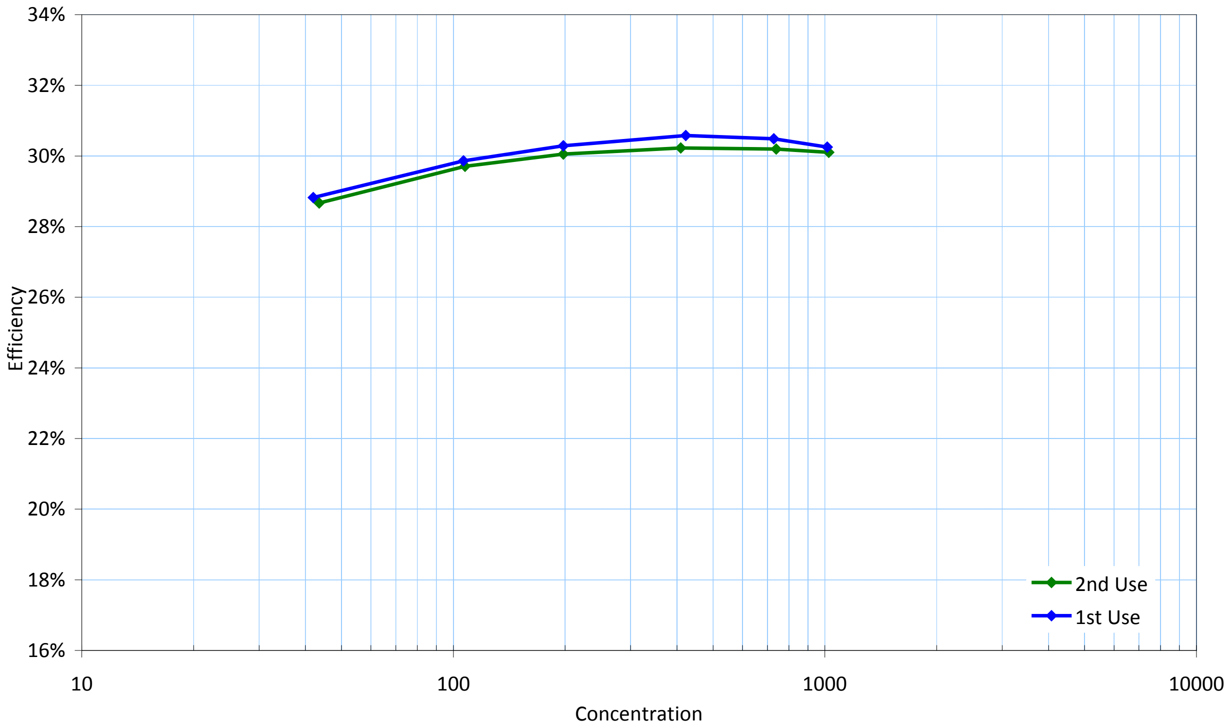


Figure 6: Efficiency versus concentration for solar cells on 1st and 2nd use substrates.

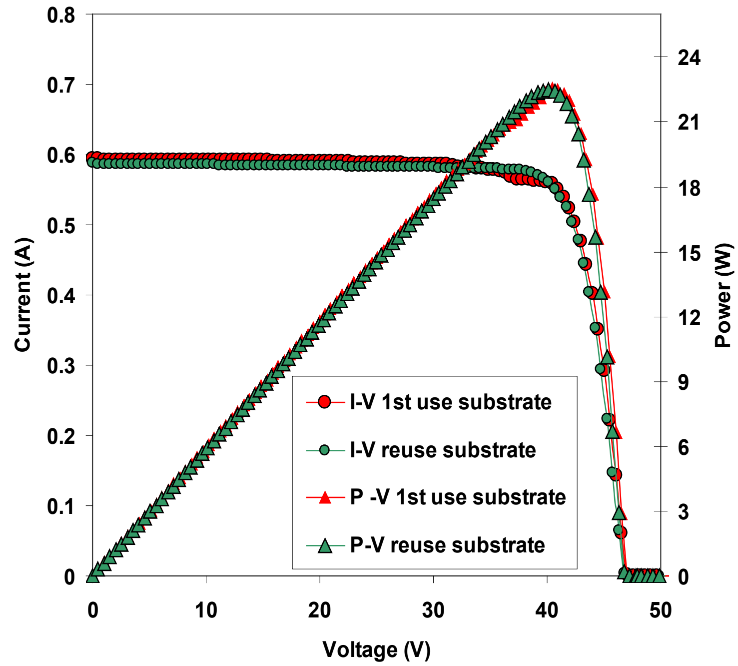


Figure 7: Operating characteristics of modules using first- or second-use substrates.

Appendix D

The milestone for this subtask was to demonstrate a printing process pick yield of > 90% for one COI lot. Pick yield is defined as: Pick yield = (# cells picked up by the stamp / # of cells available for pick up)*100. This milestone was met. Figure 8 presents pick yield data for Lot 27, which was a 10 wafer lot. The average pick yield for this lot was 99.6%, with the pick yield of each wafer being >99%. Figure 9 presents the pick yields of nine COI lots, consisting of 73 wafers. The average pick yield of these nine lots is 98.4%.

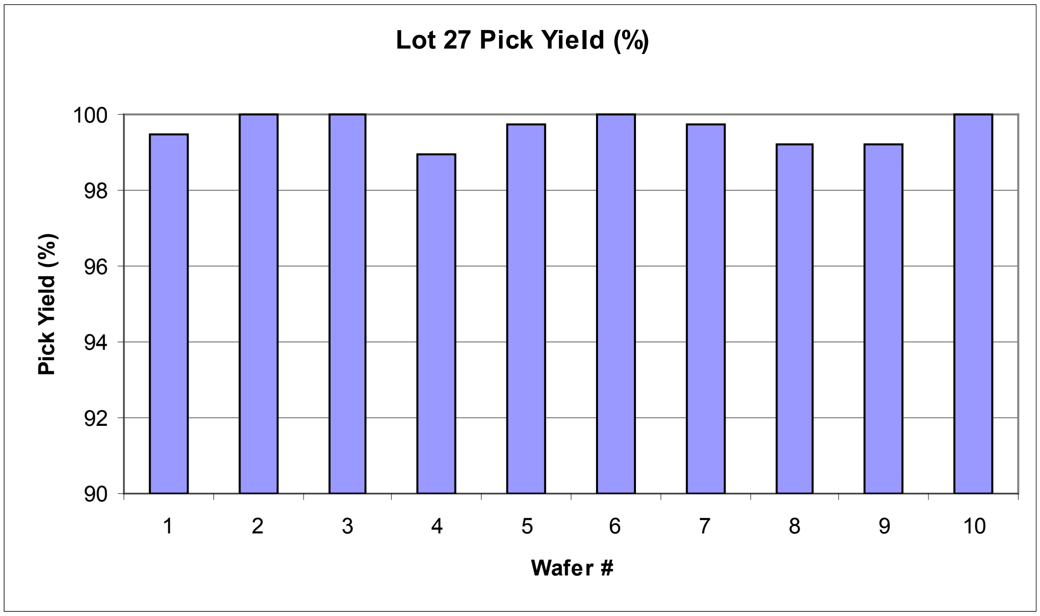


Figure 8: Pick yield for Lot 27.

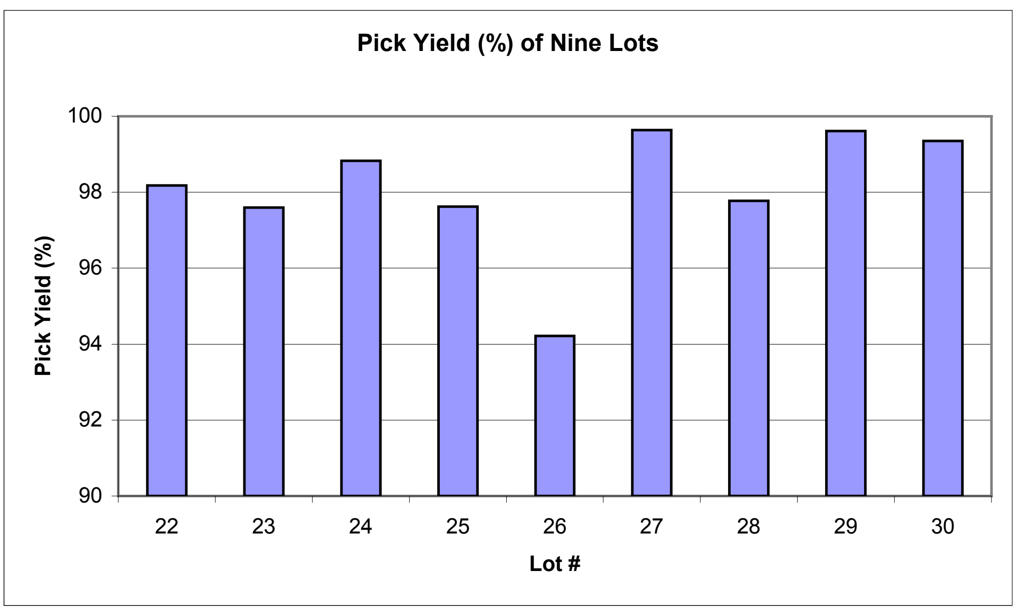


Figure 9: Pick yield for Lots 22-30.

Appendix E

The deliverable for this subtask was a 100 mm COI wafer with a transfer yield of >90% and a representative transfer yield report for one COI lot. The transfer yield is defined as: Transfer yield = (# printed cells on the target / # cells available for pick) *100 or alternatively, Transfer yield = (pick yield * print yield) / 100. One printed wafer with a transfer yield of 95.6% was delivered to NREL for verification. Figure 10 presents the transfer yield of lot 27, which was a 10 wafer lot. The average transfer yield of this lot was 95.5%. Figure 11 presents the transfer yield of nine lots, consisting of 73 wafers. The average transfer yield of each of these lots is 95.0%.

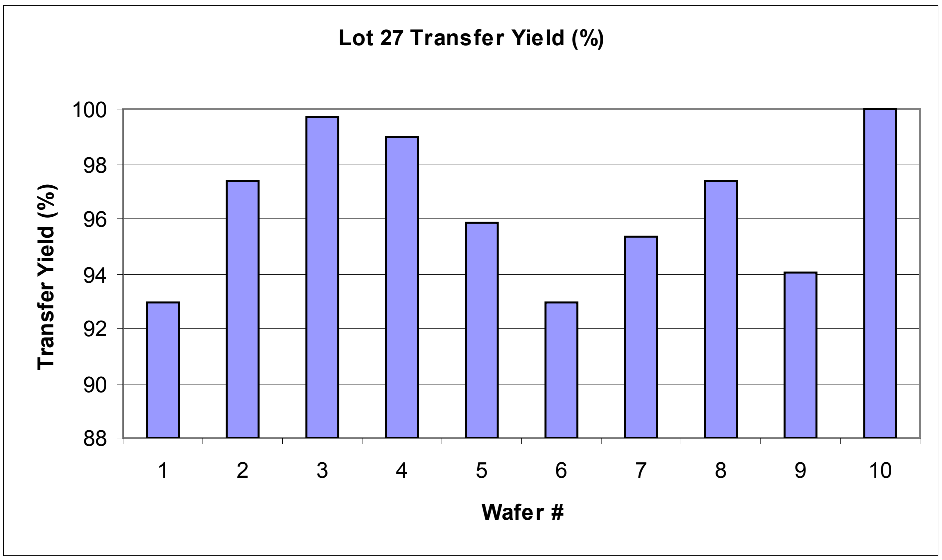


Figure 10: Transfer yield of lot 27.

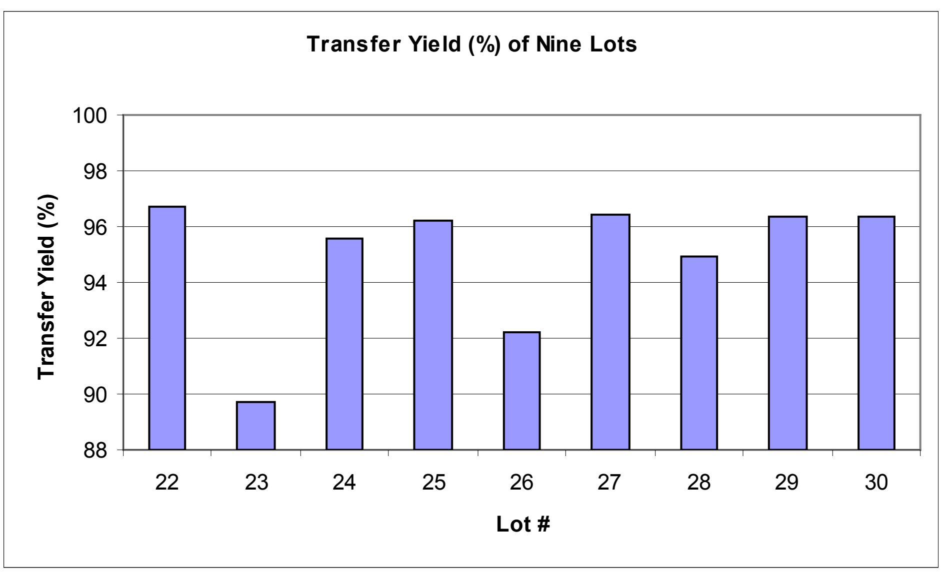


Figure 11: Average transfer yields of lots 22-30.

Appendix F

The milestone for this subtask is to run three cell-on-interposer (COI) lots on second generation (production) printing tools with an average transfer yield of 90% for 100 mm wafers. This milestone was completed and the average transfer yield of the three lots was 96.5%.

A total of 18 printed 100 mm alumina target wafers (3 COI lots) were used to demonstrate this milestone. Transfer yield data for target wafers processed on second-generation printing tools are presented in Figure 12. The average transfer yield for the complete data set was 96.5% (6608 cells printed onto 6840 sites), which exceeds the target of 90%. One target wafer, wafer 40-8, exhibited lower than 90% transfer yield. This was due to a source wafer defect from which cells were missing before the pick operation began.

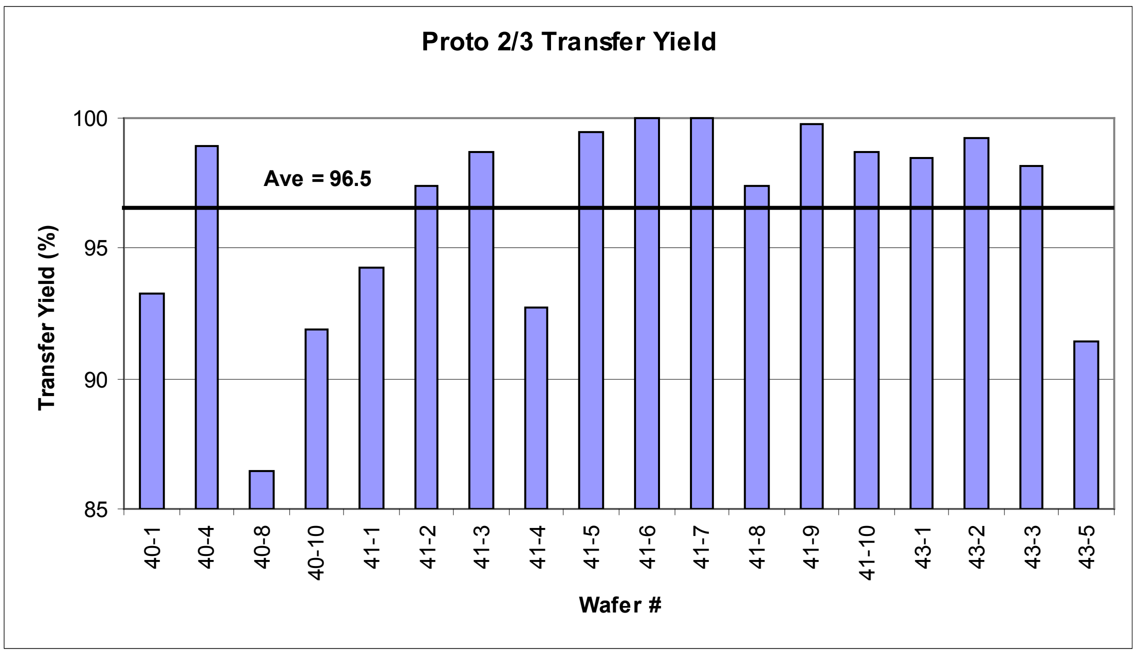


Figure 12: Transfer yield of 100 mm wafers, using Proto 2 and Proto 3.

Appendix G

The deliverable for this subtask is a 150 mm interposer wafer with more than 750 interposer die. This subtask was completed and one 150 mm interpose wafer with 1024 die was delivered to NREL.

As a first step, several 150 mm wafers with a 100 mm pattern were printed to demonstrate the ability to polish, laser ablate vias, screen metal paste and fire the larger wafers. Figure 13 presents a picture of this wafer, along with a 100 mm printed wafer. A new mask was deigned for 1024 dies on a 150mm wafer. This layout is presented in Figure 14.

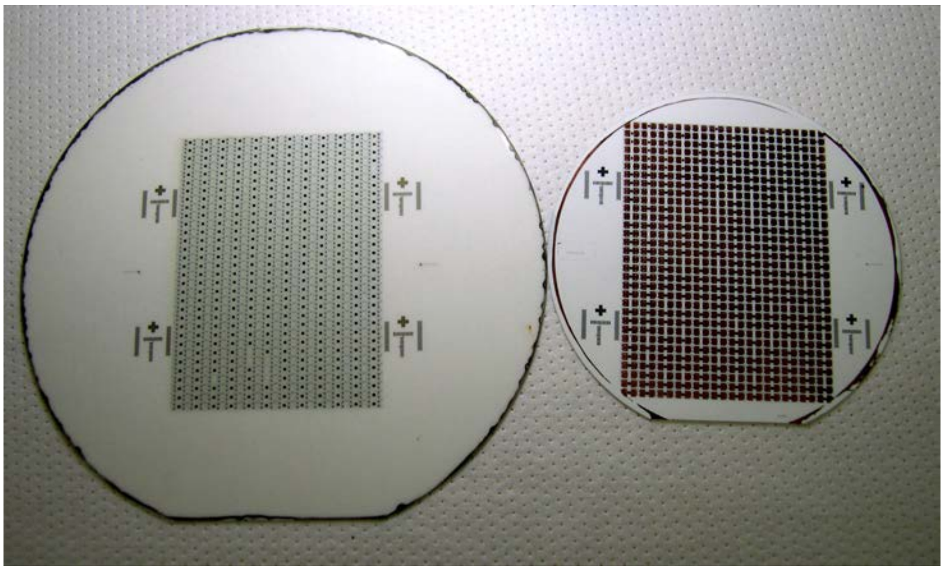


Figure 13: Photo of printed 150mm and 100 mm COI wafer.

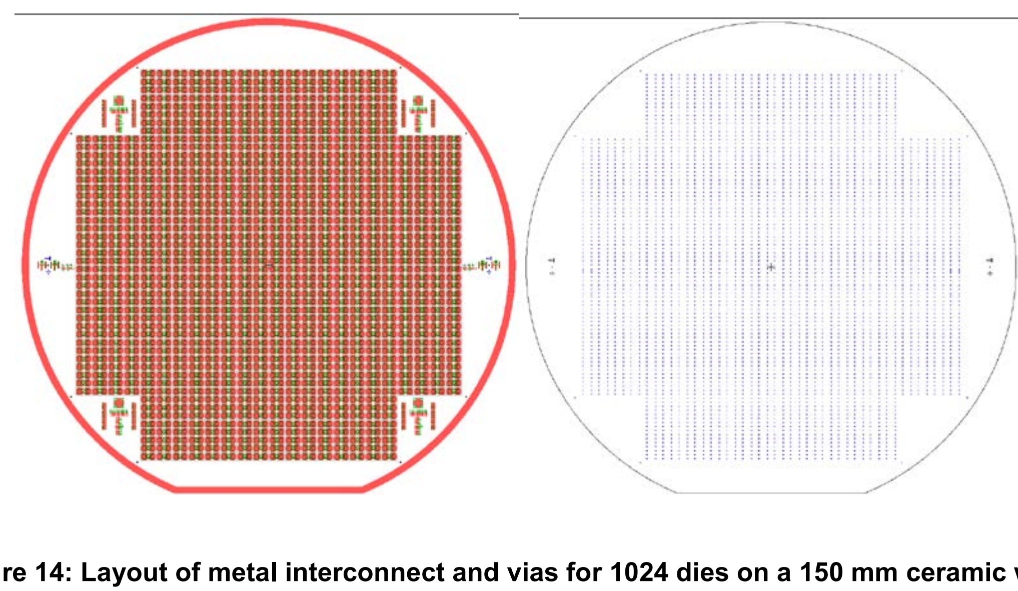


Figure 14: Layout of metal interconnect and vias for 1024 dies on a 150 mm ceramic wafer.

Appendix H

The milestone for this subtask is a demonstration of a 150 mm printed ceramic wafer with a transfer yield of >85%. Printing experiments on eight 150 mm ceramic wafers, each with 1024 printing sites, were performed to demonstrate this milestone. Transfer yield data for these eight wafers are presented in Figure 15. Printing on six wafers, 38-1 through 39-3, was performed in Proto 1 (1st generation printing tool) while printing on wafers 42-1 and 42-2 was performed on Proto 3, a second-generation printing platform. The transfer yield of the six wafers printed on Proto 1 averaged 99.0% while that of the two wafers printed on Proto 3 were 92.9%. The lower transfer yield observed on the new platform printer was determined to be caused by a stamp edge effect that removed solar cells from the target after they had been printed. This has been addressed. The average transfer yield of the eight printed wafers is 97.5% which exceeds the target of 85%. A photographic image of wafer 42-1 (printed on Proto 3) is shown in Figure 16. This wafer is populated with 965 cells out of 1024 sites (94.2% transfer yield).

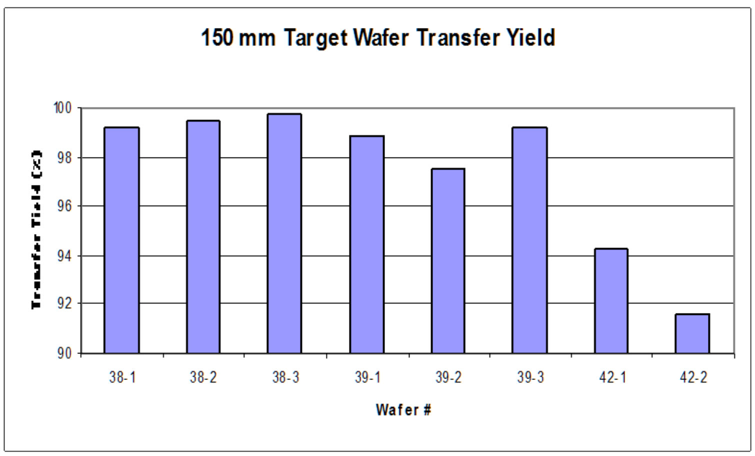


Figure 15: 150 mm Target Wafer Transfer Yield.

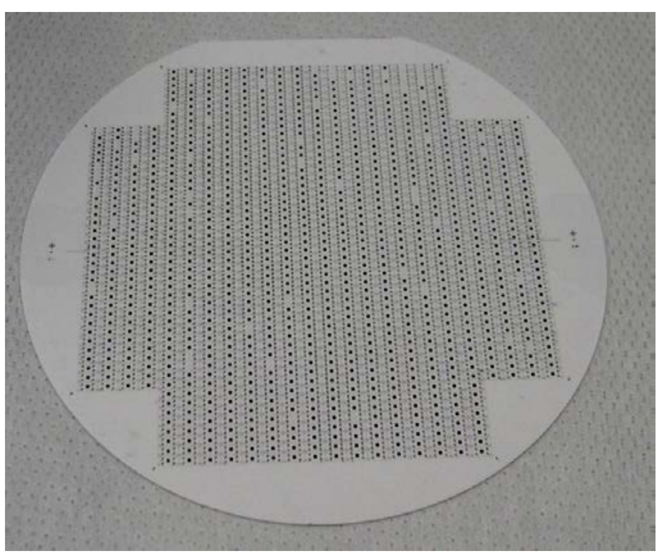


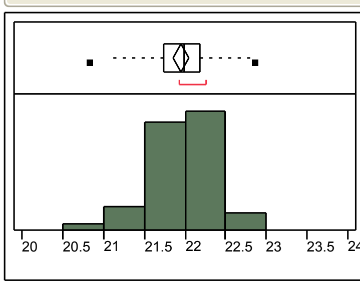
Figure 16: Photographic Image of Wafer 42-1.

Appendix I

The milestone for this subtask is documentation of a scalable module assembly process used to produce > 25 modules with module aperture efficiency of >20%. A scalable module assembly process was developed and refined for the manufacture of modules in a production-like manner. A revision-controlled traveler document was used to track the progress of each module through the assembly process. This document specified the parameters and/or related revision-controlled instruction documents for each step in the process flow. Completed travelers for each fabricated module are kept on file at Semprius for future reference. This exercise was the first step towards developing an automated high volume process for the manufacture of < $1/W modules. More than 50 modules were produced over a period of three months. Figure 17 presents the module efficiency distribution for 50 modules. The average module efficiency was 21.95% with all of them >20%. 95% of the modules were in the range 20.9% to 22.9%, suggesting that a tight module efficiency distribution in high volume manufacturing is achievable.

Distributions

Module efficiency, %



Quantiles

100.0%	maximum	22.8613
99.5%		22.8613
97.5%		22.8496
90.0%		22.2598
75.0%	quartile	22.179
50.0%	median	21.9893
25.0%	quartile	21.7422
10.0%		21.4887
2.5%		20.9166
0.5%		20.8406
0.0%	minimum	20.8406

Moments

Mean	21.950727
Std Dev	0.3632718
Std Err Mean	0.0513744
Upper 95% Mean	22.053968
Lower 95% Mean	21.847487
N	50

Figure 17: Module efficiency distribution.

Appendix J

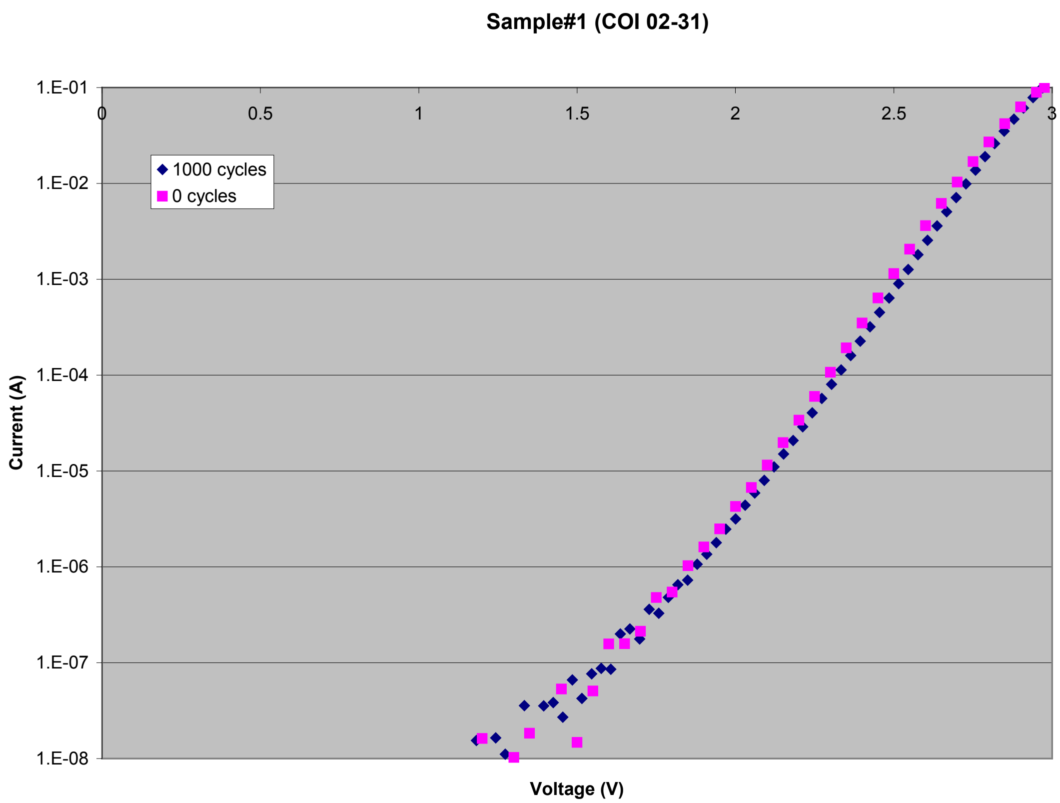
The milestone for this task is simultaneous thermal cycling of 10 receivers at NREL and at Semprius per IEC 62108, Section 10.6. Semprius has provided thermal cycling samples to NREL per the SOW and NREL has agreed to perform the testing with no further assistance from Semprius staff. This deliverable is completed since there were no performance metric associated with this task.

The receivers characterized at Semprius completed 1000 thermal cycles (-40 to 85C, IEC Section 10.6, TCA-1) in the 1st week of January, 2011. There were no electrical failures (opens or shorts) observed during forward biasing, which constituted approximately 5,000 on/off duty cycles. After completion of the thermal cycling, the performance of the receiver was measured relative to a control sample to quantify the relative power degradation due to the accelerated aging process. Table 5 shows the extracted light-IV parameters measured using an Oriel solar simulator. None of the receivers show any statistically significant change in performance after thermal cycling. The worst receiver (S9) dropped in performance by only 0.55% compared to the initial relative performance compared to the control sample. For reference, the IEC 62108 specification (Section 10.2.2.2) requires that the receivers can drop in performance no more than 8.0%, so all ten receivers passed the test.

Table 5: Power degradation of 10 receivers after 1000 thermal cycles, relative to a control sample

1000 Thermal Cycles (-40 to 85C)									
Sample ID	Pmax (mW)	Isc (mA)	Voc (V)	Imp (mA)	Vmp (V)	FF	Pr_initial (%)	Pr_final (%)	**P_degrade (%)**
Control	44.726	18.997	2.729	18.22	2.455	0.863	100.00	100.00	**0.00**
S1	46.789	20.09	2.723	19.793	2.364	0.855	103.50	104.61	**1.07**
S2	47.954	20.461	2.722	19.779	2.425	0.861	105.57	107.22	**1.56**
S3	44.928	19.385	2.728	18.531	2.425	0.850	100.22	100.45	**0.23**
S4	46.095	19.653	2.728	18.778	2.455	0.860	101.30	103.06	**1.74**
S5	46.7	20.131	2.724	19.024	2.455	0.852	101.30	104.41	**3.07**
S6	45.644	19.609	2.72	18.826	2.425	0.856	100.50	102.05	**1.54**
S7	45.972	19.821	2.719	19.7	2.334	0.853	101.35	102.79	**1.41**
S8	46.773	20.009	2.718	19.536	2.394	0.860	102.43	104.58	**2.09**
S9	44.66	19.162	2.719	18.421	2.424	0.857	100.40	99.85	**-0.55**
S10	45.018	19.585	2.717	19.044	2.364	0.846	99.29	100.65	**1.37**

In addition to the IEC 62108 specification, the shunt and series resistance of the sample was also monitored via dark-IV testing before and after thermal cycling. None of the samples after thermal cycling showed any significant changes in shunt or series resistance. Figure 18 shows examples of dark-IV sweeps from two samples before and after thermal cycling.



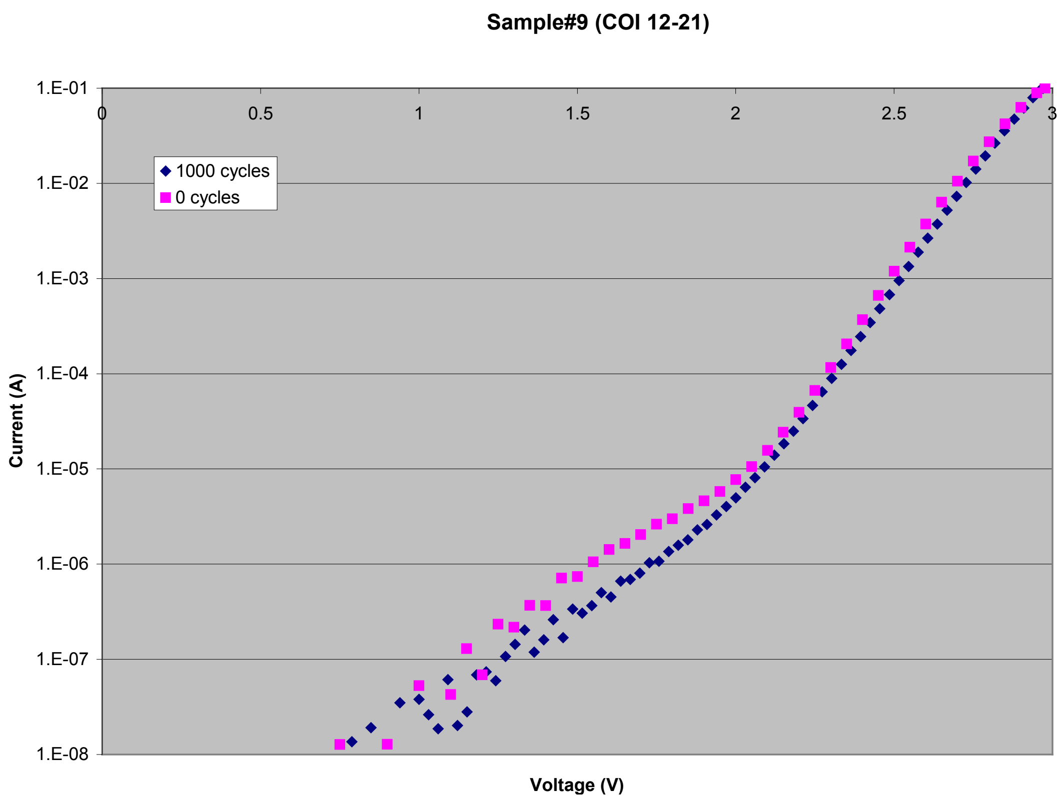


Figure 18: Dark-IV sweep before and after thermal cycling for two of the Semprius samples.

Appendix K

The 3J cell efficiency of three cell-on-interposers (COI) was determined at NREL at 800X concentration, 25˚C and spectrum ASTM G173-03. The average cell efficiency was 41.2%. Figure 19 presents the efficiency versus concentration plots of one of the cells. The report is available upon request.

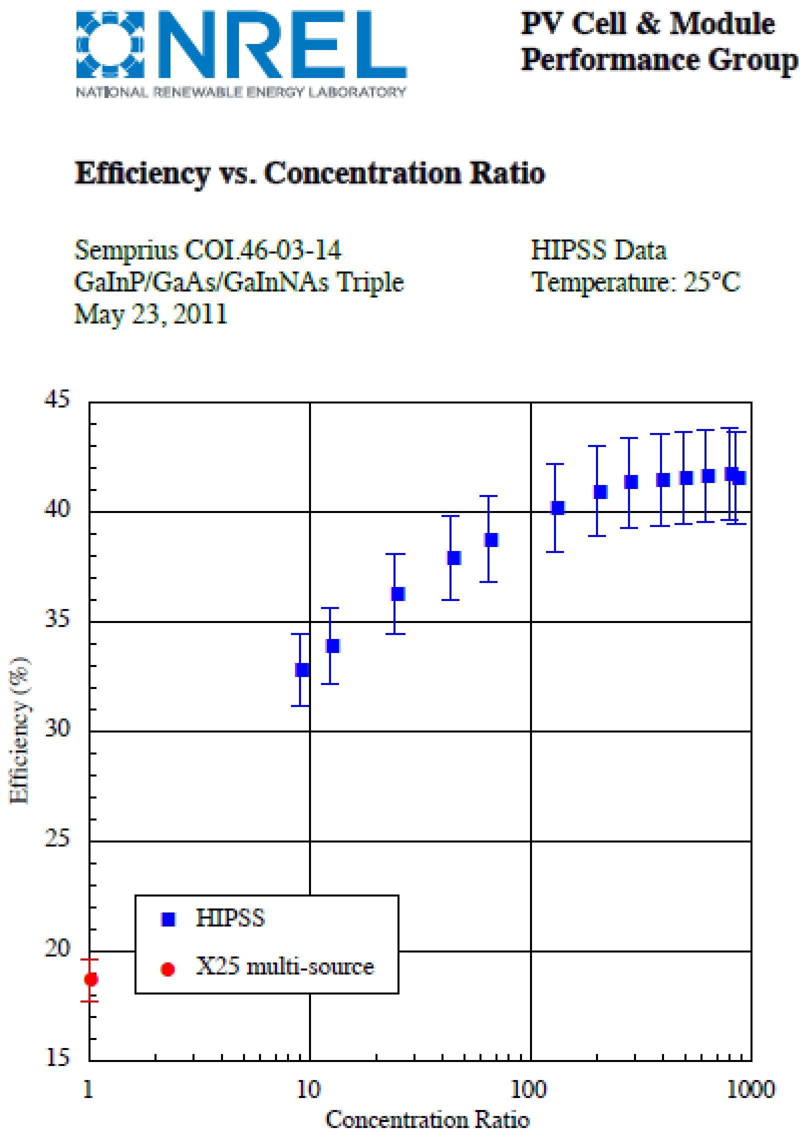


Figure 19: Efficiency versus concentration ratio of one COI.

Appendix L

	Wafer Fab	Module
Annualized Capacity (kW)	500	10
Power per Module (W)*	68.0	68.0
Modules per Qtr.	1,838	37
Modules per Mo	613	12
COI Device Yield*	72%	72%
Module Yield*	100%	100%
Interposer per Wafer	1024	1024
Cells per Source	6144	6144
Wafer Fab Hours per Year[+]	8640	8640
Assumed Availability[+]	85%	85%
COI Wafers per Hour	0.90	-
Source Wafers per Hour	0.15	-
Modules per Hour	-	0.02
COI wafer Run Rate required, min per wafer	66.9	-
Source wafer capacity required, wafers/year	1290.6	
Module Run Rate required, min per module		2996.4

*Current data, will be updated with new data
+ From SOW

Appendix M

Semprius Confidential Information Removed Intentionally

Appendix N

Semprius Confidential Information Removed Intentionally

Appendix O

One of the subcontractor's value propositions is the re-use of GaAs substrate multiple times, thereby reducing the cost of the substrate per Watt in high volume production. The milestone for this subtask is a comparison of the performance of devices from epi wafers with two re-uses to the performance of devices from 1st use substrates.

The subcontractor reclaimed spent gallium arsenide wafers by chemical mechanical polishing and sent the reclaimed wafers for epitaxial growth. The figures below present data for printed dual-junction InGaP/GaAs solar cells, grown on 1st use, 2nd use and 3rd use substrates. Figure 20 presents internal quantum efficiency curves for cells grown on the three substrates. The results are equivalent, within measurement error. Figure 21 presents the results of concentration measurements of solar cells on first-use, second-use substrates and third use substrates, using the unfiltered spectrum of a xenon arc lamp. The results are equivalent, within the measurement error.

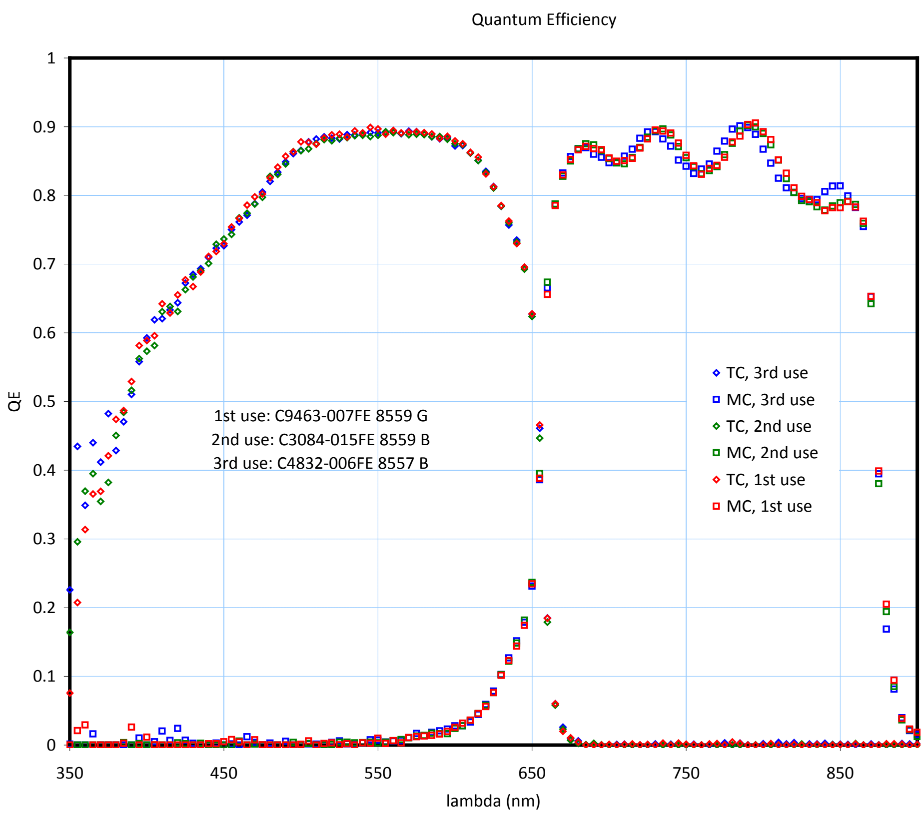


Figure 20: Quantum efficiency of solar cells on first-use, second-use and third-use substrates.

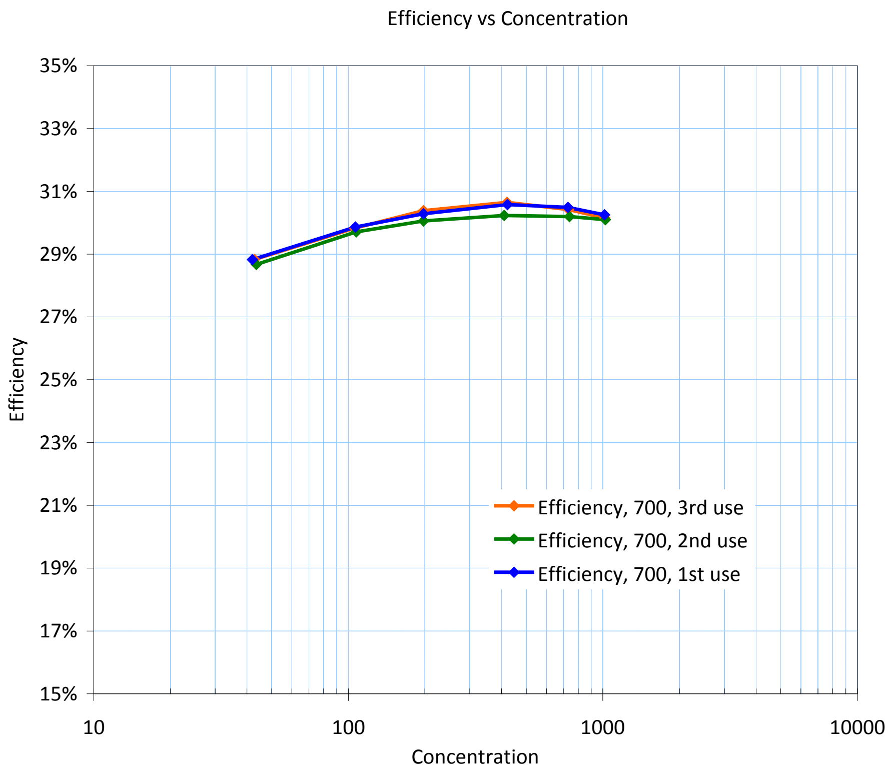


Figure 21: Efficiency versus concentration for solar cells on 1st, 2nd use and 3rd use substrates.

Appendix P

The milestone for this subtask is to report the maximum print array size and the results of the stamp size optimization process. The process-of-record Semprius CPV printing process employs a stamp that has a 4x8 post array within a 60mm diameter circular aperture. The post array has an x pitch = 4.890 mm and a y pitch = 2.475 mm. The active post area of this stamp is 254 mm2 (x dimension = 14.67mm; y dimension = 17.32mm). To determine the maximum printing area within the aperture, a stamp with post array extending to the edges of the full aperture was fabricated. This new stamp had a post array with the same x and y pitches as the POR stamp. Experiments were performed to determine the maximum print area of this stamp. Transfer printing parameters for the full post array stamp were the same as those used when printing with the POR stamp.

Figure 22 shows the results of printing 3J solar cells to a 150mm glass wafer. The solid box indicates the reported area using the full post array stamp. An overall area covering an 8x13 array was demonstrated. The four missing cells in the last column were correlated to missing cells on the source wafer. The overall area of this printed array spans 1016 mm^2 (x dimension = 34.23 mm; y dimension = 29.7 mm). This area is larger than that of the POR stamp printable area, shown in the dotted box, by a factor of four. The stamp aperture size is shown in the dashed circle enveloping the printed cells.

It was observed that cells near the edges of the stamp aperture were not transferred. Some of these cells were in fact not picked from the source wafer. In an effort to understand the potential size of the pick field, a second experimental stamp fabricated with a full post array extending to the edges of a 95 mm aperture was used for transfer printing experiments. Figure 23 shows experimental results of printing 3J solar cells to tape using this stamp. The transfer printed cells span a region of 53.8 mm in the x dimension and 79. 2 mm in the y dimension. This corresponds to the full area of the source wafer used for this printing experiment. Though the transfer yield was not 100% (missing sites and multiple cells are seen in regions of the print field), this demonstration indicates that a transfer printing area on the order of the source wafer dimensions is feasible.

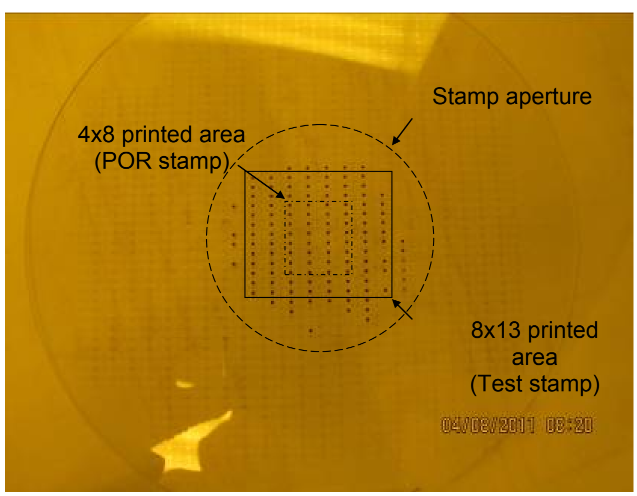


Figure 22: Photo of transfer printing results using full post array stamp (60mm aperture) – 3J cells to 150 mm glass wafer.

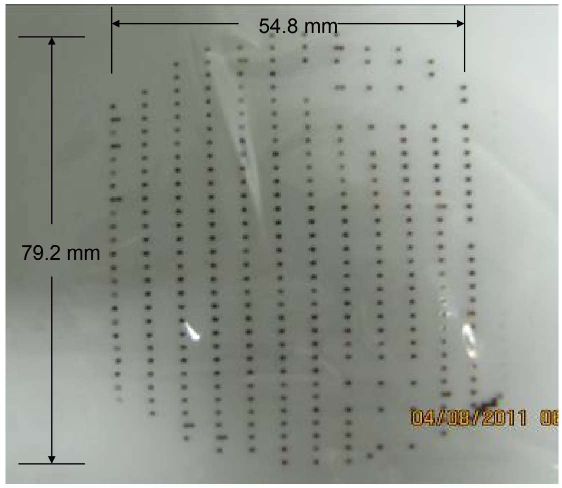


Figure 23: Photo of transfer printing results using full post array stamp (95mm aperture) – 3J cells to tape.

Appendix Q

The deliverable for this subtask was a 150 mm COI wafer with a transfer yield of >95% and a representative transfer yield report for one COI lot. The transfer yield is defined as:

Transfer yield = (# printed cells on the target / # cells available for pick) *100 or alternatively,

Transfer yield = (pick yield * print yield) / 100.

One printed wafer with a transfer yield of 96.4% was delivered to NREL for verification. Figure 24 presents the transfer yield of 29 wafers for 5 COI lots. The average transfer yield of these wafers was 96.9%. These 29 wafers were processed using 3-junction source wafers, and were printed on Proto 2 or Proto 3.

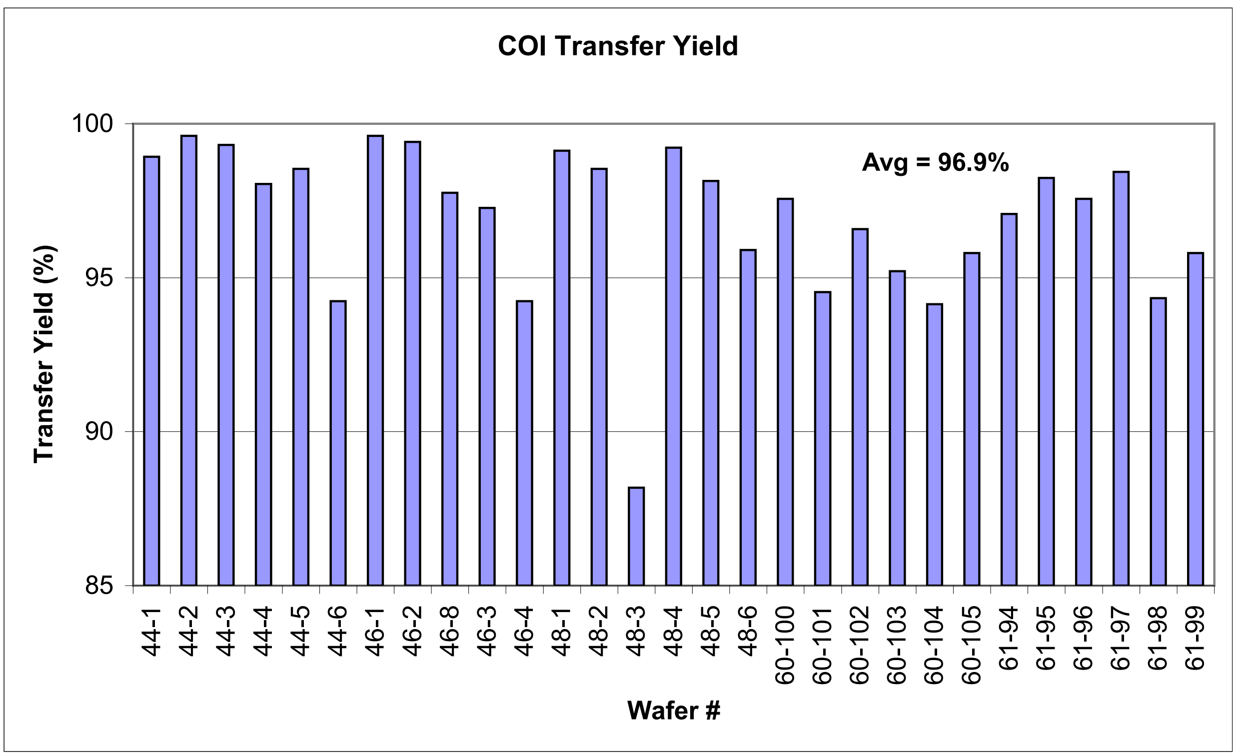


Figure 24: Transfer yield of 150 mm wafers, using Proto 2 and Proto 3.

Appendix R

The data collection form that will be used to collect throughput data on each process step is given below. This throughput data for each process step will be summarized in a table.

		Process	Tool	Run Time (min)	# of wafer processed	Throughput
1	Ops	Lot Start	N/A			
2	Wet	Solvent Clean	Solvent Hood			
3	Films	O2 Descum	Asher			
4	Photo	Adhesive Coat	Coater			
5	Photo	Cure	Inert Gas Oven			
6	Films	Evaporate Cr	Evaporator			
7	Films	O2 Descum	Asher			
8	Photo	Coat, SC-1827	Coater			
9	Etc.	Etc.				

Semprius Throughput Data Collection Form

Date: ________

Initials: ________

Process Step: ____________________

Tool: ____________________

Lot ID: ____________________

# of wafers: ____________________

Start time: ____________________

End time: ____________________

Process time (minutes): 0

Step Throughput (wafers/hour): ____________________

Semprius Approval:

____

Appendix S

Module efficiency was determined at NREL at ASTM 2527 test conditions (850 W/m2 DNI, 20°C ambient temperature, wind speed <4 m/s), and using the ASTM 2527 regression. The module aperture efficiency was found to be 28.3±1.7%. The IV plot and parametric data is presented in Figure 25.

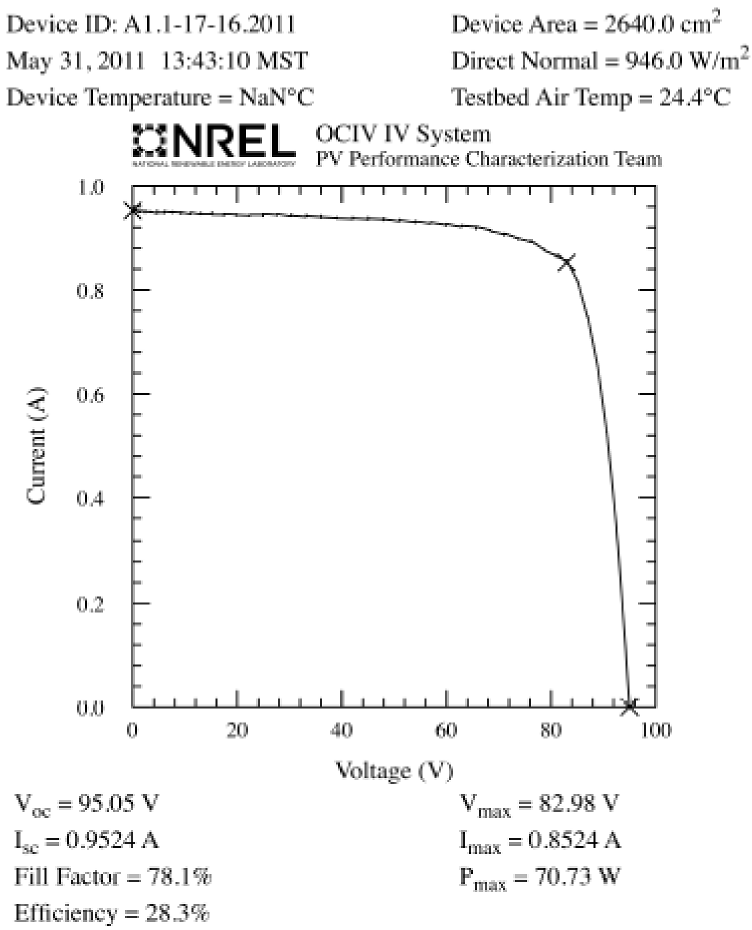


Figure 25: IV curve of module tested at NREL, and parametric data.

Appendix T

Figure 26 presents the energy yield in kWh_{ac} per kW_{dc} installed for twelve months of operation of the first RD&D system installed at Tucson Electric Power. The annual energy yield of the system was 2500 kWh/kW. The primary goals of this field testing were validation of the technology and assessment of long term performance. The modules from this system have now been replaced by recent 3-junction Alpha modules. Figure 27 presents the AC efficiency of RD&D-2. This system was installed in September, 2011 and was the first system based on the pre-commercial Alpha design.

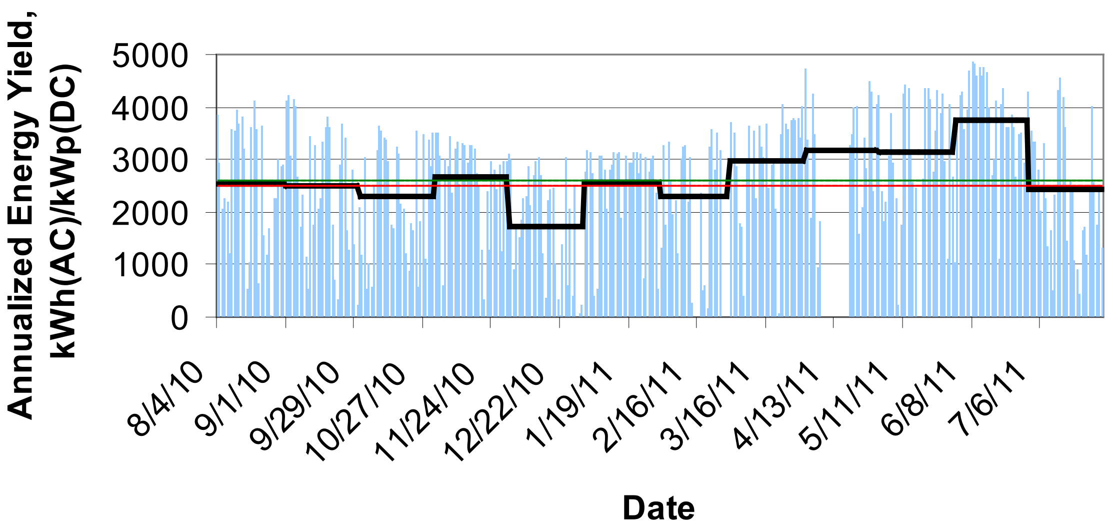


Figure 26: Energy yield of the 1 kW RD&D system at TEP.

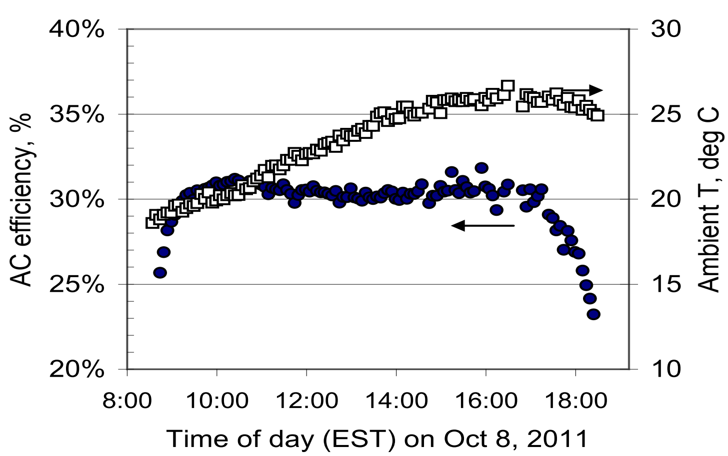


Figure 27: AC efficiency of the recent 2.8 kW RD&D-2.