National Renewable Energy Laboratory
Innovation for Our Energy Future
A national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy

Cost and Reliability Improvement for CIGS-Based PV on Flexible Substrate

26 September 2007 – 25 September 2008

S. Wiedeman
Global Solar Energy, LLC
Tucson, Arizona

Subcontract Report
NREL/SR-520-45213
March 2009

NREL is operated for DOE by the Alliance for Sustainable Energy, LLC
Contract No. DE-AC36-08-GO28308

Cost and Reliability Improvement for CIGS-Based PV on Flexible Substrate

26 September 2007 – 25 September 2008

Subcontract Report
NREL/SR-520-45213
March 2009

S. Wiedeman
Global Solar Energy, LLC
Tucson, Arizona

NREL Technical Monitor: Harin S. Ullal

Prepared under Subcontract No. ZXL-6-44205-13

National Renewable Energy Laboratory
1617 Cole Boulevard, Golden, Colorado 80401-3393
303-275-3000 • www.nrel.gov

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency and Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

Contract No. DE-AC36-08-GO28308

This publication was reproduced from the best available copy
Submitted by the subcontractor and received no editorial review at NREL

NOTICE

This report was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or any agency thereof.

Available electronically at http://www.osti.gov/bridge

Available for a processing fee to U.S. Department of Energy
and its contractors, in paper, from:
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone: 865.576.8401
fax: 865.576.5728
email: mailto:reports@adonis.osti.gov

Available for sale to the public, in paper, from:
U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
phone: 800.553.6847
fax: 703.605.6900
email: orders@ntis.fedworld.gov
online ordering: http://www.ntis.gov/ordering.htm

Printed on paper containing at least 50% wastepaper, including 20% postconsumer waste

Executive Summary

Leveraging the experience gained in successfully developing and operating a 4.2$MW_{p/}$yr CIGS production line for several years, Global Solar Energy initiated an ambitious scale-up plan in 2006. Now in the final stages of the first phase of the plan, 75MW_p/yr of combined manufacturing capacity is being installed at new production facilities in Tucson, AZ and Berlin, Germany. The physical plants in both Tucson and Berlin are complete, facilitated and capable of self-sufficient and independent operation with trained personnel now in place. All of the tool sets required for planned Phase 1 operation are complete in Tucson, and nearly complete in Berlin.

While the scale of the plant expansion is rapid, the new production tools represent an evolutionary progression of the Global Solar CIGS technology. Manufacturing cost has been reduced by increased automation, higher materials utilization, and greater capacity with higher rates in all tools. These advancements garner reduced capital expense, a smaller factory floor area requirement, and greater productivity in addition to reduced direct product cost. During Phase 2 of this TFPPP subcontract the production lines were completed with the "Gen2" equipment for these new factories, and the processes were brought on line. Successful transfer of the processes from the existing "Gen1" equipment was assured through exhaustive cross-testing and measurement using both "Gen1" and "Gen2" equipment during the transition. Significant process optimization at the higher production rates of the "Gen2" equipment and cost reduction as embodied in the goals of this subcontract have been accomplished during this phase of the TFPPP subcontract, as described in this report. Product reliability and product design for durability has also been a successful focus of the effort in Phase 2 of TFPPP.

Table of Contents

List of Figures

List of Tables

Task 1: Enhanced Module Reliability **(Objectives)**

1. Identify, characterize and quantify degradation and failure mechanisms in the PV stack and cell interconnect as well as encapsulation structure and complete module package.
2. Design meaningful stress tests for flexible and rigid thin film CIGS modules.
3. Develop a finite element model predicting mechanical post-lamination stresses at module operating conditions (daily and seasonal temperature cycles).
4. Explore solutions to eliminate failure & degradation mechanisms via process changes, advanced alternate encapsulation, protective coatings, structural elements and complete package.
5. Verify and optimize long-term product reliability.
6. Improve product appearance and cost.

Rigid Product - Testing and Reliability

Glass-based product usually exhibits better outdoor stability than flexible PV product, as the glass itself is impervious to moisture and oxygen ingress. However, potential degradation mechanisms do exist for glass-based product, and stability must be carefully evaluated to achieve the required 20-40 year service life. Outdoor field tests and accelerated tests are important to determine durability, failure modes and their causes. [1]

At an installation in Springerville, AZ a variety of PV products have been installed and are monitored for daily performance over the long term by Tucson Electric Power (TEP). The earliest CIGS PV using glass-glass fabrication by GSE continues to generate power in the original array, with no replacements or drop-outs of individual modules. The performance over increasing time has shown substantially stable behavior, although recent data is unavailable due to the failure of a large transformer connecting the inverter to the grid. TEP has advised that they plan to replace the failed transformer and restart data collection.

One potential failure mechanism for glass-based PV is moisture and O_2 ingress at the edges of the module. Various “edge seals” have been considered to avoid this effect. An evaluation of the selected edge seals was conducted on strings laminated in glass/backsheet modules. Edge seals were applied to six test modules, and six additional test modules that were otherwise identical were used as controls. Modules were qualified by light-soaking outdoors for three days followed by pulsed-light measurement. Module efficiencies at this stage ranged between 8.3% and 9.9%. All modules were stressed in damp heat and periodically removed for measurement followed by six hours of light-soaking and re-measurement. After 1960 hours damp heat treatment, the samples with edge sealant were on average unchanged in power from their starting power, while the mean power from the controls degraded to approximately 94% of their starting power. The difference between the two sets was statistically significant with 90% confidence. The two sets primarily differed in open-circuit voltage. The results were interpreted to indicate a real effect that justifies further investigation for edge seals. The results are shown graphically in Fig. 1.1.

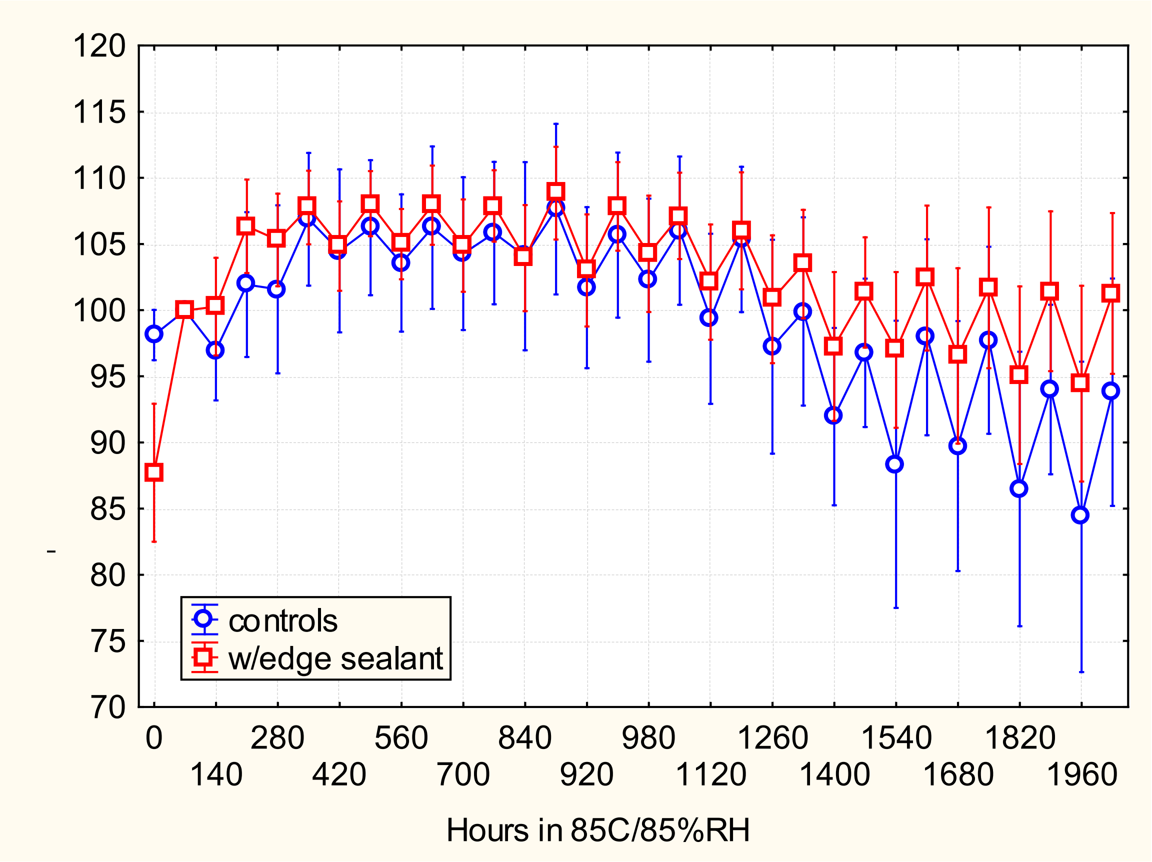


Figure 1.1. *The mean relative power output of 2 groups modules (with and without edge sealant) vs. exposure time in damp heat (85/85). The regular point-point, low-high variation during the measurement is due to sequential measurement before, and then after light soaking upon each removal from the damp-heat exposure.*

The potential impact of voltage bias, and possible interactions with corrosion mechanisms as a mode of degradation has also been studied at GSE. Modules stressed in damp heat (85°C/85%RH) were maintained in the dark under open-circuit conditions. A test was conducted to determine if modules stressed in damp heat under forward bias are subject to accelerated corrosion and failure. This information is valuable for better understanding module reliability under actual operating conditions. It has been frequently observed that modules stressed by damp heat require a period of light-soaking for maximum power output. Consequently, another goal of the test was to determine whether continuous forward-bias during accelerated testing had an affect on light-soaking characteristics.

When no clear difference in response due to bias in the dark under accelerated (85/85) conditions were noted, the test was repeated for longer times, nearly 2000 hours) to look for accelerated corrosion or related failure. The mean Pmax of modules in each group is shown in Fig. 1.2. Modules that were forward-biased during damp heat stress were found to deteriorate more slowly than non-biased modules. The results were statistically significant to greater than 99% confidence.

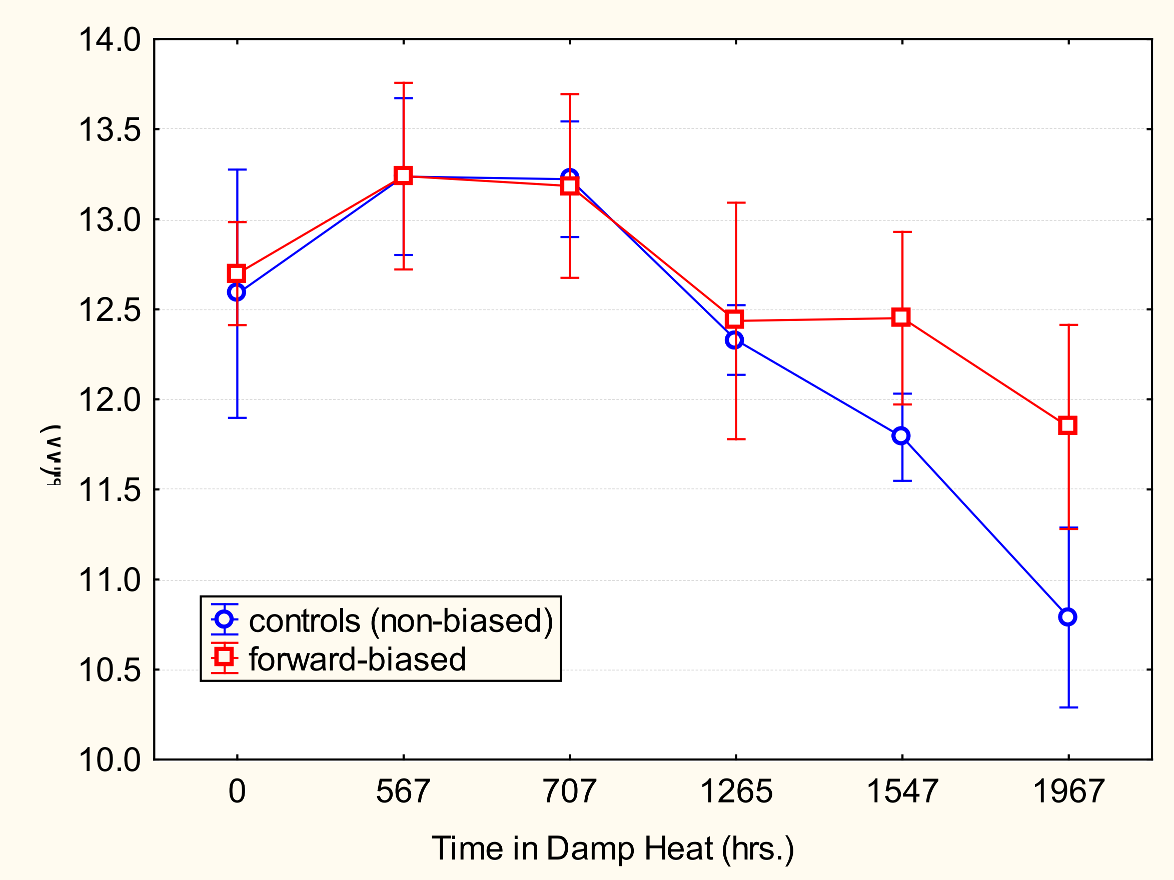


Figure 1.2. *Mean P_{max} of modules packaged in glass/backsheet; forward-biased near V_{max} and controls (non-biased) in damp heat testing in the dark.*

Since electrochemical corrosion mechanisms are driven by differences in potential, failure mechanisms may be different in light as compared to dark conditions. Other studies were conducted at GSE to determine the impact of corrosion under illuminated conditions using accelerated tests.

Twelve glass modules were fabricated and randomly assigned to two groups. Modules in one group were maintained at their individual Vmax (under AM1.5 illumination) during damp heat (85/85) treatment. Modules in the second group were not voltage-biased. After 560 hours of treatment, no statistical difference was observed between the two groups (Fig. 1.3). However, the two groups differed in their response to light-soaking following each treatment interval. Modules maintained at forward bias declined in Pmax by 1-4% upon lightsoaking. Modules not biased generally increased in Pmax upon lightsoaking, and the magnitude of improvement increased with increasing treatment time. In any case, no difference in light-soaked performance under standard conditions was noted in the two groups held at different voltage biases under illumination in this accelerated test.

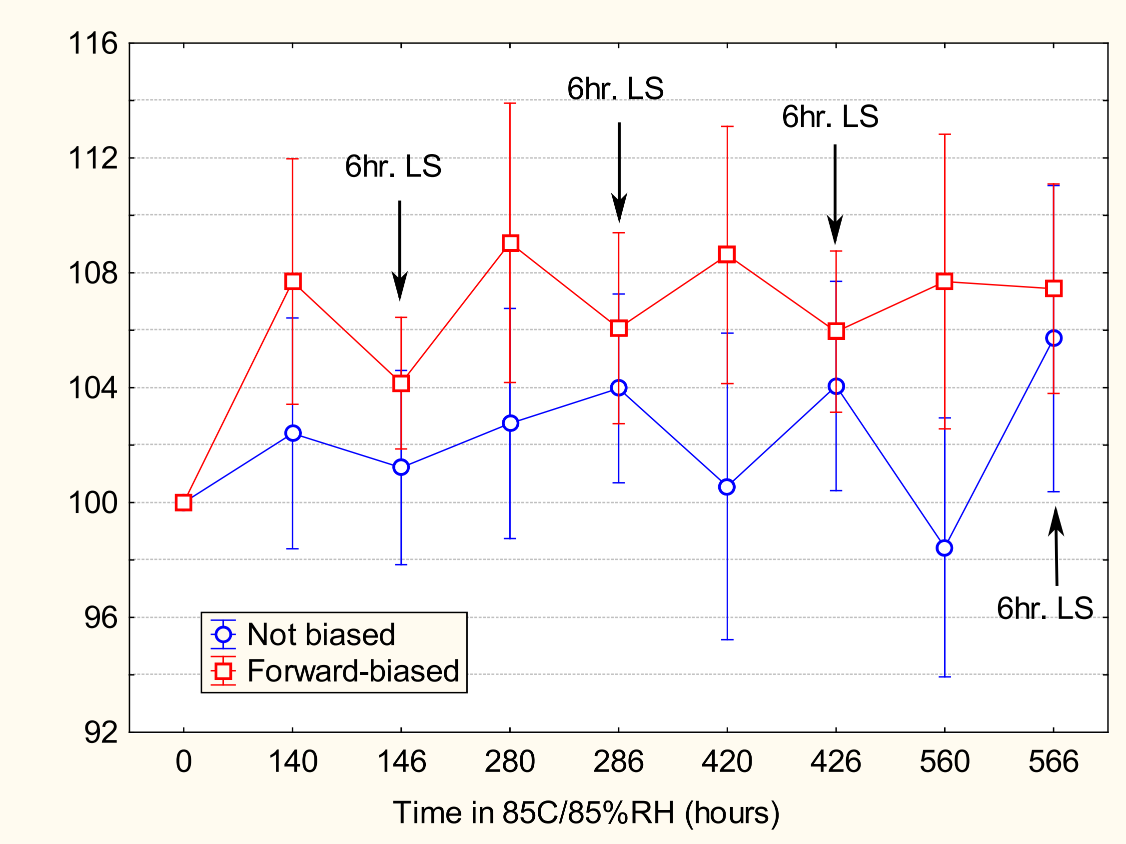


Figure 1.3. *Mean relative Pmax of CIGS strings laminated in glass, non-biased and biased at* V_{max}*, during damp heat treatment.*

Other testing at GSE included special test structures that were developed to evaluate the reliability of the cell interconnects within strings or modules. The focus of this evaluation was finding changes in series resistance. Test structures were exposed to thermal cycling and damp heat. Variable results were obtained and further experimentation is required for better understanding.

Changes in construction materials or processes used for module fabrication usually demand reliability testing, so reliability tests were initiated for strings of cells fabricated using a new TCO process for instance, to confirm the absence of ill effects. Generally, cells or modules made with the standard process and materials are used as “controls” for comparison to results from the “new” process or method using accelerated testing (usually 85/85 damp heat testing). Other examples of the rigor required for process changes include the tests done for new materials for electrically connecting cells, which were procured and evaluated against the standard material for adhesion and module performance, before and after stress testing.

Long-term testing of strings and modules stored in inventory was also initiated.

Rigid Product – Determination of Thermal Coefficients for IV Parameters

Thermal coefficients for IV characteristics were measured for glass modules fabricated from Gen2 strings. The evaluations were conducted outdoors under cloudless conditions. A portable IV tester, calibration cell, and a transparent window box (to limit wind cooling) were utilized. Module temperature was monitored by an adhesive thermocouple attached to the back of the module. Utilizing specially-fabricated structures, tests were conducted to determine the temperature differential between a thermocouple mounted directly on the back of the string and the exterior surface of the backsheet. The difference was found to be less than 2°C. Average thermal coefficients are shown in Table 1.1.

Table 1.1. Thermal coefficients for Gen2 strings in glass modules

Vmax (%/C)	Imax (%/C)	Pmax (%/C)	Voc (%/C)	Isc (%/C)	FF (%/C)
-0.49	-0.13	-0.59	-0.39	0.03	-0.24

Flexible Product - Testing and Reliability

Several new fabrication methods for flexible PV product, using various approaches for interconnecting cells were evaluated outdoors for their application in flexible modules. Six modules of each stringing approach (A-C) were fabricated into ~7W, 10% efficient flexible modules; a standard GSE product design. The modules were deployed outdoors in early summer in Tucson. One group experienced extreme power degradation (C), a second group experienced rapid degradation followed by slow degradation to 85% of initial power (B), and a third group (A) varied somewhat during the period but generally maintained output without degradation (Figure 1.4). The degradation of groups B and C was dominated by fill factor reduction. Analysis of the IV curves indicated that modules from groups B and C experienced increased series resistance. After 10 months outdoors, one of the stringing approaches, type A, continues to demonstrate stable performance Modifications have been made to the production processes to incorporate the important aspects learned in this test.

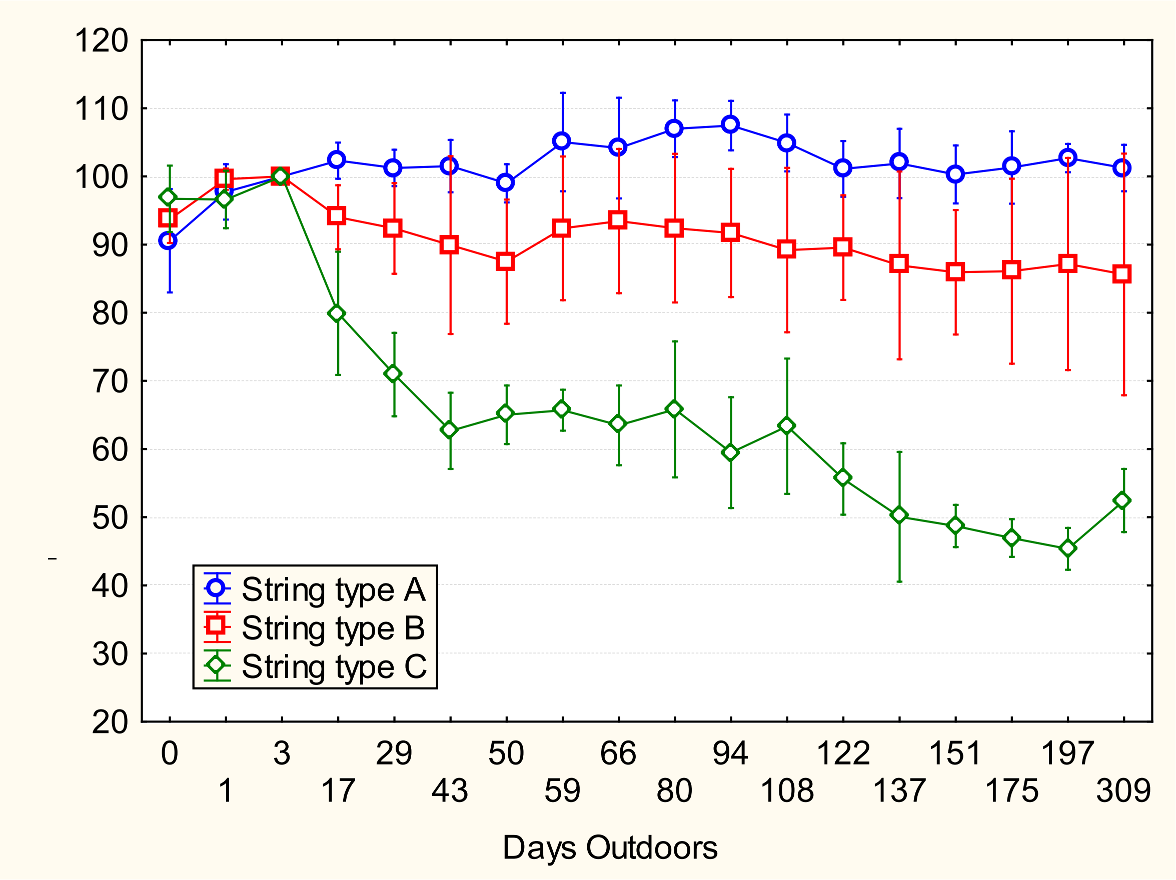


Figure 1.4. *Mean relative P_{max} of flexible modules fabricated by three stringing techniques and deployed outdoors in Tucson.*

Accelerated testing was used on a comparative basis to look at GSE product made using larger “Gen2” cells vs. “Gen1” cells. Flexible modules were fabricated from Gen2 cells with the same packaging as a standard product at GSE. Six modules were stressed in damp heat and six modules were deployed outdoors. The modules deployed in damp heat failed at a rate similar to the standard product fabricated from Gen1 cells. After 62 days outdoors, the other module set deployed in typical outdoor use still averages over 100% of initial power. Further time is required for any effects to become apparent. These types of tests eventually serve to build a link between accelerated and typical outdoor testing in terms of implied failure rates.

Although performance under “standard” conditions typically warrants the greatest study, some degradation mechanisms tend to show effects more rapidly at non-standard conditions. For example, failure mechanisms owing to increasing shunts in the PV product might be expected to impact weak light performance more rapidly than that under AM1.5 intensity. To identify any response of this nature, GSE fabricated modules using prototype Gen2 cells and characterized module performance at variable intensity before and after stress testing in damp heat. For exposure times less than 1000 hours, no significant change in the weak light module performance was observed.

Again, all major process changes are generally tested for reliability and environmental durability. For the transition at GSE from “Gen1” to the larger “Gen2” cells, tests were conducted to evaluate the reliability of flexible and glass modules fabricated from Gen1 cells, with the back contact deposited either in the Gen1 or Gen2 coaters. Results will be forthcoming in many studies such as this involving the significant elapsed time often required to observe any differences in behavior.

Task 2: CIGS Coating Cost Reduction **(Objectives)**

1. Increase processing rate for CIGS deposition by at least 25% with a high-bar goal of 50% (from 12-in/min to 15-in/min and potentially 18-in/min).
2. Modify effusion sources as necessary to ensure adequate cross-web uniformity at increased absorber formation speeds.
3. Reconfigure In and Ga sources to allow improved homogenization of In-Ga at the higher CIGS deposition rates and reduced time for mixing by diffusion.
4. Re-optimize CIGS process parameters for device efficiency at the high processing rates and altered In-Ga delivery.
5. Evaluate alternate sodium delivery, for efficiency, control and uniformity; and high process rates, implement if successful into the standard process.
6. Evaluate thinner CIGS layers. Reduce flux rates to achieve less than 1.0 μm CIGS thickness and re-optimize CIGS process conditions to maximize efficiency for thin absorber layers.

Economy of Scale – Factory Completion

As scalability is a key advantage of the thin film approach, particularly using the roll-to-roll processes for thin film coating that GSE has pioneered, overall cost reduction is heavily dependent on factory scale-up to significant size. During the 2nd phase of this Thin Film Partnership subcontract substantial progress has been made toward completion of the GSE plants in Tucson and Berlin (40 MWp and 35 MWp capacities respectively). A rough chronology of major events throughout the 2nd phase include:

- Further required planning and construction of the GSE production facilities in both Tucson and Berlin and related equipment were carried out concurrently, saving time but increasing risk.
- Demolition of the Tucson (Rita Road Site) 103,000 sq. ft. building interior was completed.
- Construction of the new interior started on 6/15/2007. The objective was to prepare the facility for installation of new tools that began arrival in October. Building completion was staged to accommodate the tools as they arrive.

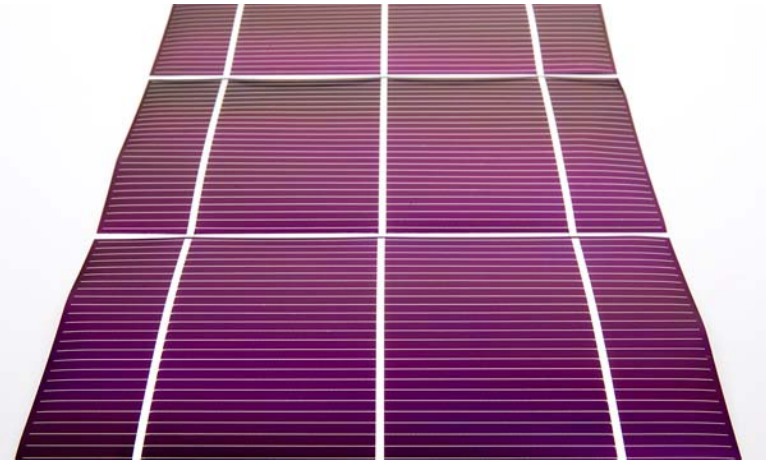
- The building was completed generally from north to south, with temporary barriers erected to separate active construction areas from completed areas receiving production tools.
- Facilities such as chilled water, compressed air, electricity, exhaust, and air conditioning were brought up and distributed dynamically as required for the production tools as they arrived.
- Production tools were generally checked and accepted once at the suppliers' sites and then checked and accepted again after final installation at GSE (either Tucson or Berlin).
- Production tools were installed and facilitated as they arrived from diverse fabricators. Complete sets of thin film coating equipment (back contact, absorber, heterojunction formation and front contact roll-to-roll coating tools) were operational midway through phase 2.
- Transfer and development of the process for the thin film coating steps was initiated (back contact, absorber, heterojunction and front contact steps), concurrently with the installation of additional tools. For instance, the majority of the hardware for the first installed CIGS system (CIGS5) was demonstrated to be robust, reliable and proven capable for depositions extended to 600m web lengths while the second system (CIGS6) began installation.
- Remaining process tools were installed and qualified, including tools for printing, slitting, "tabbing", "stringing" and measurement functions.
- Evaluations were conducted as necessary to successfully increase web lengths from 300 meters to 600 meters in length, from 12.5" to 13" in width and from the smaller "Gen1" to the larger "Gen2" cell format. All of these changes capitalize on the economies of scale built into the design of the new factory processes and equipment. An equipment integration plan required the Gen2 processes to be individually qualified against Gen1 processes with known metrics. Wherever the approach required web interchangeability between the old and new production tools, modifications were made to the Gen1 equipment to allow it to process the wider web.
- Tests were conducted in CIGS deposition tools to determine the accuracy of the in-situ sensors and develop the control parameters that lead to CIGS with characteristics similar to the films deposited in the Gen1 production line. All deposition tests were conducted at a web speed of 0.61 m/min (24 inches/min). The metrics evaluated for these first optimizations were coating thickness, composition, adhesion, morphology, visual appearance, and solar cell performance. Initially, achieving a sufficient and controllable supply of selenium was a notable problem.
- Cell performance was evaluated by applying other coatings (besides CIGS) in the Gen1 line, and fabricating Gen1 cells (68cm^2). By the fourth such test, gross control set points had been derived that resulted in a

maximum efficiency of 8.6%. Ongoing optimization of the thin film and other factory processes continue to increase measured cell efficiencies and reproducibility.

Figure 2.1. *The new Global Solar Energy manufacturing facility in Tucson* (*10,220m*^{2}).

Figure 2.2. *A GSE tool for roll-to-roll absorber (CIGS) deposition at the new manufacturing facility in Tucson.*

Figure 2.3. *Roll-to-Roll equipment for one of the "back-end" processes in the new factory (front contact collection grid printing).*



P_{mp} (W): 39.5

V_{mp} (A): 7.3

I_{mp} (A): 5.4

V_{oc} (V): 10.3

I_{sc} (A): 6.7

Figure 2.4. *A view of the thin film CIGS-based PV strings on metal foil (and nominal string electrical characteristics) that represent the typical product of the new GSE factory.*

Absorber (CIGS) Deposition Process

Successful CIGS deposition invokes a multidimensional parameter space that must be well understood and well controlled. Multisource co-evaporation offers perhaps the greatest flexibility and potential in device engineering on an atomic level. This potential comes at the cost of severe engineering challenges in scaling a process requiring multivariate control under extreme conditions in a harsh and difficult environment.

Compositional control and uniformity of copper, gallium and indium is crucial to achieving product performance and yield. Cross-web uniformity is governed chiefly by the design and control of the effusion sources and the geometry of the deposition zone. Down-web compositional uniformity is more a function of temporal control and stability of the effusion sources. In the design of the equipment for the new factories, GSE intentionally increased the degrees of freedom and also designed the systems for higher deposition rates and capacities. These factors presented further challenges in the engineering, and in the process development. At the end of the second phase, GSE had demonstrated satisfactory control and uniformity in CIGS composition, as shown below. Nonetheless, further improvement is anticipated in these areas. A typical cross-web composition is shown in Fig. 2.5. for the CIGS deposition equipment at the new GSE factories operating at a 61-cm/min web rate.

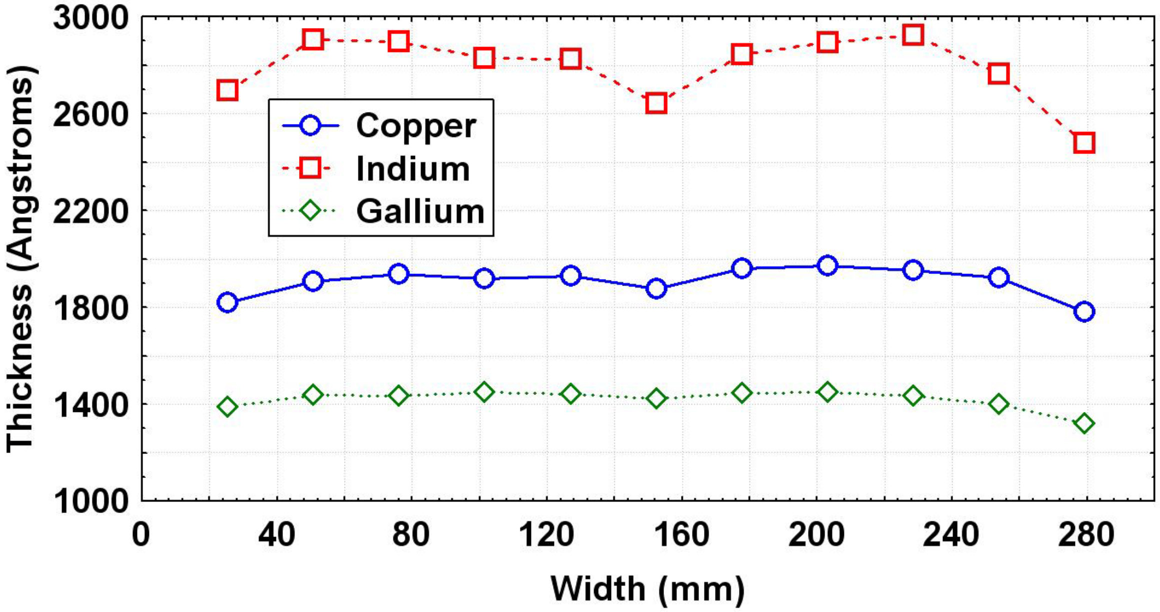


Figure 2.5. *Equivalent thicknesses of copper, indium, and gallium in a typical CIGS film (across the web width) as measured by ex-situ XRF.*

Fortunately, compositional ratios of Cu/(In+Ga) and Ga/(In+Ga) are more critical than absolute equivalent thicknesses of the individual elements, or than total thickness of the CIGS layer itself. These quantities are plotted in Fig. 2.6 for the same web in Fig. 2.5.

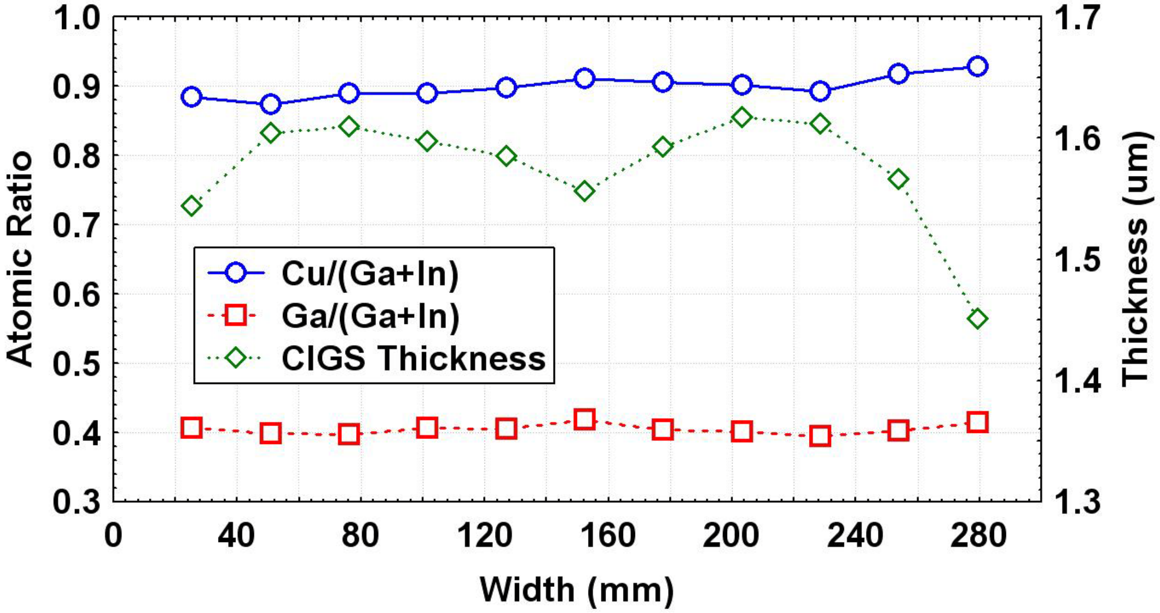


Figure 2.6. *Atomic ratios and thickness of a CIGS film (across the web width) as measured by ex-situ XRF.*

Considerable effort in process control methods at GSE have resulted in uniform compositional control both across and down-web at the high web coating rates required.

Fig. 2.7 shows the equivalent thicknesses for copper, indium and gallium as a function of down-web location for a typical deposition.

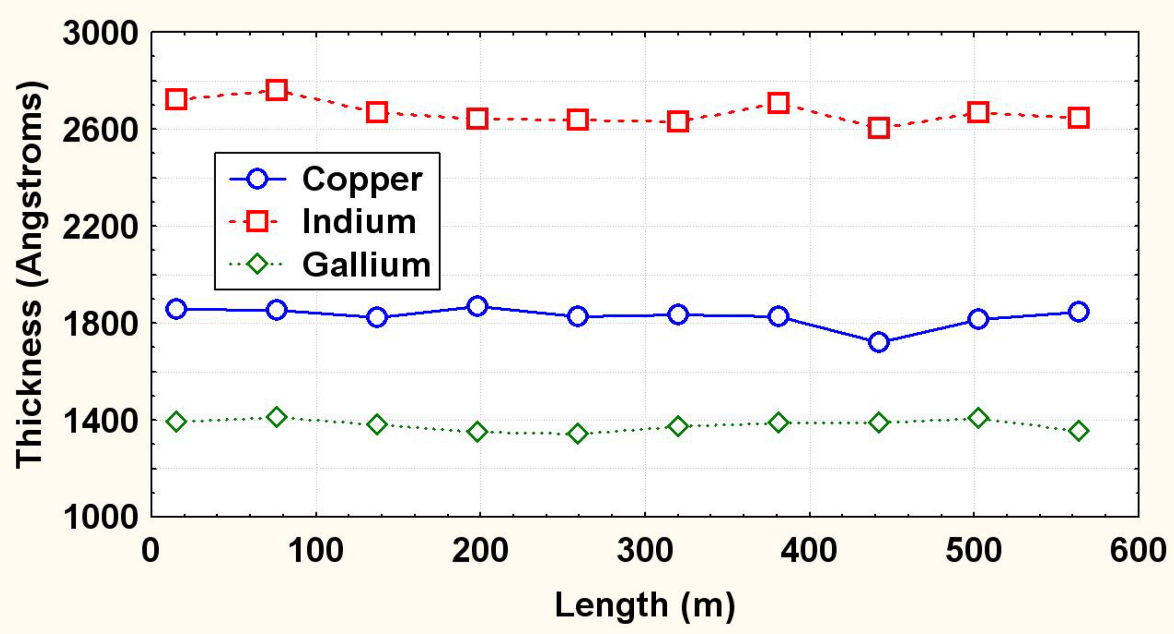


Figure 2.7. *Equivalent thicknesses of copper, indium, and gallium in a typical CIGS film (down the web length) as measured by ex-situ XRF at the web center.*

The cost reduction in the CIGS process (and other processes) during phase 2 were largely addressed through improvements to process control, engineering, operational procedures and process setpoints that were all directed toward running at high deposition rates, and for increasing web lengths. High deposition rates and increasing web lengths are effective in reducing cost, but only if cell efficiency and yield can be maintained concurrently. Current plans call for increasing web length to 1 km through all tools within several months. Deposition rates for the CIGS process are slated to remain at levels between 19 and 24-in/min.

Process Chemistry Relating to Optimization

In optimizing process setpoints, including processing rates and temperatures, it is useful to gain as much insight into the materials interactions as possible. For instance, it is important to understand the state of the starting substrate, Mo-coated stainless foil, in terms of its composition, contamination level, oxidation, tendency toward selenization as the process proceeds, etc. Knowing the relative changes in interfaces throughout the device under “standard” processing conditions allows better interpretation of how changes made to increase reaction rates might impact important interfacial reactions. Toward that end, through collaboration with the laboratory at UNLV directed by Dr. Clements Heske, GSE has obtained data on the surface condition at important steps in the device formation process using XPS. This data was obtained as a ‘baseline’ for standard conditions on both the front and backside of the substrate, shown in Fig. 2.8.

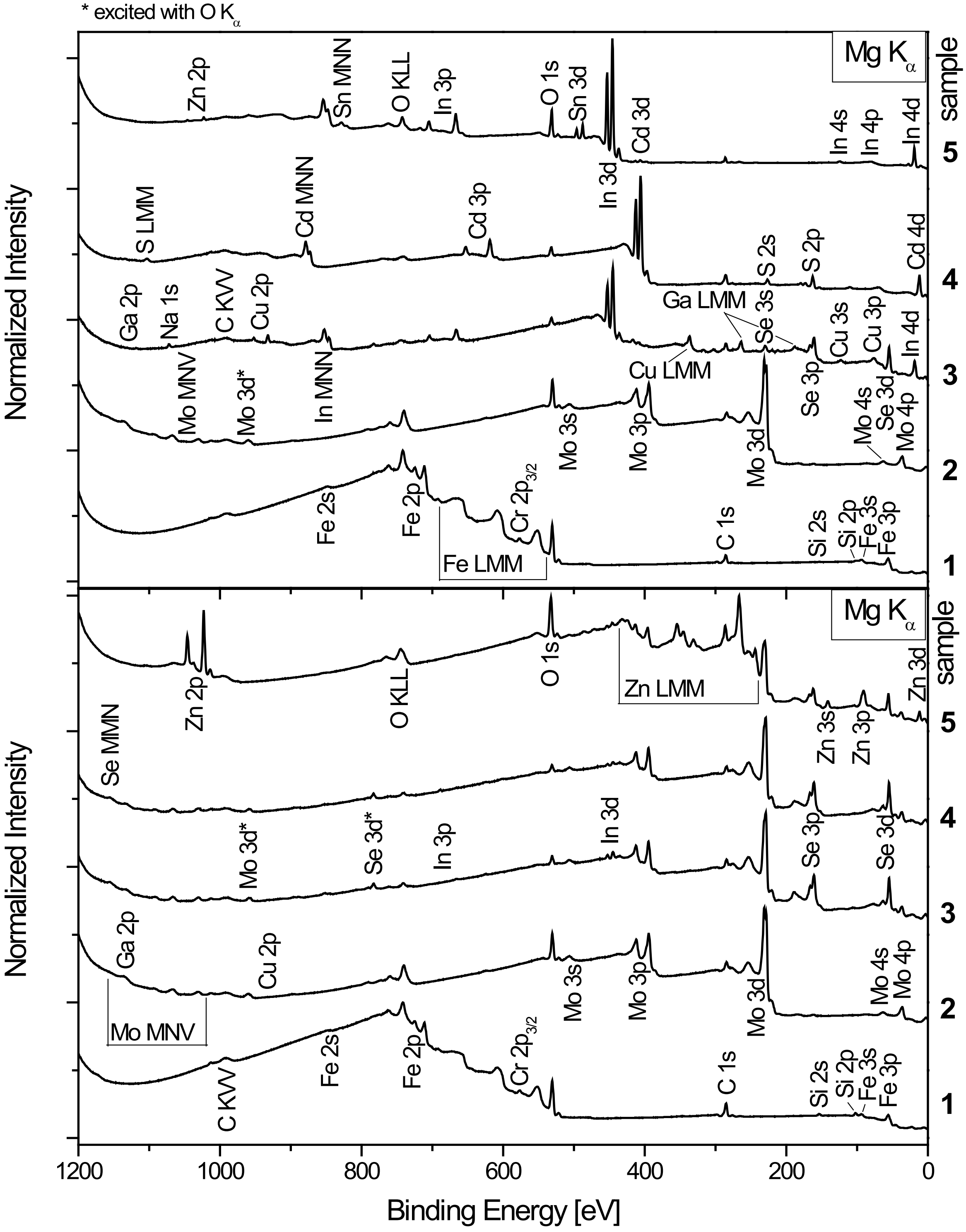


Fig. 2.8 *XPS survey spectra of the front (top panel) and back side (bottom panel) of the investigated test structures.*

More detailed interpretation of the meaning of the data is given by Dr. Heske in his report of 5-2008 to NREL under the TFPPP initiative. The data indicates some conversion of oxides of moly to selenides during processing, and the transport of some constituents of the CIGS deposit to the backside of the substrate.

Task 3: Front Contact Cost Reduction **(Objectives)**

1. Develop a low-cost process for the transparent front contact TCO coating.
2. Improve deposition rate of the TCO process, while re-optimizing the process to maintain large-area cell efficiency above 12.5%.

Front Contact (TCO) Process Scale-Up

Two approaches have been pursued to reduce front contact costs: a low-risk approach based on evolutionary changes to the proven, existing method, and a higher risk approach based on the development of novel techniques for TCO deposition. The initial approach for a high-risk tact in phase 1 produced TCO having suitable properties for sheet resistance, optical transparency and growth rate. Further, the estimated cost of the technique was very attractive. However the effort was stopped when evidence indicated incompatibility between this process and the device stack and substrate used at GSE in the roll-to-roll process. Some equipment has been located and placed in the factory to continue the high risk approach in phase 2, but the machinery is not yet operational. Most of the effort in phase 2 for the low-cost TCO task has been dedicated toward low-risk approaches, some of which are described below.

The first TCO roll coater (TCO5) of the new design was delivered and installed at GSE during phase 2 of this subcontract. Subsequently, multiple identical tools have been received, placed, facilitated and put into service at both the Tucson and Berlin facilities (Fig. 3.1). These TCO deposition tools were designed to be capable of well-controlled, uniform, high rate deposition using a dense array of cathodes in a roll-to-roll approach.

Comprehensive plans were developed for bringing the tool on-line and integrating the process. The first major goal of the plan was to demonstrate coating capability and solar cell metrics comparable to those produced by the Gen1 TCO manufacturing equipment, applying a “hook and loop” approach where webs could be split and processed on a comparative basis in both “Gen1” and “Gen2” process equipment.

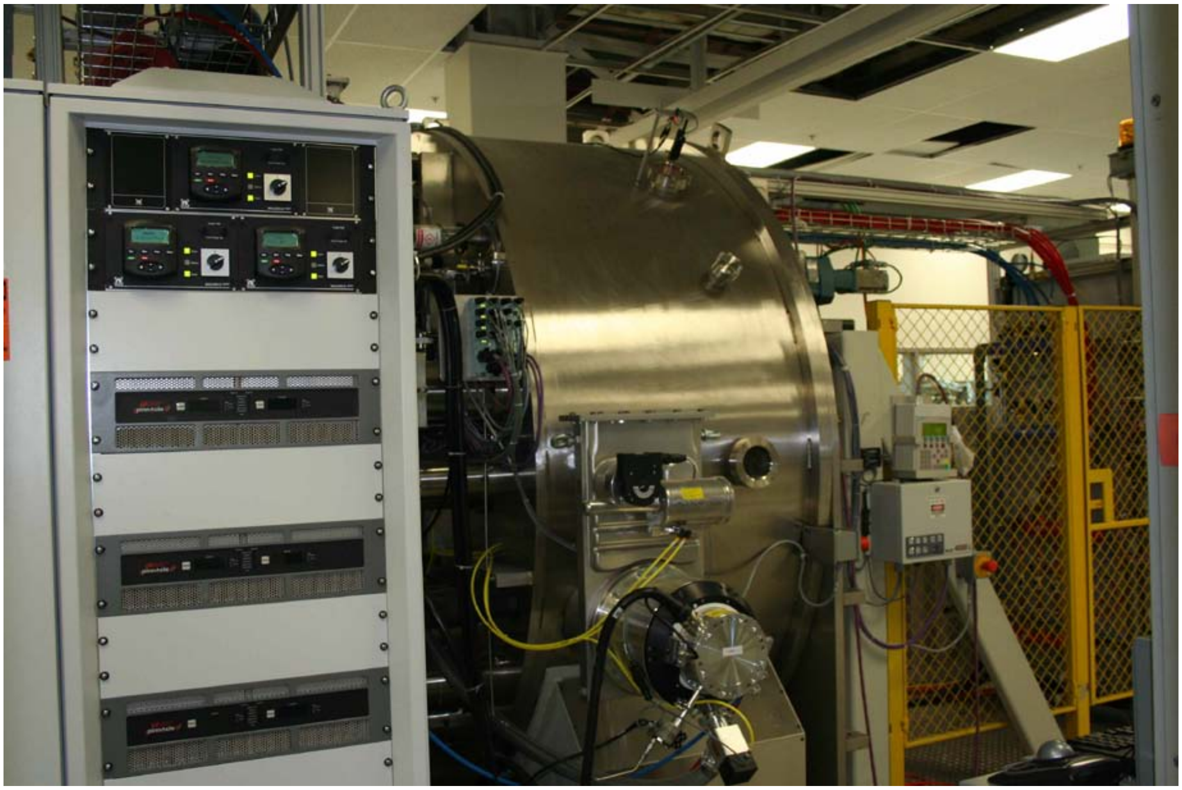


Figure 3. 1 *The front contact (TCO) is deposited by pulsed DC magnetron sputtering.*

Subsequent to installation, campaigns have been initiated more fully utilize the equipment design to deposit at high rates, using high utilization sputtering targets, both factors being intended to reduce costs.

One example was the modification to attain more powerful magnet packs on the TCO targets to determine if faster deposition rates could be achieved. Faster deposition rates enable increased line speed and increased productivity for lower costs. With the new magnet packs, it was demonstrated that TCO cathode power could be decreased from 1400W to 1100W and maintain identical deposition rates. At an applied power of 1400W, cathodes with the new magnet packs allowed web speeds to be increased nearly 30%, with no loss in solar cell performance. All production systems were subsequently converted to the new packs.

These approaches are most often iterative, in that device performance is impacted by interactions so that changes in one parameter setting demand re-test of other parameter settings to garner full benefit. An example was a test conducted to evaluate the effect on cell performance of reduced power applied to deposit the insulating ZnO coating. For test conditions, the pulsed power to the insulating layer targets was adjusted so that the power delivered to the targets was reduced by half, with no effect on the deposit thickness. Statistical analysis indicated no difference between the test samples and controls generated on the same lot (Table 3.1).

	Mean Test	Mean Control	t-value	df	p	Valid N Test	Valid N Control	Std.Dev. Test	Std.Dev. Control	F-ratio Variances	p Variances
Vmax	392.006	388.207	1.2626	166	0.208504	96	72	20.4722	17.6049	1.352254	0.182483
Imax	1786.153	1801.885	-0.83086	166	0.407244	96	72	137.0707	96.6604	2.010909	0.002303
Pmax	701.409	699.42	0.21189	166	0.832454	96	72	68.4228	46.9965	2.119682	0.001075
Voc	558.676	556.575	0.8884	166	0.375612	96	72	16.1677	13.717	1.389254	0.146521
Isc	2164.221	2172.617	-0.70681	166	0.480674	96	72	77.3668	74.6076	1.075333	0.752715
Fill Factor	57.914	57.838	0.11926	166	0.90521	96	72	4.677	3.1294	2.233678	0.000484
Efficiency	10.195	10.166	0.21193	166	0.832421	96	72	0.9945	0.6831	2.119691	0.001075
Rsh	853.78	976.034	-1.54358	166	0.124595	96	72	489.7579	531.4812	1.177641	0.454469
Rse	3.806	3.88	-1.32529	166	0.186898	96	72	0.3333	0.3827	1.31795	0.208519

Table 3.1 Statistical comparison of IV parameters between reduced power i-ZnO and controls.

Some effort during phase 2 was applied toward evaluations of the alternative sputtered TCO material. The alternative material is being evaluated as both an insulator against the buffer and as the front electrode. A variety of sputtering conditions were evaluated for their affects on solar cell performance. A wide distribution of cell efficiencies resulted from all deposition conditions evaluated, although maximum efficiencies were comparable to the standard production process. No conclusions could be reached due to the diminished yield. The higher performing solar cells were fabricated into strings for reliability testing of flexible and glass laminated modules outdoors and in damp heat. The first results of the reliability tests will be described subsequently.

Task 4: Back Contact Cost Reduction and Efficiency Improvement

(Objectives)

1. Evaluate substrate properties and analyze resulting impacts on device performance.
2. Quantify impacts of reduced Mo thickness and correlate to device performance.
3. Examine low-cost alternate back contact materials for partial substitution of Mo and compare device performance and other properties against the established baseline.
4. Demonstrate increased device efficiencies and reduced process costs through material savings and increased process speeds.
5. Integrate alternate sodium delivery to maximize adhesion and efficiency at the higher CIGS web processing rate.

Materials Substitution and Reduced Cost

Substantial opportunity to reduce total cost often exists in the form of material substitution, using either less expensive grades of a constituent from a current supplier, or equivalent materials that are available at better prices from new vendors. This opportunity is driven by a growing diversity of global sources for some materials, new and better techniques for meeting materials requirements, and a growing recognition of the importance of the PV market and a desire to enter that market as a materials supplier.

In one case, an alternative grade of stainless steel became available from our primary supplier. Analysis revealed that some components of the alloy were found in higher concentration than in our baseline stainless steel. The advantage of the alternate stainless foil was less difficulty in processing into roll form, equating to lower price and better characteristics in some areas. However, the performance of production lots fabricated on the new alloy was significantly lower than that of the controls fabricated on the standard stainless steel. Several of the new alloy's characteristics were quantified to determine assignable cause for the reduced performance.

In another instance two new suppliers of stainless steel and another supplier previously investigated were evaluated. The supplier previously investigated (and found unsuitable) was re-considered because new cleaning techniques had been applied to their product. Upon re-evaluation of the latter by processing several of the new coils through the production line, the product was again found to lead to inadequate performance. However, both of the new suppliers were found to provide performance comparable to the qualified supplier. Additional, more extensive qualification tests are planned for these new potential suppliers in the future.

Besides the substrate itself, the materials used for the back contact coating also represent a significant expense, and thus an opportunity to reduce costs. [2] Alternative suppliers of chromium and molybdenum were evaluated to better understand the potential effects of common impurities on the performance and yield of the resulting PV product. Four lots of each supplier and material were processed through standard production. When compared to controls, no statistically significant difference in lot performance was seen between any of the alternative suppliers for either target type.

Preliminary studies like these are often used as a basis to evaluate still other suppliers and materials preparation methods, where potential cost savings warrant, as illustrated by the evaluations below that were made during phase 2.

- Sputtering cathodes from two suppliers were received and evaluated. The simpler, more robust and serviceable of the two cathodes was down-selected for utilization in the new Gen2 sputtering systems.
- Sputtering targets compatible with the Gen2 molybdenum sputtering chambers were procured from multiple suppliers. The molybdenum targets, prepared by different techniques, were evaluated in one of the Gen1 sputtering chambers with a fixture to accommodate the new target geometry. The targets were installed on a Gen2 cathode and evaluated for compatibility with the cathode, coating deposition rates on a moving web, and the condition of the target surface after extended sputtering periods. A supplier for the new targets was down-selected.
- Molybdenum targets fabricated by a less costly technique (than the production standards) were evaluated in the Gen1 equipment. Deposition rates under standard conditions were evaluated first. No significant differences in deposition rates were observed. Test lots made with the alternative targets were processed in the production line into solar cells and their performance was compared to the baseline molybdenum targets. The conversion efficiency of cells made with the new targets was significantly lower than cells made from the standard targets.

The performance difference was attributed to specific impurities not found in the standard targets.

During Phase 2 significant progress has been made using re-selection and substitution of materials and suppliers for the back contact. Many, although not all, of the trials yielded positive results and were down-selected for production use.

"Gen2" Back Contact Equipment Installation and Characterization

As previously mentioned, the increase in deposition rate and length purposely designed into the "Gen2" deposition tools for all thin film coating steps is an integral part of the cost reduction plan at GSE. Installation of the first roll coater for the back contact (Mo5) was completed in early January of Phase2. Similar to the deposition tool for the front contact, the first major goal was to demonstrate coating and solar cell metrics comparable to those produced by the Gen1 back contact manufacturing equipment, applying the "hook and loop" approach. The capability of Mo5 to produce individual solar cells with efficiency greater than 10% was demonstrated within a few depositions.

However, the first test webs coated in Mo5 had significant mechanical defects in the form of scuffs, scratches, and impressions. These defects were correlated with shunted solar cells. Modifications were made to shielding in the web path to guarantee sufficient clearance. The rollers and other components controlling the web motion were adjusted to linearity with tighter tolerances. The mechanical defect density was dramatically by these actions. However, defects continued to be present at a reduced level down the web length.

Non-uniform web tension was hypothesized to explain some physical defects. A number of tests were conducted to explore parameters that could provide more uniform tension, including web temperature and coating stress. Presently, this line of investigation is ongoing, and no means have been determined to completely eliminate these remaining defects.

At GSE, the Mo coating thickness is typically characterized by XRF. Along the majority of a typical web, the Mo thickness uniformity is +/- 3%, with the thinnest coating occurring in the web center (Fig. 4.1). Thinner Mo coating is frequently observed in the first 100m of deposition. The source of this effect is under investigation.

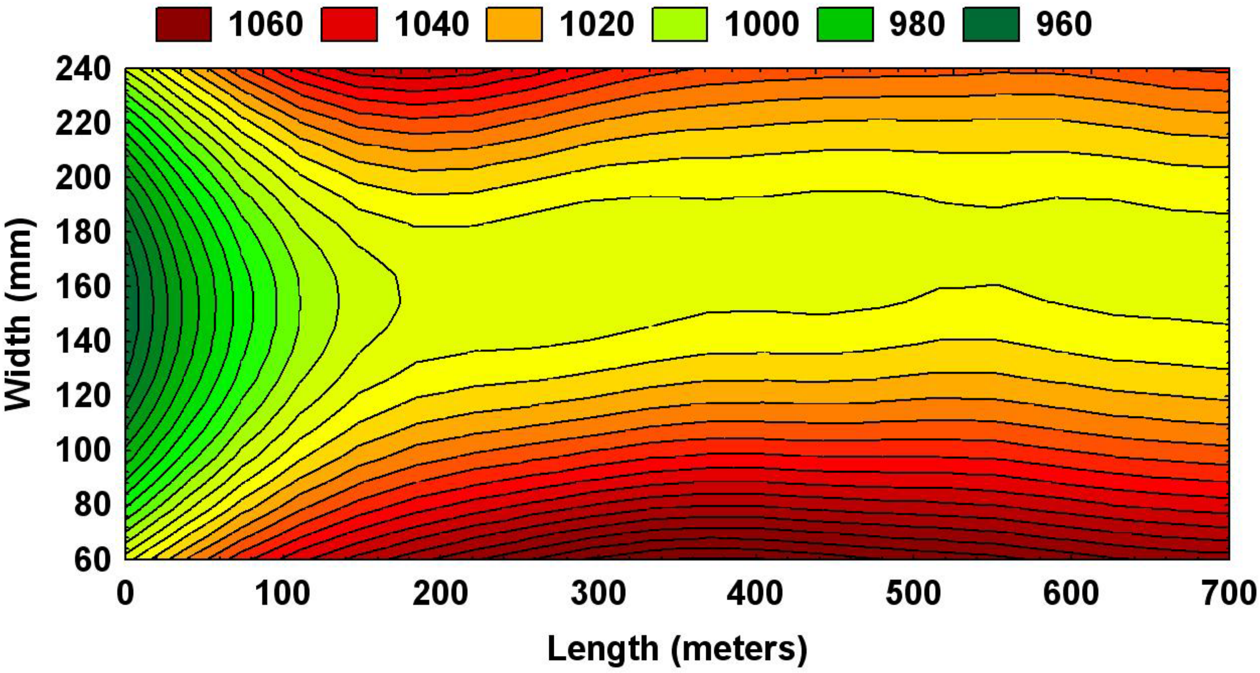


Figure 4.1. A contour plot of Mo thickness (a.u.) down and across the web as measured by XRF (distance weighted least squares fit).

Summary

GSE has executed on plans to build two new factories (Tucson and Berlin) with a combined capacity of 75 MW_p and commence production of thin film CIGS PV using roll-to-roll processing of foil substrates, a first in PV accomplishments. Production equipment has been built, delivered, installed and started. Most production processes in the new factories have been successfully transferred from the “Gen1” equipment, with one remaining process nearing completion of its development on the “Gen2” equipment. Incorporating many of the goals of the NREL TFPPP program, cost and performance improvement campaigns have been re-initiated and have begun to accrue benefit. Continued testing of module reliability in rigid product has reaffirmed extended life expectancy for standard glass product, and has qualified additional lower-cost methods and materials. Expected lifetime for PV in flexible packages continues to increase as failure mechanisms are elucidated, and resolved by better methods and materials. Significant cost reduction has been enabled in the front contact process through designs having better materials utilization, and in the back contact process through enhanced vendor and material qualification and selection. The largest cost gains have come as a result of higher processing rates, greater automation and improved control in all process steps, an integral part of this TFPPP program. The process speeds for which the new factory equipment has been designed have been realized. The new processes and equipment have been individually qualified with “Gen1” material of known properties to be capable of 10%-12% efficiency in large area cells. [3]

Future Plans

Some minor work remains to fully integrate one “Gen2” process step into full production, eliminating dependence on any of the “Gen1” processes and bringing factory production under all “Gen2” processes. Attention has already migrated to the optimization necessary to further increase yields in all steps and maximize production rates. This effort will continue, basically to balance rates in all steps, eliminate unscheduled interruptions to production and incrementally increase final product (assembled string) yields. GSE is slated to move to 3-shift, 7-day operation in March, 2009 in Tucson. The Berlin facility is scheduled to fully ramp production later in 2009.

Concurrent with these efforts, process optimization will continue to further increase performance (maximum and average large cell efficiency), along with continued cost reduction. A large opportunity for cost reduction remains at the TCO deposition step, and we have recently identified another novel pathway for a low cost initiative here. Identification (and elimination) of the causes of defect generation will also continue in order to reduce performance variability in final product. Defect generation is often minimized through minor modifications to the production equipment or operational procedures.

Finally, evaluation of product durability and expected lifetime must continue for both rigid and flexible products. A high level of interest in flexible “building-integrated” concepts such as “rolled roofing” products incorporating PV, coupled with accelerating development of effective “barrier coatings” for polymer materials serve to maintain activity levels on lifetime evaluation in flexible packages.

In brief, the planning and construction phase is complete. Installation, integration, process and equipment validation is nearing completion, and now effort will shift to issues primarily related to PV production rate, cost and quality – the end game.

References

[1] J.S. Britt, E. Kanto, S. Lundberg, M. E. Beck, “CIGS Device Stability on Flexible Substrates”, 4th World Conference on Photovoltaic Energy Conversion (IEEE), 2006, pp. 352-355

[2] J.S. Britt, R. Huntington, J. VanAlsburg, S. Wiedeman, M. E. Beck, “Cost Improvement for Flexible CIGS-Based Product”, 4th World Conference on Photovoltaic Energy Conversion (IEEE), 2006, pp. 388-391.

[3] J.S. Britt, S. Wiedeman, U. Schoop, D. Verebelyi, “High-Volume Manufacturing of Flexible and Lightweight CIGS Solar Cells”, 33rd PVSC (IEEE), San Diego, CA, May 11, 2008,

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Executive Services and Communications Directorate (0704-0188). Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ORGANIZATION.

1. **REPORT DATE** *(DD-MM-YYYY)* March 2009	2. **REPORT TYPE** Subcontract Report	3. **DATES COVERED** *(From - To)* 26 September 2007-25 September 2008

4. **TITLE AND SUBTITLE** Cost and Reliability Improvement for CIGS-Based PV on Flexible Substrate, Phase II: 26 September 2007 – 25 September 2008	5a. **CONTRACT NUMBER** DE-AC36-08-GO28308
	5b. **GRANT NUMBER**
	5c. **PROGRAM ELEMENT NUMBER**
6. **AUTHOR(S)** S. Wiedeman	5d. **PROJECT NUMBER** NREL/SR-520-45213
	5e. **TASK NUMBER** PVB91210
	5f. **WORK UNIT NUMBER**
7. **PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)** Global Solar Energy, LLC 4475 S. Houghton Rd Tucson, Arizona 85747	8. **PERFORMING ORGANIZATION REPORT NUMBER** ZXL-6-44205-13
9. **SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)** National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401-3393	10. **SPONSOR/MONITOR'S ACRONYM(S)** NREL
	11. **SPONSORING/MONITORING AGENCY REPORT NUMBER** NREL/SR-520-45213

12. **DISTRIBUTION AVAILABILITY STATEMENT**

National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

13. **SUPPLEMENTARY NOTES**

NREL Technical Monitor: Harin S. Ullal

14. **ABSTRACT** *(Maximum 200 Words)*

Leveraging the experience gained in successfully developing and operating a 4.2-MWp/yr CIGS production line for several years, Global Solar Energy initiated an ambitious scale-up plan in 2006. Now in the final stages of the first phase of the plan, 75-MWp/yr of combined manufacturing capacity is being installed at new production facilities in Tucson, AZ, and Berlin, Germany. Both physical plants are complete, facilitated, and capable of self-sufficient and independent operation with trained personnel now in place. All of the tool sets required for planned Phase 1 operation are complete in Tucson, and nearly complete in Berlin. While the scale of the plant expansion is rapid, the new production tools represent an evolutionary progression of the Global Solar CIGS technology. Manufacturing cost has been reduced by increased automation, higher materials utilization, and greater capacity with higher rates in all tools.

15. **SUBJECT TERMS**

PV; manufacturing; scale-up; plant expansion; automation; materials utilization; capacity; process optimiization;

16. **SECURITY CLASSIFICATION OF:**			17. **LIMITATION OF ABSTRACT**	18. **NUMBER OF PAGES**	19a. **NAME OF RESPONSIBLE PERSON**
a. **REPORT**	b. **ABSTRACT**	c. **THIS PAGE**			
Unclassified	Unclassified	Unclassified	UL		19b. **TELEPHONE NUMBER** (*Include area code*)