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Executive Summary:

The goal of this project is to provide a commercially viable Ag-free metallization technology that will both reduce cost and increase efficiency of standard silicon solar cells. By removing silver from the front grid metallization and replacing it with lower cost nickel, copper, and tin metal, the front grid direct materials costs will decrease. This reduction in material costs should provide a path to meeting the Sunshot 2020 goal of \$1 / W_{DC}. As of today, plated contacts are not widely implemented in large scale manufacturing. For organizations that wish to implement pilot scale manufacturing, only two equipment choices exist. These equipment manufacturers do not supply plating chemistry. The main goal of this project is to provide a chemistry and equipment solution to the industry that enables reliable manufacturing of plated contacts marked by passing reliability results and higher efficiencies than silver paste front grid contacts.

To date, there have been several key findings that point to plated contacts performing equal to or better than the current state of the art silver paste contacts. Poor adhesion and reliability concerns are a few of the hurdles for plated contacts, specifically plated nickel directly on silicon. A key finding of the Phase 1 budget period is that the plated contacts have the same adhesion as the silver paste controls. This is a huge win for plated contacts. With very little optimization work, state of the art electrical results for plated contacts on laser ablated lines have been demonstrated with efficiencies up to 19.1% and fill factors ~80% on grid lines 40-50 um wide. The silver paste controls with similar line widths demonstrate similar electrical results. By optimizing the emitter and grid design for the plated contacts, it is expected that the electrical performance will exceed the silver paste controls. In addition, cells plated using Technic chemistry and equipment pass reliability testing; i.e. 1000 hours damp heat and 200 thermal cycles, with results similar to silver paste control cells.

100 cells have been processed through Technic's novel demo plating tool built and installed during budget period 2. This plating tool performed consistently from cell to cell, providing gentle handling for the solar cells. An agreement has been signed with a cell manufacturer to process their cells through our plating chemistry and equipment. Their main focus for plated contacts is to reduce the direct materials cost by utilizing nickel, copper, and tin in place of silver paste. Based on current market conditions and cost model calculations, the overall savings offered by plated contacts is only 3.5% \$/W versus silver paste contacts; however, the direct materials savings depend on the silver market. If silver prices increase, plated contacts may find a wider adoption in the solar industry in order to keep the direct materials costs down for front grid contacts.

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Background:

Single print silver paste is still considered the mainstream manufacturing metallization method for front grid contact formation on standard silicon p-type solar cells per the ITRPV technology roadmap. [1] Double printing technology is the second most widely used front grid metallization process. [1] The additional alignment, printing and drying steps required for the double printing process enable smaller grid line widths with less silver usage. [2] Yingli has been using the double print technology in mass production for several years reporting sub 50 micron line widths compared to a line width of 63 microns reported for their single print process. [2] The cell level efficiencies that they report are 17.72% for single print and 17.93% for double print and they use a different silver paste for double print versus single printing.[2] The ITPRV roadmap states that for double printing an alignment accuracy of 10 um (+/- 3 sigma) will be required. [1] Although double printing has not been adopted by every solar cell manufacturer, for this project, we will consider double printing as the state of the art silver paste process for comparison to the ASL plating process.

Even with all the advances in silver paste technology, the ITRPV still predicts that plated contacts will reach 20% market share of solar cell production by the year 2027 [1]. One of the main limitations for silver paste technology is the need for a high phosphorous (P) surface concentration in order to get fill factors (FF) close to 80%. The high P surface concentrations result in parasitic recombination losses in the emitter which limits J_{sc} and V_{oc}. [3] It is also believed that there will be a limit to how small of a line width the silver paste process can actually achieve. In spite of the significant decrease in line width and silver usage of the past five years, ITRPV roadmap indicates that the “finger-width reduction also seems to have slowed down recently as compared to previous years”. [1] Therefore, plated contacts are still relevant and are expected to provide a solution to the current limitations of silver paste such as contacting low resistivity emitters and achieving small, unbroken line widths. Different process sequences have been experimented with for plated contacts. The ITRPV roadmap differentiates between “plating on seed layer” and “direct plating”. The Alternative Seed Layer (ASL) process developed by Technic would be considered a “direct plating” technology. Companies that are currently utilizing copper plating in production would be considered “plating on seed layer” technologies. Sunpower has been copper plating in production for 5-10 years; however, they have an advanced architecture cell and they do not plate nickel directly on the silicon surface. First Solar (Tetrasun) is no longer in production and it was believed that their process flow incorporated an adhesion layer between the silicon and nickel plating that was most likely deposited using a dry process such as sputtering.[4] Multiple research organizations and companies report gains in efficiency for silicon heterojunction solar cells when using copper plating; however, for this architecture, copper is generally plated onto a transparent conductive oxide layer (or an adhesion layer on the TCO). [5-7] BP Solar was the only solar company to implement in high volume production “direct plating” of nickel on silicon followed by copper plating, called “buried groove” technology. In fact, there are still BP solar modules with plated solar cells in the field today which demonstrates the reliability of the plated contacts; however, this process was expensive. [3] In 2009, Suntech Power Holdings introduced a “direct plating” process. Suntech used a laser patterning process to define the grid; however, this process was not a “groove” like the BP solar process. Suntech implemented the laser-doped selective emitter (LDSE) which was plated directly with nickel and copper. It is believed that this technology suffered adhesion issues preventing it from making it to market. [8]

Although “direct plated” contacts are not currently in mainstream manufacturing, multiple research organizations and equipment vendors have recently been publishing papers with successful results for plated contacts.[3, 9-12,16] RENA Technologies is an equipment vendor with multiple tools in the solar industry. Back in 2010, RENA was publishing papers about their plating tool for the formation of plated contacts. However, RENA disappeared from the literature for a few years, resurfacing in 2014 with different equipment for plating contacts. [11] RENA has partnered with Fraunhofer and MacDermid, a chemical manufacturer, to publish papers demonstrating adherent and reliable plated contacts on laser ablated solar cells. [3,11,16] Recent papers by RENA and industrial partners such as Trina, Motech, and Jinko have been found in the literature [3,16]. RENA’s utilizes LIP plating for single sided processing of solar cells. The backside remains dry and electrical contact is made to the backside through brushes that are dragged across the Al paste. The solar cells are moved through the tool using rollers in a horizontal conveyor. Although RENA has developed a unique mechanism for moving the cells through the tool while claiming to keep the backside of the cell dry, it is believed that the brushes used for electrical contact often scratch the solar cell as it is moved through these brush contacts. [13]

MECO is a tool vendor that partnered with IMEC to develop a process for plated contacts.[9,12] It is inferred that MECO uses Atotech plating chemistry. [13] MECO also has a tool at another research organization and it is believed to be using MacDermid chemistry. The MECO plating tool is basically a modified version of an existing tool design that they sell in the connector industry. The solar cell is clamped at the top edge and processed through the line vertically with both sides wet. The MECO tool can be used to plate one sided cells or bi-facial cells. Although this sounds impressive on paper, the electrical connection for the direct plating process is only at the top edge of the solar cell. This may result in very poor uniformity across the solar cell during plating. [13] In addition, LIP plating is most effective when the backside of the cell is kept dry, out of solution. It is unknown how well the LIP version of the MECO plating tool works. Although the MECO and RENA tools are currently available for purchase, there are still major modifications required to make these tools successful in high volume manufacturing. Therefore, there is still a market for an LIP plating tool that is robust and manufacturable.

There are different process flows utilized for plated contacts. Both Fraunhofer and IMEC utilize a process flow in which the silicon nitride ARC layer is opened using laser ablation, then nickel is directly plated on the silicon followed by copper, a thin silver layer and an anneal step to form NiSi.[9,10] However, the anneal step would need to be after the copper plating step if tin were used as the solderable layer instead of silver due to the low melting temperature of tin. An “interim anneal” is also proposed after the 1st plated nickel step.[14] Table 1 below compares 3 different flows for the front grid metallization step to the flow for double printing the front grid with silver paste. Plating Laser 1 flow is similar to the flow proposed by Fraunhofer and IMEC most recently. In this flow, annealing is performed after the copper plating step such that the nickel/copper stack is annealed together. It is unknown if the adhesion results published by Fraunhofer and IMEC are directly comparable to the adhesion testing method used throughout this project. Currently, there is no universally accepted specification, process, or accepted values that exist today for front grid contacts. Historically, adhesion testing has been performed as a process control measure for metallization deposition and as an indicator for long term reliability performance. Recent work across the industry is discrediting the process and connection to long term module durability.[15] The 10 experts interviewed in Milestone 2.1 were unaware of any correlation to peel test and long term reliability. In a recent publication, Fraunhofer states that *"…the module construction community neither fully agrees on the minimum required adhesive strength for module construction, nor on measurement details itself."* [14] Therefore, it is very difficult to compare adhesion results generated during this project period with adhesion results published in the literature.

Table 1: Possible Front Grid Contact Metallization Process Flows

	Ag Paste	Plating: Laser 2	Plating: Laser 1	Plating: Wet Etch
1	Screen Ag Front	Laser Process	Laser Process	Screen Resist
2	Dry Paste	Clean	Clean	Etch
3	Align	Ni plate	Ni Plate	Clean
4	Screen Ag Front	Anneal	Cu Plate	Ni plate
5	Dry Paste	Ni etch	Anneal	Strip Resist
6	Fire	Clean	Clean	Anneal
7		Ni Plate	Sn Plate	Ni etch
8		Cu plate		Clean
9		Sn Plate		Ni Plate
10				Cu Plate
11				Sn Plate

Therefore, as demonstrated in the discussion above, plated contacts are still relevant and expected to enter mainstream solar cell manufacturing in the next few years. Two equipment manufacturers have increased the visibility of their plating equipment within the last 3-3.5 years. However, neither plating tool appears to be a turnkey addition to existing solar cell manufacturing lines. Plating chemistry is also an important factor in the success of a plated contact process; however, there is very little published about specific plating chemistry and the impact on the plated contact performance. Further development of Technic's ASL process can provide the chemistry and equipment solution required to bring plated contacts into mainstream manufacturing.

Project Objectives:

The goal of this project is to provide a commercially viable Ag-free metallization technology that will both reduce cost and increase efficiency of standard silicon solar cells. By replacing the standard Ag paste front grid metallization process currently used in manufacturing with the Alternative Seed Layer (ASL) process in which nickel and copper are plated directly on silicon, we expect to reduce the front grid materials costs. In 2014 when this project began, the Sunshot 2020 goal was \$1 / W_{DC}. A reduction in front grid materials costs was expected to help achieve this goal. However, it appears that this goal has already been achieved 3 years early due to drastic price reductions observed over the last year. Sunshot released updated goals for 2030 to reduce the LCOE by 50% down to a value of \$0.03 / KWH. In order to achieve this, the sustainable module price would need to be \$0.30 / W. [17] At the Go-No/Go review for this project in March of 2016, the module cost was estimated to be \$0.67/ W. The cost model formulated for plated contacts in 2016 showed a 5.7% decrease in module costs. However, over the next year, the module costs drastically reduced to \$0.353 / W. A portion of this cost reduction comes from lower silver paste usage and lower cost of silver paste. It is assumed that the silver paste materials costs dropped 52% since 2016. In 2016, direct materials costs for plated contacts were 82% lower than direct materials costs for silver paste. In today's current market, plated contacts are only 44% lower in direct materials costs than silver paste. There is still a 3.4% \$/Watt cost reduction at the module level expected for plated contact versus silver paste contacts given today's market conditions. However, this may not be enough savings to encourage adoption of plated contacts. The direct materials costs for silver paste cells are directly related to the price of silver. Silver metal prices have been low for the past 3 years, less than half the silver price observed in 2011. If silver prices would suddenly increase to the levels seen in 2011, it would most likely add \$0.015 / W to the cost of the module – a 4% increase in cost. This increase in cost coupled with the projected savings of using non-silver containing plated contacts may motivate cell manufacturers to adopt plated contacts as a replacement for silver paste front contacts.

Technic has implemented useable manufacturing equipment and processes for plating nickel, copper, and tin on silicon utilizing ASL technology throughout this project. Technic has the unique advantage of being both a chemistry and equipment manufacturer for over 50 years. Therefore, plating solutions and LIP equipment were developed together to ensure successful integration. During this project, Technic demonstrated that the ASL process can produce consistent and adherent plated contacts with state of the art electrical performance compared to silver paste controls. These results were demonstrated throughout the "red flag" testing task of the project. In addition, Technic delivered and installed Phase 1 tooling at ASU for further testing of the ASL process in their pilot line. Testing of the Phase 1 equipment both at ASU and Technic provided feedback necessary to design the Phase 2 tool that was built and installed during budget period 2.

Throughout budget year 2, Technic demonstrated that plated contacts are compatible with standard module fabrication and reliable as shown by passing standard reliability testing such as damp heat and thermal cycling. Technic's Phase 2 demo tool was built, installed, and exercised over a larger scale plating demonstration of 100 cells. The plating demonstration confirmed that Technic's tool design provides repeatable results. In addition, Technic's tool has advantages compared to the competition when it comes to cell handling and footprint. Technic identified a customer that agreed to a testing plan to evaluate Technic's chemistry and tooling on their solar cells.

Data from the larger scale plating evaluation on Technic's demo tool was incorporated into a cost model to compare plated contacts to screen printed contacts. As expected, the materials costs are lower for the plated contacts than for the silver paste contacts; however, the additional laser opening step adds to the capital equipment cost for the plated contacts. Overall, a decrease of ~3.4% $/Watt can be realized for plated contacts versus silver paste contacts; however, this cost savings is less than expected at the onset of this project. It is believed that plated contacts will be a great alternative to screen printed silver paste contacts if there is volatility in the silver market that causes a rise in module costs for cells containing silver.

The following is a detailed description of the Tasks and Milestones for Phase 1 of this project as originally specified in the SOPO.

Task 1: "Red Flag" Testing

In this task, electrical, adhesion, and cell level reliability data will be gathered for plated contacts in order to identify "red flags". At the end of this task, the goal is to deliver a repeatable process with acceptable electrical and adhesion results. An early look at cell level reliability and lamination of plated cells will mitigate potential problems that may arise during module level reliability testing in budget period 2.

Subtask 1.1: Measure electrical performance of ASL processed Al-BSF cells

Aluminum back surface field (Al-BSF) cells from the same supplier will be processed and IV tested to determine the repeatability of the current ASL process. This task will include the purchase of a current-voltage (IV) Tester, cells, and ASL supplies. In addition, solar cells will be characterized at Arizona State University (ASU).

Milestone 1.1 : Qualify cell supplier by processing and IV testing 25 cells. Measure variation across 25 cells from same supplier and compare to silver paste controls if available. IV data measured by Technic and ASU will be delivered to DOE.

Subtask 1.2: Identify appropriate adhesion metric

Literature searching, voice of the customer, and initial adhesion testing will be performed in order to identify the appropriate adhesion test for plated contacts. Massachusetts Institute of Technology (MIT) will perform micro structural investigation of the metal-silicon interface. Results will be used to optimize the metal-silicon interface for optimum adhesion.

Milestone 1.2 : Perform literature search to determine the appropriate adhesion metric for plated lines. Perform initial testing on samples to verify metric. A report will be delivered to DOE.

Subtask 1.3: Identify appropriate metric for dry heat cell level reliability test

Plated cells will be annealed in dry heat and electrically tested before and after annealing to determine change in pseudo fill factor (pFF) after annealing. This initial testing will be used in correlation with failure analysis to identify correlation between drop in pFF and signs of poor reliability performance. Results will be used to optimize metal stack to improve reliability performance of the plated solar cell.

Milestone 1.3 : Perform initial testing on plated cells using dry annealing (initial testing at 200°C for 500 hours) and characterize failures. A report including the pFF results for 10 cells and a suggested metric for future testing will be delivered to DOE.

Subtask 1.4: Characterize metallization adhesion

Adhesion testing will be performed on cells with plated contacts according to the method identified in subtask 1.2. Micro structural investigation of the metal-silicon interface will be used to guide process optimization.

Milestone 1.4 : Perform adhesion test using the method identified in Task 1.2 and demonstrate on 10 cells with plated sunny-side contacts. A report will be delivered to DOE.

Subtask 1.5: Perform initial lamination of cells

Lamination of 1 x 1 coupons will be performed to identify potential issues with lamination of cells with plated contacts. Failure analysis will be performed to identify areas for process improvement.

Milestone 1.5 : Laminate 1x1 coupons and show less than 20% change in power output after lamination. A report will be delivered to DOE.

Task 2: Phase 1 Tool

In this task, the Phase 1 tool will be designed and built based on Technic's prior experience and input from the technology consultant (subtask 2.1). The Phase 1 tooling will be installed in ASU's pilot line. Process optimization of the ASL technology will be performed using the Phase 1 tooling and data gathered will be used to update the cost model and demonstrate a path to the desired cost reduction for silver-free plated contacts. Testing of the Phase 1 tooling will provide feedback needed for the Phase 2 pilot tool design. In addition, plated cells will be compared to the silver paste baseline to show that the plated cells meet or exceed the silver paste baseline.

Subtask 2.1: Identify technical market barriers and opportunities

Technology consultant will provide input on what metrics the customer wants to see and feedback on necessary cost reduction for customer to implement this technology. In addition, technology consultant to provide information to help ensure the tool design will intersect with the optimum cell architecture that is likely to utilize plated contacts.

Milestone 2.1 : Voice-of-customer understood via first-hand survey and technology consultant input. Key process parameters are qualified and the technology adoption pathway is identified. A report will be delivered to DOE.

Subtask 2.2: Install Phase 1 tool at ASU site

Phase 1 tooling will be installed in ASU's solar cell pilot line.

Milestone 2.2 : Tool installed and operational at ASU. Deliver signed acceptance checklist and photo of first solar cell that has been processed.

Subtask 2.3: Optimize processing

ASL process will be optimized on the Phase 1 tooling in order to achieve average efficiency results that are equivalent or better than the screen printed baseline. Subset of cells will be sent to NREL (or certified 3rd party) to verify results.

Milestone 2.3 : Demonstrate that the plated cell baseline meets or exceeds the screen printed cell baseline by showing that the average efficiency of 20 plated cells meets or exceeds the screen printed baseline by 2% relative. The IV data measured at ASU and the NREL (or certified 3rd party) verification data will be delivered to DOE.

Task 3: Phase 2 Tool

Learning from Phase 1 tool will be used to optimize the Phase 2 tool design. Proposed design changes for the Phase 2 tool should be tested if applicable.

Subtask 3.1: Initial design of Phase 2 tool reviewed and initiate testing of new components

Proposed improvements of Phase 2 tool design should be reviewed and hardware provided for testing the improvements, if applicable. Proposed Phase 2 design will be reviewed by the team.

Milestone 3.1 : Review of initial design for Phase 2 pilot tool. Hardware made available for initial testing of new components for Phase 2 design. A report will be delivered to DOE.

Budget Period 1 Go/No-Go Decision Point

The cost model will be updated with Phase 1 tool operational data and a path to realize the necessary cost reduction identified in Task 2.1 will be demonstrated. A realistic, practicable path to reach key process parameters with Phase 2 tool is identified. The average efficiency of plated cells meets or exceeds that of the screen printed baseline.

The following is a detailed description of the Tasks and Milestones for Phase 2 of this project as originally specified in the SOPO. Budget Period 2 encompasses Tasks 4, 5, and 6.

Task 4: Narrow Line Research

Subtask 4.1: Research on narrow line patterning

In this task, sub-recipient will experiment with laser patterning parameters including laser power, scan speed, focusing, pattern dimensions, masking layer properties, SiNx properties, and post processing cleans. The goal is to develop narrow line patterning process compatible with plating that can demonstrate line widths less than or equal to 40 microns. This patterning process will be developed with an emphasis on line width uniformity. Use of a masking layer is unique for patterning of the SiNx layer with a laser and it may lead to a more robust and manufacturable laser patterning process.

Milestone 4.1: Narrow line patterning process that can achieve uniform line widths with <15% standard deviation ((Line width standard deviation /average line width)*100) across a batch of 12 cells. Process specification will be delivered to DOE that demonstrates a 1% relative gain in Jsc for cells with 80 plated lines, line width ≤ 40 μm, versus screen printed control cells with 72 lines.

Task 5: Reliability Testing on Laminated Cells

This task will focus on reliability testing of laminated and tabbed solar cells that have plated front side metallization with wide line widths of approximately 300 microns. Testing will include thermal cycling (TC) and damp heat (DH) similar to industry standard testing described in the Photovolatic Solar Testing Specification for Crystalline Silicon Modules, IEC 61215.

Subtask 5.1: Initial reliability screening of laminated cells with plated lines.

Plated cells will be laminated and tested for an initial look at reliability. The tests will be Damp Heat 85°C/85% RH and Thermal Cycling (negative 45°C to 85°C).

Milestone 5.1: Perform initial damp heat and thermal cycling reliability tests and monitor change in power pre and post testing. Recommend changes to final process based on these results.

Subtask 5.2: Lamination of cells

Plated cells will be laminated into 2x2 tabbed modules for reliability testing.

Milestone 5.2: Passing criteria for a minimum of 2 modules (8 plated cells) is that the relative loss in power is less than 10% for each module when compared to the pre-lamination testing. Laminated cells ready for reliability testing.

Subtask 5.3: Final Thermal Cycling (TC) Testing

2x2 laminated modules will be tested at negative 45 to plus 85°C, 200 cycles. Electrical testing will be performed before and after TC.

Milestone 5.3: Passing criteria for a minimum of 2 modules (8 plated cells) is that the relative power loss after 200 cycles of thermal cycling is less than 5% for each module when compared to the initial module power. Results will be compiled for internal and external presentations.

Subtask 5.4: Final Damp Heat (DH) Testing

2x2 laminated modules will be tested in 85°C/85% RH for 100 h. Electrical testing will be performed before and after DH.

Milestone 5.4: Passing criteria for a minimum of 2 modules (8 plated cells) is that the relative power loss after 100 h of DH is less than 5% for each module when compared to the initial module power. Results will be compiled for internal and external presentations.

Task 6: Phase 2 Tool

This task will focus on the installation and operation of a demo plating tool at Technic in order to run customer demos and gather tool performance data required to market this plating tool to customers. Tool performance data will be used to finalize the cost model and verify the proposed cost reduction for plated contacts.

Subtask 6.1: Narrow line plating demonstration on Technic hardware.

Technic will acquire pre-patterned solar cells from at least 2 commercial vendors. These cells will enable plated line widths that are less than or equal to 40 microns. Technic will ask the vendors to verify that the provided cells are good quality and have consistent line widths across cells.

Milestone 6.1: Plated lines widths less than or equal to 40 microns achieved on 20-25 pre-patterned cells from at least 2 commercial vendors. Plated line widths will be measured using a contact profilometer. IV and profiler data will be compared to silver paste controls. The results will be published in an agreed upon format with the commercial vendors and the publication will be shared with the DOE.

Subtask 6.2: Plating Tool Installation

Plating tool installation at Technic Lab

Milestone 6.2: Demo plating tool will be installed at Technic. A site acceptance checklist will be completed and delivered to the DOE verifying that the tool is operational.

Subtask 6.3: Large Scale Plating Evaluation

Technic's demo tool will be used to process 100 pre-patterned cells. Tool performance parameters such as breakage rate, drag out, expected through put and chemistry / rinse water usage will be monitored over the 100 cells. IV data, line width, and thickness data will be randomly sampled throughout the 100 cell evaluation.

Milestone 6.3: Tool and cell performance for a large scale plating evaluation of 100 pre-patterned cells on Technic's demo tool will be reported to the DOE. Metrics will include breakage rate, chemistry drag out, expected through put, and cell / rinse water usage. A subset of the 100 cells will be used to measure and report IV properties, line width and plating thickness uniformity. Cell performance and tool performance data will be incorporated into the cost model and submitted to the DOE in order to verify the proposed cost reduction for plated contacts. Learning from this evaluation will be incorporated into a continuous improvement plan. If at this time, the proposed costs cannot be met, the DOE and Technic will agree to the appropriate path for process optimization in order to reduce additional costs from the process. Finally, a publication highlighting the tool and chemistry performance will be completed and distributed to the DOE

Subtask 6.4: Tool Performance Comparison to Competition

Technic's demo tool will be compared to the competition and the advantages of Technic's tool design will be highlighted.

Milestone 6.4: Comparison of Technic's tool design and metrics to the competition. A market competitiveness report will be provided to the DOE demonstrating the competitive advantages of Technic's tool design and the market for Technic's tool. DOE has the option to submit report to national lab staff for third party review of methodology and results. Technic's US manufacturing plan will be updated with this information.

Subtask 6.5: Customer Engagement

Technic will identify and engage with customers interested in the installation of Technic's plating tool. Technic will review the plating tool design with customers for feedback on the design. Technic will discuss customer's process requirements and selection critieria required for implementation of plating chemistry and tooling at their facility. In addition, Technic will run customer samples to demonstrate the robustness of the Technic chemistry and plating tool.

Milestone 6.5: Technic and the potential customer will agree to a testing plan that includes the criteria that the customer wants to meet prior to purchasing the tool. The signed testing plan agreement between Technic and the potential customer will be submitted to the DOE. This agreement will include the testing start date and period of performance.

Project Results and Discussion:

All Milestones were met through the course of this project. Table 2 summarizes the Milestones completed for Budget Year 1.

Table 3 summarizes the milestones completed for Budget Year 2. Discussion below will focus on the highlights and learning acquired from each Milestone and supporting documentation to show that the milestones were clearly met.

Table 2: Milestone Summary for Budget Year 1

SOPO Task # M.S. #	Task Title and Milestone Description	Performer	Task Start Date	Milestone Completion Date			
				Original Planned	Revised Planned	Actual	Percent Complete
1.1	Measure electrical performance of ASL processed AL-BSF cells	Technic, ASU	10/1/14	12/31/15		1/31/15	100%
1.2	Identify appropriate adhesion metric	MIT	10/1/14	12/31/15		8/2/15	100%
1.3	Identify appropriate metric for dry heat cell level reliability data	ASU, Technic	1/31/15	3/31/15		4/15/15	100%
1.4	Characterize metallization adhesion	MIT, Technic	3/31/15	6/31/15		12/21/15	100%
1.5	Perform initial lamination of cells	ASU, Technic	4/1/15	9/30/15	10/30/15	11/25/15	100%
2.1	Identify technical market barriers and opportunities	Jim Rand	1/2/15	3/31/15		3/31/15	100%
2.2	Install phase 1 tool at sub-recipient site	Technic, ASU	1/2/15	6/30/15		3/23/16	100%
2.3	Optimize processing	ASU	7/21/15	9/30/15	11/30/15	5/31/16	100%
3.1	Initial design of Phase 2 tool reviewed and initiate testing of newcomponents	Technic	10/1/14	9/30/15	11/30/15	3/23/16	100%

Table 3: Milestone Summary for Budget Year 2

SOPO Task # M.S. #	Task Title and Milestone Description	Performer	Task Start Date	Milestone Completion Date				Progress Notes
				Original Planned	Revised Planned	Actual	Percent Complete	
4.1	Demonstrate patterning and plating process capable of line widths < 40 microns	ASU	Y1	6/30/17	9/30/17	9/29/17	100%	Demonstrated Feasibility
5.1	Initial screening of reliability performance using Damp Heat 85C/85% RH and Thermal Cycling (neg. 45C to 85C)	All	Q9	3/31/17		4/13/17	100%	Passed
5.2	Successful Lamination of 2x2 tabbed moduels for reliability screening	All	Q11	3/31/17	9/30/17	9/29/17	100%	Passed
5.3	Final Thermal Cycling (neg. 45C to 85C, 200 cycles) on 8 single cell modules	All	Q12	12/30/17		2/6/18	100%	Passed
5.4	Final Damp Heat Testing (85C/85% RH, 100h passed) on 8 single cell modules	All	Q12	9/30/17		1/23/18	100%	Passed
6.1	Narrow line plating demonstration on Technic Hardware - pre patterned solar cells from two vendors (20-25 cells)	Technic	Q10	3/31/17	9/30/17	9/29/17	100%	Plated Cells Same as or Better than Screen printed controls
6.2	Plating Tool installation at Technic Lab	Technic	Q10	9/30/17		10/20/17	100%	Success
6.3	Large scale plating of 100 cells on Technic demo tool	Technic	Q13	12/30/17		1/23/18	100%	Excellent cell to cell repeatability
6.4	Demonstrate advantages of Technic Demo Tool versus competition	Technic/ Jim	Q13	12/30/17		1/23/18	100%	Technic tool has smaller footprint and unique cell handling
6.5	Identify customer interested in installation of Technic plating tool	Technic / Jim	Q13	12/30/17		1/23/18	100%	Cell manufacturer signed agreement

Milestone 1.1: Qualify cell supplier by processing and IV testing 25 cells. Measure variation across 25 cells from same supplier and compare to silver paste controls if available. IV data measured by Technic and ASU will be delivered to DOE (Delivered January 31, 2015)

25 cells were processed using Technic's ASL process per the wet etch plating steps listed in Table 1and IV tested.

Table 4 below summarizes the electrical results for these 25 cells and compares the data to the silver (Ag) paste control cells. All of this electrical data was measured by ASU.

Table 4: IV data for 25 plated cells compared to 3 Ag paste control cells

	Jsc	Voc	%FF	%Eff	Pff	Peff	Rshunt (ohm-cm^2)	Rseries (ohm-cm^2)
Average of 25 Plated Cells	32.5 ±0.6	0.62 ±0.006	71.7 ±7.2	14.4 ±1.5	78.1 ±7.6	15.7 ±1.6	1160 ±982	1.5 ±0.8
Average of Top 10 Plated Cells	32.7 ±0.5	0.623 ±0.004	76.3 ±1.4	15.5 ±0.2	81.3 ±1.1	16.5 ±0.3	1529 ±1028	1.0 ±0.4
Average of 3 Ag Paste Controls	35.0 ±0.1	0.629 ±0.002	78.7 ±0.4	17.3 ±0.1	82.6 ±0.3	18.2 ±0.2	3185 ±179	0.7 ±0.1

The silver paste controls have a higher efficiency than the plated cells. One reason for this is that the plated cells have much wider lines than the silver paste controls due to the wet etch patterning method used. The plated lines are approximately 230 microns wide versus ~62 microns wide for the silver paste control lines. Other patterning methods will be investigated in order to reduce the line widths of the plated samples. Although, it is expected that once this plating process is adopted by a cell manufacturer, they will most likely adopt their own proprietary patterning process to achieve the line widths they require for their cell architecture. Improvements made to the ASL process, such as improved rinsing and handling, did improve the R_{shunt} parameter. As you can see from

Table 4, the R_{shunt} is higher for the top 10 plated cells. The use of new tanks designed as part of the Phase 2 tool component testing (Milestone 3.1) results in a higher R_{shunt} most likely due to better rinsing. In addition, the R_{series} component for these cells is higher than desired; however, contact resistance studies are planned at ASU for Q3. In addition, failure analysis planned by MIT during Q3 will help to trouble shoot this issue.

Completion of this milestone demonstrates that the ASL process is repeatable over 25 cells. In addition, implementation of improved rinsing directly correlated to improved electrical results, specifically comparing the best 10 cells to the total 25 cells plated. Challenges identified during this milestone include reducing the line width that results from the resist and wet etch patterning process and improving the series resistance.

Milestone 1.2: Perform literature search to determine the appropriate adhesion metric for plated lines. Perform initial testing to verify metric. A report will be delivered to DOE. (Delivered August 2, 2015)

Both qualitative tape testing and quantitative pull testing were identified as key adhesion metrics through literature searching and voice of the customer information gathered in Milestone 2.1. A tape testing procedure was developed to standardize tape testing across the research labs in this project. In addition, a qualitative pull testing set-up was identified for MIT to use. Per Milestone 2.1 report, the industry norm for adhesion testing ranges from 1 to 2.5 N/mm which is significantly reduced from the value of 4 N/mm quoted a few years ago. In addition, these values are an average and some companies report a minimum specification – sometimes as low as 0.59 N/mm. Given this information, Technic will target an average adhesion value of 1.2 N/mm with a minimum value of 0.5 N/mm. This metric will be applied to quantitative pull testing performed per Milestone 1.4.

Milestone 1.3: Perform initial testing on plated cells using dry annealing and characterize the failures. Report change in pFF after dry heat annealing at 200°C for 10 cells for 500 hours. (Delivered April 15, 2015)

The dry heat annealing test was developed by Fraunhofer as an accelerated test to look at the long-term effects of copper metallization on silicon solar cells. The idea behind this test is that as the solar cell is subjected to heat over time, any copper migration into the space charge region (SCR) will show up as degradation in pFF. The nickel barrier layer should prevent copper migration into the SCR. It is hoped that this test will help to confirm the thickness of the nickel barrier layer required to prevent copper migration.

10 plated cells (Ni/Cu) and 2 Ag paste controls completed 500 hours or greater of dry heat annealing at 200°C. A normalized pFF of 1 would indicate no change in the

cells after dry heat annealing. During this test, 7 out of the 10 cells had a normalized pFF of 0.93 or greater. 3 of the cells had a pFF with <0.93; however, these cells also had probable cause for failure such as existing shunts, thin Ni barrier, and damage. These results demonstrate that the plated cells do not fail catastrophically during this extreme test. 4 cells pass Fraunhofer's criteria of a normalized pFF of 0.95. Lock in Thermography Imaging (LIT) was also performed during this test. The LIT images correlate well with the normalized pFF results. In addition, samples that initially have non-ohmic (reverse bias) shunts perform poorly during dry heat annealing. In addition to LIT imaging, SEM cross sections were also prepared to look at the plated interfaces after dry heat annealing. There was no obvious explanation for the shunted areas as a function of these cross sections; however, the images did show issues that required modification to the process flow in order to improve the interface quality. Modifications to the process flow did improve the issues of poor interface quality between the plated Ni and the silicon.

The dry heat annealing test was a successful way to look at the nickel barrier performance for copper plated solar cells. Results confirmed that a thin nickel barrier (<200 nm) is not an effective diffusion barrier during this test. Samples tested show that a nickel barrier layer of 500 nm or greater is effective to prevent copper diffusion during this test. In addition, no catastrophic failure was observed.

The recommendation for the dry heat annealing metric is: 1) Perform LIT prior to dry heat annealing and test only samples with clean reverse bias LIT images and 2) Anneal samples for 500 hours at 200°C. pFF should be measured before and after annealing. A normalized pFF of 0.95 and higher is considered passing.

Milestone 1.4: Adhesion test passed. Adhesion test using method identified in Task 1.2 demonstrated on 10 cells with plated sunny-side contacts. Report delivered to DOE. (Delivered December 21, 2015)

Peel testing was performed on both silver paste controls and plated solar cells in order to generate confidence in the test procedure. Ribbon similar to what is used in industry is first hand soldered onto the busbars. A 180° pull angle is used with a pulling speed of 200 mm/min using the ADMET eXpert 5600 Series Universal Testing System. This force tester gage has a load limit of 2.2 lbf (9.786 N) ~ 4.893 N/mm. The samples are secured to a vacuum plate for peel testing and the force required to pull the ribbon away from the cell is measured. The adhesion strength is the force per unit width of the ribbon. Quantitative peel testing was performed on 10 cells with plated Ni/Cu/Sn front grid (27 bus bars) and 5 cells with Ag paste front grid (15 bus bars).

Both plated cells and Ag paste cells demonstrate passing average adhesion strength of >1.2 N/mm:

- Average for 10 plated cells (27 bus bars) = 2.0 ± 1.2 N/mm
- Average for 5 Ag paste cells (15 bus bars) = 1.7 ± 0.9 N/mm

Figure 1 shows the high level quantitative results of this experiment. There is a tester limitation ~ 5 N/mm at which the pull tester abruptly stops. To continue testing, the sample was adjusted and the tester restarted. The overall data in Figure 1 refers to the measurements including the tool stopping & being restarted. The 1st pull data is only measurements until the tool stops. The data between the overall & 1st pull is fairly similar but included for completeness.

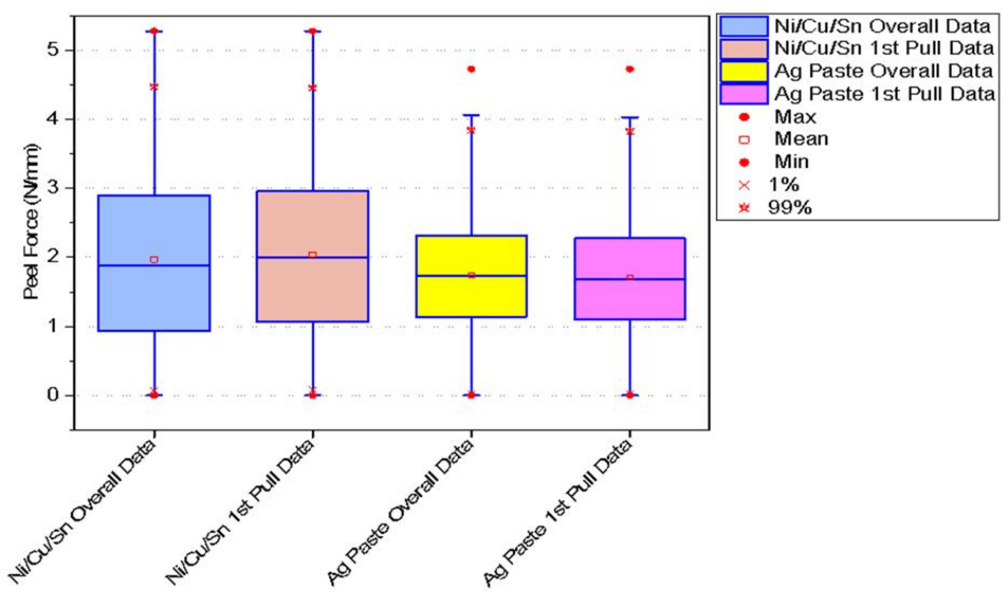


Figure 1: Peel Test results for Plated Contacts and Silver paste controls.

These results demonstrate that the adhesion performance of the plated solar cells is similar to that of Ag paste cells. This is a huge win for plated cells. The lowest average adhesion for a plated cell is 1.3 N/mm. The lowest average adhesion of a silver paste cell is 1.0 N/mm. Therefore, both the plated and the Ag paste cells pass average adhesion / cell > 0.5 N/mm. In literature, the max peel test values are typically reported along with the average values. Figure 2 below shows the max values based on calculation of the 95th percentile for each cell as a function of grid metallization. The average of the 95th percentile values for plated cells is 3.85 ± 0.43 N/mm and the average for the Ag paste cells is 3.11 ± 0.51.

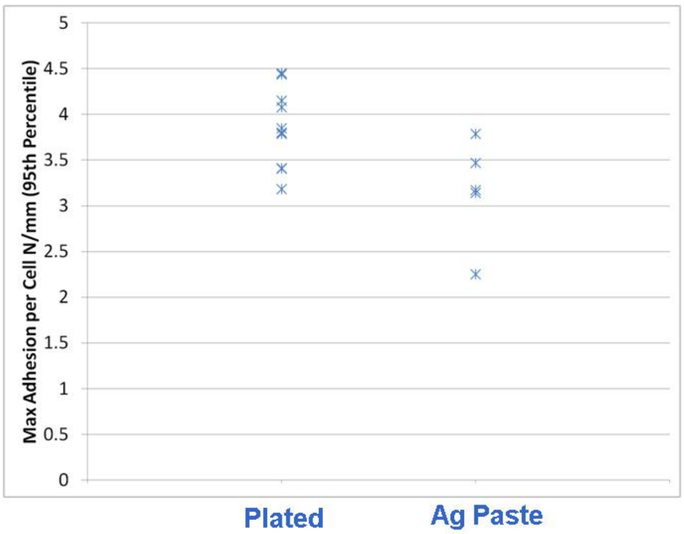


Figure 2: Comparison of max adhesion values per cell for plated and Ag paste front grid metallizations (based on 95th percentile).

Milestone 1.5: Initial lamination of cell showing less than 20% change in power output. Report delivered to DOE. (Delivered November 25, 2015)

ASU performed an initial lamination of a plated cell and tested IV before and after lamination. The cell was processed through the wet etch process and plated at Technic using nickel, copper, and tin. The pre and post IV results show a ~3% relative increase in power output post encapsulation which is within the metric specified for this milestone. Figure 3 below shows a picture of the encapsulated cell. Figure 4 & Table 5 compare the IV results before and after lamination. Success of this milestone demonstrates that the ASL plating process is compatible with lamination. This is a critical step towards successfully understanding the reliability performance of the plated cells in budget year 2.

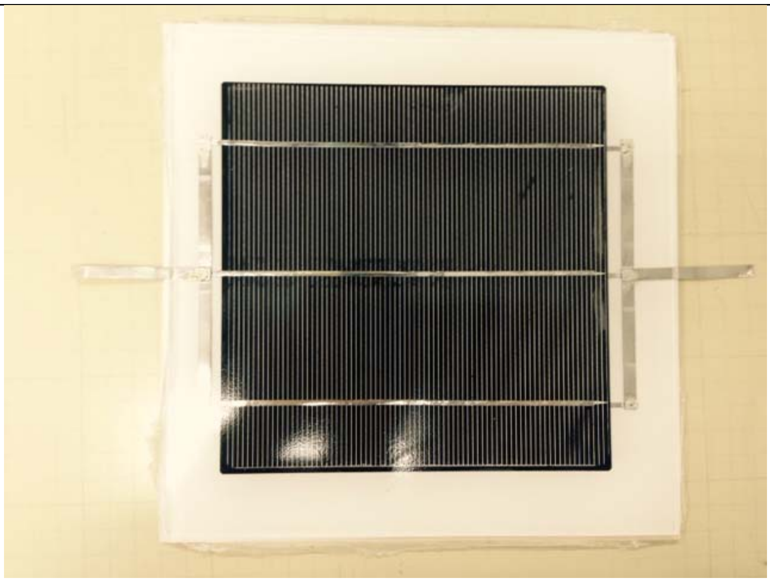


Figure 3: Picture of encapsulated solar cell with plated nickel, copper, and tin front grid metallization.

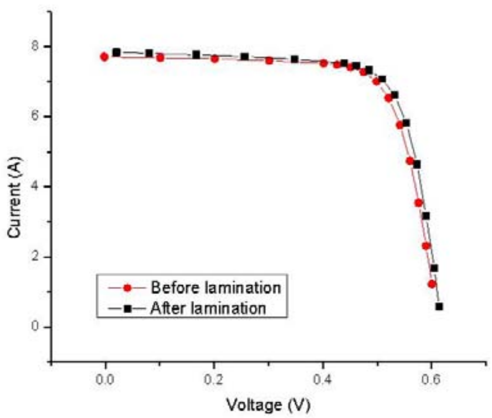


Figure 4: IV curve before and after lamination

	Before Lamination	After Lamination
Pmp	3.50	3.61
V_{OC} (V)	.611	.617
J_{SC} (mA/cm^2)	32.3	32.3
FF (%)	74.2%	74.5%
Eff (%)	14.6%	14.8%
pFF (%)	80.2%	79.3%
R_{series} (Ω-cm^2)	1.35	1.07
R_{shunt} (Ω-cm^2)	739	458

Table 5: IV results before and after lamination

Milestone 2.1: Voice-of-customer understood via first-hand survey and technology consultant input. Key process parameters are qualified and the technology adoption pathway is identified. A report will be delivered to the DOE. (Delivered March 31, 2015))

Based on the voice of the customer information collected by J.A. Rand and reported in Milestone 2.1, development of a plating tool and chemistry to enable the replacement of silver paste contacts with plated contacts does make sense. J.A. Rand states in his report, "A primary goal should be to stay as close to the mainstream module materials as possible to minimize potential complications with reliability, and to offer the highest level of reassurance to the customer". This statement aligns with Technic's current development plan to implement plated contacts on the mainstream low cost solar cell architecture with a standard silicon emitter and aluminum paste backside. Overcoming adhesion issues that are associated with plated contacts is critical for this technology to be adopted in manufacturing. However, since the specific standards for metal adhesion are still "a work in progress", providing the industry with good reliability data and a clear understanding of the metal contact architecture required to achieve this data will be necessary. Two other areas are viewed as being important for successful adoption of plated contacts: 1) Demonstration of a lower breakage rate and less disruption to the manufacturing line when breakage occurs and 2) Education of the PV industry concerning waste management for plating chemicals. In addition to the expected cost savings and improved electrical performance, achieving good reliability data and demonstrating manufacturability, as discussed above, will contribute to greater market success for plated contacts.

Milestone 2.2: Tool installed and operational at ASU. Deliver signed acceptance checklist and photo of first solar cell that has been processed. (Delivered March 23, 2016)

Three LIP plating tools were built by Technic and delivered to ASU in February 2015. After completing the required facilities work, the tools were installed by Technic the week of July 13th. Nickel and copper plating chemistries were poured into two of the tools July 2015. The tin plating chemistry was poured into the tool March 9, 2016. The first Ni/Cu/Sn plated cell was processed on March 10, 2016 and is shown in Figure 5. The site acceptance test passed and a copy of the signed checklist was submitted to DOE.

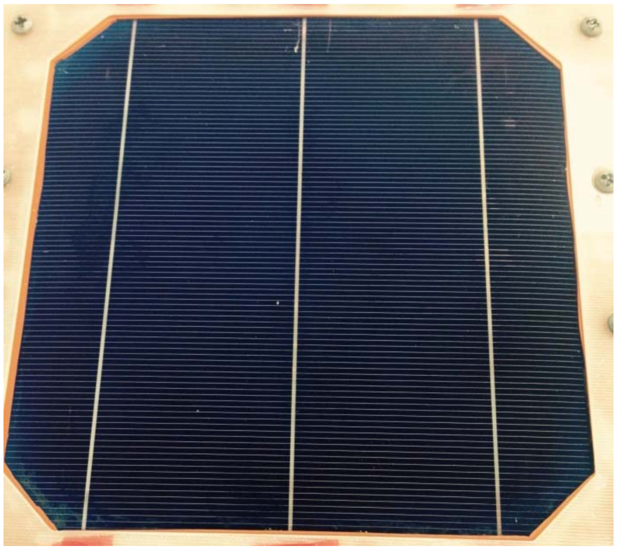


Figure 5: Ni/Cu/Sn plated solar cell.

Milestone 2.3: Optimize processing at ASU – plated cell baseline meets or exceeds screen printed cell baseline. The average efficiency of 20 plated cells meets or exceeds screen printed baseline by 2% relative. I-V data measured by ASU delivered to DOE. NREL (or certified 3rd party) verified efficiency on subset of cells. (Delivered May 31, 2016)

23 plated cells and 3 controls cells were used for this milestone. 15 of the 23 plated cells were IV tested and then sent off for other experiments. 8 of the 23 plated cells were sent to NREL after IV testing in order to gain 3rd party verification. The cells used were pre-patterned, partially completed cells from Fraunhofer. Fraunhofer performed laser ablation of the ARC layer which resulted in 20-30 micron grid line openings (after plating lines grow to ~40-45 microns). Three silver paste controls purchased from Fraunhofer were included as control cells. These cells had the same grid layout as the cells for plating. The silver paste controls had a grid line width between 40-45 microns. IV data for the 23 plated cells and 3 controls cells was measured at 3 locations: 1) Technic, ASU, and NREL. Table 6 below summarizes the efficiency measurements for all of the 23 plated cells. These measurements include the 15 cells measured at Technic only and the 8 cells measured at all 3 locations. Included also in Table 6 are the control cell results. This data shows that the average efficiency of the plated cells MEETS that of the control cells by less than 2% relative.

Table 6: Efficiency Results for 23 Plated Cells vs 3 Control Cells. Subset of 8 cells measured at Technic & ASU – RESULTS from NREL added 06/20/16

	Plated Cells (23)			Control Cells (3)		
	Technic	ASU	**NREL**	Technic	ASU	**NREL**
Average	18.75%	18.77%	**18.78%**	18.74%	18.81%	**18.88%**
Standard Deviation	0.15	0.19	**0.15**	0.27	0.31	**0.18**
% relative from Control	0.05% > control	0.21% < control	**0.53% < control**			

Note: Line widths for control cells & plated cells similar: ~40-45 um

Table 7 below compares the 8 plated cells that were measured at Technic, ASU, and NREL. There is no statistical difference observed between these measurements. Therefore, milestone 2.3 has been met and includes 3rd party verification that the efficiency measurements are accurate.

Table 7: Efficiency results for 8 plated cells and 3 control cells measured at Technic, ASU, and NREL.

	8 plated cells			3 control cells		
	Technic	ASU	**NREL**	Technic	ASU	**NREL**
Average	18.67%	18.72%	**18.76%**	18.74%	18.81%	**18.88%**
Standard Deviation	0.15	0.27	**0.16**	0.28	0.31	**0.18**

The raw IV measurements from Technic, ASU, and NREL were submitted along with the Milestone 2.3 completion report.

Milestone 3.1: Review of initial design of Phase 2 pilot tool. Hardware made available for initial testing of new components for Phase 2 design. A report will be delivered to DOE. (Delivered March 23, 2016)

The performance and manufacturability issues that were identified while testing the Phase 1 tools fed into a complete redesign for the Phase 2 demo plating tool.

The Phase 2 frameless holder design works best with the Phase 2 tank design which incorporates a spout for recirculating the solution versus spargers. The Phase 2 tank design has increased mass transport compared to the Phase 1 design. This enables faster and more uniform plating. Figure 6 below compares the %standard deviation for plated cells on the Phase 1 and Phase 2 hardware. The plated solar cells were measured on the profiler to gather grid line thickness and line width in 12 locations across the cell. Bus bar thickness was also measured in 9 spots. As Figure 6 shows, the Phase 2 hardware results in lower % standard deviation for both the grid line thickness & width compared to both Phase 1 tools. The bus bar %standard deviation results are a bit inconsistent across the Phase 1 tools.

Table 8 below lists the critical issues observed with the Phase 1 equipment design and the changes that will be implemented in the Phase 2 pilot tool with the expected improvement related to that change.

The Phase 2 frameless holder design works best with the Phase 2 tank design which incorporates a spout for recirculating the solution versus spargers. The Phase 2 tank design has increased mass transport compared to the Phase 1 design. This enables faster and more uniform plating. Figure 6 below compares the %standard deviation for plated cells on the Phase 1 and Phase 2 hardware. The plated solar cells were measured on the profiler to gather grid line thickness and line width in 12 locations across the cell. Bus bar thickness was also measured in 9 spots. As Figure 6 shows, the Phase 2 hardware results in lower % standard deviation for both the grid line thickness & width compared to both Phase 1 tools. The bus bar %standard deviation results are a bit inconsistent across the Phase 1 tools.

Table 8: Problems solved with Phase 2 Pilot tool design

Issue	Phase 1	Phase 2	Improvement
Footprint concerns	Conveyor	Hoist	More flexibility in design Smaller footprint expected
Leaking Wafer Holder	Frame	Frame-less	Less breakage expected More Manufacturable Less bubble entrapment
Long term durability of plating contacts	Brush	Pin	Pin contacts more durable over time and gentler to wafer – less damage
Inefficient fluid flow	Spargers	Spout	Increased mass transport Better wetting of substrate Improved Uniformity
Difficult light maintenance	Light tubes	Enclosed array	Easy access to light array from underside of plating tank.

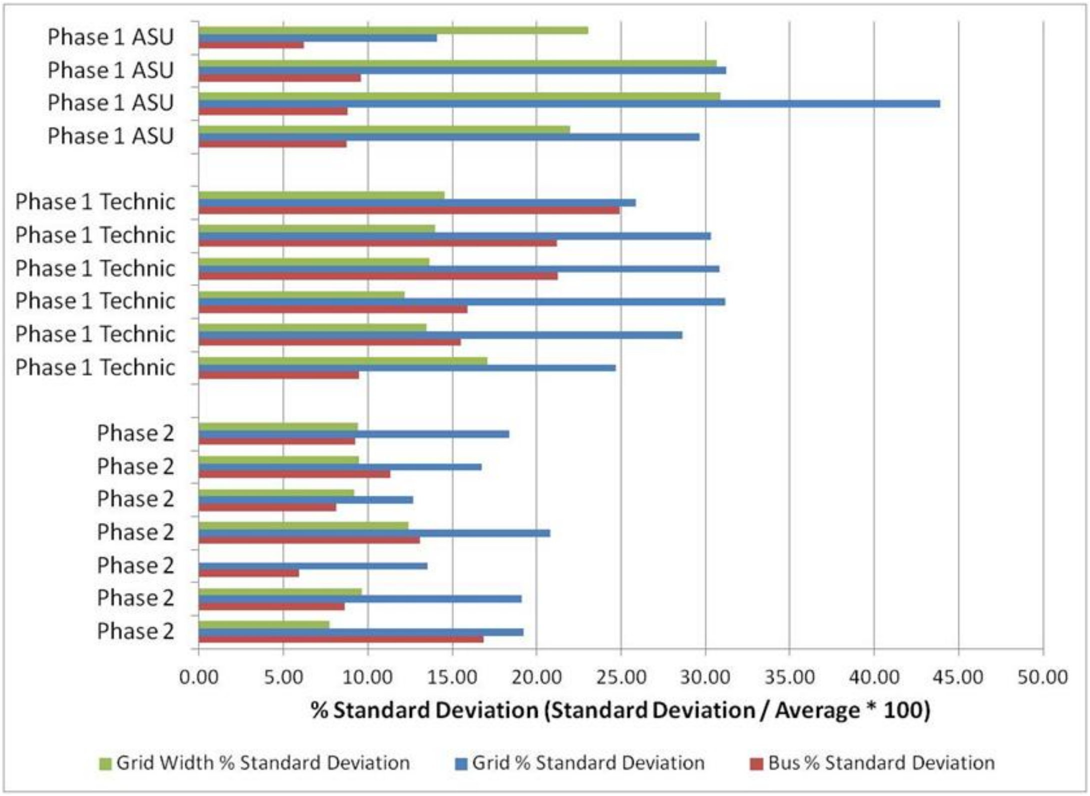


Figure 6: Comparison of %standard deviation for plated grid line and bus bar thickness and grid line width across Phase 1 and Phase 2 equipment hardware.

The new Phase 2 LIP plating tank design also enables faster plating rates for Cu plating on grid lines less than 45 microns in width. This increased plating rate in copper can be achieved due to the increase mass transport from the new design. In addition the new Phase 2 LIP plating tank design incorporates better light and anode placement. With these design changes, the current density (amps per square foot, ASF) that can be applied to the solar cell can be increased from 30-60 ASF up to 90-120 ASF. It was not possible with the Phase 1 design to plate copper at 120 ASF. Since the copper plating step is one of the longest steps in the ASL process, this reduction in plating time will increase the throughput possible in the Phase 2 pilot tool.

State of the Art efficiencies ranging from 18.6 – 19.1% can be achieved using both the Phase 1 and Phase 2 LIP plating tank designs. However, in the Phase 2 LIP plating tank the copper plating time required to achieve the same thickness is shorter. As shown in Figure 7, there is a grid line thickness optimum that provides the maximum efficiency while balancing the improvement in series resistance from thicker metal with the increase in shading from wider lines (i.e. wider lines result from thicker metal). For this study, the plated cells and the silver paste controls have the same number of lines per cell. In addition, the cells used for this study have an emitter that is optimized for silver paste. It is believe that through optimization of the front grid design and the emitter resistivity, the plated cells can achieve a higher efficiency than silver paste cells due to better contact resistance, line conductivity, and shape of the plated lines.

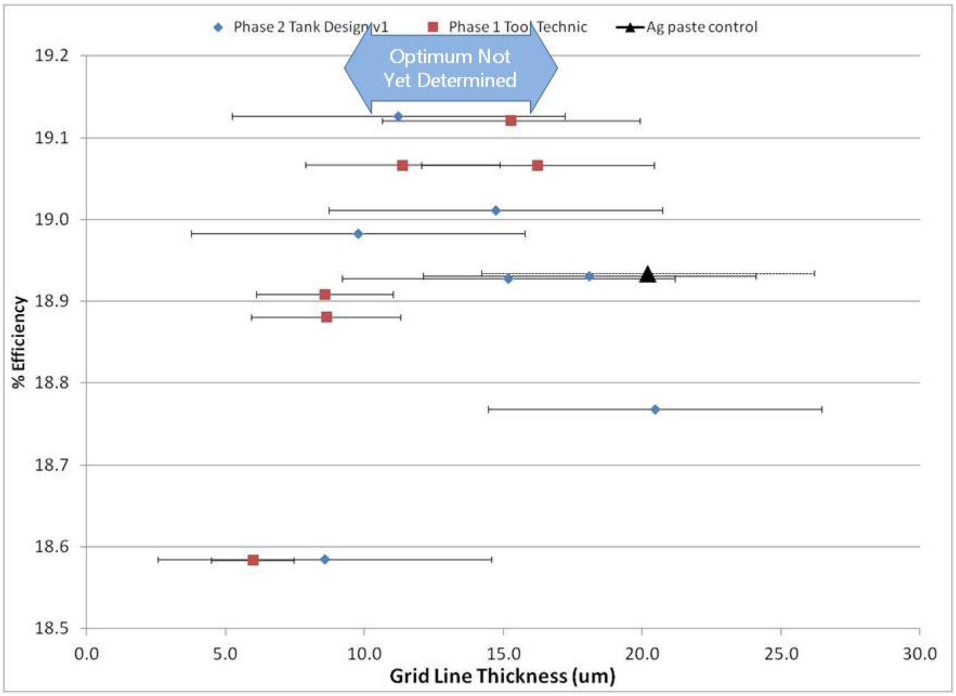


Figure 7: State of the Art efficiencies for plated contacts compared to the silver paste control results.

In conclusion, Technic has completed the initial design of the Phase 2 pilot tool. The design of the Phase 2 pilot tool is significantly different from the initial Phase 1 equipment. The wafer transport system, cell holder, and solution flow in the tanks have been redesigned. Hardware has been built to test out the new Phase 2 designs for both tank and cell holder. Improved plated uniformity and increased plating rates are possible with the Phase 2 design. In addition, improved etching and rinsing with the Phase 2 design resulted in passing adhesion (see Milestone 1.4) and state of the art IV results.

The Key Process Parameters (KPP) to achieve for the Phase 2 pilot tool are:

1. Uniform metal thickness over a 156 x 156 mm solar cell plated front grid: measured by % standard deviation across cell <20%.

2. Increased copper plating rate: measured by copper plating time less than or equal to 5 minutes.
3. Compatibility with laser based process that can generate fine line openings: measured by state of the art IV properties demonstrating efficiencies greater than or equal to the screen print controls.
4. Wafer handling approach that does not damage the wafer surface yet makes good electrical contact: measured by low breakage rate and reduced scratching on the backside of the cell.

It was demonstrated in the Go No-Go deliverable that Technic's initial Phase 2 demo plating tool has been designed to achieve these KPP's.

Budget Year 2:

Milestone 4.1: Demonstrate patterning and plating process capable of line widths less than 40 um by sub-recipient research efforts. Specification for process shows a 1% relative gain in Jsc for cells with 80 plated lines, line width <40 um versus screen printed control cells with 72 lines. (Delivered September 29, 2017)

ASU developed an indirect laser ablation approach for forming narrow grid lines in the SiN ARC layer. The goal is to develop a narrow line patterning process compatible with plating that can demonstrate line widths less than or equal to 40 microns. This patterning process is to be developed with an emphasis on line width uniformity. ASU patterned 13 cells with this indirect laser ablation approach. Plating of the laser ablated lines was performed at ASU using Technic supplied plating chemistry and equipment. The average line width was 35.11 microns with a 10.8% standard deviation across the batch. As a comparison, the average line with for the silver paste line is 93.1 microns.

ASU modeled the expected J_{sc} reduction based on shading only for plated fingers that are 35 microns wide versus silver paste fingers that are 93 microns wide. The J_{sc} for the unshaded regions was 38 mA/cm^2, taken from QE measurements. The silver paste cells were modeled with 72 fingers and the plated cells were modeled with 80 and 150 fingers. Model calculations indicate that the plated cell with 80 fingers has a potential J_{sc} gain of 2.59% versus the silver paste cell with 72 fingers. However, as the plated fingers are increased to 150 in number, the potential J_{sc} gain is decreased to 0.96%. This modeling exercise shows that a laser processing specification that results in ~35 micron line width that has a grid line design of 80 lines will theoretically provide a 2.59% increase in J_{sc}. This milestone has been completed.

Milestone 5.1: Initial reliability screening of laminated cells. Change in power pre and post testing. Recommendation on processing and lamination procedure for final testing based on results from screening. (Delivered April 13, 2017)

Initial reliability testing was performed on both wet etch and laser ablated samples plated at Technic. ASU fabricated single cell modules from the plated and silver paste control cells. Damp heat testing for 1000 hours at 85°C/85% was performed at NREL and thermal cycling testing (-45°C to 85°C) was performed at Case Western Reserve University. This was a small sample set intended for an early look at reliability of the plated contacts. The plated cells used for this testing were similar in electrical performance to the silver paste controls. Table 9 lists all the cells individually and compares the cell efficiency measured pre and post reliability testing. The wet etch samples have lower efficiency than the laser ablated samples due to the wider lines resulting from wet etch patterning. The wet etch patterned lines can be up to 3 times the width of the screen printed controls. In addition, the %P_{max} change is also listed for each cell. This is the change in max power after comparing the P_{max} measured before and after reliability testing. Typically cells with less than a 5% P_{max} change are considered passing. Only one out of the 20 plated cells tested had a P_{max} change greater than 5%. It was determined that this cell had a processing issue and missed a critical step in the processing flow that resulted in poor performance during reliability testing.

Table 9: Summary of plated cells & control cells tested

#	ID	Patterning: Process Flow	Testing TBD	Pre %Efficiency	Post %Efficiency	%Pmax Change
1	***Control F1***	***Silver Paste Control for Laser Samples***	***Damp Heat***	*18.6*	*18.5*	*-0.67*
2	**MLAF21**	**Laser Ablation: Ni-Cu / Anneal / Sn**	**Damp Heat**	17.9	18.4	2.74
3	**MLAF23**	**Laser Ablation: Ni-Cu / Anneal / Sn**	**Damp Heat**	17.8	18.0	1.52
4	**MLAF25**	**Laser Ablation: Ni-Cu / Anneal / Sn**	**Damp Heat**	18.3	18.0	-1.64
5	**MLAF32**	**Laser Ablation: Ni-Cu / Anneal / Sn**	**Damp Heat**	18.2	17.7	-2.89
6	**MLAF30**	**Laser Ablation: Ni-Cu / Anneal / Sn**	**Damp Heat**	17.9	17.7	-0.91
7	*ECN Control 1*	*Silver Paste Control for Wet Etch*	*Damp Heat*	*18.1*	*18.0*	*-0.41*
8	No ID #2	Wet Etch: Ni / anneal / etch / Ni-Cu-Sn	Damp Heat	15.3	14.8	-2.25
9	MKRECN_372	Wet Etch: Ni / anneal / Ni-Cu-Sn	Damp Heat	14.6	13.8	-5.37
10	MKRECN_366	Wet Etch: Ni / anneal / etch / Ni-Cu-Sn	Damp Heat	16.2	15.8	-2.34
11	No ID #1	Wet Etch: Ni / anneal / etch / Ni-Cu-Sn	Damp Heat	15.1	15.1	-0.04
12	MKRECN_368	Wet Etch: Ni / anneal / etch / Ni-Cu-Sn	Damp Heat	16.3	15.9	-2.77
13	***Control F3***	***Silver Paste Control for Laser Samples***	***Thermal Cycling***	*18.6*	*18.2*	*-2.00*
14	**MLAF24**	**Laser Ablation: Ni-Cu / Anneal / Sn**	**Thermal Cycling**	17.6	17.0	-3.30
15	**MLAF46**	**Laser Ablation: Ni-Cu / Anneal / Sn**	**Thermal Cycling**	18.4	18.1	-2.10
16	**MLAF48**	**Laser Ablation: Ni-Cu / Anneal / Sn**	**Thermal Cycling**	18.4	17.9	-3.19
17	**MLAF47**	**Laser Ablation: Ni-Cu / Anneal / Sn**	**Thermal Cycling**	18.2	18.1	-0.66
18	MKRECN_239	Wet Etch: Ni / anneal / etch / Ni-Cu-Sn	Thermal Cycling	16.5	16.1	-2.51
19	MKRECN_389	Wet Etch: Ni / anneal / etch / Ni-Cu-Sn	Thermal Cycling	15.7	15.5	-1.56
20	NKRECN_390	Wet Etch: Ni / anneal / etch / Ni-Cu-Sn	Thermal Cycling	16.1	15.8	-1.99
21	MKRECN_378	Wet Etch: Ni / anneal / etch / Ni-Cu-Sn	Thermal Cycling	16.2	16.0	-1.69
22	MKRECN308	Wet Etch: Ni / anneal / etch / Ni-Cu-Sn	Thermal Cycling	15.3	14.8	-3.24
23	MKRECN312	Wet Etch: Ni / anneal / etch / Ni-Cu-Sn	Thermal Cycling	14.9	14.3	-4.28

Table 10 shows more detailed reliability results for laser ablated, plated cells compared to the silver paste controls. All plated cells perform similar to the Ag paste control and show less than 5% change in power post testing which is a passing result.

Table 10: Reliability results for laser ablated, plated cells in single cell modules.

Sample	Test	Δ Pmax (% rel)	Δ FF (% rel)	Δ Voc (% rel)	Δ Isc (% rel)	Δ Eff (% rel)
Control	*1000 h DH*	-0.7	-0.3	0.6	-1.0	-0.3
1	*1000 h DH*	-1.6	-0.8	0.5	-1.3	-0.8
2	*1000 h DH*	-0.9	-1.1	0.5	-0.3	-1.1
3	*1000 h DH*	-2.9	-1.9	0.3	-1.3	-1.9
4	*1000 h DH*	2.7	0.7	1.3	0.8	0.7
5	*1000 h DH*	1.5	-0.3	1.3	0.5	-0.3
Control	*200 TC*	-2.0	-1.1	0.0	-0.8	-2.2
1	*200 TC*	-2.1	-0.8	0.2	-1.3	-1.6
2	*200 TC*	-0.7	-0.4	0.0	-0.3	-0.5
3	*200 TC*	-3.2	-1.8	0.0	-1.3	-2.7
4	*200 TC*	-3.3	-4.1	0.2	0.8	-3.4

Table 11 shows the results for the wet etch cells – cell MKRECN372 with the known processing issue was removed from the sample set. Unfortunately, there were not enough cells to have a silver paste control in the thermal cycling test. However, all the cells show passing results, with power changes less than 5%. Further reliability tests are planned with a larger sample size and more silver paste controls.

Table 11: Reliability results for wet etch, plated cells in single cell modules

#	ID	Δ Pmax (% rel)	Δ FF (% rel)	Δ Voc (% rel)	Δ Isc (% rel)	Δ Eff (% rel)
Control	*1000 hr DH*	*-0.4*	*0.3*	*0.6*	*-1.3*	*0.3*
1	1000 hr DH	-2.8	-1.3	-0.3	-1.1	-1.3
2	1000 hr DH	-2.3	-1.1	0.2	-1.5	-1.1
3	1000 hr DH	-2.3	-1.4	0.0	-0.9	-1.4
4	1000 hr DH	0.0	1.0	0.8	-1.7	1.0
1	200 TC	-2.5	-1.1	-0.2	-1.1	-2.4
2	200 TC	-2.0	-0.4	0.0	-1.4	-1.9
3	200 TC	-1.6	-0.4	0.2	-1.2	-1.3
4	200 TC	-1.7	-0.3	0.2	-1.4	-1.2
5	200 TC	-3.2	-2.5	0.7	-1.2	-3.3
6	200 TC	-4.3	-2.2	-0.2	-1.8	-4.0

Based on this initial evaluation, the following is the process recommendation for further reliability testing. Both wet etch and laser ablation patterning demonstrate passing results; however laser ablation patterning results in line widths ≤ silver paste controls. Therefore, cells with good laser ablation patterning are preferred for future reliability testing. Technic plating chemistry and process result in passing reliability results. In addition, ASU's procedure for hand-soldered interconnection and layup using commercially-available module materials produces reliable modules. Recommendation is to continue with this process. Single cell lamination to create modules for Milestone 5.3 & 5.4 is recommended based on this testing.

Milestone 5.2: Successful lamination of 2x2 tabbed modules for reliability screening. (Delivered September 29, 2017)

ASU fabricated two 2x2 modules by hand soldering using solar cells purchased from Fraunhofer and plated at Technic using Ni/Cu/Sn. The 2x2 modules were tested using an outside module curve tracer (with an uncertainty of ±0.6 Watt) at an ASU reliability lab. Both modules had a pre P_{max} of 18.3 W based on the addition of the Pmax values for each individual cell in the module. The post P_{max} value measured using the ASU module curve tracer was much lower than expected as shown in Table 12. However, given the uncertainty of the tester, these modules can be considered passing as shown in Table 12.

Table 12: Results for Module 1 and Module 2 post lamination and outdoor testing using the ASU module curve tracer with an uncertainty of ±0.6 W.

	Module 1	Module 2
Pre Pmax (W)*	18.3	18.3
Post Pmax(W)	15.9	16.5
Post Uncertainty (W)	0.6	0.6
% Change	-13.3	-10.0
% Uncertainty	3.8	3.6
Min % Change	-9.6	-6.4
Max % Change	-17.1	-13.7

During the hand soldering of the 2x2 modules, ASU noticed that the backside ribbons did not solder well. These ribbons are soldered to the Ag paste tabs that were fabricated at Fraunhofer prior to plating the cells at Technic. Suns V_{oc} measurements indicated that the power drop was due to series resistance. Further investigation showed that 65% of the voltage drop is due to poor contact on the rear of the cell. The soldered connections to the plated bus bars did not show any issues. A calculation was performed to correct for the poor ribbon to cell contact at the rear of the cell. With this correction, the power loss would be <1.5% for both modules. After Milestone 5.1 testing was completed, it was determined that using single cell modules for future reliability testing would be better than using 2x2 modules so that the impact of the plating and not the module fabrication can be assessed. The results from Milestone 5.1 indicate that there is not a problem hand soldering and laminating the single cell modules. In fact, the single cell modules tested in Milestone 5.1 showed very low %FF loss post lamination. Since demonstrating good rear solder joints on a 2x2 module is not critical to the rest of the DOE project, this milestone was passed. All future reliability testing will be performed on single cell modules.

Milestone 5.3: Final Thermal Cycling Testing – negative 45°C to 85°C, 200 cycles passed. Passing criteria for a minimum of 2 modules (8 single cell modules) is that the relative power loss after 200 thermal cycles is less than 5% for each module when compared to the initial module power. Results compiled for internal and external presentations. (Delivered February 6, 2018)

ASU made 15 single cell modules from 12 cells plated at Technic and 3 silver paste controls cells. Three different cell architectures were represented within the 12 plated cells; i.e. Mono-BSF, Mono-PERC, and Multi-BSF. For the plated cells, the ARC layer was patterning by the cell manufacturer using laser ablation. After encapsulation and testing, the modules were exposed to light soaking at ASU and tested post light soaking. For light soaking, the samples were placed outdoors at open circuit for one day in clear-sky conditions. Samples received ~8.5kWh/m^2 of insolation. The average air temperature during light-soaking was ~24°C with an average wind speed of 1.3 m/s; this corresponds to a roughly-estimated average cell temperature of 47°C. Next the modules were shipped to NREL for thermal cycling (-40°C to 85°C). NREL completed 175 out of the 200 cycles required for this milestone before shipping the cells back for testing. Interim IV testing was performed at ASU. The remaining 25 thermal cycles were completed in February 2018 by ASU and the final IV results are presented below.

Table 13 shows the cell breakdown for each cell architecture and encapsulation material. Figure 8 shows the change in IV parameters including P_{max} from post light soaking to post thermal cycling. The purple line shows the change in P_{max}. All but 4 of the cells show a P_{max} gain after thermal cycling. One of the silver paste controls shows a power loss and actually fails the milestone criteria which is P_{max} loss <5%. The power gain observed for the majority of the cells can be explained by looking at the light soaking results. Figure 9 shows the P_{max} values for each cell before and after light soaking and after 200 thermal cycles. All of the cells, except the Multi-BSF, show a drop in P_{max} after light soaking. This drop in P_{max} from light soaking is partially recovered post thermal cycling except in the case of two plated MONO-BSF cells and one of the Mono-BSF silver paste cells. For the Multi-BSF cells, although there is not a significant drop in P_{max} after light soaking, there is a gain in P_{max} after thermal cycling. These results will require further study to fully explain what is going on. This research is not required by this milestone but will be part of an ASU Ph.D. thesis. Since all of the 12 plated cells pass the milestone criteria of less than 5% P_{max} loss (P_{max} post thermal cycling - P_{max} post light-soaking), this milestone is considered complete.

Table 13: Change in P_{max} for Cells Post 175 thermal cycles

Mono BSF	Mono PERC	Multi BSF	Ag Paste Control – Mono BSF
44	7	6	22 (Ag Paste)
47	15	9	23 (Ag Paste)
51	18	11	24 (Ag Paste)
52	19		
53			

= EVA

= TPO

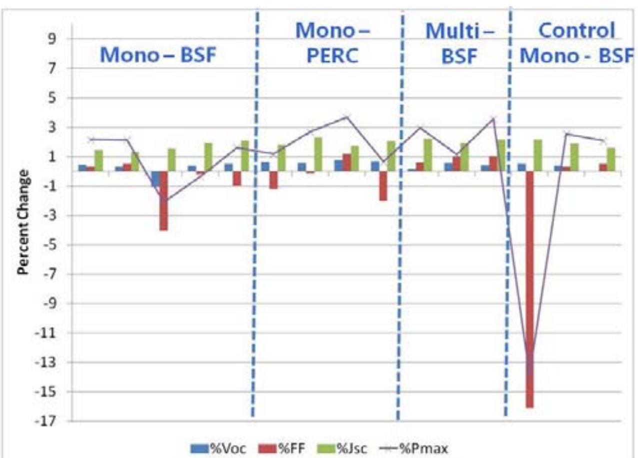


Figure 8: Change in IV parameters from post light soaking to 200 thermal cycles.

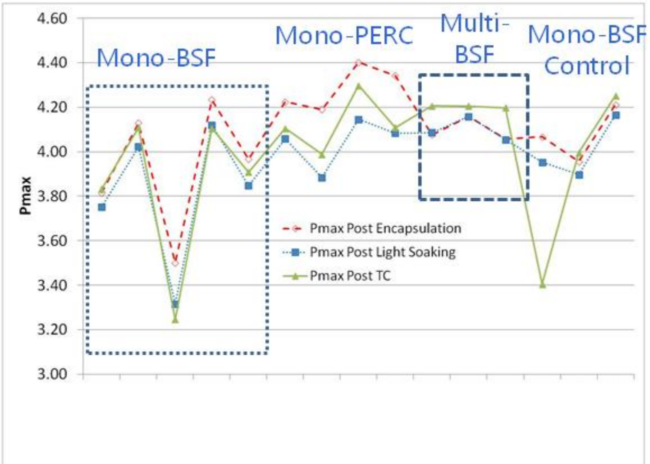


Figure 9: Comparison of P_{max} values after each step

Milestone 5.4: Final Damp Heat Testing. 85°C/85% RH, 100h passed. Passing criteria for a minimum of 2 modules (8 single cell modules) is that the relative power loss after 100 h DH is less than 5% for each module when compared to the initial module power. Results compiled for internal and external presentations. (Delivered January 23, 2017)

15 cells plated at Technic and 3 silver paste controls cells were made into single cell modules at ASU. Three different cell architectures were represented within the 15 plated cells; i.e. Mono-BSF, Mono-PERC, and Multi-BSF. The Mono-BSF cells included 5 cells plated with Technic's boric acid-free nickel plating chemistry and 3 cells plated with a standard sulfamate nickel plating bath. ASU made the single cells modules using either EVA or TPO. After encapsulation and testing, the modules were exposed to light soaking at ASU. For light soaking, the samples were placed outdoors at open circuit for one day in clear-sky conditions. Samples received ~8.5kWh/m^2 of insolation. The average air temperature during light-soaking was ~24°C with an average wind speed of 1.3 m/s; this corresponds to a roughly-estimated average cell temperature of 47°C. After characterization, the modules were shipped to NREL for damp heat testing (85°C, 85%RH) for 672 hours. Although this milestone calls for only 100 hours of damp heat testing, the industry standard is 1000 hours. Therefore, these cells will continue testing for 328 hours to achieve the 1000 hours of testing time. These results are not required for this milestone but will be useful to have. The following data is the interim results obtained after 672 hours.

Table 14 shows the cell breakdown for each cell architecture and encapsulation material. Figure 10 shows the change in IV parameters including P_{max} from post light soaking to post damp heat. The purple line shows the change in P_{max}. All of the cells show a gain in P_{max} post damp heat. Within the Mono-BSF plated cells, there is little difference between the cells plated with Technic's boric acid-free nickel and the standard sulfamate nickel (in the green box). In addition, the cells in the orange box had TPO instead of EVA for the module. Again, no difference is observed for these encapsulation materials.

Table 14: Cells tested as a function of cell architecture and encapsulation material

Mono BSF	Mono PERC	Multi BSF	Ag Paste Control – Mono BSF
35	3	5	1 (Ag Paste)
36	20	7	2 (Ag Paste)
41	13	12	3 (Ag Paste)
49	17		
50			
31			
32			
33			

= EVA
= TPO

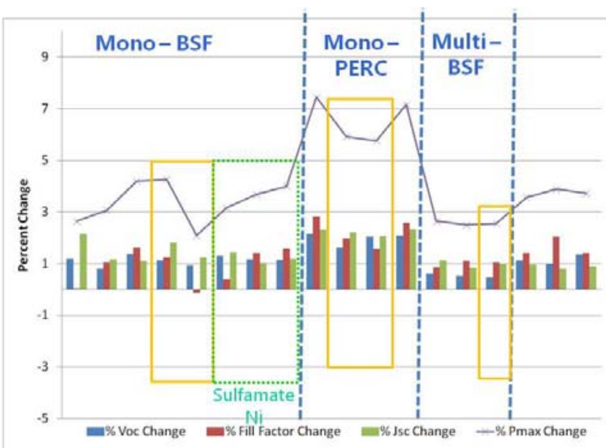


Figure 10: Change in IV parameters as a function of damp heat testing. Green box from cells plated with a sulfamate nickel plating bath instead of Technic's boric acid free bath. Orange boxes from cells encapsulated using TPO instead of EVA.

The gain in P_{max} for all the cells can be explained by looking at the post light soaking results. Figure 11 compares the P_{max} value for each cell pre & post light soaking and post damp heat testing. All the cells show a slight decrease in P_{max} post light soaking. All the cells show a recovery post damp heat testing. Therefore since the change in P_{max} is calculated as P_{max} (post damp heat) minus P_{max} (post light soaking), the P_{max} change is positive showing a power gain post damp heat testing.

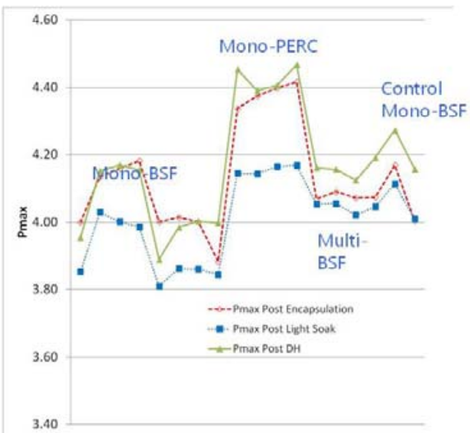


Figure 11: Comparison of Pmax Values after each step.

Given these results, all 15 plated cells pass this milestone. The impact of light soaking and the P_{max} recovery post damp heat testing is very interesting and will be studied further as part of an ASU Ph.D. project.

Milestone 6.1: Narrow line plating demonstration on Technic hardware. Plated line widths less than or equal to 40 microns. IV and profiler data comparing to silver paste controls. Data compiled for publication. (Delivered September 29, 2017)

Laser patterned cells from Fraunhofer and Cell Manufacturer A were used to complete this milestone. 21 laser ablated cells from Fraunhofer were plated by Technic. In addition, Fraunhofer supplied 18 silver paste cells for comparison. The pre-plating line width of the Fraunhofer laser ablated cells as verified by Fraunhofer was 19.0 ± 0.3 microns. The median line width of the 21 cells post plating is 40 microns. The IV results are similar for the plated cells versus the Ag paste controls. 20 laser ablated cells were provided by Cell Manufacturer A. The pre-plating line width of these laser ablated cells is 14.4 ± 0.5 microns. The median line width of the post plated cells is 39 microns.

A contact profilometer was used to measure 24 lines (Fraunhofer) and 30 lines (Cell Manufacturer A) across the cell for both thickness and line width. In addition, a Sinton IV tester was used to measure the IV properties of the plated cells (and the control cell from Fraunhofer). Table 15 below summarizes the results for the cells from Fraunhofer.

Table 15: 21 laser-ablated cells from Fraunhofer- plated at Technic & 18 Ag paste controls from Fraunhofer

	Avg Grid Thk (um)	Avg Grid Width (um)	% Eff	% FF	Isc (A)	Voc (mV)	# cells Profiled	# cells IV Tested
Fraunhhofer Ag Paste Controls	21.8 ± 1.2	41.9 ± 2.6	19.23 ± 0.24	79.18 ± 0.74	9.26 ± 0.04	638 ± 0.9	4	18
Fraunhofer Laser Ablated, Technic Plated	12.3 ± 0.9	41.0 ± 1.6	19.13 ± 0.23	78.71 ± 0.60	9.30 ± 0.05	636 ± 0.7	21	21

The plated cells have a very similar width to the silver paste controls but are much thinner; i.e. ~12 microns for the plated cells versus ~22 microns for the silver paste controls. The plated cells also have lower contact resistance and better line conductivity than the silver paste controls. The IV results show a very similar performance for the silver paste controls and the plated cells.

The cells provided by Cell Manufacturer A had 2 different architectures: 12 Mono PERC and 8 multi cells. Cell Manufacturer A provided IV data for comparison on both silver paste cells and also laser ablated cells that Cell Manufacturer A had plated. Technic used the IV data from these plated cells to adjust Technic's IV tester to read a similar I_{sc} on the Technic plated cells. Table 16 below summarizes the results.

Table 16: Summary of Cells from Cell Manufacturer A

Cell Manufacturer A	Avg Grid Thk (µm)	Avg Grid Width (µm)	%Eff	%FF	Isc (A)	Voc (mV)	# cells Profiled	# cells IV Tested
PERC Mono Printed Controls	n/a	n/a	20.9	79.54	9.75	660	0	200
PERC Mono Technic Plated	**11.0 ± 2.1**	**39.2 ± 3.6**	**20.0 ± 0.4**	**78.75 ± 0.77**	**9.57 ± 0.07**	**646 ± 4**	**12**	**12**
PERC Mono Plated-Vendor	*n/a*	*n/a*	*20.7*	*80.27*	*9.61*	*654*	*0*	*50*
Multi Printed Controls	n/a	n/a	18.7	79.93	8.98	633	0	100
Multi Technic Plated	**9.7 ± 0.4**	**38.3 ± 0.8**	**18.6 ± 0.2**	**80.28 ± 0.34**	**9.01 ± 0.05**	**626 ± 1**	**8**	**8**
Multi Plated - Vendor	*n/a*	*n/a*	*18.4*	*80.27*	*8.88*	*629*	*0*	*50*

The Technic plated Mono-PERC had a lower efficiency and V_{oc} than both Cell Manufacturer A's plated and Ag paste cells. The cells did have handling damage; i.e. scratches that could impact V_{oc} and in turn lower efficiency. The Technic plated multi cells perform very similarly to the Cell Manufacturer A's plated & Ag paste cells for efficiency and fill factor. The V_{oc} is again slightly lower for Technic plated cells versus Cell Manufacturer A's processed cells.

The results from this milestone demonstrate that narrow line patterning is compatible with Technic's plating chemistry and equipment. The desired plated line widths can be achieved with electrical performance close to silver paste controls (in some cases equivalent, some cases slightly lower performance). However, this data is collected on solar cells not specifically designed for plated contacts---the grid design and emitter are based on designs for silver paste contacts. A performance advantage may be realized by modifying the design to take advantage of the lower line resistivity and contact resistance of plated contacts.

This milestone has been completed and a publication has been prepared.

Milestone 6.2: Plating tool installation at Technic Lab complete. Site acceptance test passed. First solar cells processed. Signed acceptance checklist which verifies tool operation. (Delivered October 20, 2017)

Technic's demo tool is designed for single sided light induced plating (LIP). A picture of this demo tool as installed at Technic is shown in Figure 12. This demo tool design can be scaled up to volume manufacturing of 2560 cells/hour. Figure 13 illustrates a possible layout for the volume manufacturing tool. In this layout, a hoist transport system will transfer a small batch of cells at the same time to the process chambers. As shown in Figure 14(a), the process cell is shallow and the cell holder positions the cell face down over the process chamber. Chemistry is delivered to the front side of the solar cell through an up-flow spout. The process cell is designed to ensure that the backside and edges of the solar cell are not exposed to the plating solution and therefore do not plate. Figure 14 (b) shows the solar cell being held to the metallic plate through a unique method that is very gentle and requires no frame, clips, or brushes. The cells are transported via a hoist and are kept with the metallic plate holder throughout the processing cycle so the contact to the backside is stationary through the entire process.

Technic's volume manufacturing tool will include the anneal module so that the overall footprint of the tool includes the cleaning, plating, and annealing steps. The overall footprint of Technic's volume manufacturing tool is designed to be ~700 square feet.

Figure 12: Demo plating tool installed in Technic's laboratory.

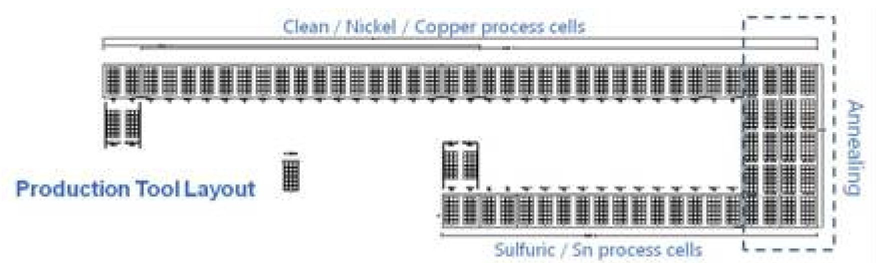


Figure 13: Proposed Tool Layout for Technic's Volume Manufacturing LIP Plating Tool at ~2560 cells/hour.

(a)

(b)

Figure 14: (a) Plating cell in operation in line with other process cells. (b) View of solar cell held on cell holder without frame, clips, or brushes.

Technic's demo plating line has been installed and tested. The site acceptance checklist has been completed and signed verifying that the tool is operational. Three cells were run on through the demo plating line. Acceptable IV properties were obtained. The plated stack thickness is on the high side; however, there is room to adjust the plating parameters to achieve the desired line width and stack thickness.

Milestone 6.3: Large scale plating evaluation of 100 cells. Exercise Technic demo tool over 100 cells. Determine tool performance; i.e. breakage rate, drag out, expected through put & chemistry / rinse water usage over 100 cells. Determine cell performance by measuring IV properties and plating thickness uniformity over a subset of cells. Report cell performance over plating run. Incorporate tool performance data into cost model and submit to DOE to verify the proposed cost reductions for plated contacts. Continuous improvement plan and publication incorporating the large scale evaluation submitted to DOE. (Delivered January 23, 2018)

A mixture of 100 mono and poly solar cells representing 9 different cell designs (5 different cell manufacturers) were processed on Technic's demo tool in order to study tool performance and process stability. All the cells were IV tested and 50 cells were measured on the contact profilometer to look at grid line width and stack thickness. Figure 15 below shows the %efficiency measured for all the 100 cells, each symbol represents a different cell type/vendor combination. The 50 cells measured on the contact profilometer are shown by the blue diamonds, red squares, and green triangles. As shown in Figure 15, some of the cell types/vendors perform better than others. The poorer performing cells had non-optimized laser processing which resulted in poor electrical performance. The cells represented by the blue diamonds are Mono-BSF cells purchased from Fraunhofer. Overall these cells performed well electrically; however, the first 15-20 cells were impacted by a contamination issue resulting in lower %efficiency than expected. Once the contamination issue was identified and corrective action taken, the cells show improved %efficiency close to 19%.

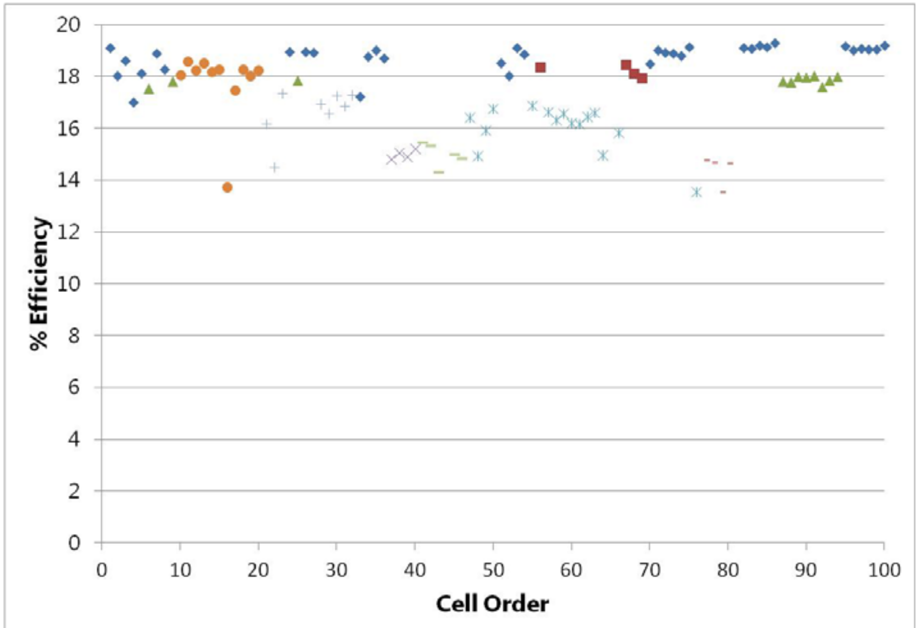


Figure 15: % Efficiency versus cell order: Blue Diamonds = Vendor 1A (Mono-BSF), Red Squares = Vendor 2C (Multi-BSF), Green Triangles = Vendor 2B (Multi-BSF)

In order to look at the consistency in electrical performance from cell to cell across the 100 cell plating demonstration, box plots were generated per cell type/vendor for three of the cell type/vendor combinations with reliable laser patterning. Figure 16 shows box plots for %Efficiency, %Fill Factor, I_{sc}, and V_{oc}. The tight interquartile range demonstrates the consistency from cell to cell. Some flyers are noted for Vendor 1A resulting from the contamination issue discussed above. The "N" under each Vendor ID represents the number of cells represented in that particular split.

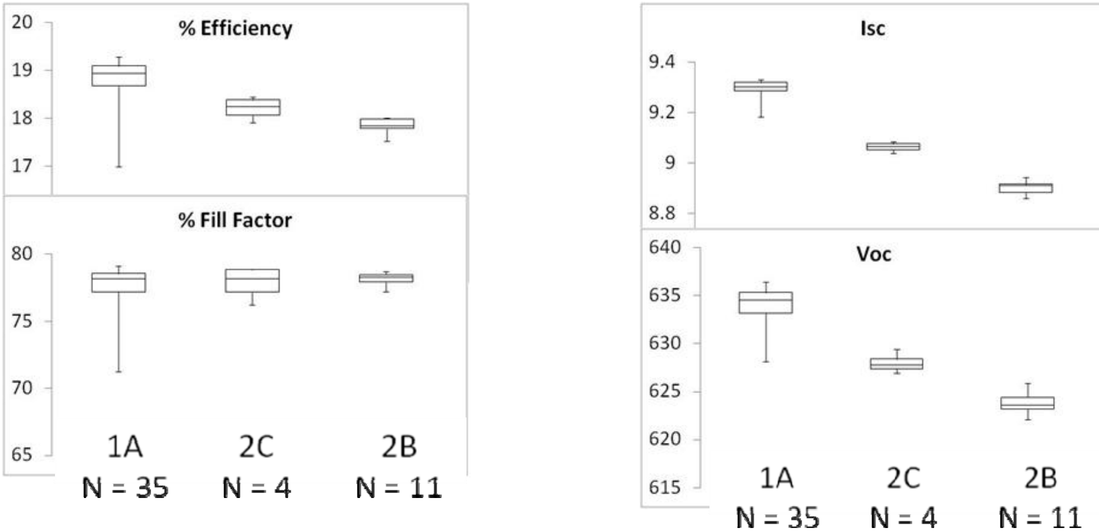
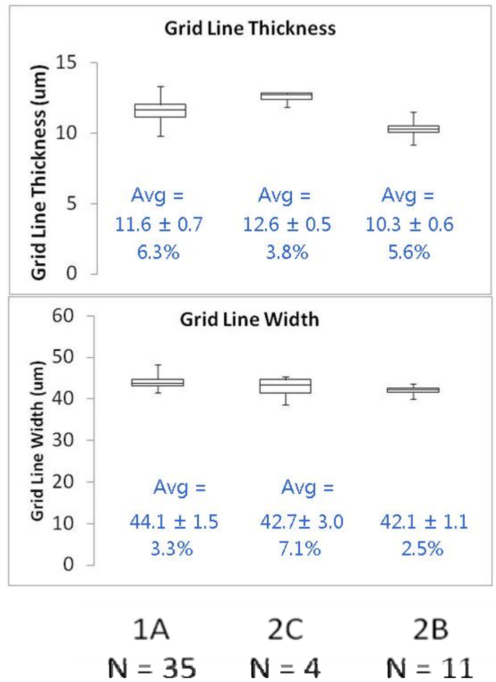


Figure 16: Box plots showing tight interquartile range for IV results from plated contacts for Vendor 1A, Vendor 2C, and Vendor 2B. A contamination issue in the cleaning step caused the flyers observed for Vendor 1A.

The same cells represented in Figure 16 were measured on the contact profilometer for grid line thickness and width. As shown in Figure 17(a), 14 lines were measured across the solar cell. Figure 17(b) summarizes these measurements by cell type/vendor. The interquartile range is very tight for these measurements indicating excellent cell to cell repeatable of the plating process on Technic's demo tool.

The performance of the plated cells is expected to be better than silver paste cells if the design for the plated cells incorporates changes to the emitter and grid layout. For this evaluation Vendor 1A, also referred to as Mono-BSF, did not re-design the emitter or the cell design for plated contacts. In a previous evaluation [18], the plated Mono-BSF cells from Vendor 1A performed similarly to the Mono-BSF controls from the same batch of cells. For this 100 cell evaluation, a contamination issue at tooling start-up impacted the initial 15-20 cells plated. The cleaning step contaminated the cells which in turn impacted the IV properties. The performance of the plated Mono-BSF cells was impacted by both this contamination issue and also by wider lines which increased shading. According to Figure 18, the plated Mono-BSF cells perform slightly worse than the silver paste controls, except for Isc. Vendor 2C also supplied silver paste controls cells for the same batch of cells that were plated during this evaluation. These cells will be referred to as Multi-BSF. The details of the cell and emitter design are not known for these cells. Again the Isc for the plated cells is slightly higher than the silver paste controls. The other factors, % Efficiency, % Fill Factor, Voc are slightly worse than the silver paste controls. Vendor 2 suggested a stack thickness of ~8-10 microns for this cell design; however, the cells plated in this evaluation had a stack thickness closer to 12 microns. Therefore, if less metal is plated on these lines to achieve narrower line widths, there should be an improvement in the electrical results. The plating parameters were not dialed in for this evaluation since the goal was to keep the processing consistent from cell to cell.



(a) (b)

Figure 17: Contact profilometer measurements to look at grid line thickness and grid line width from cell to cell. (a) Example of sites across the cell measured on the contact profilometer – 2 lines at each site. (b) Comparison of grid line thickness and grid line width measurements for 3 cell types.

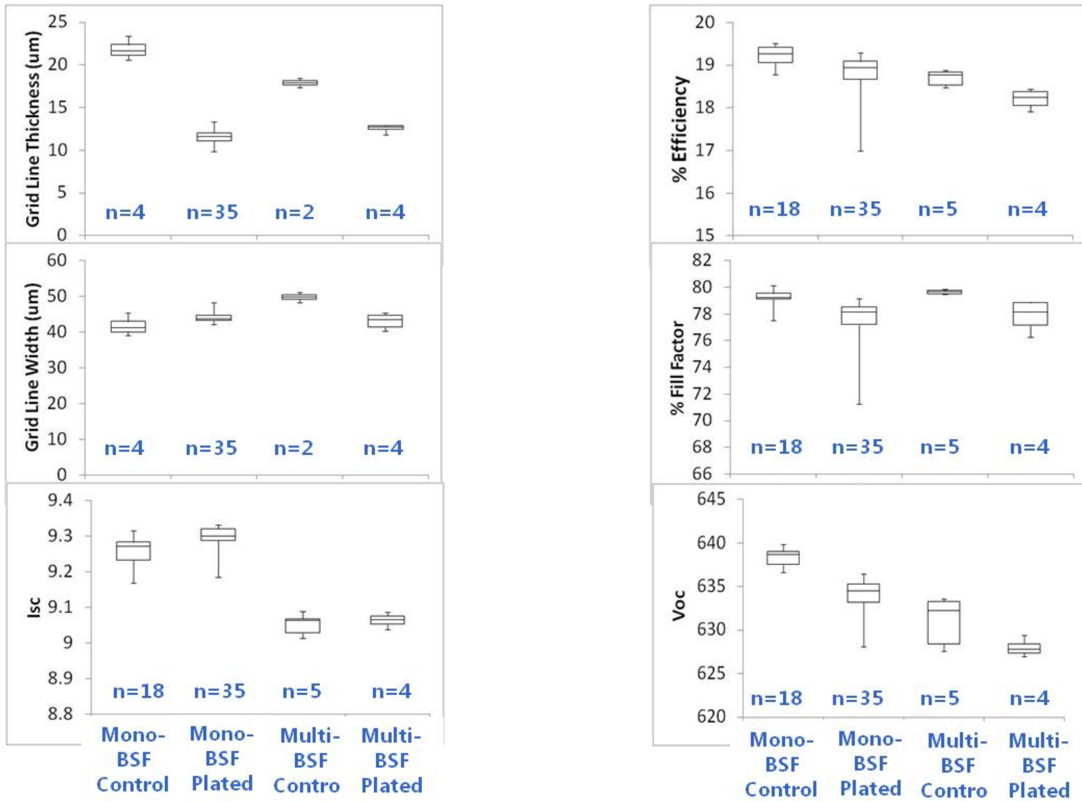


Figure 18: Box plots comparing plated and silver paste controls for Vendor 1A, Mono-BSF, and Vendor 2C, Multi-BSF. Plated grid line thickness and width greater than desired. Silver paste controls perform slightly better than plated cells in all parameters except Isc.

Another purpose of this evaluation is to investigate the chemistry and tool performance across 100 cells. In a previous publication, the numerous advantages of Technic's boric acid-free plating bath were discussed. [19] This boric acid-free plating bath has a stable pH over time and deposits a nickel layer with low stress. This plating bath has been formulated in conjunction with Technic's LIP plating tool to ensure that the chemistry and tooling are optimized. Within cell plating uniformity of nickel was discussed previously and can be tweaked by optimizing the light distribution and the anode placement within the plating chamber. For this evaluation, Technic's boric acid-free nickel plating bath was monitored over 78 days (100 cells plated). Figure 19 shows that the pH of this nickel bath did not change over these 78 days and no pH adjustments were needed. As discussed in a previous publication, boric acid containing nickel plating baths require more frequent pH adjustment. [19]

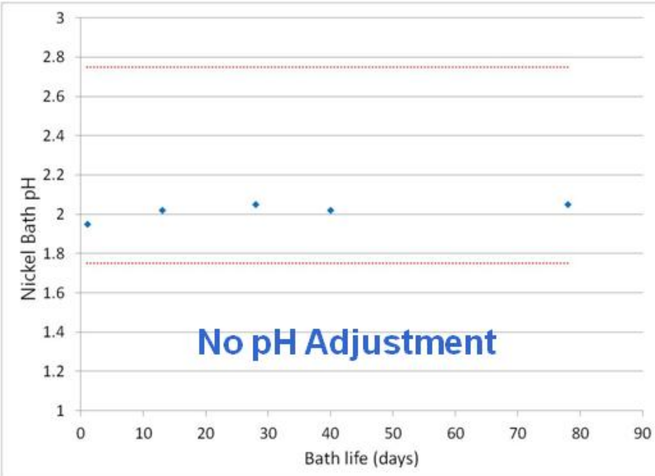


Figure 19: Stable pH over 78 days – 100 cells plated over 52 days.

After nickel plating and rinse, the cell is immediately plated with copper using LIP. Technic is currently testing two versions of copper plating baths for solar cells. The copper bath used in this evaluation requires only 2 additives; whereas, standard copper plating baths, such as those used in the semiconductor industry, require 3 additives. Maintaining the copper additives is critical to obtain good results and is also the most costly part of plating. The Cu additive, called the brightener, is consumed both actively during plating and passively in the bath over time. This component must be monitored frequently to ensure that it is in specification. In a high volume manufacturing environment, automated monitoring and dosing would be recommended. A rule of thumb for Cu brightener in a manufacturing environment is 400 mL/1000 Amp-hr. Figure 20 shows that the Ni and Cu metal concentrations in the plating baths were maintained within plus or minus 10% during the 78 days of monitoring (100 cells plated in 52 days).

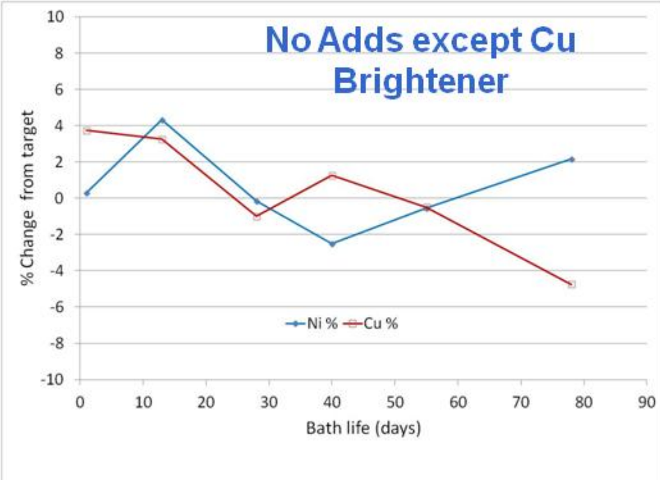


Figure 20: Change of Ni and Cu Metal from target is less than +/- 10% over 78 days of plating (100 cells)

Technic also uses unique tin plating bath for light induced plating. The tin plating bath incorporates a single component additive which produces tin deposits with extremely low organic levels. Tin plating baths generally change color and turn cloudy over the life of the plating bath. Typically, the cloudy appearance is explained as the oxidation of stannous tin salt to stannic compounds, which are colloids in the presence of dissolved air. [20] For typical, direct electroplating, this cloudy appearance of the bath is not a concern; however, for LIP deposition of tin, the cloudy bath will limit the amount of light reaching the solar cell. Figure 21 shows the %Sn metal from the target for both stannous (Sn^{2+}) and stannic (Sn^{4+}) tin. The stannous tin is maintained by Sn metal additions when needed. Over the 78 days of bath life, one tin add was made. As expected, the stannic tin increases over time. After 78 days, the stannous tin increased over the initial by 50%; however, the bath was still operating. The maximum stannous tin tolerated by the bath is still being determined. In addition, Technic's tool design greatly increases the life of the tin bath since the majority of the bath is kept in a closed environment and only small amounts of solution are circulated into the process tank during plating.

Based on the chemistry monitoring performed over this 100 cell plating evaluation, the Technic demo plating tool design is very compatible with the chemistry. The anodes are capable of replenishing the Ni and Cu metal lost due to plating and drag out. The Sn chemistry will require tin additions due to the nature of tin oxidation. In order to better understand the drag out associated with the demo plating tool, careful monitoring of metal contamination in the nickel and copper stagnant rinse tanks was performed. Nickel and copper metal was measured in the rinse tanks over the 100 cells plated. The metal concentration is in ppm so the accuracy of the measurements will increase when the ppm levels are higher. The stagnant rinse tanks had 35 L of water. Using the metal concentration in the plating baths, rinse tank volume, and average metal concentration per cell, the drag out volume per cell can be calculated. The exact drag out volume calculated is confidential but the drag out volume used for the cost model was determined to be 0.5 ml/cell.

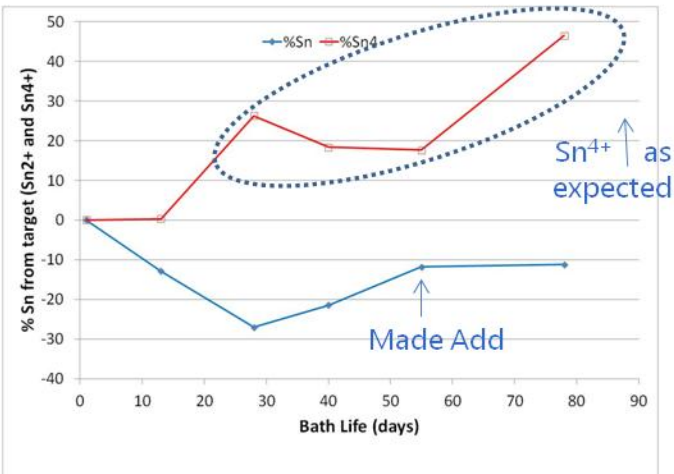
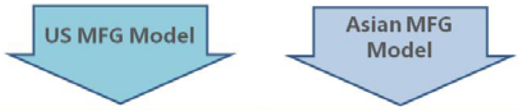


Figure 21: Stannous and Stannic Tin over bath life of 78 days

The cost model prepared for the Go-No/Go review in 2016 was updated with the tool performance data collected during this 100 cell evaluation. Since 2016, the solar industry has seen a drastic decline in module pricing. In 2016 a module cost of \$0.67 per Watt was used, this module cost has been lowered to \$0.35 per Watt based on current research. [21]. In order to meet this very low module cost, many of the inputs into the cost model had to be lowered in value. Figure 22 lists the model highlights comparing the values used in 2016 to the values used for this 2018 cost model. Paste costs must be lower in order to meet this very low module cost. It is assumed that silver paste cost is cut in half from the 2016 estimate. This, of course, has a major impact on the cost of direct materials for silver paste cells and how that compares to the direct materials costs for plated cells. The breakdown of the direct materials costs for plating chemicals is not shown. The chemical price, replenishment requirements, drag out, and metal plated (layer thickness) are all included in calculating the direct materials cost for plating. In 2016, the plating direct materials cost was 17% the silver paste direct materials cost. With the decline in module pricing and the lower silver paste price, plating direct materials costs are 55% of silver paste costs in 2018. This still translates to a 1.4% savings at the module level.



Model Highlights	1/2016 Est	1/2018 Est
Labor	US Based Labor Rates	20% of orig. (US)
Mod Eff	16.5%	17.5%
Paste Costs	Ag $935, Al $50	≈50% reduction, Ag $497, Al $25
Elec. Cost	$0.38/W	50% reduction
Module Materials	US Based Costs	40% reduction
Si Material Util.	0.55	0.73
Depreciation	$0.08/W	$0.05/W
Silicon	$20 /kg	$15 /kg
Final Module Cost (ex factory)	**$0.67 /W**	**$0.353 /W**

Figure 22: Comparison of Cost Model Inputs for 2016 versus 2018. Large drop in module cost observed.

In addition to direct materials costs, other factors included in the cost model are cap ex, waste water handling for plating chemistries, and expected efficiency gains for plated contacts. As expected, the capital expense costs for LIP are higher than for screen printing. An additional $9 million dollars are needed to implement the plating process compared to the estimates for screen printing. This translates into an added $0.004 $/Watt.

Arizona State University modeled the total efficiency gain possible with plated contact versus screen printed contacts. They looked at the impact of reduced shading due to smaller line widths, improved metal conduction for pure copper, and improvement in emitter materials. This model was based on the screen printed results that they achieve with their in house pilot line. The model shows an efficiency gain of +0.57% absolute.

Factoring in the module baseline efficiency, benefit of LIP due to reduced materials costs, benefit of LIP due to Efficiency gain, and Penalty in Depreciation Cost, there is still an overall cost reduction moving to plated contacts but it is very small at ~3.4% $/W. This comparison is valid for today's low silver price. If the silver price increases, then the silver paste cost will most likely have to increase since there is very little margin left in the silver paste cost. This increase will directly impact the module cost for silver paste contacts. This silver price increase would have no impact on the module cost for plated contacts. Therefore, the volatility in the silver market may have the biggest impact on the adoption of plating into solar cell manufacturing.

In conclusion, Technic designed and installed a manually operated plating line compatible with Technic's nickel, copper, and tin plating chemistries. 100 cells were run through this manual plating line over the period of 52 days. The plating baths were monitored over a period of about 78 days. IV parameters were measured over the 100 cells and showed consistency from cell to cell. In addition, grid line thickness and line width were collected for 50 out of the 100 cells and demonstrated consistency from cell to cell. The plated cells do not show a performance boost over the silver paste controls. They perform similar or slightly worse than the controls. However, the thickness plated during this evaluation was above the target and resulted in line widths greater than 40 microns. All 100 cells were run at the same parameters to ensure consistency from cell to cell. A grid line width less than 40 microns should result in a higher %efficiency for these plated cells based on our previous investigation.[18]

Although module prices have dropped significantly over the last two years, the cost model still shows a cost reduction for plated contacts versus silver paste contacts of 3.4% $/W relative. This may not be a large enough savings for cell manufacturers to move from silver paste. However, if silver prices start to rise, the savings from plated contacts will also increase and it may be motivation to move from silver paste to plated contacts.

Milestone 6.4: Demonstrate advantages of Technic demo tool versus competition. Comparison of Technic tool design and metrics to competition. Include competitive advantages of Technics tool design and market for Technic's tool. Market "competitiveness" report and Technic's US manufacturing plan. (Delivered January 23,2018)

Technic's tool competitors are MECO DPL (Besi Company) and RENA IncellPlate®. MECO has pilot tools installed at research organizations in Europe and Asia. Previously a company in Malaysia had a MECO tool but that effort has been ended. RENA has a pilot tool installed at a Cell Manufacturer A in Asia and may also have a tool at Fraunhofer – but it may be an older generation. The main competition for chemistry is MacDermid Enthone.

Technic's demo tool is designed for single sided light induced plating (LIP). The electrical contact is made to the metalized backside of the solar cell using a metallic plate. The cell is held to the metallic plate through a unique method that is very gentle and requires no frame, clips, or brushes. The cells are transported via a hoist and are kept with the metallic plate holder throughout the processing cycle so the contact to the backside is stationary through the entire process. Chemistry is delivered to the front side of the solar cell through an up-flow spout. The process cell is designed to ensure that the backside and edges of the solar cell are not exposed to the plating solution and therefore do not plate. Technic's tool will include the anneal module so that the overall footprint of the tool includes the cleaning, plating, and annealing steps. Our competitors do not include annealing capability within the footprint of the plating tool; therefore, the annealing tool footprint must be added to the plating tool footprint to understand the total footprint for the process.

Similarly to the Technic tool, the RENA IncellPlate® is also designed for single sided LIP. However, their design uses brushes to make electrical contact to the metalized backside. The cells are transported similar to a conveyor belt so the cells are moved underneath the stationary brushes which can lead to scratching on the backside of the solar cell. In addition, it is possible that the edges and backside of the solar cells may get wet during the movement through the solution. The plating module footprint is similar to Technic's footprint but does not include the annealing module. With the annealing module footprint added, the total footprint is more than double Technic's footprint.

In contrast to the Technic and RENA tool, the MECO tool is designed to do both single sided and double-sided plating. The cells are held vertically using a spring clip so that the front and backside of the solar cell are exposed to the cleaning/plating solution. The cells are moved through the solution on an endless horizontal track. Since the clips that provide the electrical contact are immersed in the solution, this tool includes a module to strip the clips of plated metal after each process cycle. The plating module footprint is about 3 times the size of the Technic tool – that is without the annealing module. Once the annealing module is added, the MECO tool is almost 4 times the size of the Technic tool.

The hoist transport system that Technic uses transfers a small number of cells at a time; therefore, if a process chamber/bath goes down, the number of total cells impacted will be minimized. Since the Technic tool is more modular in design, certain sections of the tool can be taken down without impacting other sections to ensure that some processing continues. The design of the MECO and RENA tools are more conveyorized such that all the cells in the line will most likely be scrapped if a problem occurs that requires shutting down a portion of the tool.

Technic has co-developed chemistry and tooling ensuring that all the chemistries work well with LIP. MECO and RENA use MacDermid chemistry in their tools. Technic found that the nickel bath was more effective for LIP after certain modifications were made. In addition, Technic was able to eliminate boric acid from the nickel plating bath resulting in a more stable pH over time and less health impact. Technic has tested copper plating baths with 2 or 3 additives and both perform well for solar using

Technic's demo plating tool. Technic's tin bath was specifically formulated to stay clear during operation for LIP.

In summary, Technic's tool has advantages in 1) transport (less scrap from a tool incident), 2) Size (smaller footprint), 3) electrical contact (gentle and stationary), 4) process cell design (backside & edges kept dry), and 5) chemical / tooling compatibility. MECO and RENA have more visibility due to partnerships with research institutions and manufacturers. They both have tools in locations that are exercising plating on solar cells in order to gather more learning. Technic is newer to solar manufacturing so there is less visibility and testing. Technic demo tooling installed in Technic R&D facility will enable more demo activity with cell manufacturers to increase Technic's visibility in the solar industry.

Milestone 6.5: Identify customer interested in installation of Technic plating tool. Testing plan and critieria from customer that must be met for tool purchase to move forward. Signed agreement by the customer submitted to DOE. The agreement should include the testing start date and period of performance. (Delivered January 23, 2018)

Cell Manufacturer A signed an agreement to evaluate Technic's solar cell chemistry and equipment. They will be providing Technic with solar cells and Technic will be processing them on the demo tool. The first step in the agreement will be to pass reliability of a full module (60 cells) that is plated with Technic chemistry on Technic's demo tool. Based on this result, further testing will be defined. The testing started Nov. 27th, 2017 and will continue for 6 months.

Significant Accomplishments and Conclusions:

1. In Milestone 1.4, passing adhesion was achieved for plated contacts. This is a significant achievement because one of the challenges associated with plated contacts is adhesion. The testing methodology used was sound and carefully executed. The results show that plated contacts perform as good as or even slightly better than the silver paste controls. This data should enable cell manufacturers to more easily embrace plated contacts as an alternative to silver paste contacts.
2. In Milestone 2.2, Phase 1 custom built plating equipment was installed at Arizona State University (ASU) for use in their student led solar cell pilot line. This is significant because it provides a test bed for Technic's chemistry and equipment outside of Technic's facility. For more than 2 years, our chemistry and equipment has been used by ASU graduate students and post docs. Both the bath maintenance and equipment operation has been easily mastered by

students with no prior plating experience. Cell manufacturers are often concerned with implementing plating in the solar industry due to lack of experience with plating. However, the experience with ASU indicates that the learning curve for implementing plating on solar cells may be less than expected. Although the equipment ASU has would not be applicable to large scale manufacturing, it is still useful for research studies that can prove out the benefits of plating on solar cells.

3. In Milestones 5.1, 5.3, and 5.4, passing reliability results were obtained for plated contacts. Reliability is a concern for cell manufacturers with any new change, specifically a change that includes copper. Previous studies have been published by Fraunhofer, IMEC, Rena, Meco showing passing reliability results for plated contacts. However, since Technic's chemistry and process are slightly different than what was used in these published studies, it is important to show that Technic's chemistry and process do not negatively impact reliability. It is expected that any cell manufacturer that implements plated contacts will perform reliability testing on their own solar cells; however, these results show that Technic's process and chemistry has been demonstrated to be reliable.
4. In Milestone 6.2, Technic built and installed Phase 2 demo plating equipment that can be scaled to large scale manufacturing. This is a significant accomplishment because the currently available plating tools are less than ideal as described in Milestone 6.4. One cell manufacturer expressed the need to have more competition in the area of solar cell plating chemistry and tooling. Installation and operation of this demo plating tool proved that this tool design works as expected. This accomplishment will enable Technic to have data and a working demo plating tool to show to potential customers.

Challenges:

1. During the course of this project Technic faced challenges associated with the changing market conditions for solar. The cost of solar continued to decrease and the silver paste manufacturers continued to lower cost. The continued improvements in silver paste technology enabled smaller line widths and lower cost due in part to lower silver usage. As the cost gap between plating contacts and silver contacts decreased, most solar cell manufacturers reduced their investment in research for plated contacts. Therefore it was difficult by the end of year 1 to find a partner that would install a prototype tool in their facility. This resulted in a modification of the year 2 plan so that a manual demo plating line could be installed in Technic's research lab. We found that the majority of the cell manufacturers were more likely to send solar cells for demo's rather than setting up a plating line in their facility.

Inventions, Patents, Publications, and Other Results:

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5. Karas, J. (2016). Metal plating as an alternative to silver for silicon solar cell contacts. ***MRS Spring Meeting***, 2016. (invited oral presentation)

6. Karas, J., Bailly, M., Jain, H., Reblitz, T., and Bowden, S. (2016). Process improvements in laser ablation and light-induced plating for silver-free silicon solar cell contacts. ***MRS Spring Meeting***, 2016. (oral presentation)

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Path Forward/Commercialization Plan:

Technic's Silver Free Metallization Technology, known internally as the Alternative Seed Layer (ASL) technology, is comprised of both chemistry and plating equipment. The current market for the ASL technology will first be discussed below and then the US manufacturing plans for chemistry and equipment will be described.

The cost to install solar has decreased by more than 70% since 2010. This decrease in cost has led to a dramatic increase in solar installations. In the last decade, solar has experienced an average growth rate of 68%. This growth rate has been driven by the declining cost of solar which has now become "affordable". Solar module costs decreased 64% from 2011 – 2016. The cell cost from 2011 to Q1 2017 has decreased by 73%. Solar cell metallization is approximately 20% of the solar cell costs. A solar module manufactured with ASL metallization will provide a savings of 3.5% $/W. This savings does not appear to be enough motivation for cell manufacturers to switch their existing silver paste lines to plating.

Although, the current market is slow for plated contacts, specifically for standard diffused junction cells, this market may change quickly if silver prices increase. For the last few years, the impetus to replace silver for frontside contacts has been slowly decreasing. This is due in part to the low price of silver and also to the advances made in silver paste technology and screen printing technology. These advances have reduced the line width and the quantity of silver paste required per cell. In addition, it appears the silver paste manufacturers have taken advantage of the consistently low silver prices and drastically reduced the paste cost over the last year and a half. The cost of silver paste has declined ~50% since 2016. Figure 23 shows the silver metal price from 2000 – 2017. According to Figure 23, silver prices reached close to $50/troy ounce in April 2011 because of economic uncertainty and other factors. Although it quickly retreated, the price did stay unusually high for the next two years. The risk of silver prices increasing again to the level of 2011-2012 is constantly being discussed amongst silver experts. Currently, the cost of silver paste is not that much higher than the cost of the silver in the silver paste. Therefore, if the cost of silver increases, the silver paste manufacturers will have very little margin and will be forced to increase the cost of the silver paste which will in turn increase the overall module costs. However, since the ASL technology uses metals such as nickel, copper, and tin, the increase in silver price will not impact the cost of the ASL process – there is no risk of increased pricing and profitability will remain steady. Therefore, the total solar module costs savings with ASL can be calculated as a function of increasing silver price as shown in Table 17.

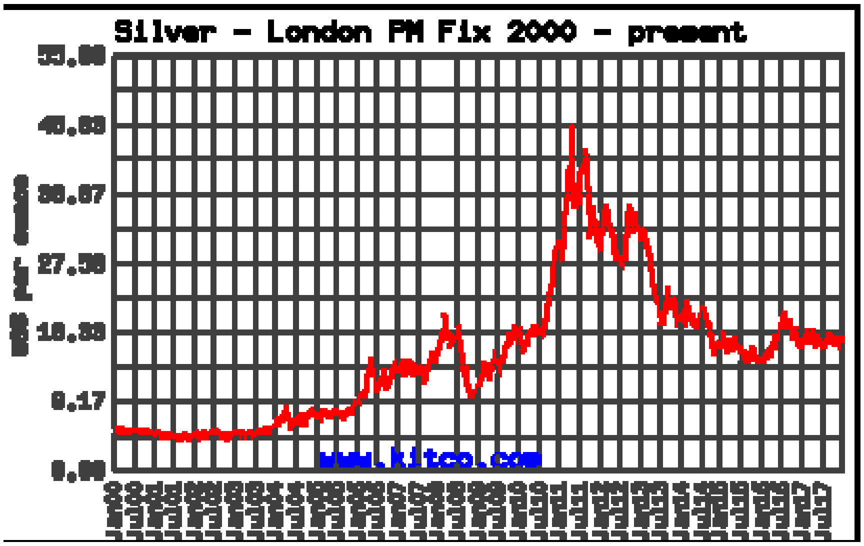

Figure 23: Silver prices from 2000-2017 showing spike in 2011.

Table 17: Impact of Silver Metal Cost on Total Module Cost for Ag Paste vs. ASL Modules.

Silver Metal Cost ($/troy ounce)	Ag Paste Metallization Cost ($/W)	Total Ag Paste Module Cost ($/W)	Total ASL Module Cost ($/W)	Cost Savings
17	0.0172	0.370	0.357	3.5%
20	0.0200	0.372	0.357	4.1%
25	0.0247	0.377	0.357	5.6%
30	0.0294	0.381	0.357	6.7%
35	0.0342	0.386	0.357	8.1%

It is difficult to predict at what cost savings the ASL technology will become attractive to solar cell manufacturers. There is a possibility that plated contacts will not be realized in manufacturing on the standard diffused junction, low cost solar cell with BSF. Much of this will depend on the silver price and how the silver paste manufacturers react to the silver market. However, future solar cell designs may not be able to use silver paste for various reasons and will require the introduction of plated contacts. Technic's chemistry offerings can be marketed to a wide variety of solar cell architectures. Technic's chemistry has been demonstrated on PERC cells, heterojunction cells, and n-type bifacial cells with one side metalized prior to plating to provide electrical contact to the backside. However, Technic's equipment is currently limited to light induced plating on a single side at a time; therefore, this tool design will work for cell architectures that have a metalized backside prior to plating so electrical contact can be made while plating the front side

Due to the changing market conditions and sharp decrease in module pricing, Technic's commercialization plan will be modified to match the current market conditions. With the current market conditions and the fact that almost all solar cell manufacturers have left the US, the ASL technology will only bring marginal increases to the job market and minimal solar module cost savings. However, if the silver prices increase or if solar cell architectures that require plating become mainstream, the demand for plating will likely increase as well as the impact Technic's ASL technology.

Technic's US manufacturing plan going forward will be discussed first in terms of chemistry and then in terms of equipment. Technic has been formulating and manufacturing proprietary chemistry in the US for over 50 years. Technic has also been engineering and manufacturing plating and ancillary equipment for over 30 years. Thousands of chemistry products are produced in the Technic Cranston, RI facility. Although Technic sells its products worldwide and employs 49% of its workforce outside the US, over 90% of the products are manufactured in the US. Those products that are manufactured outside the US are typically just the blending of products and not true manufacturing.

The current products required for the ASL process are being manufactured in Technic's Cranston, RI liquid lab. The liquid lab is where small volume products are manufactured. As the volumes increase the manufacturing will be moved into the large volume manufacturing area in Cranston facility.

The solar plating equipment fabricated for Year 2 of the SolarMat 2 is currently designed and manufactured in Technic's equipment facility in Pawtucket, RI. Technic has an additional equipment manufacturing facility in Clearwater, FL. For large volume orders, the manufacturing is split between both facilities. For ASL plating tools that same concept is implemented. If cell manufacturers started adopting the ASL Technology in large scale manufacturing, up to 45 jobs could be added to the US Technic facilities.

The target market for Technic's ASL technology is at solar cell manufacturing locations. Since Technic is a US manufacturer, we would prefer selling our technology to US solar cell manufacturers; however, there are currently no solar cell manufacturers in the US that can utilize the ASL Technology. In order for the technology to be successful it must be adopted by a cell manufacturer in Asia. Technic has communicated with several cell manufacturers in Asia and currently we are working with one Asian cell manufacturer to demonstrate our plating technology. Since Technic will continue to manufacture the ASL products in the US, gaining mass production business in Asia will allow Technic to expand the manufacturing area and add additional manufacturing jobs.

The main competitors for plating equipment manufacturing are RENA and Meco. RENA has produced pilot scale copper plating tools and has one known installation at a solar cell manufacturer. However, this tool is not running production but still in testing. Meco's tool has a reputation in the industry for not being able to adequately handle solar cells; i.e. the clamping mechanism has been shown to cause cracking. RENA and MECO are all using existing plating tool designs from the PWB, Semiconductor and Connector industries. Technic's R&D tools are designed and built for solar cell plating and utilize light induced plating (LIP) methods.

Technic is a financially sound company committed to copper plating on solar cells. Because Technic has a very diverse product line, we are not severely impacted when a single industry has a significant downturn like the solar industry has experienced. RENA relies heavily on the solar industry for their revenue and this downturn has prevented them from continuing many of their new technology developments. Technic has been the only equipment company that continues to invest in developing new tools for copper plating on solar cells.

The main competitors for copper plating on solar cells are Dow Chemical and MacDermid Enthone. Dow Chemical has had the most success with their silver plating on silver paste process chemistry; however, this approach is no longer cost effective and most lines running this process have been shut down. Dow and MacDermid Enthone have had minimal success with copper plating. These chemical companies rely heavily on equipment companies to develop a complete system to make replacement of silver paste with copper plating attractive to the cell manufacturers. The plating tool is an integral part of developing a repeatable and reliable copper plating process for silicon solar cells. Technic has a big advantage over their chemical competitors because we design and manufacture plating equipment in-house.

Several products have been produced since Technic began solar projects in 2007 and are shown in Table 18. These products are currently manufactured in the US, and it is expected that subsequent products generated from Technic's solar cell projects will also be manufactured in the US.

Technic is a US Headquartered company with global operations and is strongly committed to maintaining manufacturing in the US. Technic has been very successful and profitable manufacturing proprietary chemistries and equipment for many different industries. Solar is a brand new market for Technic's electroplating chemistry and equipment. Technic remains committed to bringing ASL technology to the solar cell manufacturing industry.

Table 18: Solar Products Developed by Technic since 2007

Item #	Product	Use	Innovation
1	TechniSol UV-PR	Low cost masking of ARC layer prior to wet etching	Mask can be left on during LIP plating
2	TechniSol Ag 2460	LIP Ag plating over silver paste	Compatible with LIP
3	TechniSol 240 Activator	Removes oxide post laser ablation	Little damage to remaining ARC layer
4	TechniSol Ni 2428	Deposits Ni on silicon emitter with and without rectification	Boric Acid Free bath
5	TechniSol 2463 Cu	Deposits copper over nickel layer without rectification	Uniform, low stress copper deposited
6	TechniSol Sn 2480	Deposits tin over copper layer for solderable layer	Uniform solderable tin. Bath does not cloud with age.

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