For the United States Army
U.S. ARMY SOLDER SYSTEMS CENTER - NATICK,
ATTN:
STEVEN TUCKER
GENERAL GREENE AVENUE
NATICK MA 01760-5000

PowerFilm
Ultra Flexible PV Phase 1 SBIR OPTION

REFERENCE: CLIN- 1005

Option period Final Report on
Contract No. W911QY-18-P-0174
(Ultra Flexible PV phase I SBIR - OPTION)

Final

Dates Covered: 22 August – 21 February 2019
Phase 1 Option: 1 April - 31 May 2020

Submitted by

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Distribution Statement:
Approved for public release: distribution unlimited.

Project Description

The modern Military has an ever-increasing need for power, in particular light-weight portable power with high power densities and decreased deployed foot print. Currently packable panels are made from light weight Amorphous Silicon or carbon fiber backed crystalline silicon. The challenge for the amorphous silicon technology resides in the power conversion efficiency (watts per unit area); while the carbon fiber backed crystalline silicon, cells lack field durability and flexibility. The solution to this is to take the benefits of the two different technologies and combine them to produce a solar fabric that has high power conversion and ultra-flexibility. To achieve the two greatest challenges of this project, compound curve tolerance and high efficiency, PowerFilm proposes the following solution; to make an ultra-flexible photovoltaic sheet on a flex substrate with tiles of high efficiency crystalline silicon.

1.0 Flex Circuit Design

1.1 Flex Circuit Design

Integration of the solar modules into a complete array requires that back side contacts of the solar cell be available for series and parallel connections. By series connecting the cells, voltage (V) can build from one cell to the next, like-wise parallel connection of a series string of cells to the next series string of cells will build Amperes (A). A backing structure was used to make the connection between the back of the cells and the wiring between cells. The backing structure needs to match the artwork and traces on the back of the solar cell. PowerFilm measured the artwork on the back of the cells then had commercial Printed Circuit Boards (PCB's) manufactured to those design files, then the interconnect between the PCB's and solar cells was verified. All of this had to be done via measurement since the artwork files for the cells were not available from the manufacturer of the solar cells.

PowerFilm began the contract measuring and verifying the spacing and width of the silver traces on the back of the cells. Artwork was drawn in a PCB program to these measurements; during the first month of the contract the focus was on getting the two to be a perfect match. This was accomplished using a very simple design as shown in figure 1 below.

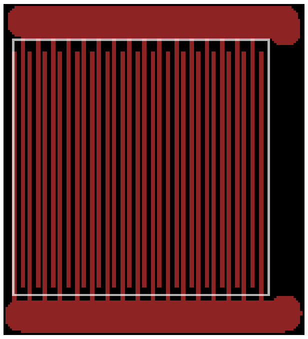


Fig 1

Features were then added to allow for the series and or parallel connection of the cells. This included front and back side contacts along with plated through holes; this gave PowerFilm adequate freedom to interconnect the cells in many possible scenarios. Additional features were optimized to decrease the total area of the artwork and aids such as non-plated through holes to help with alignment of the solar cell to the PCB. In addition, different designs were tested for solder paste interconnect optimization (solder paste is used to electrically connect the solar cell to the PCB). The designs are valid for either flex circuitry or rigid PCB's. The optimized 2cm x 2cm and 1cm x 1cm circuit designs are shown in figures 2 and 3 below.

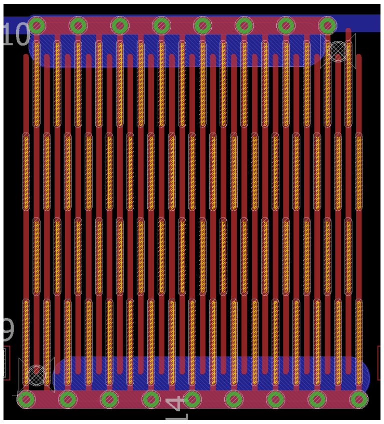


Fig 2 2cm x 2cm artwork

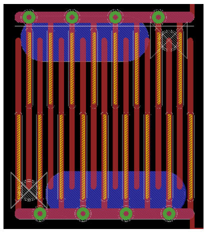


Fig 3 1cm x 1cm artwork

1.2 Cell and Flex Circuit Verification

Cell and flex circuit verification is making sure that the artwork matches the solar cell's printer interconnect. Since the artwork was unavailable from the manufacturer of the solar modules this had to be measured. Both the width of the traces on the back of the solar cell and the spacing between the traces are critical - if either one is off a little then the layout will creep or shrink which could result in a short on the cell. Using a high magnification microscope and a calibrated high magnification ruler the exact trace width and spacing was determined and verified. This spacing and trace width was used for the artwork designs shown above which was verified below with perfect alignment. See figure 4 below.

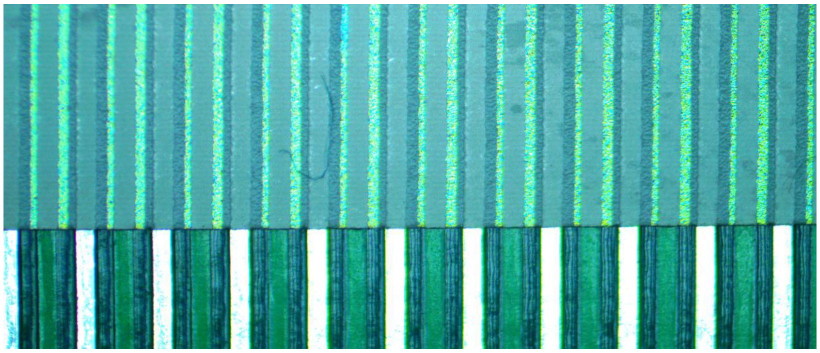


Fig 4 PCB traces to Cell trace alignment

1.3 Flex Circuit Procurement

The initial thought of the ideal medium for the backer to the solar cells was thought to be a flex circuit. A flex circuit would enable the series connection between the cells while providing the interconnect to the back of the individual cells. PowerFilm tried to procure flex circuits from both US and overseas suppliers. The lower cost solution was overseas suppliers; the best price for small quantities from over seas was about $1.10 per square inch. With a 15% cell efficiency post cutting, it would take about 15 square inches per watt, adding about $16.50 per watt to the cost of the solar array. This was deemed too expensive for the goals of this contract; the alternative was to use thin rigid PCB's. The thin PCB's were then interconnected together to make a solar array.

2.0 Cell Cutting

2.1 Cell Cutting Laser

One of the key components for making an ultra-flexible high efficiency solar module is the small cell size. Standard crystalline solar cells are 156 x 156 mm and the back contact solar cells are 125mm x 125mm, in order to get down to the desired size of 20mm x 20mm and 10mm x 10mm one of two things had to happen. Options were to purchase cells of this size from the manufacturer or figure out how to cut them down to the correct size. The industry standard for cutting traditional mono crystalline cells is to use a laser cutter to score the cell then snap it. This process is similar to how glass is cut; it is scored with a carbide or diamond wheel then snapped. However, SunPower cells are not your typical run of the mill solar cell, they have a heavy copper backing for the interconnect. Because of the backer they cannot be scored then snapped, they have to be cut through and through with a laser.

PowerFilm had a number of different lasers at its disposal to try cutting the cells. In addition to the array of lasers a system had to be set up to host the laser so that precision cuts could be made of the desired size. The first few months of the contract were spent building a platen for cell cutting and programming a X-Y gantry to do the cell cuts, in parallel everything from a 60-watt CO2 laser 10Watt Mecco and a 20-watt fiber laser were used to test cell cutting. Eventually success was accomplished and a direct coupled 20-watt laser mounted on the X-Y Gantry gave excellent cuts. The key was having a Gaussian beam that was reaching the cutting surface vs a flat top beam.

When we profiled the beam, we found the laser output to be a flat top. To restore the Gaussian beam, we removed a fiber optic cable and lenses which put the fiber laser output through a single lens onto the cutting platen.   The good gaussian beam and flat top is shown in figure 5 and the X-Y gantry is shown in figure 6 below.

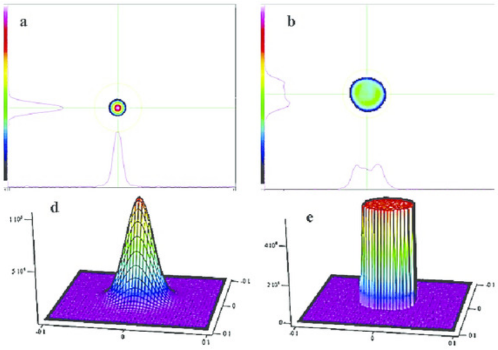


Fig 5 Gaussian Beam (left) and Flat top beam (right)

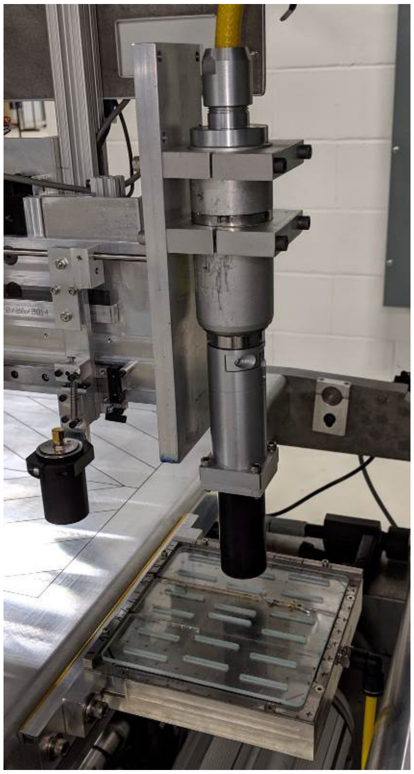


Fig 6 Laser, X-Y Gantry and Cut Platen

2.2 Cell Cutting Performance

Cell cutting performance was deemed to be the most important element of the contract to be successful. This was initially though to be an easy task, and cutting cells is very easy, however when you take into account the performance of the cells that are cut the task is anything but trivial. In order to make this project successful PowerFilm needed cells to be cut on all for sides with a fill factor greater than 55%. To give a reference point SunPower cells come from the factory with a fill factor between 75-81%. The conversion efficiency of the cells is about 21%, so a SunPower cell with a fill factor of 55% will give a conversion efficiency around 15%.

The beginning of the contract PowerFilm set out to cut cells believing that this was an easy task. However, after cutting the first few cells and measuring those cells the Fill Factors (FF) were in the low 30's. This was deemed unacceptable so further investigation found a number of factors for the defects, the biggest being shunts created during the cutting process. In the end PowerFilm figured out the cause of the shunts, this was determined to be from the heavy copper backer that is used for making the connections to the cells. The material was being evaporated by the laser and deposited on the edges of the cell inducing said shunts. Further, high fill factors were initially achieved on a few of the non-peeled solar cells, and when we were investigating what was different between these and others - we found that the high fill factor cells actually cut between the fingers. This then led PowerFilm to investigate the removal of the fingers before cutting.

The final technique was to mechanically remove some of the copper traces from the back of the cell (See figure 7 below), align those areas with the laser cutting channels in the glass backer, apply a vacuum to those channels to suck the debris away, and utilize a high powered 20-watt Gaussian laser beam. Once this was accomplished, excellent cuts were very easy to obtain, and PowerFilm achieved cuts with fill factors as high as 80%. This high fill factor meant that almost no damage was being done to the cells.

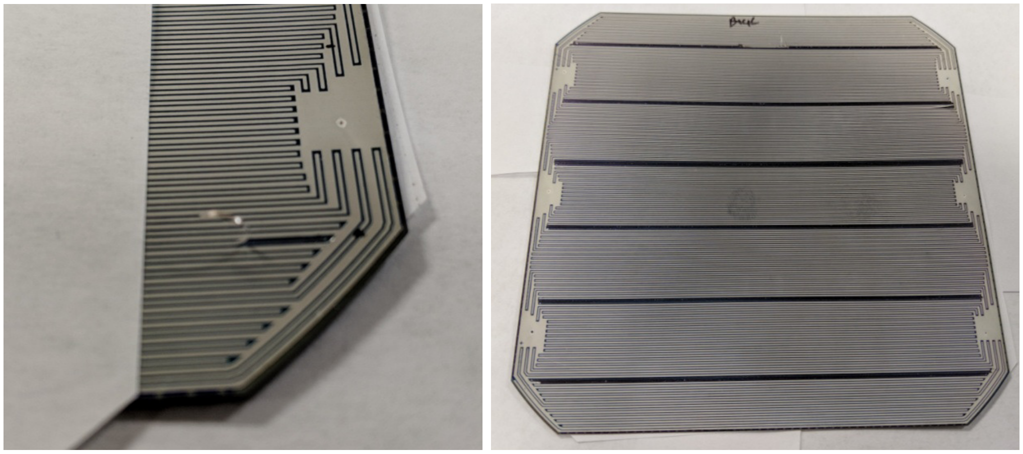


Fig 7 Start of peeling up a finger (left) and cell prepped for cutting (right).

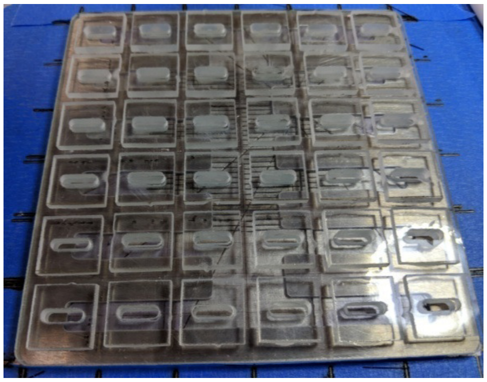


Fig 8 Glass backer with cut channel used on the cutting platen.

Figure 10 below shows the tabulated results of cutting the peeled copper backer cells.

# of passes	Laser speed	Frequency		Fill Factor Full sun	1/3 cell	FF 1/4sun
1	15mm/s	20khz		76	r	71
1	15mm/s	20khz		73	m	58
1	15mm/s	20khz		78	l	
1	10mm/s	20khz		72	r	55
1	10mm/s	20khz		62	m	35
1	10mm/s	20khz		70	l	47
1	5mm/s	20khz		71	r	55
1	5mm/s	20khz		65	m	41
1	5mm/s	20khz		72	l	55
1	3mm/s	20kHz		79	r	79
1	3mm/s	20kHz		74	m	61
1	3mm/s	20kHz		74	l	58
1	1mm/s	20kHz		75	r	65
1	1mm/s	20kHz		70	m	48
1	1mm/s	20kHz		80	l	80
1	3mm/s	20kHz	Peeled	80	r	78
1	3mm/s	20kHz	Peeled	78	m	73
1	3mm/s	20kHz	Peeled	80	l	78

Fig 10 Gap Cut with 20-watt Fiber laser Full and 1/4 Sun FF

3.0 Stencil Design

3.1 Stencil Design

For this project to function electrical contact needs to be made between the solar cells and the backer or PCBs. The initial thought in the proposal was to use solder paste and place it on the PCB prior to mounting the solar cell then reflow the solder to compete the electrical connection. This was tested and found to be successful, however optimization of the solder paste required for the connections was deemed to be an important factor in overall performance.

Too much paste would mean shorts on the cells could result, like-wise not enough solder paste would result in increased resistance between the cell and the PCB therefore reducing the output of the cell. A series of experiments which manipulated the line width of the paste as deposited by the stencil on the PCB and line length was used to find the optimum electrical interconnect. The results were a solder paste width of 50% of the trace width and 50% of the trace length; this gave great electrical performance with no electrical loss. The yield for assembling the cells was about 86% with 1 out of 8 cells being a dead short.

Figure 11 shows the 1cm x 1cm 50% pad with 50% paste final design (orange cross hatched) and Figure 12 shows the 50% as applied on the PCB.

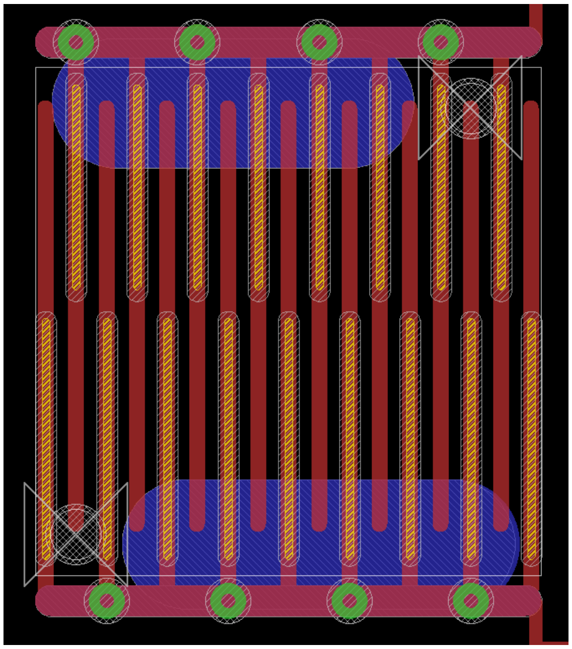


Fig 11 1cm x1cm 50% pad with 50% paste.

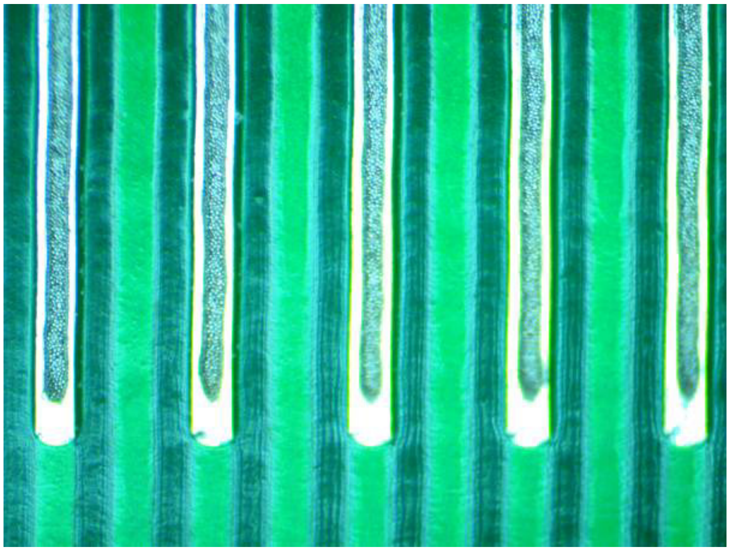


Fig 12 an image of the 50% paste as applied on the PCB.

3.2 Stencil Procurement and Testing

Using PCB stencils from rapid stencil building shops in the US was deemed an excellent method for acquiring and testing the stencils. Two types of stencils were available from these vendors, Stainless Steel and polyimide. Polyimide is cheaper material used for stencils, however PowerFilm needed greater precision than the polyimide stencils could provide. As a result, only stainless-steel stencils were used throughout this contract. Typically, stencils could be designed, ordered, and delivered within two to three days. All the stencils performed as expected with no issues found, figure 13 below shows the 1cm x 1cm PCB and stainless stencil.

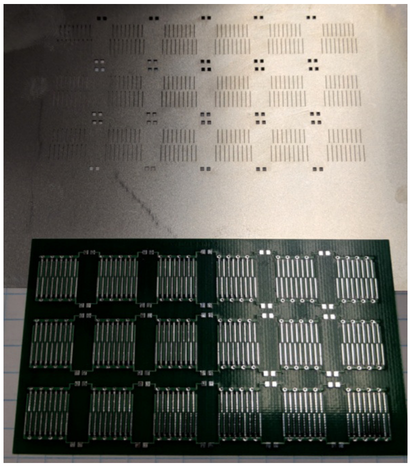


Fig. 13 1cm x 1cm stainless stencil and PCB

4.0 Cell Mounting and Array Assembly

4.1 Cell Mounting

Cut cells - either 1cm x 1cm or 2cm x 2cm - are mounted in the same method; solder paste is applied to a thin PCB via a stainless-steel stencil, and cells are then edge aligned to the PCB and placed into position. After the entire array is assembled, the PCB is placed in a PCB oven to reflow the solder. The reflow process then completes the electrical connection between the solar cell and the PCB. Throughout the contract the yield remained high with 1 out of 8 cells per array resulting in a dead short. Mounted 2cm x 2cm cells are shown in figure 14 below.

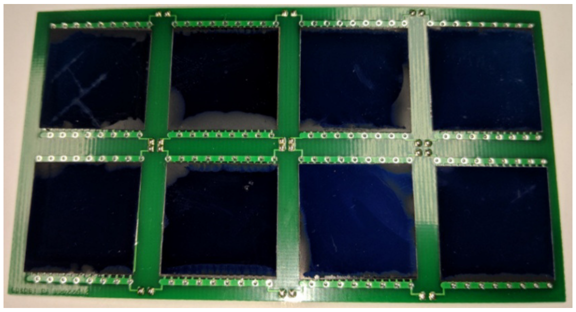


Fig 14 2cm x 2cm array of mounted solar cells.

4.2 Array Assembly

In the initial proposal it was thought that the assembly of the solar arrays was to be on polyimide flex circuits. Thus, eliminating the need to interconnect series strings of cells and only be concerned with parallel connection for increasing current. However even using the lowest cost overseas flex circuit provided meant a cost increase in raw materials of about $16 per watt. This was deemed too high early on in the contract, so an alternative interconnect method was used. Using Litz wire as an electrical connection between cells, an array or series string of cells could be assembled. Powerfilm has used Litz wire as the interconnect between PowerFilm foldable cells for almost two decades. Litz wire has more than demonstrated itself in the field, with accelerated flex counts greater than 3000 without any degradation to the wire or interconnect. Flexible crystalline arrays were wired in series to form a 2cm 1x4 array up to a 36 cell 1cm x 1cm panel. This method was more than adequate to demonstrate several proof of concept arrays for the contract.

A 2cm 1 x 4 is shown in figure 15 with the Litz wire interconnect, in addition the back side of the 16 cell 2cm x 2cm is shown in figure 16.

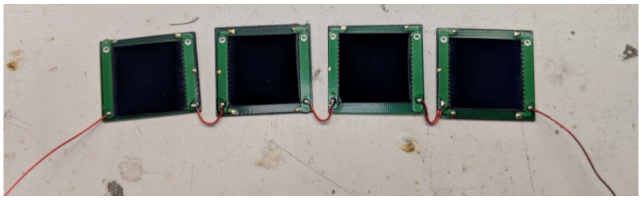


Fig 15 1x4 string of Cells with Litz wire.

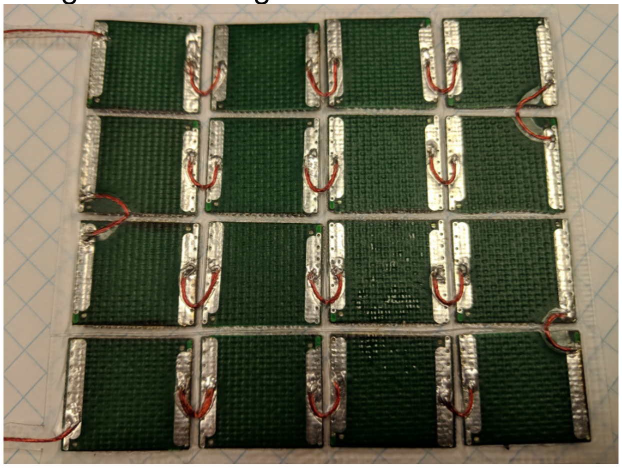


Fig 16 Back side of 4 x 4 or 16 cell arrays.

A 1 x 4 2cm string was put together to demonstrate power, with cells above 52 FF chosen for the array. The power output of the array was about 0.293 watts or 73.25mW per cell, scaling this up a full meter squared would be 138.88 watts or 13.8% efficient. Fig 17 below shows the IV curve for the 4-cell string. This has met the power objective of the contract.

I-V Test Report

- **Module ID = 2cm x 2cm 4 in series**
- **Date/ Time = 2/22/2019, 10:20:39 AM**
- **Voc (V) = 2.510**
- **Isc (A) = 0.212**
- **Vmp (V) = 2.003**
- **Imp (A) = 0.146**
- **Pmp (W = 0.293**
- **Fill Factor = 55.147**
- **Efficiency (%) = 0.029**
- **Rs (Ohm) = 1.368**
- **Rsh (Ohm) = 38.881**

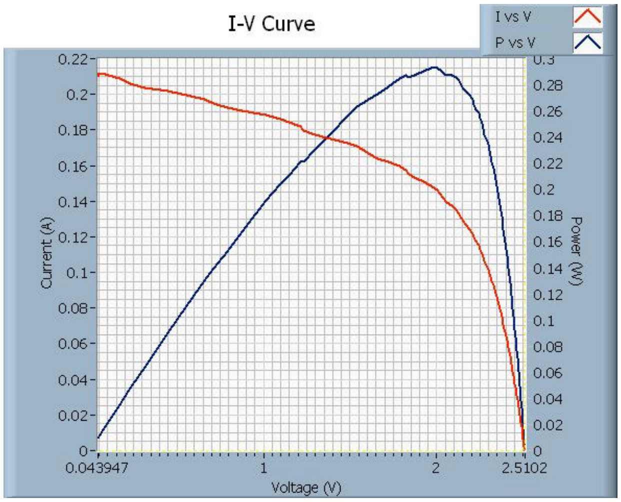


Fig 17 IV curve of the 4 cell series string.

5.0 Array Encapslulation

5.1 Array Encapsulation

PowerFilm has long been the leader in thin light weight flexible solar cell and encapsulation. The industry standard for crystalline cell encapsulation is Glass front side with 0.018” Ethylene Vinyl Acetate (EVA) adhesive between the cells and glass, in addition behind the crystalline cells. The thinnest EVA available from current suppliers is 0.012” thick EVA which is twice as thick as the industry standard for thin film amorphous cells. Prior to this contract PowerFilm had been encapsulating SunPower solar cells with 0.006” thick Thermal Polyurethane (TPU) and 0.002” Ethylene Tetrafluoroethylene (ETFE).

Initial 2cm x 2cm arrays were encapsulated with a front and back side stack of 2mil ETFE with 6mil TPU. This was deemed too thick for what is to become ultra-flexible photovoltaic solar module. To increase flexibility the encapsulation stack was changed to a 0.002” ETFE with 0.002” TPU front with a 0.002” TPU / Litelock fabric backer. The resulting encapsulation stack is shown in figure 18 below.

ETFE 2mil (Film)
TPU 2mil (adhesive)
C-Si Cells
2mil TPU(adhesive)
Fabric

Fig 18 diagram of the encapsulation stack.

Testing the 2cm x 2cm and 1cm x 1cm arrays to meet the threshold and objectives of the contract was accomplished. The 2cm x 2cm had a single axis radius of curvature of 12mm while the 1cm x 1cm had a single axis radius of curvature 5.5mm. Both arrays meet the threshold of 25mm while only the 1cm x 1cm array would meet the 10mm objective for the contract. Figure 19 below shows the 1cm x 1cm array draped over a 6.35mm radius. Figure 20 below shows curvature around a complex radius to demonstrate drape, the complex radius was a 2.5in sphere.

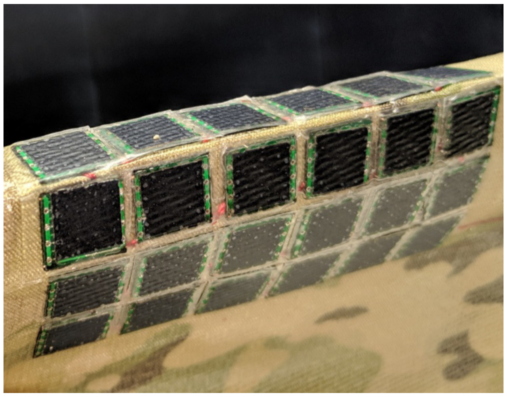


Fig 19 1cm cells wrapped around a 6.35 radius rod.

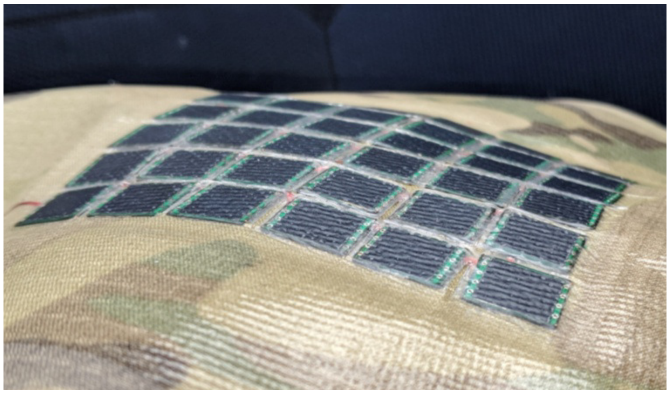


Fig 20 1cm x 1cm cells mounted on Litelock Fabric

6.0 Assembly of Solar Array Automation

6.1 PC board Vendor Selection

One of the key aspects of the ultra-flexible solar array is the tiled solar cells. In order to manufacturer the quantities of solar blankets required by the Military the process needed be automated. The concept that was proposed was to use existing manufacturing technology to assemble the solar tiles into large solar arrays. Part of that process was to examine and test if Surface Mount Technology (SMT) could in fact assemble the solar tiles onto Printed Circuit Boards(PCB's).

PowerFilm reviewed the SMT equipment and potential vendors with such equipment to see if it was a good fit. The optimal situation was to use a local PCB assembly house to do such operations, Matrix Circuits LLC. They are an Iowa Company based just outside of Mt. Pleasant, about a 2 hour drive from PowerFilm Inc. PowerFilm already used Matrix for the assembly of PCB's for solar boost circuits. As such Powerfilm worked with Matrix on this overall process. The end result was a tiled PCB with 45 solar cells on it, as shown in Figure 21.

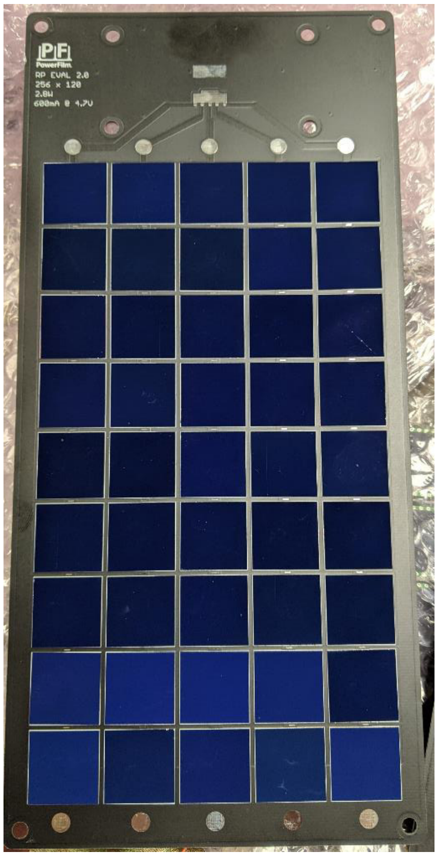


Fig. 21 SMT assembled solar array with 45 cells.

6.2 Design of PCB for Automated Assembly

A big part of the PCB assembly at Matrix Circuits was having a PCB that would work with their machines for the automated assembly process. PowerFilm designed the board shown in Figure 22 to work with the SMT equipment at Matrix. The boards used in the Phase 1 portion of the contract were designed to be hand loaded and hand reflowed. The board for automation needed to be compatible with the machine on a couple of different items. It needed to be big enough that it could be screen printed - the process that loads the solder paste onto the PCB. It needed to have Fiducials - objects or images that are part of the PCB that the vision camera in the SMT machine could see to know the exact placement of the PCB in the machine. It also needed to have enough placement locations for solar tiles such that the operators of the machine could see what was happening during that process.

The board shown in Figure 22 did just that, four fiducials were placed in the four corners of the Board, and an array of 45 locations for solar cells on the board to give the machine operators time to see and adjust the placement parameters. In the end, Matrix ended up going to a larger nozzle, higher placement pressure and slower head speed to perfectly places the 45 solar cells shown in Figure 21 above.

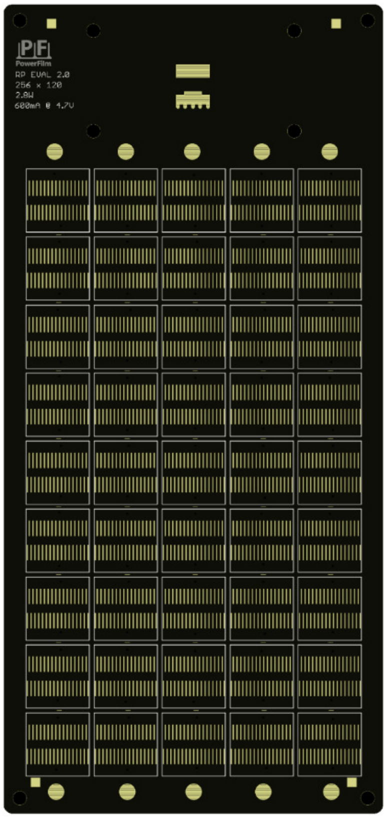


Fig. 22 - Top of PCB with 4 Fiducials (small yellow squares).

6.3 Process and Method for Transporting Cells to PC Board Vendor

Since the solar cells are cut and tested in one location, they need to be shipped to the PCB assembly house (Matrix Circuits) for assembly. They also have to be in a form factor that Matrix could use on their automated assembly equipment. SMT machines are usually fed parts in either reels (aka Tape and Reel) or in trays. Under the contract extension, PowerFilm located a vendor that could load the parts into tape and reel. In addition, PowerFilm also located feeder trays that could be loaded at the station where the cells were tested. Due to the limited time of the phase one extension, trays were used for the transportation of the solar cells to Matrix Circuits. However, the information needed to get cells into tape and reel was also figured out. Solar cells are shown in tape and reel in Figure 23, as well as in feeder trays which is shown in Figure 24.

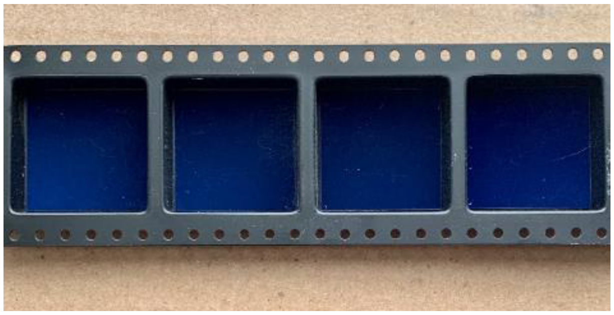


Fig. 23 Solar Cells in Tape and Reel.

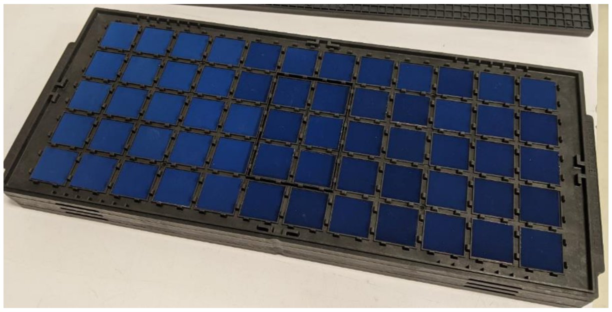


Fig. 24 Solar Cells in Feeder Trays.

6.4 Reflow Oven Recipe

Part of the process of fully connecting the solar cells to the PCB involves solder paste and metal contacts. These contacts are on the back of the solar cells in addition to the front of the PCB, and heat is required to flow the solder between the solar cell and the PCB. To much heat and you risk damaging the solar cells, to little heat and the electrical connection between the solar cell and the PCB can be compromised. On a SMT line a reflow oven is used to heat up the PCB, solder, and parts to get an ideal electrical connection. Solar cells are quite different than most SMT parts and therefor would require a custom solder profile to achieve good electrical connection with minimal impact on the performance of the solar cells.

PowerFilm did the vast majority of the research and development of the solder temperature range in house. We started at the top of the recommended range for the solder paste and worked our way through to the bottom of the range. Although this work wasn't accomplished in a SMT reflow oven it did prove effective as a starting point for Matrix's SMT reflow oven. It only took Matrix three tries to get a board that bonded the cells adequately without cracking the solar cells. This array of cells that was successfully reflowed is shown in Figure 21. The sample oven profile is shown in Figure 25.

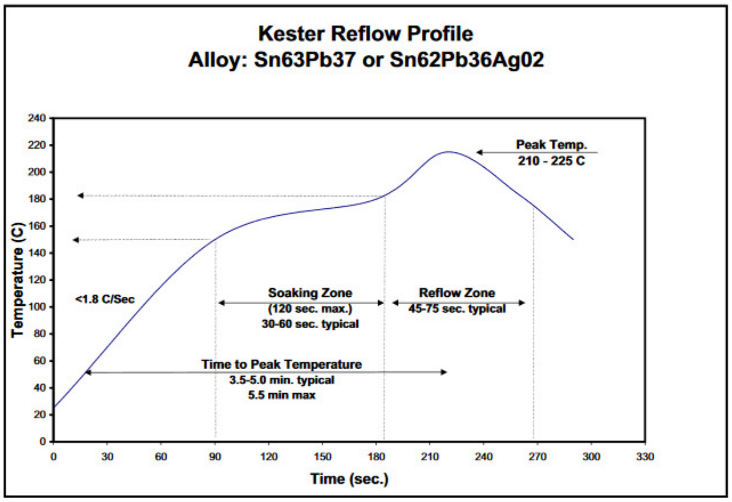


Fig. 25 Reflow Profile for the Solder Paste used in the Assembly of the Solar Cells.

7.0 Accelerated Testing

7.1 Module Fabrication

PowerFilm used the assembly techniques that were developed in the phase one contract to assemble the modules required for the accelerated testing. For the scope of the accelerated testing, including Thermal Cycling, Flexure and Flutter testing and Damp Heat, 2cm solar cell tiles were used in 4 x 4 arrays mounted on light weight fabric. The Thermal Cycle test sample is shown in Figure 26.

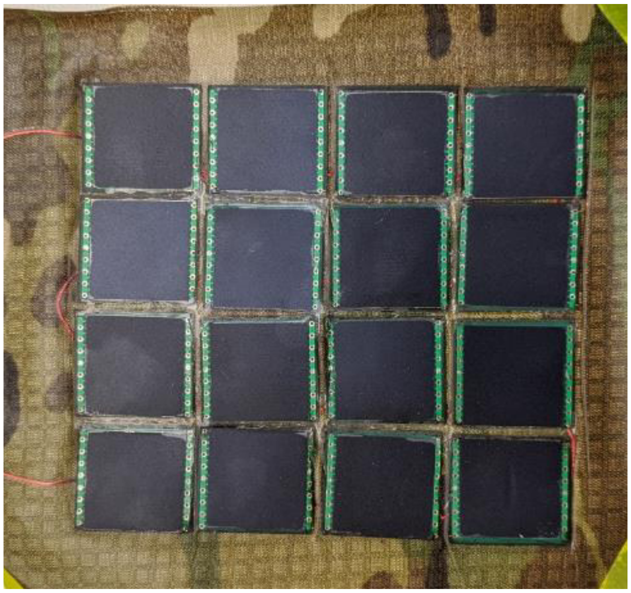


Fig 26 Thermal cycle test sample.

7.2 Thermal Cycling

The sample numbered "6V" ran for 25 cycles between -50 deg F and 160 deg F. The Summary Table of the IV curves is shown in Figure 27.

IV curves Csi 6V Thermal Cycle						
	Voc(V)	Isc(A)	Vpp(V)	Ipp(A)	Pmp(W)	FF
Pre 100%	10.05	0.07	7.835	0.063	0.494	70.49
Pre 25%	8.819	0.017	7.081	0.015	0.104	70.49
Post 100%	10.04	0.068	8.024	0.061	0.486	70.66
Post 25%	9.178	0.018	7.237	0.015	0.11	67.042

Fig. 27 Summary Table of IV curves, Thermal cycle.

The 4 x 4 array did excellent through Thermal Cycle, as Voltage of the module remained the same or increased as a result of running this test. Power (Pmp) was almost unchanged - as well as short circuit current (Isc) and Power Point Voltage (Vpp). If anything, the module got better throughout the thermal cycling test. PowerFilm thinks that this is a result of shunts along the edges of the cells, or internal shunts, increasing their internal resistance - thus improving the power point voltage.

7.3 Flexure and Flutter Testing

The test sample "#4" ran for 1 hour with wind speeds of 25-70 miles per hour, 15 mins at 25 miles per hour 15 mins at 55-60 miles per hour then 30 mins at 60-70 miles per hour. These conditions represent flexure and flutter in the field, although the duration of the test was only one hour it is designed to quickly bring defects or flaws to the surface. At the end of the testing IV cures of the panel were preformed to examine for electrical damage to the solar cells. Figure 28 shows the pre and post electrical data at 25% and Full sun under the LED simulator.

IV curves Csi #4 Flutter test						
	Voc(V)	Isc(A)	Vpp(V)	Ipp(A)	Pmp(W)	FF
Pre 100%	8.952	0.071	7.231	0.065	0.459	74.199
Pre 25%	8.187	0.018	6.664	0.016	0.107	72.321
Post 100%	8.996	0.069	7.249	0.063	0.456	73.156
Post 25%	8.22	0.018	6.605	0.016	0.104	70.564

Fig. 28 Summary Table of IV curves.

In summary there was very little change to the solar cells used in the Flexure and Flutter testing, there was no catastrophic damage and all measurements were with in the error of measurement. In the Phase 2 portion of the contract PowerFilm would recommend that we work with Natick to run similar tests in their wind tunnel for an extended period of time. The Cells mounted in the test fabric before flutter testing are shown in Figure 29.

Fig. 29 Flutter test sample #4 loaded in the test fixture.

7.4 Damp Heat

Damp heat sample “#3” was run for a total of 1008 hours at 85 deg C / 85% relative humidity. This test is the industry standard in the field of photovoltaics (solar cells) for indication of the long-term durability of a solar module. Figure 30 shows the summary data for the Pre / initial solar cell data along with 168-hour, 336-hour, and 1008-hour data points. The passing criteria for the solar industry after 1000 hours is no more than a 20% drop in output power. Between the “Pre 100%” Pmp of 0.463W to “1008 hrs 100%" Pmp of 0.416W, the power drop was only 11%.

IV curves Csi #3 Damp Heat

	Voc	Isc	Vpp	Ipp	Pmp	FF
Pre 100%	10.055	0.07	8.011	0.058	0.463	65.378
Pre 25%	8.626	0.017	6.086	0.012	0.075	51.579
168 hrs 100%	9.977	0.069	7.924	0.057	0.452	65.811
168 hrs 25%	8.682	0.018	6.24	0.013	0.084	53.265
336 hrs 100%	9.951	0.066	7.885	0.055	0.437	66.102
336 hrs 25%	8.638	0.017	6.211	0.013	0.081	53.87
1008 hrs 100%	9.815	0.065	7.782	0.053	0.416	65.66
1008 hrs 25%	8.607	0.017	6.219	0.013	0.08	54.18

Fig. 30 Summary Data for Damp Heat.

The main conclusion here is that the encapsulation is protecting the array as good as or better than an industry standard glass encapsulated solar module.

8.0 Summary and Conclusions

Overall PowerFilm feels the Phase 1 and Phase 1 option SBIR Ultralight Weight Photovoltaic projects were a huge success. These contracts took a number of great ideas and put them into reality. PowerFilm feels that this technology could be the low cost, high performance, durable, light weight solar module of the future for the Military.

Flex Circuit Design

The PCB artwork that was designed under this contract worked very well, and for this type of a design - no further work is needed. Matching the back-side cell traces to the PCB, without having the original artwork from the cell manufacturer, was also completely figured out and no further work would be required on this task going forward. The only disappointing finding under this task was the cost of using flex circuitry to back the cells.

Cell Cutting

This task was thought to be one of the easier tasks going into the contract, however what was discovered is that cutting a Sun Power® solar cell and keeping the performance high is no easy feat. In the end it required specialized cutting platen, a focused gaussian laser beam, and removal of the back-side metal on the solar cell. Without this contract this would not have been known, however success was had and cell cuts were made without affecting the solar cell performance. The task that would be left to figure out in a phase 2 would be to remove the copper traces for the cross cuts. A couple of methods to achieve this would be to screen print an etchant that would dissolve the copper traces from the back of the cell. An alternative to that would be to use mechanical CNC system to grind or cut away the traces as well. Both are deemed very doable and would be explored in a future contract. A long shot would be to get the manufacturer to make the cells with custom traces on the back that would be specifically design for this application.

Stencil Design

This task was also considered a success; the stencil is the means to put down the solder paste to which bonds the cell to the PCB. There was concern that the alignment between the cell and the PCB would be super critical. However, what PowerFilm found out was the cells would self-align to the traces on the board almost every time. What was not discovered, was the reason that 1 out of 8 cells was a dead short. It's impossible to visually see connection between the cell and the PCB, however recently PowerFilm has been using x-ray technology to look for defects in the crystalline products and this could be accomplished with the 1cm and 2cm cells as well.

Array Assembly

Array assembly was also considered a success, everything from stringing together the cells, encapsulating, and even mounting on fabric - was pretty much standard operation here at PowerFilm. The greatest need in assembly would be an alternative to using Litz wire between the cells. One thought would be to use small pieces of flex circuit between the cells during the automated assembly and mounting of the cells onto the arrays of PCB. A surface mount machine could pick and place small flex circuits into solder paste between each of the cells to provide the electrical interconnect. This would provide the benefit of building on a flex circuit without adding the high cost of a flex circuit for the whole backer.

Array Encapsulation

Using the encapsulation materials that were designed for thin film amorphous products to build the highly flexible crystalline array worked flawlessly. What would be needed in the future would-be long-term testing to prove out how well these thin encapsulants protect the cells. Standard long-term testing such as Damp Heat, QUV, Thermal Cycling and Vibration would determine the long-term viability of these newly designed and encapsulated arrays of solar modules.

Automated Assembly

The SBIR Phase 1 option proved out the concept to use SMT equipment to mount the solar tiles on PCB's. This proved to be highly successful and relatively easy to do. Only minor tweaks to placement pressure, machine nozzle size, and part acceleration were required to have success. These tests were performed on mechanical samples only - a SBIR Phase 2 contract will allow for full electrical excellent cells to run through the same process.

Accelerated Testing

Accelerated testing can throw a wrench in any project, as it brings out the flaws in materials and design. Between PowerFilm's years of experience in the field of solar modules, and the well thought out design - the ultra-flexible solar array showed almost no damage through out the accelerated testing. PowerFilm will continue to perform accelerated testing on the solar modules through the SBIR Phase 2 two contract, as any change in design or material must be retested before being fielded.

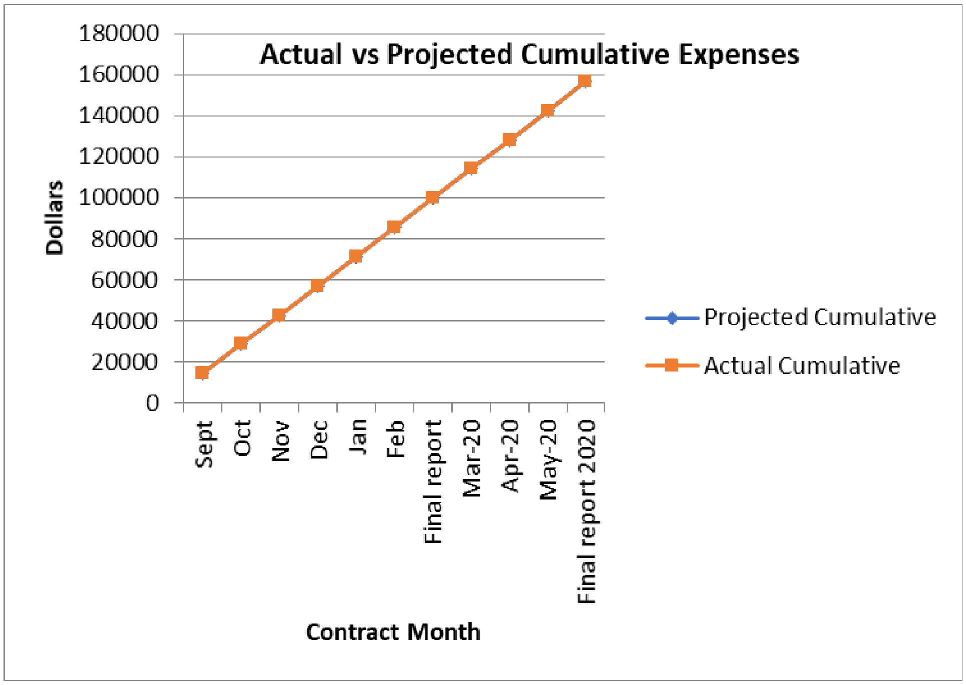
8.0 Point of Contact

Point of contact for this report is Brad Scandrett, 515.292.7606 ext 101, bscan@powerfilmsolar.com.

Incl:

Appendix 1: Estimated cumulative expenses by month with actual cost table
Appendix 2: Contract expenditures
Appendix 3: Gantt chart

Appendix 1: Estimated Cumulative Expenses by Month with Actual Cost Table



Month	Projected Expenses	Projected Cumulative	Actual Cumulative
Sept	$14,247.94	$14,247.94	$14,247.94
Oct	$14,247.94	$28,495.88	$28,495.88
Nov	$14,247.94	$42,743.82	$42,743.82
Dec	$14,247.94	$56,991.76	$56,991.76
Jan	$14,247.94	$71,239.70	$71,239.70
Feb	$14,247.94	$85,487.64	$85,487.64
Final report	$14,247.94	$99,735.58	$99,735.58
Mar-20	$14,247.94	$113,983.52	$113,983.52
Apr-20	$14,247.94	$128,231.46	$128,231.46
May-20	$14,247.94	$142,479.40	$142,479.40
Final report 2020	$14,247.94	$156,727.34	$156,727.34

Appendix 2: Contract Expenditures

Contract Expenditures through the end of June 2020

Natick cSi Fabric Contract												
W911QY18P0174												
Contract Date: August 21, 2018												
Direct Expense Category												**Total Expenses**
	Sep-18	**Oct-18**	**Nov-18**	**Dec-18**	**Jan-19**	**Feb-19**	**Mar-19**	**Mar-20**	**Apr-20**	**Jun-20**	**May-20**	**To Date**
Direct Labor	4,127.75	3824.92	5924.33	2677.97	4377.02	6567.97	272.2	3510.72	3163.53	4280.84	1034.1	39,761.35
Labor Overhead (246.0%)	10,154.27	9,409.30	14,573.85	6,587.81	10,767.47	16,157.21	669.61	8,636.37	7,782.28	10,530.87	2,543.89	97,812.92
Total Labor Cost	14,282.02	13,234.22	20,498.18	9,265.78	15,144.49	22,725.18	941.81	12,147.09	10,945.81	14,811.71	3,577.99	137,574.27
												-
Direct Materials	81.70	111.12	27.16	0	101.09	47.64	0	45.99	445.17	27.78	0	887.65
												-
SUBTOTAL	14,363.72	13,345.34	20,525.34	9,265.78	15,245.58	22,772.82	941.81	12,193.08	11,390.98	14,839.49	3,577.99	138,461.92
G&A (18.5%)	2,657.29	2,468.89	3,797.19	1,714.17	2,820.43	4,212.97	174.24	2,255.72	2,107.33	2,745.30	661.93	25,615.46
Total Costs	17,021.00	15,814.23	24,322.53	10,979.94	18,066.01	26,985.79	1,116.05	14,448.80	13,498.32	17,584.79	4,239.91	440,113.57
Labor Hours	89	96	151.4	52	93.5	129.5	5	73	72.5	73.5	20	855.4

Appendix 3: Gantt Chart

	Aug-Sept	Sept-Oct	Oct-Nov	Nov-Dec	Dec-Jan	Jan-Feb	March	April	May
Ultra Flexible PV Task 1: Flex Circuit Design									
1.1 Flex Circuit Design	■	■	■	■	■				
1.2 Cell and Flex Circuit Verification	■	■	■	■					
1.3 Flex Circuit Procurement	■	■	■	■	■	■			
Ultra Flexible PV Task 2: Cell Cutting									
2.1 Cell Cutting Laser	■	■	■	■	■	■			
2.2 Cell Cutting Performance	■	■	■	■	■	■			
Ultra Flexible PV Task 3: Stencil Design									
3.1 Stencil Design		■	■	■	■				
3.2 Stencil Procurement Testing		■	■	■	■				
Cell Mounting and Array Assembly									
4.1 Cell Mounting			■	■	■	■			
4.2 Array Assembly				■	■	■			
Array Encapsulation									
5.1 Cell Encapsulation				■	■	■			
Assembly of Solar Array Automation									
6.1 PC board Vendor selection							■		
6.2 Design of PCB for Automated assembly							■	■	
6.3 Process and method for transporting cells							■	■	
6.4 Reflow oven recipe								■	■
Accelerated Testing									
7.1 Module Fabrication							■	■	
7.2 Thermal Cycling								■	■
7.3 Flexure and flutter testing									■
7.4 Damp Heat								■	■