Automated Solar Cell Assembly Teamed Process Research

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SECTION 1 INTRODUCTION

This is the second Semiannual Technical Progress Report for the program titled "Automated Solar Cell Assembly Teamed Process Research," funded under National Renewable Energy Laboratory (NREL) subcontract No. ZAG-3-11219-01. This report describes the work done on Phase II of the program in the period from December 6, 1993 to June 30, 1994.

Spire's objective in this program is to develop high throughput (5 MW/yr) automated processes for interconnecting thin (200 μm) silicon solar cells. High yield will be achieved with these fragile cells through the development of low mechanical stress and low thermal stress processes. For example, a machine vision system is being developed for cell alignment without mechanically contacting the cell edges, while a new soldering process is being developed to solder metal interconnect ribbons simultaneously to a cell's front and back contacts, eliminating one of the two heating steps normally used for soldering each cell.

The processing system will handle round, square, or pseudo-square (round with four large flats) cells up to 15 cm across. Strings up to 2.0 m long can be assembled and arranged side-by-side to create two-dimensional module-size arrays up to 1.4 m wide. A photograph of the integrated system, designated the SPI-ASSEMBLERTM5000, is provided in Figure 1.

Figure 1 *Photograph of the SPI-ASSEMBLER 5000 cell assembly system.*

Flexible automation techniques are being incorporated wherever practical to enable the production of a variety of module designs with minimal mechanical adjustments or tooling changes. Software commands control tab length and stress-relief bend location, the number of cells per string, the number of strings per module, and the arrangement of strings in a series, parallel, or combined configuration.

Spire is teaming with Solec International, a PV module manufacturer, and the University of Massachusetts Lowell's Center for Productivity Enhancement (CPE), automation specialists, who are lower-tier subcontractors. A number of other PV manufacturers, including Siemens Solar, Mobil Solar, Ebara Solar, Texas Instruments, and AstroPower have agreed to evaluate the processes developed under this program. A program organization chart is provided in Figure 2.

Figure 2 *Project team organization, PVMaT Phase 3A program for Automated Solar Cell Assembly Teamed Process Research.*

The program is divided into two phases with seventeen tasks. Phase I extended from January 6, 1993, to December 31, 1993, and is now completed. Phase II covers efforts from December 6, 1993, to January 5, 1995. This semiannual report describes Phase II efforts from December 6, 1993, to June 30, 1994. The program tasks are listed in Table I.

Table I *Program tasks.*

Phase	Task
I	<ol style="list-style-type: none"> 1 Design definition 2 Cell loading process development 3 Cell alignment process development 4 Interconnect ribbon handling process development 5 Solder flux application process development 6 Ribbon to cell soldering process development 7 Cell string handling process development 8 In-line I-V string testing development 9 Process subassembly design 10 Process subassembly test 11 Integrated system design 12 Information dissemination
II	<ol style="list-style-type: none"> 13 In-line I-V string testing development 14 System integration and test 15 Preliminary processing evaluation (at Spire) 16 Final processing evaluation (at Solec) 17 Information dissemination

SECTION 2 TECHNICAL DISCUSSION

Phase II activities from December 6, 1993 through June 30, 1994 are described by task in this section. During this period, the various process subassemblies have been integrated and strings have been fabricated automatically for the first time. Processing evaluations have begun, and data are being collected on the accuracy and performance of the integrated system. A layout drawing of the system is provided in Figure 3.

Figure 3 Lay-out drawing of the cell assembly system (plan view).

2.1 TASK 13 - IN-LINE I-V STRING TESTING DEVELOPMENT

An in-line I-V string tester is being developed for measuring the performance of soldered cell strings under simulated sunlight. Strings up to 15 cm wide by 200 cm long can be tested. The tester consists of a pulsed xenon light source, spectral filter, lamp power supply, reference cell, test probes, electronic load, personal computer (PC), and software for control and data acquisition. A layout drawing of the lamp enclosure is provided in Figure 4.

Figure 4 *I-V tester lamp enclosure and lamp mount layout.*

A new lamp pulse forming network was designed for maximum testing throughput: an entire I-V curve is measured in a single 10 millisecond light pulse. During this reporting period, the lamp enclosure, access panels, lamp mounting components, probe assembly, electronic load circuit, and reference cell assembly were fabricated. The probe assembly makes a four-point (+V, +I, -V, -I) measurement for maximum accuracy.

The I-V tester components were assembled for bench testing prior to mounting in the Assembler. Flat, stable light pulses were obtained with a duration of approximately 8 ms at the peak, verifying the design of the pulse forming network. Tubular spectral filters for the xenon lamps were fabricated and installed in April. Testing showed that the filtered lamps produce two to three suns of light at the cell string test plane. Woven wire mesh was selected as an economical means of reducing the light intensity over the large test area (15 cm x 200 cm). Two types of wire mesh were obtained and tested in May. One of these was found to transmit the proper intensity level (100 mW/cm²) to the test plane. A full area filter was fabricated from this material and installed.

Circuitry was designed and assembled and software was written for PC control of the electronic load that sweeps the voltage and current across the cell string. Software was also written for measuring I-V curves. The measurement of I-V data from strings has begun. During each light pulse, the electronic load sweeps a complete I-V curve from short circuit current (I_{sc}) to open circuit voltage (V_{oc}) while the PC acquires 100 data values ($n = 1$ to 100) on each of

three analog channels: string voltage (V_n), string current (I_n), and reference cell short circuit current ($I_{sc-ref-n}$). $I_{sc-ref-n}$ is proportional to light intensity and is monitored first to ensure that all measurements are made at levels close to one sun and secondly to allow small corrections to be made in I_n at each I-V data point to compensate for small variations in intensity. Measurements have shown that $I_{sc-ref-n}$ varies less than $\pm 2.5\%$ during a 100-point string test. The maximum power point on the I-V curve (P_{max}) is determined by calculating $P_n = V_n \times I_n$ for each data point on the curve and selecting the maximum value. Sample data from a measured string are plotted in Figure 5.

Figure 5 One sun I-V data measured with string I-V tester.

In production, a display of a full I-V curve is not required on a routine basis. The operator will select minimum acceptance limits for I_{sc} , V_{oc} , and P_{max} . The computer will compare measured string values with the selected limits to make a pass/fail decision. If the string passes, the table of significant data is saved in a file on the hard disk and the string is transported to the string array table. If the string fails, the data table and all 100 I-V data points are saved in a file on the hard disk, the string is transported to the reject table, and an alarm sounds to alert the operator. Examination of I-V curves for failed strings will help the manufacturer diagnose the cause of string failure.

2.2 TASK 14 - SYSTEM INTEGRATION AND TEST

Prior to December, 1993, the electrical power, control wiring, and pneumatic systems for each subassembly were individually connected as needed for subassembly testing. Integrated systems for power, controls, and pneumatics were designed, installed, and tested in this reporting period.

The main power distribution box was assembled and installed on the frame underneath the ribbon reel assembly in January. This box is the point where 220 VAC from the facility is connected to supply power to the entire system. The box contains circuit breakers and some of the 220 VAC controls. AC wiring was installed to provide power to the various system subassemblies.

Two electronics chassis were assembled and installed on the frame underneath the ribbon handling subassemblies. The programmable logic controller (PLC), linear motor drivers, relays, solenoid valves, and various other components are mounted on these chassis. Power and signal wiring for these components was completed.

Three compressed air distribution manifolds were assembled, one for the loader and aligner subassemblies, one for the ribbon handling subassemblies, and one for the string handling subassemblies. The manifolds contain the filters, regulators, lubricators, gauges, and pressure switches needed for the individual subassemblies. The three air manifolds were installed and air lines were connected to the various subassemblies.

A control panel was designed to provide a number of operator control functions and displays. A photograph of the panel is shown in Figure 6. System controls allow the operator to start, pause, and emergency stop the system, reset the stepper motors, and mute an audible alarm. Ribbon controls are provided for manually driving the motors which feed the ribbon accumulator, and to toggle the ribbon clamp open and closed at the exit of the accumulators. Platen controls are used to set the cell preheat temperature and the platen vacuum level. Solder lamp controls are provided for setting the lamp voltage levels used during the automatic soldering cycle. The control panel was fabricated from the cover of a standard slope-front enclosure. Components were installed and the enclosure was mounted near the ribbon reels.

Figure 6 Control panel, cell assembler.

Due to the large size of the cell assembler system, five large red emergency stop buttons were mounted at various locations around the perimeter of the machine. These buttons are provided for operator safety and equipment protection in the event of a malfunction. One button was mounted on the operator control panel (Figure 6) while the other four were mounted in small boxes located around the machine and wired into the PLC.

Software was developed for the operator interface to the system. The operator issues commands or selects operating parameters from a PC running a Microsoft Visual Basic program, which has the graphical look and feel of a Microsoft Windows™ application. The main menu screen is shown in Figure 7. Software was written to communicate between the Visual Basic program running on the PC and the relay ladder logic language running on the PLC, which controls most of the machine functions. This link allows operator commands and selections to be downloaded to the PLC and machine conditions to be uploaded to the PC.

Figure 7 *Main menu screen, SPI-ASSEMBLER 5000.*

The process control and monitoring programs on the PLC and the PC have been enhanced with the addition of 21 different alarm conditions. When sensors indicate an alarm condition, an audible alarm is sounded and a message is displayed on the PC monitor to indicate the source of the alarm. The alarms are grouped into three categories, in order of increasing severity, as follows:

Warning - provides an audible alarm and a message on the PC monitor; machine operation is not interrupted.

Machine Pause - provides an audible alarm and a message on the PC monitor; machine operation is interrupted; motor positions and digital output states are preserved; after the fault is corrected, the operator can resume processing from the point at which the system was interrupted.

Emergency Stop - provides an audible alarm and a message on the PC monitor; machine operation is interrupted; power is removed from all stepper motor drives and all digital outputs; after the fault is corrected the system must be restarted, as for an initial power up.

A list of alarms by category is provided in Table II.

Table II *SPI-ASSEMBLER 5000 alarm conditions.*

Alarm Level	Alarm Condition
Warning	End of reel, left End of reel, right IV test failure Loader down - cannot shuttle Cell reject cassette full No cassette loaded
Machine Pause	Operator pressed pause button Ribbon loop too high, left Ribbon loop too high, right No ribbon at cutter, left No ribbon at cutter, right Conveyor rails closed - cannot convey No vacuum on transfer arm - string not picked up Ribbon dropped, left Ribbon dropped, right Low pressure, solder head cooling
Emergency Stop	Operator pressed one of five Emergency Stop buttons Object between blades Low aligner air pressure Low machine air pressure Low string transfer air pressure

2.3 TASK 15 - PRELIMINARY PROCESSING EVALUATION

Preliminary processing evaluations were done at Spire during this period using both 200 μm thick cells from Solec and 325 μm thick cells from Siemens Solar. Results of these evaluations are provided in the following sections.

2.3.1 Cell Loading Process Evaluation

The cell loader consists of a cell stack shuttle, stack elevators for loading and rejects, and a vacuum pick-up pad mounted on a 2-axis pick-and-place mechanism for transferring cells from the loading elevator to an aligner. Two quick-release cell stack carriers are mounted on a linear shuttle that transports each stack to the elevator. The shuttle allows an operator to load a stack of cells while the system is automatically feeding from another stack, resulting in uninterrupted operation. A lay-out drawing of the loader is provided in Figure 8.

Figure 8 *Lay-out of the loading and alignment systems.*

The top surface of a stack of solar cells generally tilts from the horizontal plane in a random direction due to normal variations in silicon and metallization flatness. The loader manipulator was originally designed with a flexible coupling to allow the vacuum pick-up pad to adjust to the surface of the top cell in the stack. Testing showed that the flexible coupling produced undamped harmonic oscillations in the vacuum pad when the manipulator accelerated and decelerated in moving from the cell stack to the aligner. These oscillations can easily break cells, since the cell swings back and forth rapidly as it is placed on the aligner stage.

The oscillations were eliminated by replacing the flexible coupling with a rigid coupling. As expected, tests showed that cells could not be picked up reliably from tall stacks, since the vacuum pad could not seal against the cell if the stack was not level. Further development work solved the pick-up reliability problem through two changes in the pick-up design. First, the hard

hard rubber surface of the vacuum pad was replaced with a soft sponge rubber material to increase the pad's compliance, and secondly, a light spring load was added to the vacuum pad to obtain a positive vacuum seal.

Testing of the cell loader stack height sensor indicated that the sensor did not control the stack height with sufficient repeatability for reliably picking up cells from the stack. This optical sensor has both a light emitter and receiver in the same module, and relies on reflection from the cell stack to set the stack height. An optical broken beam type of sensor was selected to improve the height repeatability. A sensor was obtained, installed, and tested. The broken beam sensor has separate emitter and receiver modules which were mounted on opposite sides of the load elevator. The stack of cells is lifted by the elevator until the top of the stack eclipses the emitter beam at the receiver. Testing showed that the broken beam sensor is more reproducible in setting the stack height and cells are reliably picked up from the stack.

2.3.2 Cell Alignment Process Evaluation

Spire engineers are working with a team from the University of Massachusetts Lowell (UML) Center for Productivity Enhancement to develop the cell alignment process subsystem. Spire has taken the lead in the mechanical design aspects, such as the design of the structural frame, the cell manipulator, the aligner stage, and the various mounting brackets. UML is developing the vision system, which primarily consists of software development for image processing and controlling the aligner manipulator and the cell loader manipulator. UML also selected the camera and the imaging board.

In operation, the loader manipulator places a cell face down on the transparent aligner stage. A monochrome CCD camera and a lamp are mounted underneath the stage, looking upwards to obtain an image of the cell. A video board installed in a PC captures the image for analysis. The cell's position is located in x , y , and θ , and the cell is inspected for defects such as chips, improper grid patterns, or upside-down placement. Rejected cells are placed in the reject stack carrier, while good cells are placed in the proper location on the conveyor belt.

2.3.2.1 Aligner Lighting Evaluations

Testing of the vision system in November, 1993, showed that images of cell contact patterns can readily be obtained, since the reflective metal contacts have excellent contrast against the dark active areas of the cell. However, problems were encountered in detecting cell edges, since the ambient background above the cell produces a pattern of light and dark regions around the cell image. These regions have a wide range of pixel intensities (shades of gray), making it difficult to reliably discriminate the cell edges.

Experiments with lighting and white backgrounds were done in this reporting period to improve the detection of cell edges. A white shutter was designed and installed to provide a uniform white background around the cell image. The shutter is mounted in a track and is driven by an air cylinder that slides the shutter over the back of the cell during image capture. The shutter then retracts to allow the cell to be picked up. Limit switches are installed to indicate shutter open and closed positions for rapid sequencing and to prevent collisions with the loader and aligner manipulators. Software was written for controlling the shutter with the aligner PC. Testing shows that the white shutter provides a background with sufficient contrast to enable cell edge detection.

While the shutter has eliminated the primary edge detection problem, further tests have identified a potential secondary source of error. The gap between the cell and the shutter (approximately 3 mm) creates a narrow shadow band of varying pixel intensity around the cell edges. It is possible to set the threshold level (shade of gray value) for edge detection such that the shadow is ignored and the cell edge is detected, but the proper threshold level can change from one time to another, possibly due to changes in ambient lighting conditions. Further testing will be done in this area to obtain more robust edge detection.

The availability of the shutter over the aligner stage has allowed the addition of a new self-diagnostic check. The shutter has been programmed to close after a cell is picked up and an image is obtained of the empty stage. The image will be processed to check for debris that could be left on the stage if a cell breaks. If debris is found, the machine will be paused and the operator will be alerted to check the aligner stage.

2.3.2.2 Aligner Mechanical Evaluations

The vacuum pick-up used on the cell aligner was originally designed with a pair of small shafts which slide in ball bearings, allowing the vacuum pad to float in the vertical (z) direction. The shafts and bearings were found to have a certain amount of play, leading to inaccuracies in cell placement in the x and y directions. A new approach which uses a miniature ball slide in place of the shafts and bearings was designed, fabricated, and installed. Tests show that the new design is more rigid and precise in handling cells, while still allowing the pad to float vertically.

Careful observations of the aligner process revealed another source of alignment error. When a cell is picked up from the aligner stage, the center of the vacuum pick-up pad must be placed directly on the center of the cell or rotational alignments will cause the cell to rotate eccentrically, introducing errors in cell placement. Since the center point of the cell is not known until after the image data are processed, the aligner pick-up cannot be placed on the cell until after imaging. Careful inspection of the pick-up operation showed that cells moved slightly on the aligner stage during placement of the pick-up, introducing an error in cell position. Testing showed that this problem can be minimized to some extent by adjusting the pick-up for parallelism with the stage, but it cannot be positively eliminated.

It was recognized early in the program that a vacuum chuck could be designed into the aligner stage to hold the cell securely and prevent it from being nudged out of position by the pick-up. This approach was not considered, however, since a conventional vacuum chuck would obstruct the view of the video camera mounted underneath the stage. The importance of holding the cell securely led to the invention of a novel vacuum chuck which is transparent to the video camera. A prototype chuck was designed, fabricated, and tested. The chuck was made from three layers of clear polycarbonate with intersecting slots and holes. The slots and holes have sharp edges which can be seen faintly on the video monitor, but they do not affect the cell image processing since the signals are below the threshold at which they would be recognized as a cell feature. Given the successful results of initial testing, a new top layer was fabricated from glass to increase its scratch resistance. A photograph of the aligner stage with the vacuum chuck and the white shutter is provided in Figure 9.

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Figure 9 *Aligner vacuum pick-up over the cell aligner stage. The white shutter is retracted to the left. The stage's vacuum chuck grooves and holes are more pronounced in this photo than they are to the aligner camera due to the camera angle.*

The vacuum chuck is connected to a vacuum aspirator assembly, which includes a venturi vacuum pump, a filter, a vacuum switch to indicate the presence of a cell, and a vacuum breaking valve for rapid and positive release of the cell after it is acquired by the manipulator pick-up. Software has been written for the aligner PC for controlling the vacuum pump and the vacuum breaking valve at the proper times in the process cycle.

2.3.2.3 Aligner Software Evaluations

Software was developed for several tasks performed by the aligner PC. Routines were written for calibrating the position of the aligner's four-axis manipulator, for calibrating the position of the video camera with respect to the manipulator, and for calibrating the number of video pixels with respect to the manipulator's stepper motor counts in x and y directions.

Software was also written for aligning square cells in x, y, and θ . This routine detects the four edges of a square cell and uses this data to calculate the cell's center point and its angle of rotation. The accuracy and repeatability of cell placement was tested and found to be less than required. For example, when the cell spacing is set to a nominal value of 0.085", measurements show that the spacing varies from 0.075" to 0.110", a range of 0.035". The repeatability of the stepper motors, motor drivers, and mechanisms for both the aligner manipulator and the conveyor

belt was tested and verified to be better than ± 0.001 ". Thus the problem was traced to the vision system software being developed by UML. One source of error was found in the cell center calculation algorithm, which used a center-of-mass calculation. A new algorithm based on intersecting diagonals was written and tests are ongoing to determine the present accuracy of the system. Ongoing work to improve lighting (described in Section 2.3.2.1) may also lead to improvements.

The amount of alignment software development time consumed by UML, a concern that the aligner code may not be sufficiently robust (sensitivity to lighting conditions, frequent computer crashes, reboots required to reset, etc.), and the potential for lack of support should the software developer leave the University in the future have resulted in a decision to pursue an alternative machine vision approach: the use of a commercial vision system from Cognex. The system includes a far more sophisticated image processing board and higher-level software tools for alignment and inspection. Cognex hardware and software has been procured, and cables have been fabricated for connecting the vision board to the camera and to the monitor. A software interface specification has been written to define the interface between the image processing software (routines which use Cognex functions) and the aligner control (UML) software.

2.3.3 Interconnect Ribbon Handling Process Evaluation

Interconnect ribbon and solder flux materials were purchased in January for process evaluations. The ribbon is electrolytic tough pitch (ETP) copper, 0.076 mm (0.003") thick and 2.54 mm (0.100") wide. The copper is coated with 13 μm (0.0005") of $\text{Sn}_{60}\text{Pb}_{40}$ solder on both sides.

Kester type 920-CXF flux was obtained for interconnect ribbon coating tests. This flux is a non-corrosive, low-solids, no-clean flux recommended by Solec for use with their cells. The flux was evaluated for compatibility with the ribbon handling tooling and for solderability to Solec and Siemens Solar cells using the light soldering process. The flux contains 4.5% solids and 95% propanol. Evaluations showed that the flux does not stick the ribbon to the tooling and does not leave a sticky or greasy residue on the cells after soldering.

2.3.3.1 Ribbon Reels and Sensors

A problem was encountered in April with the large (14" diameter) reels that hold the interconnect ribbon stock. The ribbon is packaged by the vendor on cardboard reels. These reels worked fairly well during the winter when the indoor humidity is low, but the reels bow severely when the humidity is high since the outer surfaces of the cardboard absorb water and expand more than the inner surfaces. Thus the reels pinch the ribbon tightly and cause the ribbon to slip in the drive rollers. The problem was solved by replacing the cardboard reels with plastic reels, which were designed and fabricated in May. The reels are shown in Figure 10.

Figure 10 *Plastic ribbon reels with broken-beam end-of-ribbon sensors (mounted on the brackets at lower left).*

Optical sensors are used to detect the presence of ribbon as it winds out of the supply reel and enters the flux bath. When the reel empties, the ribbon falls out of range of the sensor, signalling the PLC to disable the ribbon drive motor, trigger an audible alarm, and display a message on the monitor to signal the operator to splice in a new reel. A reflective type of sensor that combines optical send and receive units in a single package was originally chosen for simplicity in mounting and wiring. Tests in May showed that the sensor was unreliable in sensing light reflected from the ribbon through the full range of possible ribbon angles, due to the specular nature of the reflection from the solder coated copper ribbon. The sensors were replaced with broken-beam type optical sensors with separate send and receive units. Since these sensors rely on the ribbon to shadow the beam at the receiver, the ribbon angle or reflectivity is inconsequential. The sensors were temporarily mounted, tested, and found to work well. Permanent brackets were then designed to support the sensors, as shown in Figures 10 and 11.

2.3.3.2 Ribbon Straighteners

Most of the ribbon handling process development has been done using 0.100" wide by 0.003" thick ribbon. Narrower, thicker ribbon, 0.080" by 0.005", was processed for the first time in March. This ribbon was found to acquire a bend as it was pulled around the two semi-circular ribbon diverters in the flux bath, due to the ribbon's increased stiffness. The bend was sufficiently large that the ribbon did not lie flat on the conveyor belt, and so could not be held in position by vacuum. A ribbon straightener was designed, fabricated, and installed at the exit of each ribbon accumulator, just before the ribbon enters the bending die. A drawing of the straightener assembly is provided in Figure 12.

Figure 11 *Ribbon reels with broken-beam end-of-ribbon sensors.*

Figure 12 *Ribbon straightener assembly.*

The straightener has two pairs of fixed guide pins between which the ribbon travels. A movable pin can be adjusted to apply a gentle upward or downward pressure on the ribbon, as required, to remove the bend in the ribbon. This assembly was tested and found to be highly effective in straightening the ribbon.

2.3.3.3 Tab Position Accuracy

Tab position measurements made on cell strings produced during processing trials indicated the need for improved tab placement accuracy. The tab spacing distribution (measured at the ends of the tabs) varied from 1.87" to 1.93" on the cell fronts and from 1.86" to 1.94" on the cell backs. The target dimension is 1.90" with a tolerance of ± 0.02 " on the front of the cell and ± 0.03 " on the back. Careful measurements were made of the ribbon handling components but no significant misalignments were found. Two approaches to improving alignment were then investigated: increasing the grip on the tabs by the vacuum belt and improving the tab guiding tooling.

Much of the groove area in the vacuum platen under the conveyor belt was not needed for holding the tabs and cells. Unnecessary grooves were sealed off with tape as a temporary measure to see if the grip on the tabs provided by the vacuum belt could be improved. An improvement in grip was in fact observed, as increased force was required to slide a tab across the belt. On the basis of this test, a new platen was designed and fabricated which reduced the open area from 10.57 in² to 3.71 in², resulting in a platen with only 35% of the open area of the original platen.

As part of the vacuum belt testing, higher flow (lower vacuum) and higher vacuum (lower flow) blowers were obtained for evaluation. Each blower was connected to the vacuum plenum and tested for its ability to grip tabs on the belt. The higher flow blower provided less grip than the original blower, while the higher vacuum blower was the same. Thus no change in blowers was made.

Despite the improvement in vacuum holding force obtained by reducing the groove area in the platen, tab position repeatability perpendicular to the belt direction was not noticeably improved. Efforts were then directed towards improving the ribbon guides, tooling that provides ribbon alignment in the clamp and form assembly, where the ribbon is passed to the ribbon shuttle for placement on the conveyor belt. Examination of the guides showed that the aluminum was wearing from friction as the copper ribbon is rapidly pulled through the guides. As a result, the ribbons were no longer accurately positioned, as they had been when the guides were new. Replacement guides were designed to tighter tolerances and with a much longer guiding length than the original guides. The guide material was changed from aluminum to stainless steel to reduce the wearing effect of the copper ribbon. Micrometer adjustments were added as part of the redesign, a feature that allows the ribbons to be precisely repositioned, both for ease in initial set-up and for switching between cells with different tab spacings. A photograph of the new guide assembly is provided in Figure 13.

Figure 13 *Ribbon guide assembly with micrometer adjustments. Also note the ribbon straighteners located between two guide sections.*

The new ribbon guide assembly has been designed with the capability for handling three ribbons in response to the recommendation of a module manufacturer. Three tabs may be desired to minimize resistive power loss as cell sizes increase to 125 mm or 150 mm. Since only two tabs are required for the present work, components for assembling a two-tab version of the assembly were fabricated. The assembly was completed, installed, and tested in June.

The accuracy and repeatability of ribbon placement was measured in May with the original aluminum guides and remeasured in June with the longer stainless steel guides. The results are plotted in Figure 14. The cell strings made for these tests were fabricated automatically in the SPI-ASSEMBLER 5000. The ribbon guides were set to obtain a nominal spacing of 1.90". The spacing between the two ribbons soldered to the front of each cell was measured at the ends of the ribbons. The top left graph in Figure 14 shows the distribution of spacing values obtained in May with the original guides. The ribbon spacing ranges from 1.87" to 1.94" with a standard deviation of 0.017". The top right graph shows the distribution of spacing values obtained in June with the improved guides. The ribbon spacing ranges from 1.88" to 1.92" with a standard deviation of 0.009". Thus the data show that the new guides provide more accurate ribbon placement.

Figure 14 *Ribbon placement measurements before and after ribbon guide redesign. Left: aligned with short aluminum guides, May, 1994. Right: aligned with long stainless steel guides, June, 1994.*

2.3.4 Ribbon to Cell Soldering Process Evaluation

A soldering process is being developed for soldering copper ribbons to the front and back contacts of solar cells in a single heating step. A pair of high intensity lamps provide radiant energy to solder the interconnect ribbons to the solar cells. In addition, conduction pre-heating of cells is being used with light soldering to reduce thermal stress during soldering and to increase throughput. During this reporting period, the cell alignment system was integrated with the soldering system and the ribbon handling system for automatically producing soldered cell strings.

Flux is required to dissolve the native oxide on the surface of the cell contacts and allow the solder coating on the copper ribbon to wet to the cell contacts and form a durable bond. Good soldering results were obtained in Phase I of this program using Kester 2331 flux. This flux contains glycerol which tended to leave a greasy residue on the ribbons after soldering, however. Since these residues could affect the adhesion of encapsulants, leading to module delamination, an alternative flux was desired. Kester 920-CXF flux, which contains no glycerol, was obtained and tested in this reporting period, as described previously (Section 2.3.3). Testing showed that excellent solder joints can be obtained with this flux, and no greasy residue is left on the ribbons after soldering.

Soldering process parameters include the platen temperature for preheating cells and tabs, the voltage on the soldering lamps for heating the cells, the idle voltage on the soldering lamps, the heating time, and the cooling time. Typical process parameters are provided in Table III.

Table III *Typical process parameters for soldering cell strings.*

Parameter	Setting or Description
Platen temperature	140°C
Lamp voltage, heating	140 VAC
Lamp voltage, idle	25 VAC
Heating time	1.8 s
Cooling time	1.5 s
Cell type	Solec, 10.2 cm square, 200 μm Cz-Si thickness
Flux type	Kester 920-CXF
Ribbon type	0.100" x 0.003" Cu with $\text{Sn}_{60}\text{Pb}_{40}$ coating

A number of cells soldered under the above listed conditions were subjected to pull tests to measure the force required to peel the ribbon from the cell. A Chatillon model DFG-10 digital force gauge was used to record the maximum force from each tab pulled. The results, provided in Figure 15, show that good peel strengths have been achieved, averaging 432 g on the front contacts and 288 g on the back contacts when pulled at a 90° angle. Pulls at the higher end of the scale (>400 g) typically pull silicon out of the wafer or break the wafer, indicating that the solder joint is stronger than the silicon wafer. The back contacts are weaker than the front due to a lower adhesion of the back contacts to the silicon, as the failure is at the silicon-contact interface, not the solder-contact interface.

2.3.5 Cell String Handling Process Evaluation

Software development was completed in this reporting period for automatically controlling the string transfer mechanism with the PLC and the stepper motor drivers. The mechanism picks up a cell string from the conveyor belt, carries it to the I-V tester, and places it on either the reject table or the string array table, in the proper sequence with other strings to assemble a module.

Two types of air aspirator vacuum pumps were tested for picking up cell strings. Surprisingly, the less expensive single-stage model generated sufficient vacuum (125 mm Hg vacuum) to pick up a string in the same amount of time (approximately two seconds) and at a much lower air supply pressure (30 psi) than the two-stage model (70 psi). The single-stage model was selected and installed on the vacuum manifold.

Figure 15 *Solder joint pull strength distribution, 90° pull angle; soldering conditions listed in Table III.*

The process of picking up cell strings and placing them with the string transfer assembly was developed. The assembly contains a linear array of independently suspended 51 mm diameter vacuum pick-ups, one for each cell, as shown in Figure 16. Testing showed that occasionally one or more cells in a string were not acquired by the pick-up. Since the pick-up is large enough to cover the interconnect ribbons soldered to the back of the cell, the pick-up was not sealing reliably to the cell. The rubber pad on the bottom surface of the pick-up was replaced with a lower durometer material, a foam rubber with a more compliant surface. Tests showed that the softer foam rubber makes a reliable seal to the interconnected cells.

Small manual shut-off valves were obtained and installed in the vacuum lines to each vacuum pick-up. These valves allow the string transfer assembly to be configured for different length strings without changing the vacuum line plumbing.

Tests of string placement indicated the need for a vacuum breaking valve on the vacuum manifold. The vacuum breaking valve reduces the time needed to vent the vacuum system by injecting compressed air into the vacuum manifold when strings are placed on the array table. A suitable valve was obtained, installed, tested, and found to work satisfactorily.

Figure 16 *String transfer mechanism, I-V tester, and array table. Vacuum switches are mounted above each vacuum pick-up. The carrier stop assembly is mounted at the edge of the array table.*

Vacuum switches were obtained and installed on each vacuum pick-up on the cell string transfer assembly. These switches sense the presence of a cell at each pick-up, thus providing a positive indication that all cells in a string are acquired before the string is lifted and transported. They also indicate when the string is released from vacuum during placement on the string array table. All plumbing and electrical connections were completed, mounting brackets were designed and fabricated, and software was written for the PLC. Tests showed that the switch's vacuum port cannot be connected between the vacuum manifold and the pick-up, since the manifold pressure has a larger effect on the switch than the pressure at the pick-up. The pick-ups were modified to add a second vacuum line just for the switch, allowing the switch to sense the vacuum directly at the pick-up.

A carrier stop was designed and installed on the string array table to provide a fixed location for the carrier on which cell strings are placed. The carrier stop consists of a rail which extends along the entire length of the array table, at the edge next to the I-V tester, and a plate which has an edge perpendicular to the rail, as shown in Figure 16. The plate can slide along the rail to any desired location and is locked in place on the rail with a clamp. A carrier plate can be placed in a fixed, repeatable position on the array table by sliding it into the corner formed by the rail and the plate.

2.3.6 Trial Run with Siemens Solar Cells

Spire has also been working in close cooperation with engineers at Siemens Solar Industries (Camarillo, CA). Jean Hummel of SSI visited Spire in May to evaluate the operation of the assembler in a trial run. Approximately 1000 SSI cells (325 μm thick by 103 mm square) were processed into 12-cell strings. This testing complements the preliminary processing evaluation work Spire is doing with thin (200 μm) Solec cells.

All subsystems with the exception of the in-line I-V tester were installed, integrated, and processing automatically during the trial run. The major results are:

- yield (with processes not fully optimized) was measured to be 97.5 %
- processing time (with sequences not fully optimized) was approximately 5 s/cell (the goal is 4 s/cell)
- solder joint pull strengths are excellent; failures during 90° pull testing are typically in the contact or the silicon, not the solder joint
- improvements are needed in cell alignment (see Section 2.3.2.3) and in tab placement accuracy (note that this trial run was done before the ribbon guide upgrade described in Section 2.3.3.3)

Thirty of the 12-cell strings produced during the trial run were laminated at Spire in a SPI-LAMINATOR™ 350 to produce ten 36-cell modules which were shipped to Siemens for accelerated environmental testing. I-V curves show these modules have excellent fill factors and cell performance. The modules passed the environmental testing at Siemens, which included damp heat soaking, thermal cycling, and humidity-freeze cycling. These tests are important for qualifying the long-term reliability of modules made using the fluxing and soldering processes developed in this program.

2.4 TASK 17 - INFORMATION DISSEMINATION

The draft and final versions of the Annual Technical Progress Report for 1993 were written and delivered to NREL during this reporting period. Videotape of the assembler in operation was recorded at Spire on March 30. The tape was edited and delivered to NREL in April. Color photographs, slides, and cell strings were also provided to NREL for display purposes.

Stephen Hogan of Spire visited Solarex's polycrystalline silicon solar cell division (Frederick, MD) on January 26. The automated cell assembly system being developed in this program was discussed with a group of Solarex engineers. A videotape of the system recorded in November was presented. The assembly process and how it relates to Solarex's requirements was discussed. The Solarex engineers expressed an interest in visiting Spire with cells for processing trials when the system is complete.

Russel Schmit from Texas Instruments (Dallas, TX) visited Spire on February 1. A tour of the automated cell assembler was provided and the videotape filmed in November was presented. While TI's Spheral Silicon™ cells are significantly different from cells made from crystalline silicon wafers, TI is interested in whether the vacuum conveyor belt is capable of handling their cells. If so, it may be possible to replace the light soldering head with a welding head suitable for TI's cells. Spire will maintain a dialogue with TI on these issues.

Roger Little and Stephen Hogan of Spire attended the Soltech '94 conference (Jacksonville, FL) February 28 to March 2. Spire also displayed a booth in the exhibition area to promote its photovoltaic manufacturing equipment, including the cell assembler. The assembler was discussed with a number of module manufacturers, including George Roland, President of Siemens Solar Industries, and John Triebe, the Vice President of Amoco who is responsible for the Solarex operations. Discussions were also held with Jawid Shahryar of Solec International, a subcontractor to Spire under this program.

Spire contacted Richard Rosey, the President of Ebara Solar (Large, PA) and previously of Solar Web and Westinghouse. Ebara Solar is planning to commercialize the dendritic web silicon growth process originally developed at Westinghouse for solar cell production. Rosey is interested in Spire's cell assembler program and how it may be applied to thin ribbon cells. Spire will stay in touch with Ebara Solar as their production efforts begin.

Ghazi Darkazalli of Spire attended the 12th European Photovoltaic Solar Energy Conference and Exhibition (Amsterdam, Netherlands) April 11 to 15. Spire displayed a booth in the exhibition area to promote its photovoltaic manufacturing equipment, including the cell assembler. The videotape of the assembler (described previously) was presented publicly for the first time, and it generated considerable interest among the attendees.

Cheryl Keith and Jack Waite from AstroPower, Inc. (Newark, DE) visited Spire in May and reviewed the operation of the assembler. Preliminary soldering trials were done with nonfunctional 12.5 cm monocrystalline Si cells. They plan to send additional cells for further evaluations.

Spire has also been working in cooperation with engineers at Siemens Solar Industries (Camarillo, CA). Jean Hummel of SSI visited Spire in May to evaluate the operation of the assembler in a trial run. Approximately 1000 SSI cells (325 μ m thick by 103 mm square) were processed into 12-cell strings. Data was obtained on system throughput, yield, solder joint quality, and machine reliability. This testing complements the preliminary processing evaluation task Spire is doing with Solec cells.

An abstract for a paper describing the work being done in this program was written and submitted to the First World Conference on Photovoltaic Energy Conversion which will be held December 5 to 9, 1994, in Waikoloa, HI. This major PV conference combines the IEEE Photovoltaic Specialists Conference (United States), the Photovoltaic Science and Engineering Conference (Japan), and the Photovoltaic Solar Energy Conference (Europe). The title of the abstract is "Advanced Automation Techniques for Interconnecting Thin Silicon Solar Cells."

SECTION 3 CONCLUSIONS

As part of the PVMaT Phase 3A project, Spire and its team members are working on a program titled "Automated Solar Cell Assembly Teamed Process Research." The team members include lower-tier subcontractors Solec International, a PV module manufacturer, and the University of Massachusetts Lowell's Center for Productivity Enhancement, automation experts.

The program objective is to develop high yield, high throughput, fully automated processes for tabbing and interconnecting thin silicon solar cells. More specifically, the goals are to process cells at a rate (4.0 s/cell) that is twice as fast as current systems, to significantly reduce the labor required by combining tabbing and interconnecting into a single automated process, and to handle cells fabricated from much thinner silicon wafers (200 μm) than current systems can handle with high yield.

Highlights of this reporting period are as follows:

Task 13 - In-Line I-V String Testing - The design and initial bench testing of the in-line I-V tester were completed. Major activities included the development and testing of the xenon lamp power supply and the electronic load and measurements system. Tests show that the lamp pulse forming network produces a stable light pulse with a flat peak of 7 to 8 ms, more than adequate for the 3 ms measurement period. Electronics and software have been developed for sweeping the I-V curve, acquiring 100 I-V data pairs from I_{sc} to V_{oc} from the string under test, and acquiring I_{sc} data from a calibrated reference cell. Lamp intensity measurements showed that the lamps produce two to three suns through the spectral filters and the glass test stage. Wire mesh filters were tested and one was selected and installed to correct the intensity to one sun (100 mW/cm^2) at the test plane.

Task 14- System Integration and Test - Integrated systems for power, controls, and pneumatics were designed, installed, and tested in this reporting period. A main power distribution box, various electronic chassis, and an operator control panel were installed and wired. Three compressed air distribution manifolds, one for each structural frame, were installed and air lines were connected to the system subassemblies. Operator interface software has been developed in Visual Basic which provides a graphical mouse-driven user interface. Five emergency stop buttons have been installed around the perimeter of the system for operator safety. Software has been written for 21 different alarm conditions that will sound an audible alarm and provide a message on the computer monitor to identify the source of the alarm.

Task 15 - Preliminary Processing Evaluation - Preliminary processing evaluations were done at Spire using both 200 μm thick cells from Solec and 325 μm thick cells from Siemens Solar. Improvements were made in the cell loader vacuum pick-up and the optical stack height sensors for more reliable cell loading. A white shutter was added to the cell aligner stage to allow the vision system to detect cell edges. A vacuum chuck which is transparent to the vision system was devised and installed to prevent cell motion during pick up by the aligner manipulator. Cell placement accuracy was measured and found to be on the order of $\pm 0.018"$, approximately three times worse than expected. The repeatability of the mechanisms for both the aligner and the conveyor belt were measured to be less than $\pm 0.001"$. Work is ongoing to

determine the cause of the cell placement error, which apparently lies in the vision system software.

Improvements were made to the ribbon reels and end-of-ribbon sensors. Ribbon straighteners were added to handle stiff ribbon material properly. Tab position accuracy was increased by improving the ribbon guide design and reducing the open area of the conveyor belt vacuum platen. A no-clean flux (Kester 920-CXF) was evaluated which does not stick the ribbon to the tooling, allows good solder joints to be produced, and leaves no greasy residue. A soldering process with a 3.2 s cycle time is producing solder joints with good pull strengths. The string transfer mechanism has been completed with the installation of the vacuum pump, vacuum breaking valve, and compliant vacuum pick-up pads. Individual vacuum shut-off valves and vacuum switches have been added to each pick-up. A carrier stop was designed and installed on the string array table to provide a fixed location for the carrier on which cell strings are placed.

A trial run was done in May with approximately 1000 Siemens Solar cells. Cell yield (97.5%) and throughput (5 s/cell) were good, considering that the processes and sequencing were not fully optimized. Thirty 12-cell strings were laminated to produce ten 36-cell modules. The modules passed environmental tests at Siemens, including damp heat soaking, thermal cycling, and humidity-freeze cycling. These tests are important for qualifying the long-term reliability of modules made using the fluxing and soldering processes developed in this program.

Task 17 - Information Dissemination - Spire is actively disseminating information on the work done in this program to the PV industry. Spire attended and exhibited at two conferences and exhibitions, Soltech '94 (Jacksonville, FL, February/March, 1994) and the 12th European PV Solar Energy Conference (Amsterdam, Netherlands, April, 1994). Spire personnel met with representatives from several PV companies during this period for discussions on the assembler, including Siemens Solar, Solarex, Texas Instruments, Solec, and AstroPower. Videotape of the assembler in operation was recorded and delivered to NREL in April. Color photographs, slides, and cell strings were also provided to NREL for display purposes. An abstract for a paper describing the work being done in this program was written and submitted to the First World Conference on Photovoltaic Energy Conversion (Waikoloa, HI, December, 1994).

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