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Subcontractor Report

Post-Lamination Manufacturing Process Automation for Photovoltaic Modules

Final Subcontract Report April 1998—April 2002

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Spire Corporation
Bedford, Massachusetts

National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, Colorado 80401-3393

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Spire Corporation
Bedford, Massachusetts

NREL Technical Monitor: Ed Witt

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1 INTRODUCTION

This is Spire Corporation's Final Technical Report for a program entitled "Post-Lamination Manufacturing Process Automation For Photovoltaic Modules." This program was made possible by funding from the U. S. Department of Energy under National Renewable Energy Laboratory (NREL) subcontract No. ZAX-8-17647-04. The period of performance was from April 1998 to April 2002.

This program was part of Phase 5A2 of the Photovoltaic Manufacturing Technology (PVMaT) project. The Technical Monitoring Team members were Dr. Ed Witt (NREL), Dr. Martha Symko-Davies (NREL), Mr. Michael Quintana (Sandia National Laboratories), and Mr. Steve Rummel (NREL).

1.1 Objective

Spire addressed the PVMaT project goals of photovoltaic (PV) module cost reduction and improved module manufacturing process technology. New cost-effective automation processes were developed for post-lamination PV module assembly, where post-lamination is defined as the processes after the solar cells are encapsulated. These processes apply to both crystalline and thin film solar cell modules. Five main process areas were addressed:

- Module buffer storage and handling between steps
- Module edge trimming
- Module edge sealing and framing
- Junction box installation
- Testing for module performance, electrical isolation, and ground path continuity

An industry survey conducted as part of this program showed that most PV module manufacturers use little or no automation for these post-lamination processes. A typical manual process sequence is shown in Figure 1. The development and implementation of automated systems are expected to result in significant labor cost savings, improved product quality, and increased throughput. A reduction in the occurrence of repetitive stress injuries may also be achieved by eliminating product lifting and manual edge trimming tasks.

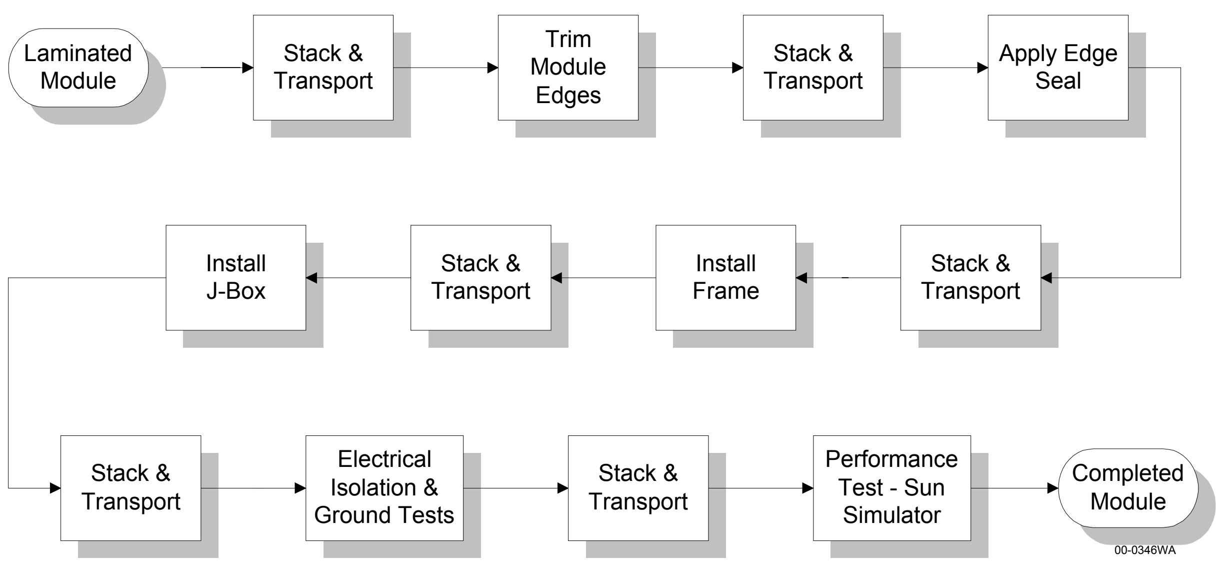

Figure 1 Typical manual process sequence for post-lamination module manufacturing.

1.2 Approach

A three-phase program resulted in the development and demonstration of new automated systems for post-lamination PV module manufacturing processes. The systems are (1) a module buffer storage system, including conveyor loading/unloading and module storage, (2) an edge trimming system, (3) an edge sealing and framing system, (4) a junction box installation system, and (5) an integrated module testing system that combines electrical isolation testing, ground continuity testing, and module performance testing. These systems were designed to be combined to form an integrated production line, as shown in Figure 2.

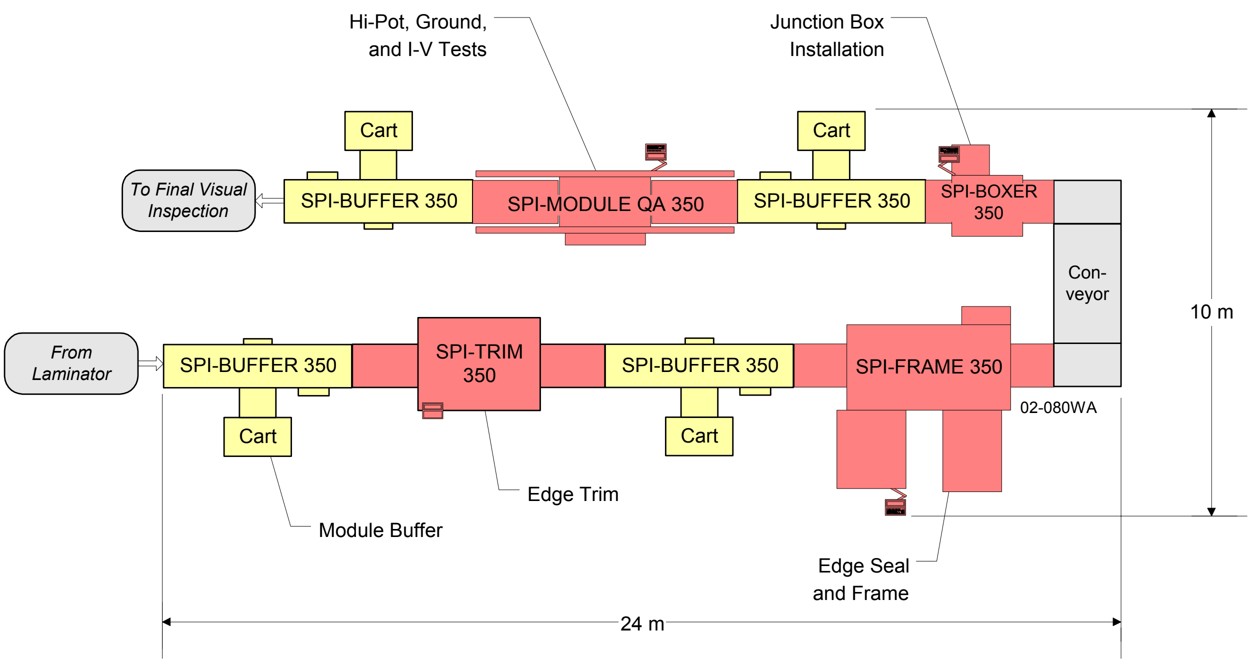

Figure 2 Automated line for post-lamination module manufacturing.

The program tasks are listed by phase in Table 1. As the prototype automation systems were developed, they were evaluated with module components from several module manufacturers.

Table 1 Program tasks.

Phase	Task
1 - April 98 to June 99	1 - Design Definition 2 - Develop Buffer System 3 - Edge Process Development 4 - Develop Integrated Test System
2 - June 99 to July 00	5 - Design Integrated Edge Process System 6 - Initial Fabrication of Integrated Edge Process System
3 - July 00 to April 02	7 - Fabricate and Integrate Edge Framer System 8 - Junction Box Process Development 9 - Develop Junction Box Installation System

Spire assembled a team for implementing this program that includes several major US module producers and the Automation & Robotics Research Institute (ARRI) at the University of Texas at Arlington (UTA). Program team members and their responsibilities are outlined in Figure 3.

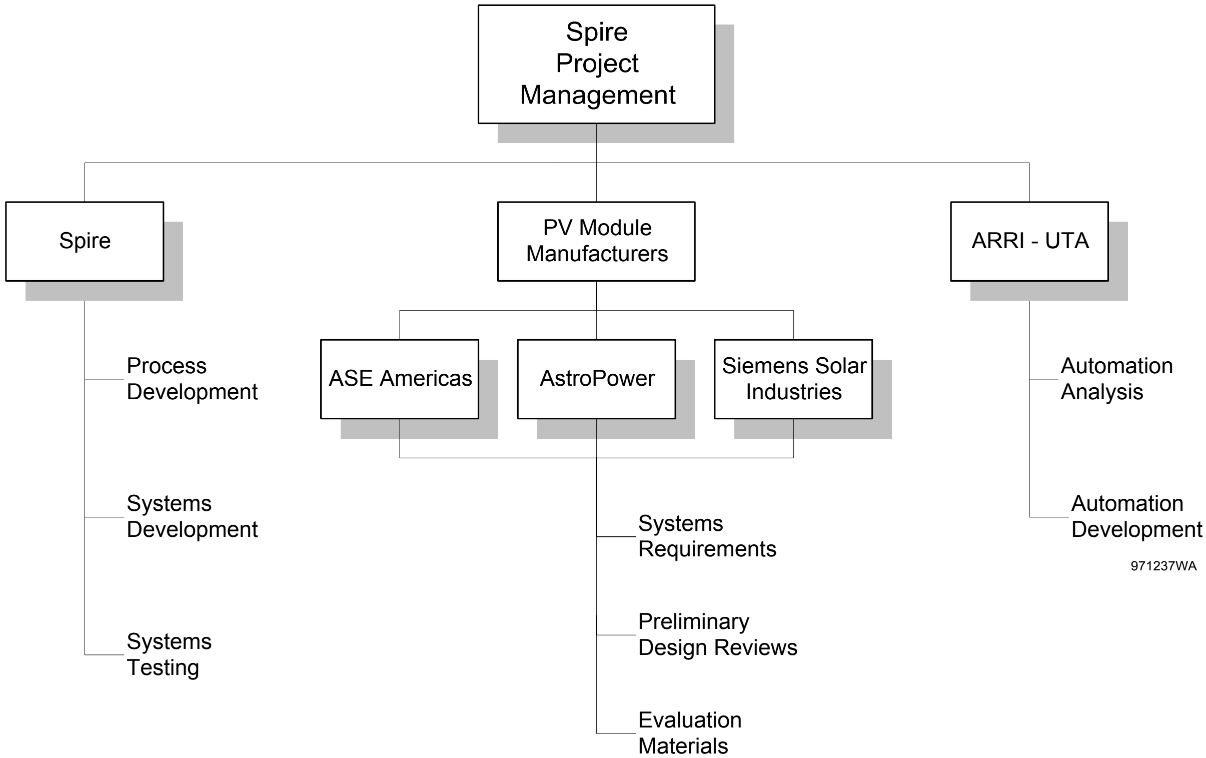

Figure 3 Program organization, Spire PVMaT Phase 5A2.

Major US module manufacturers that teamed with Spire in this effort include ASE Americas, Billerica, MA; AstroPower, Inc., Newark, DE; and Siemens Solar Industries, Camarillo, CA. These and other PV manufacturers provided information on their production requirements and feedback on Spire's systems designs. They also provided solar cell laminates and other module materials, which Spire used to evaluate the automated processes developed in the program.

2 TECHNICAL DISCUSSION

2.1 Task 1 - Design Definition

Activities completed under Task 1 include a survey of photovoltaic module manufacturers regarding post-lamination module processing and the development of a cost justification model to quantify the benefits of automation for these processes.

Spire, NREL, and ARRI met with PV module manufacturers ASE Americas, AstroPower, Siemens Solar Industries (now Shell Solar) and Solarex (now BP Solar) at the National Center for Photovoltaics (NCPV) Program Review Meeting in Denver, CO, in September, 1998, to discuss module manufacturing and automation as it relates to this program. The manufacturers were quite open in discussing their module designs and post-lamination processes, and they agreed to send sets of module components (untrimmed laminates, edge sealant, frames, junction boxes, and fasteners) to Spire. These components, along with the survey data we collected, provided valuable input for our automation design and development activities. After the survey was completed, a design definition document was written that defined the capabilities and specifications of the automation systems and provided guidance for the detailed engineering and design work completed in the development of these systems.[1]

2.1.1 Survey of PV Module Manufacturers

Spire conducted a survey of US and foreign module manufacturers to identify industry needs and practices for post-lamination module processing. This information was compiled and used to define the requirements for the new automated systems developed in this program.

A survey questionnaire was formulated with questions in nine categories: module process sequence, facility requirements, module characteristics, product tracking, buffer storage, module edge processing, junction box assembly, module testing, and module labeling. The questionnaire was delivered to twenty major PV module manufacturers in the US, Europe, Japan, and Australia. Completed questionnaires were received back from nine companies, including seven in the US. These companies collectively produced 45 MW of PV shipments in 1997, approximately 36% of the world market at that time.[2]

Individual company responses were kept confidential and pooled with the responses from other companies to create an industry profile. Spire delivered a survey report[3] to NREL and a paper based on this data was presented in September, 1998, at the NCPV Program Review Meeting.[4]

Module assembly and testing processes were found to be similar among the manufacturers. Processes done by 75% or more of the respondents include module edge trimming, edge sealing, framing, junction box installation, tracking, labeling, and storing between processes. Testing done by 75% or more of the respondents includes performance (I-V) measurement, electrical isolation (hi-pot) test, and a ground continuity test. While the processes are similar, the process sequences varied from manufacturer to manufacturer. It was concluded that the automated processes must be modular so they can be done in any order.

Spire engineers visited seven US PV manufacturers for detailed discussions on their needs for post-lamination process automation. The manufacturers were ASE Americas (Billerica, MA), AstroPower (Newark, DE), BP Solar (Fairfield, CA), Evergreen Solar (Waltham, MA), Siemens Solar Industries (now Shell Solar, Camarillo, CA), Solarex (now BP Solar, Frederick, MD), and Solec International (Carson, CA).

The site visits and survey responses identified some module assembly and testing practices that had an impact on our automation design, including the following:

- All modules that are Underwriters Laboratory (UL) listed must pass both a hi-pot test and a ground continuity test.[5] We had initially planned to include a hi-pot test in the integrated test system, but not a ground continuity test. We added a ground continuity test capability to the hi-pot test station to meet the UL requirement.
- Some manufacturers do hi-pot and ground continuity tests immediately before measuring module performance with a sun simulator. This sequence allows integrating these three tests into one station, which was our original plan. However, others measure module performance before framing the module, and do the hi-pot and ground continuity tests after framing. Therefore, we designed the integrated tester with two separate operations, one for hi-pot and ground continuity testing and one for module performance measurements, to provide the flexibility to accommodate either process sequence.

2.1.2 Cost Justification Model

A cost justification model was developed by ARRI to quantify the benefits of automating the post-lamination module assembly and testing processes. ARRI personnel visited Siemens Solar and ASE Americas to gather manufacturing data on these processes. A generic model of operational costs was constructed from this data. The cost justification model used the Total Cost Minimum Annual Revenue Requirements approach to compare the cost of manual vs. automated module manufacturing. The model assumed a 5 MW per year production level on a single shift (40 hours per week) basis. Additional assumptions for the baseline case are listed in Table 2.

Table 2 Assumptions for cost justification model, baseline case.

Parameter	Value
Cost of capital	18.6%
Depreciation period - straight line	5 years
Pay back period	5 years
Tax rate	34%
Burdened labor rate	$30/hour
Module output per shift	5 MW/year

A summary of the model results is provided in Table 3. The model showed that there is $1.19 million of cost justification for automation in the post-lamination module processes when operating on a one shift per day, 5 MW per year basis, and $2.37 million on a two shift per day, 10 MW per year basis.

Table 3 Summary of cost model results.

	Cost Justification ($)		
Process	1 shift/day	2 shifts/day	Cost Savings
Edge trim with buffer	158,370	316,740	Reduced labor
Edge seal & frame with buffer	540,789	1,081,578	Reduced labor & material cost
J-box install with buffer	158,370	316,740	Reduced labor
Integrated tests with buffer	329,582	659,164	Reduced labor
Total	1,187,111	2,374,222	Reduced labor & material cost

Sensitivity analyses were done to examine the effects of the cost of capital, the pay back period, the cost of labor, and the number of operating shifts per day on the amount of capital equipment that can be justified. A detailed report on the model was prepared by ARRI for Spire and delivered to NREL.[6]

Automation can provide additional benefits that were not considered in the cost justification analysis because they are difficult to quantify. These include a reduction in the risk of repetitive stress injuries for edge trimming and module lifting tasks, and an ability to handle large area modules that are difficult for a single operator to handle.

2.1.3 Module Throughput Analysis

A key factor for justifying automation is cycle time, the amount of time a system takes to process a module, because it has a direct effect on production capacity. Spire did a module throughput analysis to determine the annual module production capacity as a function of cycle time and module power. The analysis assumed a one shift, 40-hour/week operation, 90% equipment uptime (i.e., 10% downtime allowance for adjustments and maintenance), and 99.7% yield for the processes after lamination. Annual throughput (MW) was calculated as a function of module power (W) for three cycle times: 60, 90, and 120 seconds/module. The results are shown in Figure 4. As expected, shorter cycle times and higher module power result in greater production capacity.

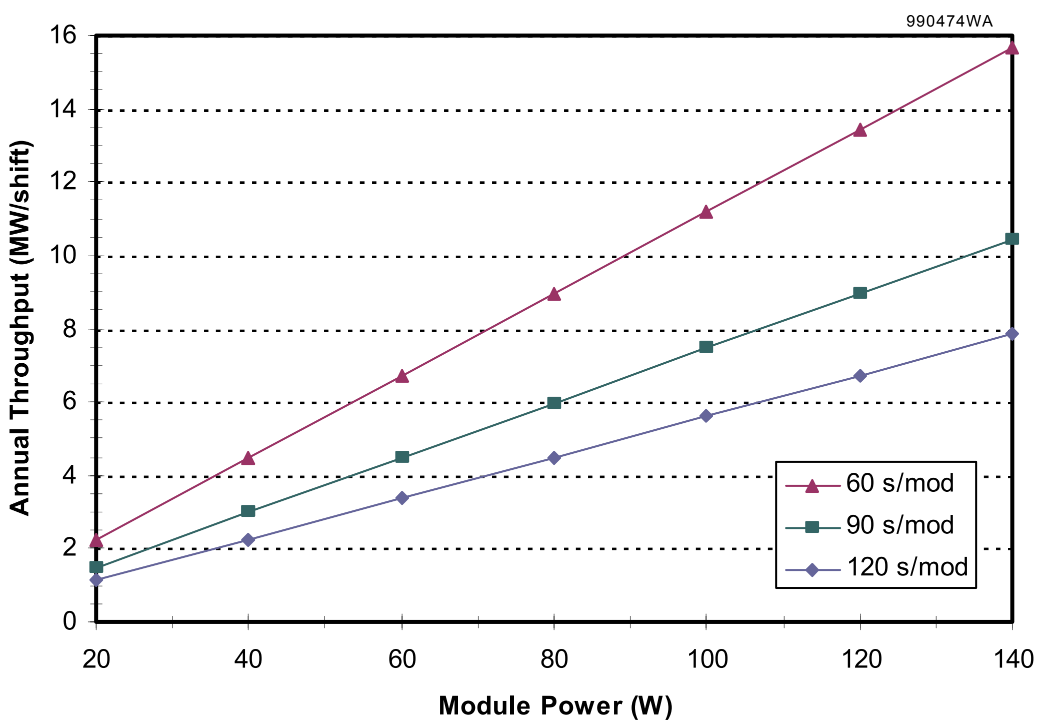

Figure 4 Annual module production capacity vs. module power for three cycle times on a single shift basis.

2.2 Task 2 - Develop Buffer System

Spire evaluated several buffer storage concepts for automatically transporting, storing, and retrieving laminates and framed modules between process steps. A vertical stacker concept was selected for detailed design and prototype fabrication, based on the simplicity of the mechanical design, the high density of storage, and the ability to use simple mobile storage carts.

2.2.1 Buffer Concept Comparison

Six alternative buffer storage concepts were identified. All of these concepts use conveyor loading and unloading for fully automated operation, and all allow product pass-through without storage to maximize throughput when the downstream process is available. They are all last in, first out buffers. The six concepts are:

- In-line elevator
- Off-line elevator
- Rotary storage
- Vertical stacker
- Pick & place onto pallet (horizontal stacker)
- Pick & place onto shelves

In-Line Elevator - In this concept, a number of empty shelves are stored below a roller conveyor. When product storage is desired, the conveyor stops when the product is at the proper position and a shelf passes through the conveyor to lift the product up above the conveyor surface. The shelf spacing must be designed to allow sufficient space between shelves for subsequent product to pass through on the conveyor. This approach uses the least amount of factory floor space of any of the six storage concepts.

Off-Line Elevator - This concept is similar to the previous concept except that a transfer conveyor moves product at a 90° angle from the main conveyor to load and unload an elevator. This design is slightly more complex than the first concept, due to the added transfer conveyor, but there is greater access to the product and to the buffer itself.

Rotary Storage - In this concept, a series of radial arms extends from a pivot point. A rotary motion moves the arms through the conveyor to lift product up for storage. While the mechanism for this storage concept is simple, the storage capacity is quite low, especially for wide modules, since the space between modules increases along the length of the arms.

Vertical Stacker - The vertical stacker uses vacuum cups to grip the bottom surface of the product. The cups are mounted on arms that lift the product, rotate it slightly beyond 90°, and place it on a pallet or cart that has a vertical support. The first product leans against the support, while subsequent product leans against previously loaded product. Since no shelves are used, the packing density and the resulting storage capacity are high. Simple, mobile carts can be used for low-cost storage. This approach cannot be used if the product is an unframed module with a junction box, since the product is not flat.

Pick-and-Place Onto Pallet - A two-axis pick-and-place mechanism with vacuum cups moves product from a conveyor to a pallet or cart. The mechanism produces a horizontal stack of product. Like the vertical stacker, no shelves are used, so the packing density and the resulting storage capacity are high. Simple, mobile carts can be used for low-cost storage. This approach cannot be used if the product is an unframed module with a junction box, since the product is not flat.

Pick-and-Place Onto Shelves - This concept is similar to the previous one, except the two-axis pick-and-place mechanism places product onto shelves to allow the flexibility to handle all types of product. The storage capacity is not as high as in the previous concept, but simple shelves on casters can be used for low-cost, mobile storage.

Ten criteria were identified for comparing the attributes of each buffer concept. These criteria were applied to the six buffer concepts to obtain comparative ratings. The criteria are:

1. Storage capacity and density (number of modules per storage unit)
2. Complexity of motions: pneumatics, hydraulics, electric motors and their controls
3. Complexity, size, and mass of structural framework
4. Estimated cost (rough order of magnitude)
5. Facilities requirements: electricity, compressed air
6. Factory floor footprint
7. Operator access for manual load/unload of product
8. Portability/mobility of stored product
9. Potential for damage to product
10. Flexibility to handle framed and unframed modules, with and without junction boxes

The ten criteria were rated on a scale of 0 to 4, with 0 being poor and 4 being excellent, for each of the six buffer concepts, as shown in Table 4. An average rating was calculated for each buffer concept, assuming that each of the ten criteria have equal weight.

Table 4 Storage buffer comparison.

Storage Concept	1 Storage Capacity	2 Simple Motions	3 Simple Structure	4 Low Cost	5 Simple Facilities	6 Small Footprint	7 Product Access	8 Product Mobility	9 No Damage	10 Product Flexibility	Average Rating
1 In-Line Elevator	2	4	3	4	4	4	0	0	4	4	2.9
2 Off-Line Elevator	2	3	3	3	3	3	3	1	4	4	2.9
3 Rotary Storage	0	4	3	3	4	3	0	0	4	4	2.5
4 Vertical Stacker	4	3	2	3	3	3	4	4	2	1	2.9
5 Pick & Place on Pallet	4	3	3	3	3	3	4	4	2	1	3.0
6 Pick & Place on Shelves	2	3	3	3	3	3	3	4	4	4	3.2

Rating scale: 0 = Poor, 1 = Fair, 2 = Average, 3 = Good, 4 = Excellent

Concept 6, pick and place on shelves, achieved the highest average rating in Table 5, while concept 3, rotary storage, was the lowest. Given the low storage capacity of concept 3, this approach was rejected. Surveys and site visits indicated that an operator often stores product manually either in vertical stacks or horizontally, on shelves, analogous to concepts 4 and 6. Mobile storage in carts was seen to be an advantage by most manufacturers. Elevator storage designs (concepts 1 and 2) do not allow for mobile storage, due to the mechanized nature of the elevator. For these reasons, concepts 4 and 6 were selected for more detailed engineering study.

Work was completed on top-level designs, including preliminary layout drawings and process sequences, for concepts 4 and 6. The main components of the shelf buffer system (concept 6) are a conveyor for transporting modules, one or more module storage carts with shelves, and a carriage with grippers and actuators in x (horizontal) and z (vertical) directions for transporting modules from the conveyor to the cart and back.

The transport carriage can use either mechanical grippers or vacuum cups for holding the module. The carriage is supported by linear rails with ball bushings in both x and z axes. The carriage height (z axis) is controlled by a motor driven belt that is programmed to pick and place modules at the conveyor height and at the height of each shelf in the cart. A pneumatic actuator moves the carriage between the conveyor and the cart (x axis) since only two positions are required in this direction.

The main components of the vertical stacker buffer system (concept 4) are a conveyor for transporting modules, one or more module storage carts for holding modules in vertical stacks, and a rotating pick-and-place mechanism for transferring modules from the conveyor to the cart and back.

Carts with casters provide flexibility and mobility for stored product. Laminates or framed modules are stored in a vertical stack with high density, since there are no shelves or dividers to space the modules apart. This design works well with flat product, but it is not suitable for uneven product, such as a module with a junction box and no frame.

During the cart loading sequence, a module is first aligned on the conveyor and then a linear electric cylinder retracts, causing an arm to rotate about a pivot point. Four vacuum cups on the arm grip the module's bottom surface. The arm rotates 100° to carry the module 10° beyond vertical, parallel to the module supports in the cart. A pneumatic cylinder extends to press the module gently against the cart (or against previously placed modules in the cart), after which another cylinder retracts to lower the module down to the floor of the cart.

An engineering comparison of the two top-level designs indicated that the vertical stacker buffer design is simpler and lower cost to produce than the pick-and-place on shelves design. The vertical stacker's storage carts are also simpler and lower cost, and they have a higher storage density because there are no shelves. Thus the vertical stacker concept was selected for detailed design and prototype fabrication.

2.2.2 Buffer Development

Spire developed detailed mechanical, pneumatic, electrical, and software designs for the vertical stacker type of storage buffer. The main buffer subsystems are a conveyor for transporting modules into and out of the buffer, a module aligner for locating a module in the proper position before lifting it from the conveyor, one or more module storage carts for holding modules in vertical stacks, a rotating pick-and-place mechanism for transferring modules from the conveyor to the cart and back, and electrical, pneumatic, and software controls. The design is shown in Figure 5.

Mechanical assembly drawings, detail drawings, and bills of material were created and reviewed, and parts were released for fabrication and procurement. The buffer was designed to handle modules from a minimum of 30 cm x 91 cm (12" x 36") to a maximum of 102 cm x 162 cm (40" x 64"). Based on this size (approximately 3 ft x 5 ft), the system was designated the SPI-BUFFER™ 350. Each cart has 51 cm (20") of storage depth, equivalent to 10 framed modules with a frame depth of 5.1 cm (2.0") or 100 laminates with a thickness of 5.1 mm (0.2").

Electrical controls and sensors were selected and wiring schematics were created. A small programmable logic controller (PLC) with digital input and output (I/O) modules was selected to control the buffer. Analog I/O was avoided to minimize cost. Operating software in the PLC was programmed in relay ladder logic.

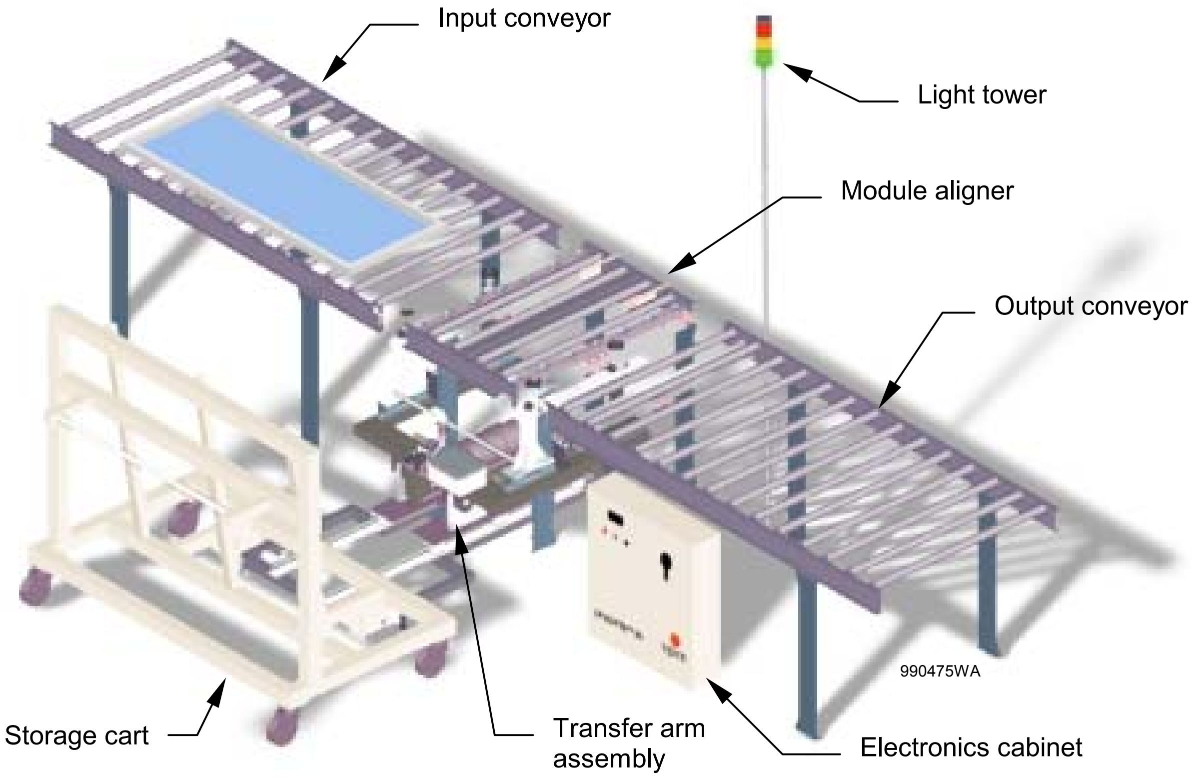

Figure 5 Automated vertical stacker buffer storage system.

A light tower with red, yellow, and green lights was provided to indicate machine status. The buffer has six main states: run, reset, automatic pause, manual pause, error, and emergency stop. Colors were assigned for each state as listed in Table 5. These color codes are in compliance with the European standard for safety of machinery, EN 60204-1, required for machines sold into the member countries of the European Union.[7]

Table 5 Color code for machine status indicator lights.

Machine Status	Color
Emergency Stop	Red
Error	Yellow flash
Pause, manual	Yellow
Pause, automatic	Yellow and green
Reset	Green flash
Run	Green

The automatic control system uses sensors for sequencing, for preventing collisions, and for verifying normal machine operation. When a sensor indicates an error condition, the machine is set to the error state, the light tower displays a flashing yellow light, and an error code is displayed on a two-digit LED display on the control panel. The error code assists in diagnosing the cause of the error condition. Approximately 20 different error codes were identified and programmed.

An emergency stop push button and cable were provided for operator safety. Either the button or the cable can be used to interrupt machine operation if a situation occurs that is hazardous or may cause damage to the equipment or modules. The cable surrounds the three conveyor sections. When the cable is pulled or the button pressed, power is cut to both the conveyor motor and the transfer arm motor and compressed air is vented from the pneumatic system. Vacuum is maintained to prevent modules from falling from the transfer arm. This reduces the chance of module breakage or operator injury from a falling module. After correcting the emergency stop condition, a reset button may be pressed to initiate the reset mode to return the buffer to its normal run state.

An electrical interface standard used by the Surface Mount Equipment Manufacturers Association (SMEMA) was selected to provide a standardized means for the buffer to communicate with upstream and downstream automation.[8] The SMEMA interface standard defines a protocol for electrical signals used for transferring product between machines. These signals allow local control, independent of a supervisory controller. This standard was incorporated into all of the automated systems developed in this program, allowing processes to be done in the order desired by the manufacturer, and allowing buffer systems to be inserted or removed at any point in a production line, as needed.

Assembly work on the prototype buffer was completed in April, 1999, including the assembly of mechanical, electrical, and pneumatic systems. A photo of the completed system is shown in Figure 6.

Figure 6 Completed SPI-BUFFER 350 during process evaluations.

Processes were demonstrated for the reset mode and three run modes: (1) aligning and transferring modules from the input conveyor to the storage cart, (2) transferring modules from the storage cart to the discharge conveyor, and (3) passing modules through, without storing in the cart. The specific run mode was determined automatically by the states of upstream and downstream automation, which was simulated by providing appropriate signals to the SMEMA connections.

Cycle times were measured prior to process optimization. The cycle time for cart loading, which includes module alignment, was measured at 72 s, while cart unloading was measured at 60 s. The motor speed on the lift arm was increased and a number of sequencing changes were made in the software. As a result, the cycle times for both loading and unloading were reduced to approximately 47 s. These cycle times include approximately 150 cm of conveyor travel at a speed of 20 cm/s, which takes 7.5 s. At this speed, and given the 409 cm total length of the conveyor system, a module takes approximately 20 s to pass through the buffer without storage.

2.3 Task 3 - Edge Process Development

After module lamination, the laminate edges are trimmed, a sealant is applied to the edges, and a frame is installed. The edge trimming process removes excess encapsulant and back cover film from the module laminate edges and disposes of the excess material. The edge sealing process applies a sealant around the module edges by dispensing a bead of sealant in a channel in each module frame section. The sealant bead approach was selected over an edge tape sealant method due to lower sealant material cost and suitability to automation. The frame sections are attached to the module and joined at the corners with fasteners. An illustration of the edge processes is provided in Figure 7.

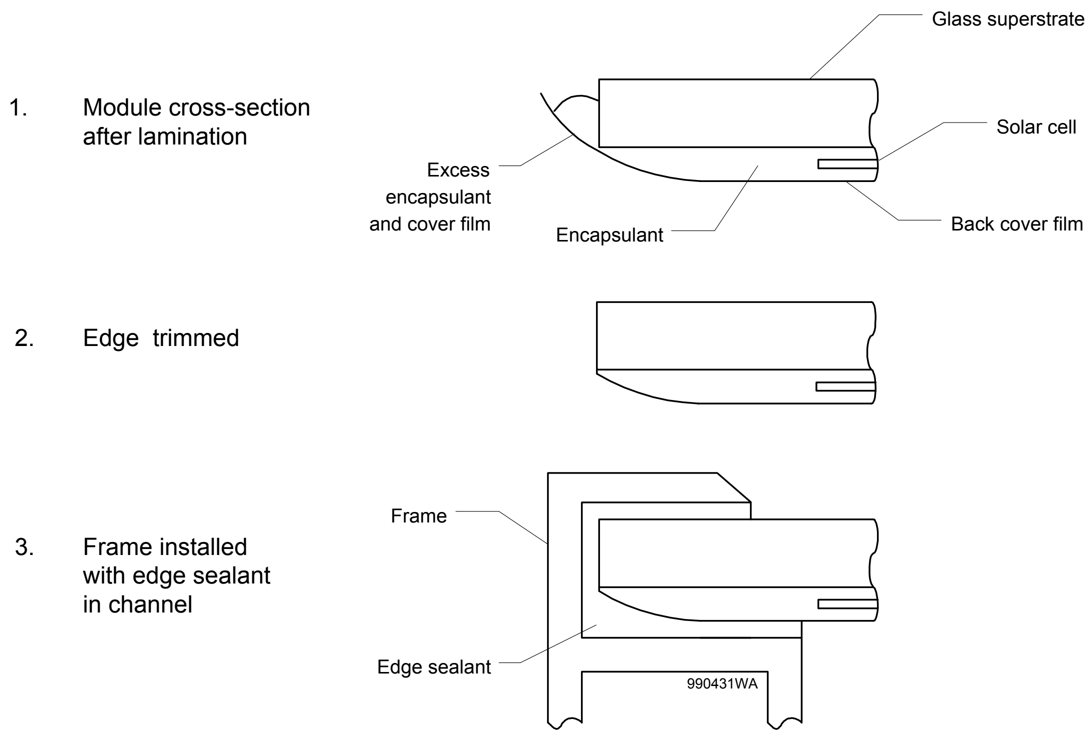

Figure 7 Module edge cross-sections after lamination, trimming, sealing, and framing. Not to scale.

ARRI developed and demonstrated module edge trimming, edge sealing, and framing processes that were designed for automation. Concepts for implementing these processes in production were defined. These concepts provided a solid basis for the prototype automation development work completed by Spire later in the program.

2.3.1 Edge Trimming Process Development

Excess encapsulant and back cover film extend beyond the glass edges after lamination, as shown in Figure 7. This material must be removed prior to applying an edge sealant. It became evident early in the development of the trimming process that two key areas must be addressed: edge sensing and edge trimming.

It is necessary to find the position and orientation of the glass edges prior to executing an automated trimming sequence. Both mechanical alignment and contact probing were considered but ruled out because of variations in the amount of encapsulant and back sheet that hangs over the glass edge. A non-contact photoelectric sensor was evaluated for finding the glass edge. The sensor emits a beam of red light and measures the intensity of the light that is reflected back from the laminate. An intensity threshold can be set to trigger a digital output when the reflected light crosses the threshold.

Glass edge sensing tests were done at ARRI with laminates made at Spire. The laminates consisted of a 3.2 mm (1/8") thick x 305 mm (12") square glass superstrate, ethylene vinyl acetate (EVA) encapsulant, and white Tedlar® back sheet.[9] This construction is typical for the PV industry. The glass edges were swiped prior to lamination, as is customary, to remove the razor sharp edge left when the glass is cut. Swiping is done by sanding or grinding the glass to produce a slightly beveled edge. Tests showed that the sensor could reliably detect the transition between the flat surface of the glass and the glass edge.

Given the red color of the light used by the optical sensor, there was a question as to whether the sensor could see the glass edge if the module had a dark blue back cover instead of a white one. ARRI tested the sensor on a Solarex module with a dark blue back cover and found that the sensor worked adequately. The color of the back surface had a definite effect on the sensor signal, but sufficient change in the reflected light was observed to detect the glass edge.

ARRI developed the edge sensing process on an Adept robot platform. An end effector was fabricated to mount the optical sensor on the end of the robot arm. Spire laminates with untrimmed edges were placed face down, in the same orientation as the lamination process, which eliminates the need to turn them over. The following procedure was developed to determine the position of the glass:

1. A module is placed at a work cell at a nominal location, and the robot moves the sensor's light beam across the module edges to find eight edge points, two per side.

2. An equation of a line defining each side of the glass is calculated from each pair of edge points found along a common side.

3. The location of each glass corner and the lengths of each side are determined by calculating the intersections of the lines.

4. Error checking is done to verify that the length of each side is correct and that the angle at each corner is 90°, within selected tolerances.

ARRI evaluated four different cutting technologies for edge trimming: spinning saw, laser, hot wire, and hot knife. The main objective was to produce a good quality cut at a speed that can achieve a cycle time of one minute per module. The Spire laminates with untrimmed edges used for the edge sensing tests were also used for the edge trimming tests.

2.3.1.1 Spinning Saw Trimming

A prototype module trimming system was set up by attaching a motor with a slitting saw blade to a robot arm, as shown in Figure 8. An optical sensor for finding the glass edge was installed on the robot arm, below the saw blade. The edge sensing method described previously was used to find the glass edge and calculate the cutting path.

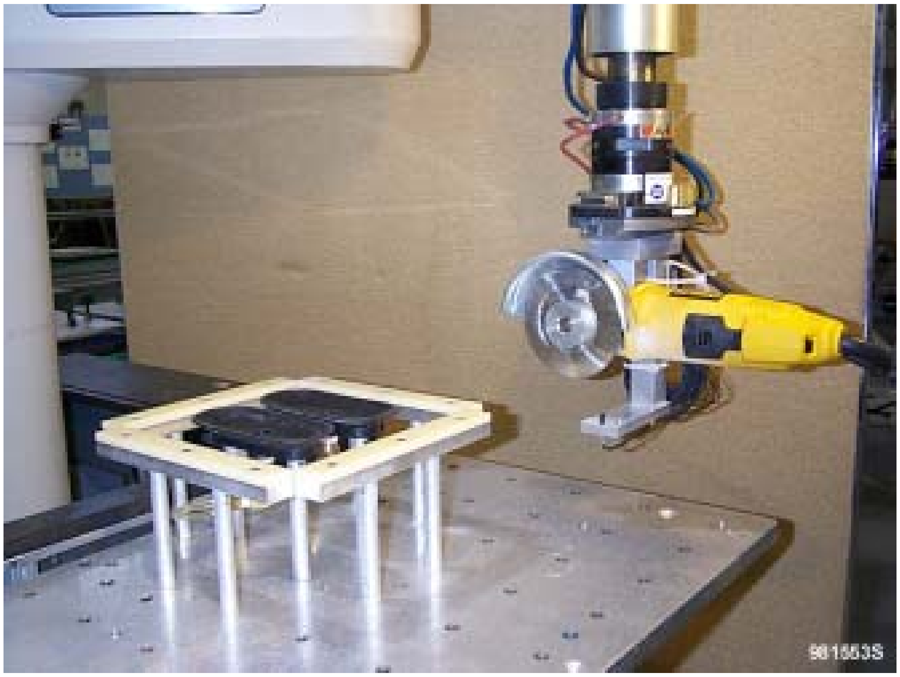

Figure 8 Spinning saw prototype setup for module trimming.

A vacuum stage, shown in Figure 8, was designed and built to hold modules securely in a face down orientation during trimming. The stage allows access to the module edges for the optical sensor, which looks up at the glass from below, and for the cutting blade.

Testing showed that the spinning saw method can provide an adequate cut finish at the required trimming rate. Three different blade thicknesses were tried. The best quality cuts were made with a 2.0 mm wide blade with chip relief. The finish of the cut material was found to be a function of traverse speed. Good finishes were obtained at 6.4 cm/s, while at 13 cm/s, the speed needed to obtain the desired throughput, the finish was fair, with increased surface roughness. At higher speeds, the saw tended to tear the material instead of shearing it, resulting in a poor finish.

Three disadvantages were identified for the spinning saw technique. First, it was observed that when the EVA did not extend past the edge of the glass, the blade bent the protruding Tedlar instead of cutting it, making this approach unsuitable for trimming modules without EVA overhang. Second, significant amounts of EVA and Tedlar debris were generated by the cutting action. The debris would require an extra cleaning process for modules. Third, if there is a sensor error that causes the blade to contact the glass, the module will be seriously damaged. For these reasons, the spinning saw approach was rejected for the module trimming process.

2.3.1.2 Laser Trimming

Samples of EVA, Tedlar, and a laminated module with untrimmed edges were sent to a laser cutting shop for trimming tests. EVA was trimmed at a rate of 20 cm/s, exceeding the nominal production rate goal. The trimmed edges were only slightly rough and have an acceptable appearance.

The same laser was used to trim laminated modules. Good edge quality was obtained when the trim rates were below 2.5 cm/s, but a rate of 13 cm/s is needed to achieve the throughput goal. The laser shop suggested increasing the number of cutting beams to increase the throughput, but this would result in a significant cost increase for the laser system. Even with a single laser beam, cost is an issue. Compared to a hot knife, the laser cutting system is approximately 100 times the cost.

A further disadvantage of the laser system is the potential for module damage. An edge sensing error that results in positioning the laser beam inside the glass edge will damage the module, since the laser must deliver sufficient power to burn through the encapsulant and the back cover material. These three key barriers, low process throughput, high system cost, and potential for module damage, caused the laser approach to be abandoned.

2.3.1.3 Hot Wire Trimming

A prototype hot wire trimming system was designed, assembled and tested with module laminates at ARRI. The robotic arm, optical edge sensor, and module vacuum stage used for the spinning saw trials were used in these tests.

At the start of a cutting pass, the cutting action of the wire was very good. However, as the wire travels along the module edge, the material in the cutting area cools the wire. The remaining wire tends to overheat and the cutting action degrades significantly. As the cutting action degrades, the wire begins to yield and eventually breaks. At much lower speeds the cutting action of the hot wire is very effective. Unfortunately, the effective cut rate is less than 20% of the required rate.

Larger wires would likely be able to sustain greater resistance to the yield problem. However, as the wire diameter increases, so does the force required to move the wire through the material. Thus, the hot wire technology does not meet the production throughput requirements.

2.3.1.4 Hot Knife Trimming

A prototype hot knife trimming system was designed and assembled at ARRI, as shown in Figure 9. The robotic arm, optical edge sensor, and module vacuum stage used for the spinning saw and hot wire trials were used in these tests.

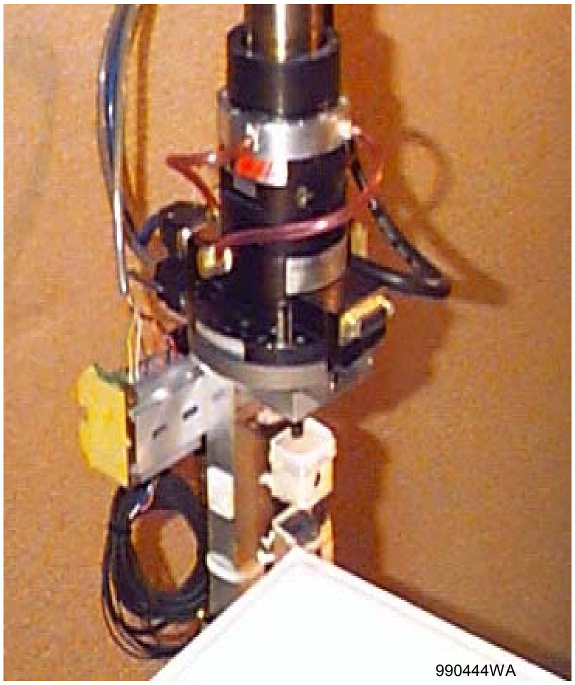

Figure 9 Hot knife prototype setup with graphite blade and untrimmed module.

The first hot knife trials were done with a graphite blade fabricated by ARRI. Edge trimming was more successful than with the hot wire due to the higher thermal capacity of the graphite blade. A good quality edge finish was achieved at a blade temperature of 340°C and a cutting speed of 6.4 cm/s. An acceptable edge finish could not be achieved at the desired throughput of 13 cm/s, however, even when the blade temperature was increased to 400°C.

Next a commercial hot knife was obtained that uses a variety of metal blades. Trials were done with various blade types, blade temperatures, and cutting speeds. A nominal offset of 1 mm was used between the glass edge and the cutting path to minimize blade wear.

Four different blade shapes were tested. One shape proved to be the most durable and also produced the best quality cuts. Cutting speeds from 13 cm/s to 23 cm/s produced good edge finishes. These speeds meet the production rate goal. Tests done at higher cutting speeds showed that the hot knife power supply could not maintain the blade temperature, and the cut finish deteriorated.

The maximum blade temperature was limited to 425°C, as specified by the knife manufacturer. At temperatures above 450°C, the blade starts to glow red and deforms easily. A temperature setting between 400°C and 425°C was sufficient to produce a good quality cut edge for cutting speeds between 3.6 cm/s and 23 cm/s.

Trimmed material (EVA and Tedlar) did not accumulate on the hot knife blade. The hot knife was able to cut through Tedlar when there was no EVA beyond the glass edge to support it, which the spinning saw could not do. Given the low cost of the hot knife system and the ability to achieve good quality trimmed edges at speeds that meet the production throughput requirements, the hot knife was selected as the best approach for the edge trimming process.

2.3.2 Edge Sealing and Framing Process Development

Automated processes were developed and demonstrated for sealing and framing the edges of trimmed modules. The sealant acts as an adhesive between the frame and the module edges and as a gasket to cushion the glass in the aluminum frame.

2.3.2.1 Sealing Process Research

Module frames typically consist of four extruded aluminum sections that are fastened together at the corners, either with sheet metal screws or corner keys. Corner keys reduce the amount of frame machining required, since a simple miter joint of identical frame sections is all that is needed. Frames assembled with screws require machining to remove the laminate channel at each corner, and drilling for clearance holes for the screws. Corner keys also provide a degree of self-alignment for the frame sections, which simplifies automation somewhat. Thus corner keys were selected for prototype process development.

The module edge sealing techniques that were evaluated include applying a foam adhesive tape to the laminate edges and dispensing a bead of sealant into a channel in the frame. Three classes of sealants were considered: RTV silicone, foam tape, and hot-melt adhesives, such as butyl rubber. A comparison of several of the sealant materials considered in this program is provided in Table 6. The butyl rubber sealant is the least expensive, at \$0.15 per module, while the foam tape is the most expensive, at \$2.50 per module, assuming a module perimeter of 274 cm (108 inch).

Table 6 Representative sealant materials considered for edge sealing.

Sealant	Features	Cure Time	Cost/Module
Dow Corning 733 Silicone RTV	One-part sealant; adheres to glass, metal, plastic, etc.	24 hours	$0.33
3M 4962 Foam tape, double sided adhesive	Closed cell neoprene foam, acrylic adhesive; adheres to aluminum, steel, plastic	None (pressure sensitive adhesive)	$2.50
H. B. Fuller HL Series Thermo-Seal Hot melt butyl	100% solids; designed for insulated glass industry; adheres to glass and aluminum	3 minutes	$0.15
Q'SO Inc. Q-17 Hot melt polymer blend	100% solids; designed for window industry; adheres to glass, vinyl, and aluminum	30 seconds	$0.28

The method of applying the sealant was also considered in selecting a module edge sealant material. Both hot melt and RTV sealants can be applied with off-the-shelf dispensing equipment. No standard equipment is available for automatically dispensing tape sealant around laminate edges, so a custom designed system is required. Given the high cost of the tape and the need to develop dispensing equipment, the tape option was discarded.

Although the RTV can be dispensed in a similar manner as the hot melt sealants, the cure time of the RTV is too long, at up to 24 hours. Handling uncured modules could have an impact on the quality of the final product. Since the hot melt sealants have much faster curing times and lower cost than the RTVs, they were selected as the best material for this application.

ARRI selected the Q'SO Inc. Q-17 material for process development and testing. Although the price is higher than the hot-melt butyl, a local representative from Q'SO was available to support prototyping efforts. Support was provided in setting up the dispensing process and obtaining sealant material and hot-melt dispensing equipment.

A hot melt pump was used to develop a process for dispensing the sealant into the channel that holds the laminate in the module frame. Frame sections were picked up by a vacuum end effector on a robot arm and moved at a constant speed past the hot melt dispensing nozzle. Uniform and consistent sealant beads were dispensed into the frame channels. The optimum dispensing rate was between 13 and 18 cm/s. A 16 cm/s dispensing rate was used for prototype process demonstrations.

The hot melt pump has temperature control for its supply tank, heated hose, and dispense head. All three components were set to 188°C. The pump motor operates at a constant speed and a screw valve permits the control of flow by varying the bypass of the sealant. An air-operated needle valve at the dispense head provides on/off control for sealant dispensing.

Pull test samples were prepared to determine the adhesive strength of the Q-17 hot melt sealant. Tests were done with aluminum to glass and aluminum to Tedlar test samples. The setup for aluminum to glass adhesion testing is shown in Figure 10. A 13 mm thick glass plate and a 13 mm thick aluminum plate were bonded together with the hot melt material. Spacers, 1.5 mm thick, were used to maintain a consistent gap between the glass and aluminum plates. Weights were added to a hook attached to the aluminum plate.

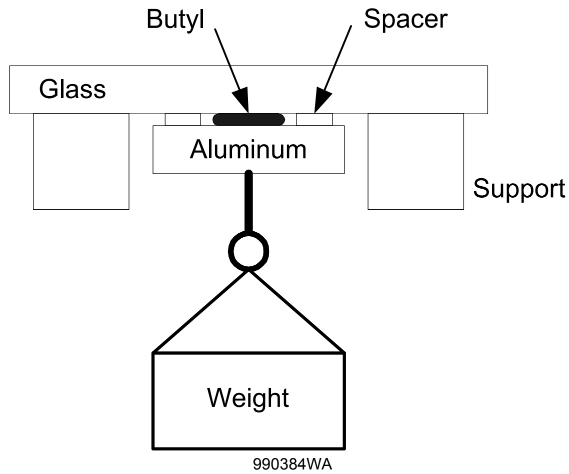

Figure 10 Sealant adhesion test setup, aluminum to glass.

The diameter of the sealant contact surface area was measured through the glass plate. The load carrying capacity of the sealant was determined by adding weight until the contact surface deformed. The weight was measured and used to calculate the sealant yield stress using the formula stress = load/area. Additional weight was added until the parts separated to determine the ultimate stress. The test results are provided in Table 7.

Table 7 Q-17 hot melt sealant strength test data, aluminum to glass.

Sealant Diameter (minimum) (inch)	Load Yield (lbs)	Load Ultimate (lbs)	Yield Stress (psi)	Ultimate Stress (psi)
1.20	13.82	15.46	12.22	13.67
1.13	12.33	13.38	12.29	13.34
1.28	15.73	17.87	12.22	13.89
Average	13.96	15.57	12.25	13.63
Standard Deviation	1.70	2.25	0.04	0.27

The setup for aluminum to Tedlar adhesion testing is shown in Figure 11. A Spire test module and a 13 mm aluminum plate were bonded together with the hot melt sealant. As in the previous test, 1.5 mm thick spacers were used to maintain a consistent gap between the Tedlar and the aluminum plate, and weights were added to a hook attached to the aluminum plate. Test results are provided in Table 8.

Table 8 Q-17 hot melt sealant strength test data, aluminum to Tedlar.

Sealant Diameter (minimum) (inch)	Load Yield (lbs)	Load Ultimate (lbs)	Yield Stress (psi)	Ultimate Stress (psi)
1.25	18.06	20.26	14.72	16.51
1.20	18.06	20.26	15.97	17.91
1.35	20.26	22.68	14.15	15.84
Average	18.79	21.07	14.95	16.76
Standard Deviation	1.27	1.40	0.93	1.06

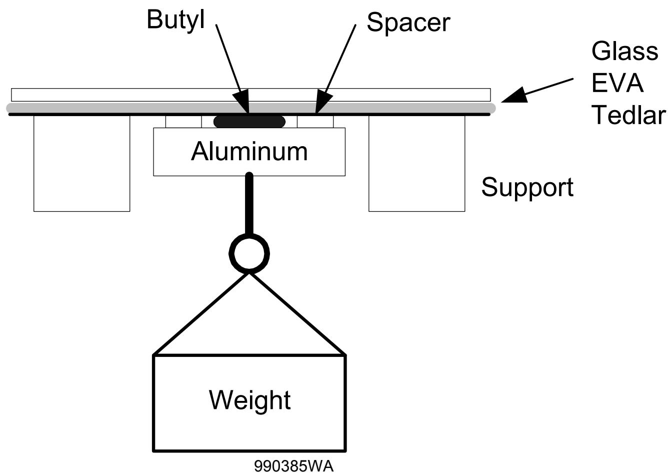

Figure 11 Sealant adhesion test setup, aluminum to Tedlar.

2.3.2.2 Edge Sealing and Framing Process Demonstration

Edge sealing and framing prototype processes were successfully demonstrated at ARRI using the same work cell used for the edge trimming process demonstration. Modules trimmed automatically by the prototype edge trimming process were used for the sealing and framing tests. Spire provided ARRI with corner keys and long extruded aluminum frames. Frame sections were fabricated by cutting the extrusions to the required length using miter cuts. Two 3/8” diameter holes were drilled in the bottom flange of each frame section to facilitate locating and holding the sections in fixtures. Similar holes are commonly used for mounting modules, so these holes do not require extra machining.

Four subassemblies were designed and built to develop and demonstrate the sealing and framing processes: a corner key inserter, an out-rigger end effector, a dispensing system, and a framer.

Corner key inserter - This prototype assembly, shown in Figure 12, inserts corner keys into both ends of two of the four frame sections. The frames are held fixed with pins through their mounting holes, while the keys are mounted on sliding carriages at opposite ends of two of the frame sections. The carriages are driven by two large opposing air cylinders that press the keys to the desired depth into mating channels in the frames.

Out-rigger end effector - A robot end effector was designed with vacuum cups for picking up frame sections and laminates. A stabilizing bar was added after initial trials for more reliable handling of laminates.

Dispensing system - The dispensing system consists of a hot melt pumping system and a fixture to hold the dispensing nozzle. The nozzle tip was set at an upward angle for three reasons: 1) to compensate for gravity, since dispensing was done close to the horizontal, 2) to direct more sealant toward the deeper top side of the channel, and 3) to avoid interference with the frame section and corner keys as they pass by the tip.

Framer - The framer installs four frame sections around the trimmed module laminate. The prototype framer is shown in Figure 13.

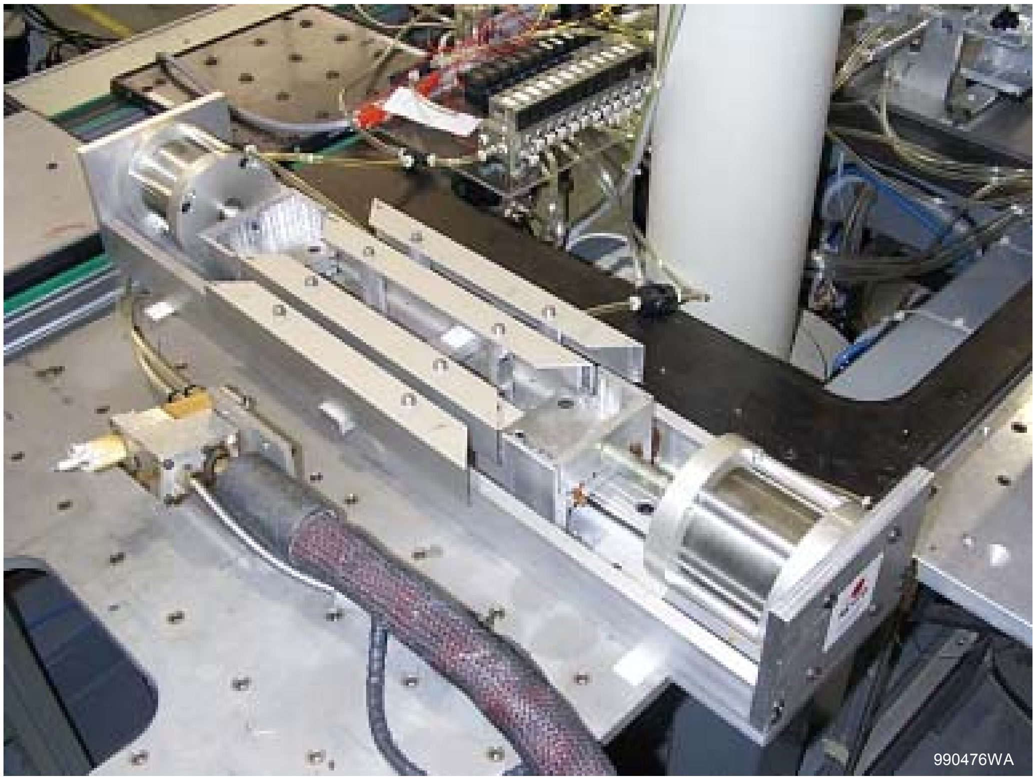

Figure 12 Prototype corner key inserter (center) and sealant dispense head (left).

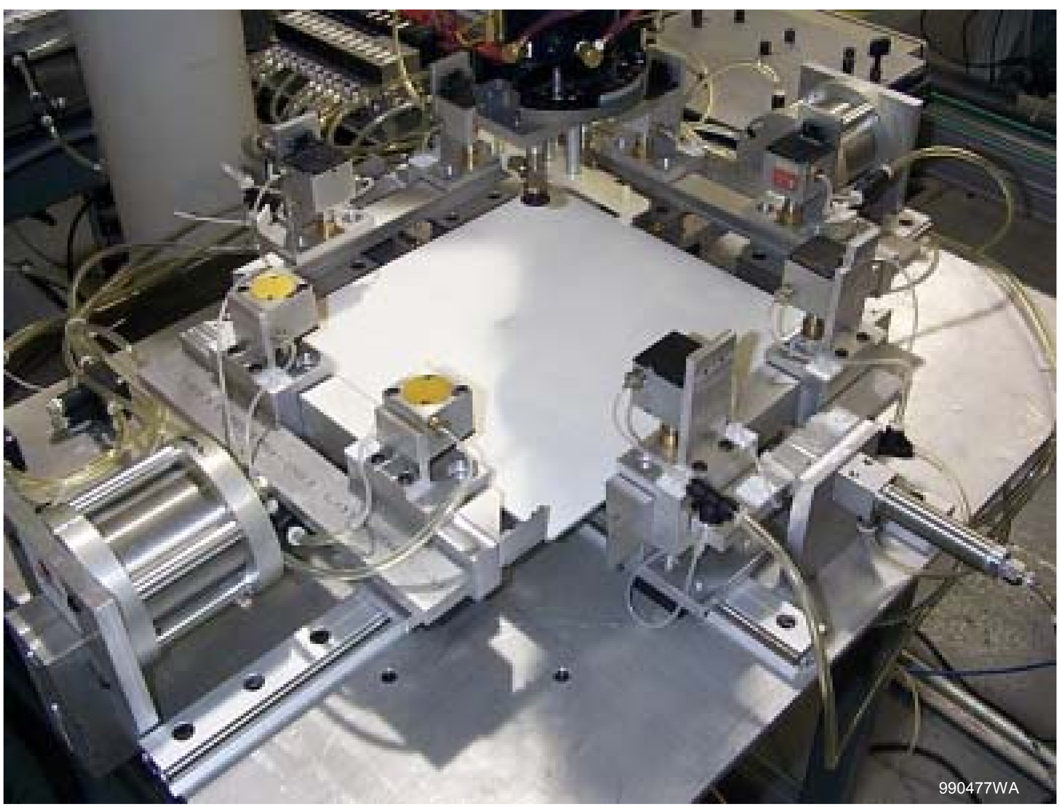

Figure 13 Prototype framer with laminate and frame sections loaded and ready for installation. Out-rigger end effector is at top center.

Several framed laminates, approximately 30 cm square, were produced with these subassemblies. The sealing and framing process was done as follows:

1. The robot with the vacuum end effect or picked up a trimmed laminate and placed it on the framer's module stand. The stand allows the module to slide freely on supporting blocks.

2. The robot picked up each frame section and moved the frame at a constant speed past the sealant dispensing tip, which filled the frame channel with sealant. The frame section was then placed in its appropriate position in the framer.

3. Pins extended through the frame's mounting holes to hold each frame section securely in place.

4. Air cylinders pressed the frame sections together. First the two frame sections without corner keys were pressed onto opposite sides of the laminate, causing the sealant in the frame channels to flow around the module edges. Then the two frame sections with keys were pressed to lock the frames together and seal the other two module edges.

2.3.3 Edge Sealing and Framing Production Prototype Concept

The experience gained by the edge sealing and framing process development work was used to develop a detailed concept for a prototype automated production edge sealing and framing system. The system consists of five main components: a conveyor system with a module aligner and lift, a two-axis frame press, a long frame subsystem, a short frame subsystem, and a Cartesian robot with a gripper for transporting frame sections. This concept formed the basis for the design of a full-scale prototype automated system that was built and demonstrated later in the program.

2.4 Task 4 - Develop Integrated Test System

An integrated test system for PV modules was developed in Task 4. The system combines a sun simulator for measuring module performance, an electrical isolation (hi-pot) tester, and a ground continuity tester. Automation was developed for transporting, aligning, probing, and testing modules.

2.4.1 Design Approach

Spire initially planned to develop a system that combines a hi-pot test with a module performance test (I-V curve measurement under simulated sunlight). However, the survey done in Task 1 identified the need to perform a ground continuity test in addition to the hi-pot and performance tests, to meet UL requirements.[5] Thus the ground continuity test was added to the hi-pot test station. Test electronics, probes, and controls were added for this test. Additional probes are needed because the continuity of each exposed conductive element (typically the four frame sections) must be tested individually. Automatic switching was added to allow the probe connections to the test electronics to be configured as needed for hi-pot or ground continuity testing.

The PV industry survey also showed that some manufacturers do hi-pot, ground continuity, and module performance tests in sequence after the module is framed, while others measure module performance before framing, and do the hi-pot and ground continuity tests after framing. As a result, our overall design strategy was changed from a single test system to a two-part system that can be configured to work with either process sequence. Two test stations were developed that can be used separately or in combination, where one station performs hi-pot and ground continuity tests and the other measures module performance.

The testing process sequence was revised to incorporate this two-step approach. In addition to improved process flexibility, the new sequence provides higher product throughput, since testing is done simultaneously at two test stations, rather than in sequence at one station.

2.4.2 Sun Simulator Development

Spire produces a series of commercial sun simulators for module testing that have a light source mounted at the top of a tower, shining down on a horizontal test plane. Spire also produces an inverted style in which the light source is located near the floor, shining up to a horizontal test plane. While both the standard and the inverted simulators can be automated, the inverted design was selected for this application because modules are typically processed face-down after lamination. Thus the modules do not need to be turned over for testing.

A new size sun simulator, designated the SPI-SUN SIMULATOR™ 350i, was designed with a test area of 102 cm x 162 cm. This simulator, shown in Figure 14, is large enough for testing most production modules without occupying excessive production floor space. The design is a modification of Spire's larger inverted sun simulator, the SPI-SUN SIMULATOR 460i.

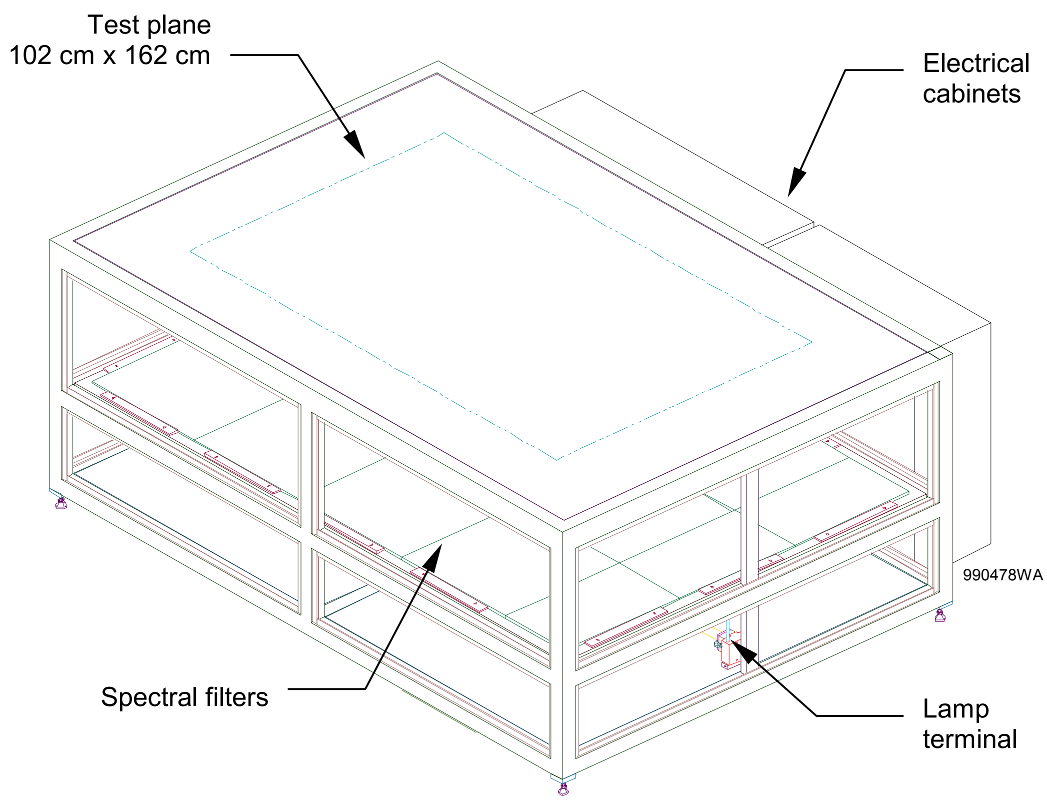

Figure 14 SPI-SUN SIMULATOR 350i design. Side panels removed to show detail.

The 350i simulator was designed with one xenon flash lamp, in place of the two used in the larger 460i, to simplify the optics and the lamp power and trigger electronics. A new pulsed xenon lamp was designed for the 350i simulator with a 195 cm arc length, 28 cm longer than the longest lamp previously used by Spire. Two of the new long xenon lamps were fabricated and tested. The lamps were made with different Xe fill pressures to evaluate this parameter on lamp performance. As pressure increases, lamps produce more light at a given voltage, but at some point the pressure becomes so high it prevents the lamp from flashing. Each lamp was connected to a simulator power supply and both flashed successfully over a range of voltages. The lamp with the higher fill pressure was selected for use in the simulator. The fill pressure is below atmosphere, so there is no explosion hazard if a lamp should break.

Mechanical assembly drawings, detail drawings, and bills of material were created and reviewed, and parts were released for fabrication and procurement. After the 350i simulator was fabricated, light spatial uniformity and repeatability tests were done to characterize its performance. The test plane irradiance was measured at 40 locations (in a 5 x 8 matrix) with a 103 mm square single crystal silicon solar cell. The uniformity of total irradiance, in percent, was calculated according to the method defined in ASTM E 927:[10]

$$\text{Uniformity} = \pm 100 \times \left(\frac{\text{Irradiance}_{\text{Max}} - \text{Irradiance}_{\text{Min}}}{\text{Irradiance}_{\text{Max}} + \text{Irradiance}_{\text{Min}}} \right) \quad \textbf{1}$$

Uniformity was measured under three conditions: 1) under ambient fluorescent room lighting, 2) with the room lights turned off, and 3) with a large sheet of heavy black paper placed over the test plane. The results, listed in Table 9, show that room lighting does not have a significant effect on the uniformity of irradiance at the test plane. The data also shows that the simulator exceeds its design specification of ±3% under all three test conditions.

Table 9 Uniformity and repeatability measurements, SPI-SUN SIMULATOR 350i.

Test Conditions	Results
Uniformity	
• Room lights on	±2.12%
• Room lights off	±2.11%
• Black background	±2.30%
Repeatability	
• Center	±0.05%
• Top left	±0.09%
• Bottom left	±0.09%
• Top right	±0.11%
• Bottom right	±0.10%

Simulator irradiance repeatability data was obtained by placing the 103 mm square silicon solar cell in a fixed location on the test plane and making 40 measurements. This test was done at five locations on the test plane: at the center and at locations near the four corners. Repeatability, in percent, was calculated by the same method as uniformity:

$$\text{Repeatability} = \pm 100 \times \left(\frac{\text{Irradiance}_{\text{Max}} - \text{Irradiance}_{\text{Min}}}{\text{Irradiance}_{\text{Max}} + \text{Irradiance}_{\text{Min}}} \right) \quad \textbf{2}$$

The results of the repeatability tests are provided in Table 9. The repeatability at all five test plane locations was ±0.11% or better, well within the ±1% design specification.

2.4.3 Test System Automation Development

Spire developed automation for testing modules with a sun simulator, a hi-pot tester, and a ground continuity tester. The equipment automatically transports, aligns, probes, and tests modules. The integrated test system, designated the SPI-MODULE QA™ 350, was designed to handle module sizes ranging from a minimum of 30 cm x 91 cm (12” x 36”) to a maximum of 102 cm x 162 cm (40” x 64”).

Mechanical, pneumatic, electrical, and software systems were developed for the test system. A long motorized belt drive system was initially considered for transporting modules through the sun simulator. The high materials cost of this design led us to search for a less expensive alternative. A pneumatic actuator was identified and selected that has sufficient stroke (218 cm) for this application and costs significantly less than the belt drive approach.

The integrated test system, shown in Figure 15, includes the following major components:

- a powered input conveyor with a module aligner
- test probes and electronics for module hi-pot and ground continuity tests
- a sun simulator with test probes for module performance measurements (I-V curves)
- two transport carriages that work in tandem to move modules from the input conveyor to the sun simulator and from the simulator to the output conveyor
- a powered output conveyor for unloading modules

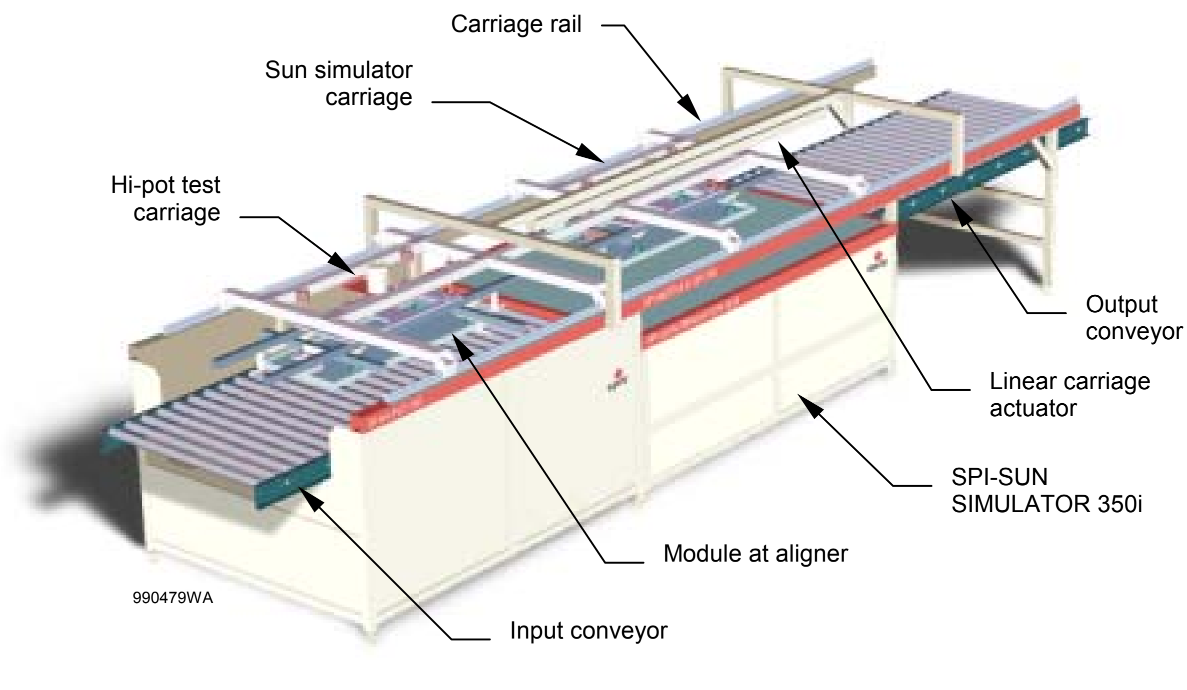

Figure 15 SPI-MODULE QA 350 automated module test system.

Modules enter the system on a powered roller conveyor and are aligned in the first section of the machine, where the hi-pot and ground continuity tests are done. The module alignment system used here is similar to the one developed for the automated buffer. A safety light curtain is provided around the hi-pot test area. The light curtain disables the high voltage to prevent electric shock.

Side panels are provided in the hi-pot test area to reduce the ambient light on the module’s front surface, to comply with ASTM E 1462, “Standard Test Methods for Insulation Integrity and Ground Path Continuity of Photovoltaic Modules.”[11] Procedure 7.1.1 of this standard specifies that the face of the module shall not be illuminated during the hi-pot test. Note that the comparable UL standard, 1703, and the comparable International Standard, IEC 1215, have no requirement for shading the module.

Spire contacted Carl Osterwald at NREL to discuss the shading issue. The module's positive and negative leads are shorted during the hi-pot test. If a module is illuminated with the intensity of full sunlight and one cell is reverse biased, the cell could have the voltage of the remaining cells in series applied to it. This voltage is typically around 20 V, much less than the test voltage, which is usually in the range of 2000 V. Thus the error in applied voltage for a reverse biased cell could be on the order of 1% in full sunlight. Room lighting, however, is typically only 5% of the intensity of sunlight, and a downward-facing module will receive only a small fraction of room lighting on its active surface. Thus the design of our automated system is sufficient to reduce the incident light on the module face to the point where it will have a negligible effect on the test.

The hi-pot test carriage assembly is shown in Figure 16. Once a module is aligned on the input conveyor, an air cylinder brings four vacuum cups down into contact with the back surface of the module. Two spring-loaded probes make contact with the positive and negative terminals on the back of the module. The module is lifted above the conveyor surface and four air-actuated probes contact the module's four frame sections. The hi-pot test is performed, the test probes are electrically reconfigured, and the ground continuity test is performed.

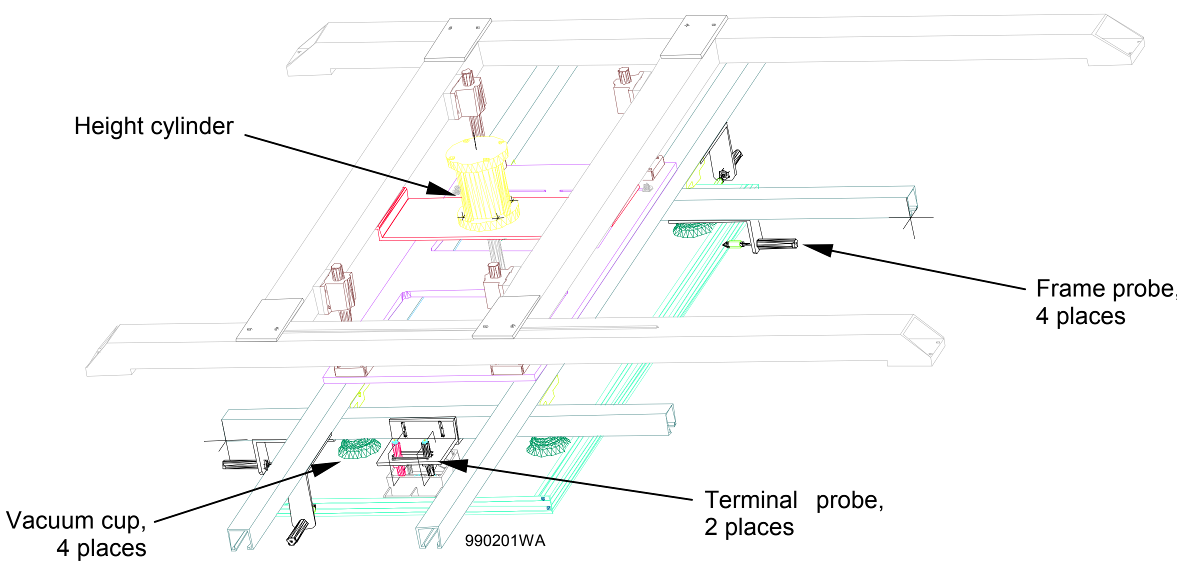

Figure 16 Hi-pot test carriage assembly.

After testing, the frame probes retract, the carriage actuator moves the hi-pot tester carriage over the sun simulator, and the module is placed on the simulator test surface. The vacuum is released, the carriage moves up, and the hi-pot tester carriage moves back to its original position.

The sun simulator carriage is shown in Figure 17. When a module has been placed on the simulator, the carriage's air cylinder pushes four spring-loaded probes (+V, +I, -V, -I) down to contact the positive and negative terminals on the back of the module. The simulator measures the module's I-V curve under one-sun conditions (100 mW/cm^2, AM1.5 Global spectrum).

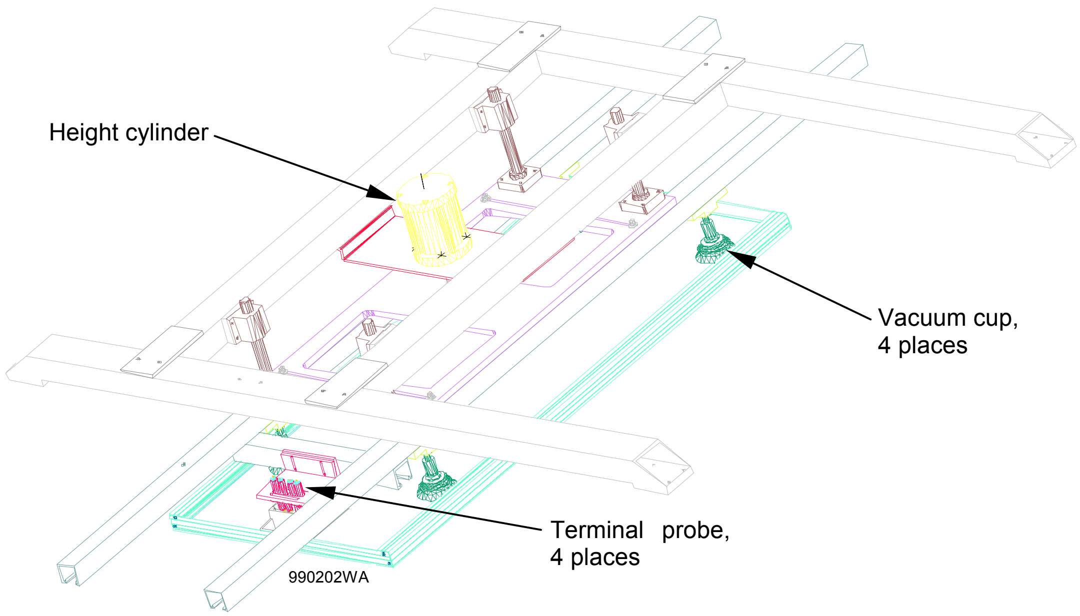

Figure 17 Sun simulator carriage assembly.

After the simulator test is completed, the module is lifted from the simulator surface with four large vacuum cups on the back surface of the module. The simulator carriage then moves the module from the simulator to the output conveyor while the next module is brought to the simulator by the hi-pot test carriage.

Both carriage assemblies are designed with the flexibility to accommodate module sizes from 30 cm x 91 cm to 102 cm x 162 cm. The carriages are mounted on ball bearing slides that ride on precision rails. The position of the carriages can be adjusted so they are centered over the modules in their aligned position. The vacuum cups, terminal probes, and frame probes can be adjusted in both x and y directions to suit the module design. If frameless modules are being tested, the frame probes can be replaced by a test frame that surrounds the module edges for hi-pot testing.

A new 32-bit Visual Basic software package was developed for test system operation using a personal computer (PC). This software operates the sun simulator, the hi-pot tester, and the ground continuity tester, acquires and analyzes module test data, and controls module alignment, transport, and probing. This integrated software approach simplifies the control system and allows the operator to deal with a single user interface. An image of the main operating screen is shown in Figure 18.

A help file was written for the test system PC in HTML format. The help file is accessible from within the testing program by pressing the F1 key or selecting Help from the menu bar.

The software that runs the hi-pot and ground continuity tests also acquires test data and stores it in a database file. The database format is compatible with Microsoft Access and Excel. Serial (RS-232) communications link the PC with the hi-pot/ground tester electronics.

The hi-pot and ground continuity test parameters (listed in Table 10) can be set by the user to configure the tests for the desired set points and acceptance levels. Parameter sets can be saved as parameter files (∗.par) and reloaded as needed, allowing different test conditions to be assigned to different module types.

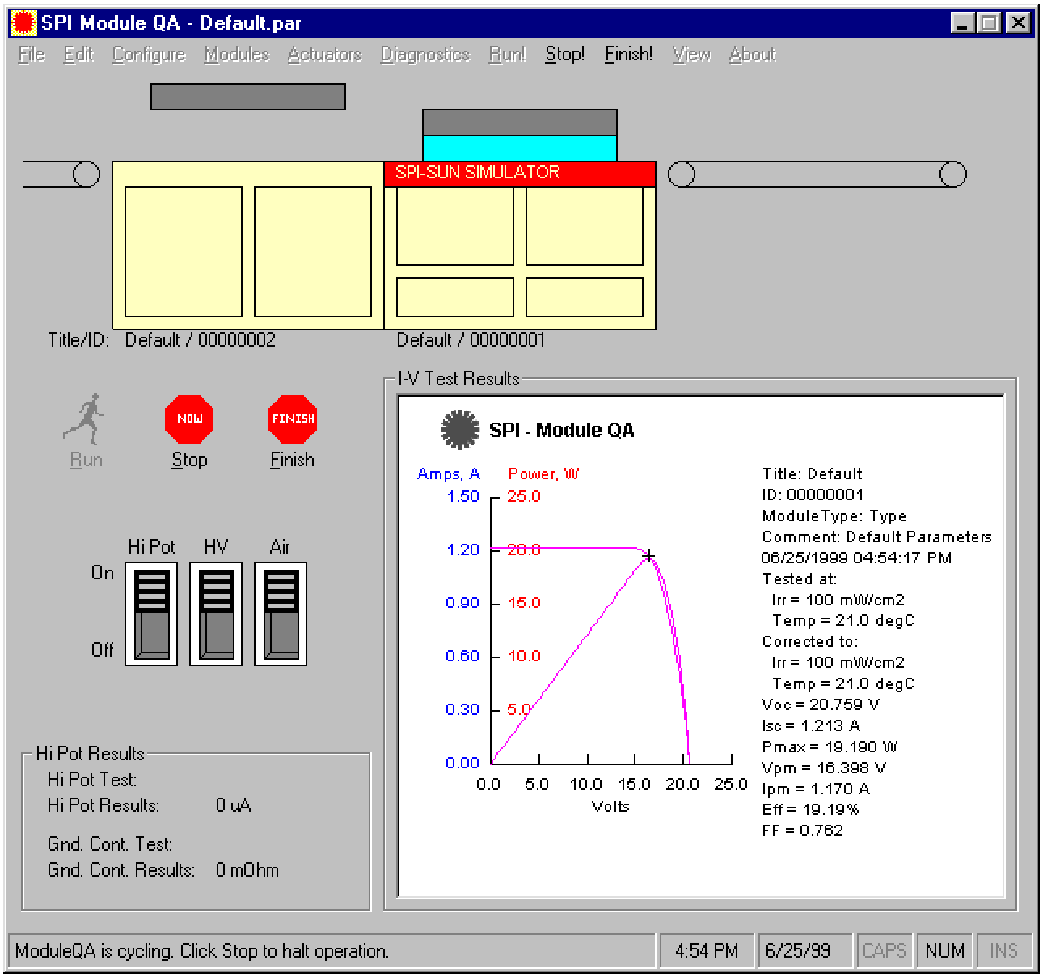

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Figure 18 Main operating screen, SPI-MODULE QA 350, with I-V data measured by a sun simulator.

Table 10 User-selectable parameters for hi-pot and ground continuity tests.

Hi-Pot	Ground Continuity
Voltage (V)	Current (A)
Current Limit (µA)	Voltage (V)
Ramp Time (s)	Resistance Limit (mΩ)
Dwell Time (s)	Dwell Time (s)

A diagnostics screen was created with buttons that run the hi-pot and ground continuity tests individually and fields that display the test results. The hi-pot test reports the pass/fail status, the applied test voltage (V), and the maximum leakage current (µA) measured during the test. The ground continuity test reports the pass/fail status, the applied test current (A), and the resistance (mΩ) measured during the test.

A bar code reader was added to the test system for automatically tracking modules by serial number and inserting test data into a database. Information on bar code readers was obtained from several vendors and reviewed. A reader with serial communications capability was selected, procured, and mounted on the hi-pot test carriage. Serial numbers are read from bar code labels on the backs of modules and sent to the test system PC, which inserts the serial numbers along with the test data in records that are saved in a database file.

System throughput was measured while testing Siemens Solar SP75 modules. These modules have a power rating of 75 W and overall (frame) dimensions of 1200 mm x 527 mm x 34 mm. The I-V test was configured to measure 50 data points per curve. The cycle time was consistently measured at 52 seconds per module when running all three tests, with the conveyors and test carriages running at moderate speeds. A photograph of the completed test system is provided in Figure 19.

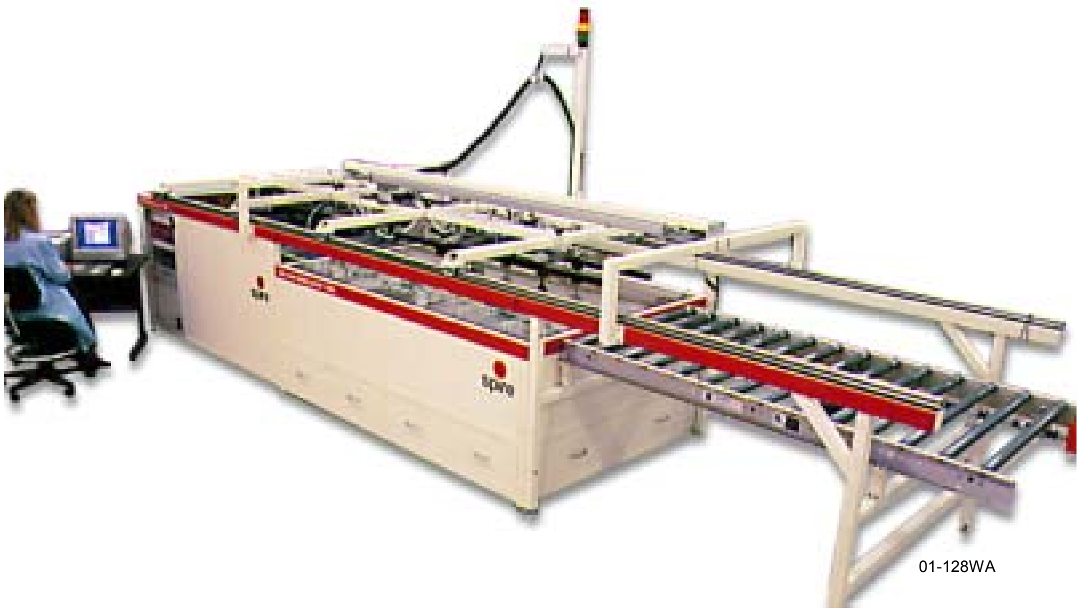

Figure 19 SPI-MODULE QA 350 integrated module test system.

2.5 Task 5 - Design Integrated Edge Process System

An integrated edge process system for photovoltaic modules was designed in this task, completed under Phase 2 of the program. This system consists of two automated machines, an edge trimmer for trimming excess encapsulant and back cover film from module edges after lamination, and an edge sealer and framer for installing edge sealant and frames on trimmed modules. Both machines have conveyors for module transport and use standard handshake protocols, allowing them to be placed together or separately to suit the manufacturer's process sequence.

2.5.1 Design Edge Trimming System

A detailed design was developed for a prototype automated production edge trimming system, designated the SPI-TRIM™ 350. The system's main components include a conveyor system, a module aligner, a module lift, a four-axis Cartesian robot, and an end-effector for edge sensing and trimming. The design is shown in Figure 20, with panels removed to show the system's functional elements.

The conveyor system has three sections: input, trimming, and output. Motor driven rollers transport modules on the input and output conveyors. The rollers are covered with urethane to provide traction and prevent damage to modules with glass surfaces. A pair of motor-driven belt conveyors is used to transport modules in the center trimming section. The belt conveyors provide clearance for positioning the module lift assemblies, while eliminating the potential for stalling which could occur if rollers were used, since trimmed material from modules could wrap around the rollers.

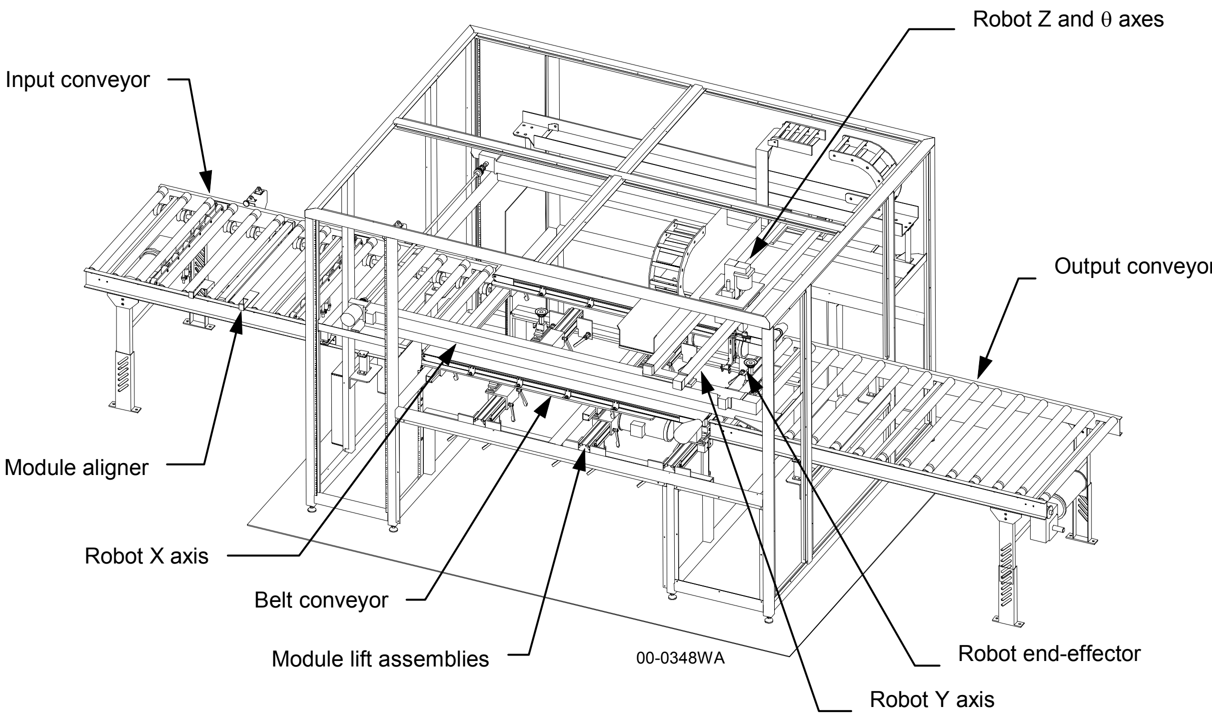

Figure 20 Module edge trimming system design; panels and doors not shown.

The module aligner, built into the input conveyor, provides coarse alignment for untrimmed modules. The aligner consists of two cross-roller assemblies, two retractable stops, an alignment arm, and optical sensors.

When the trimmer input conveyor is available and the upstream process signals that it is ready to send a module, through a SMEMA interface, the input conveyor turns on to transport the module into the aligner section of the machine. The conveyor turns off when the leading edge of the module breaks an infrared beam. The module is lifted up above the conveyor rollers by cross-roller assemblies, which contain sets of wheels that are perpendicular to the roller direction. An arm driven by an air cylinder gently pushes the module against a pair of stops on the opposite edge of the conveyor. The module is now aligned with one edge against the module stops.

An optical sensor detects when the module reaches the module stops, which signals the two cross roller assemblies to retract, placing the module back on the conveyor rollers. First the aligner arm and then the module stops retract away from the module. The module is now ready to enter the trimming area. In production, the aligned module typically waits on the input conveyor until the trimming process is completed on the previous module, since the alignment process is faster than the trimming process.

After alignment, the module is transported into the trimming section on two belt conveyors. Two long-range optical sensors are provided at the downstream end of the belt conveyors. When the module reaches the first long-range sensor, the belt conveyor is switched from its normal running speed to a slow speed. When the module reaches the second sensor, the belt conveyor is switched off. This two-speed approach allows reasonably accurate module positioning while maintaining good system throughput.

Six large rubber vacuum cups mounted on guided air cylinders grip the module and lift it up above the belt surface for trimming. These lift assemblies are mounted on rails with quick release clamps that allow the lift locations to be adjusted in x and y directions, to accommodate various size modules. Similarly, the two conveyor belts are mounted with quick release clamps that allow the belt positions to be adjusted as needed for various width modules.

Module edge sensing and trimming operations are performed by a four axis (x, y, z, and θ) Cartesian robot. All four axes are servomotor controlled. The horizontal (x and y) axes have belt driven stages with roller bearings. The vertical (z) axis is a linear electric cylinder with a ball screw and guide rods. The rotation (θ) axis is a 15 cm (6") diameter rotary table, attached to the z axis. The robot transports an end-effector with a hot knife for trimming module encapsulant and back cover material, two fiber-coupled optical sensors for finding module glass edges and a mechanical clutch between the end-effector and the robot to protect the robot from damage in the event of a collision.

Once a module is positioned on the belts, the lift system raises the module above the belts and the robot end-effector travels at high speed to each corner of the module. The robot scans the two fiber optic sensors at slow speed across two adjacent glass edges at each corner. Servo position data is captured as each sensor crosses its reflectance threshold. This position data is used to calculate the location of the glass perimeter.

The perimeter data is compared against user-specified tolerances for glass size and angle of each corner. If the glass perimeter fails this inspection, the fault condition is displayed and the module is passed out of the system without being trimmed. If the glass dimensions pass inspection, and if the hot knife is within a specified temperature range, the robot trims the four sides of the module with the hot knife. The robot can be programmed to trim at a specified distance (typically 0.5 mm) from the glass edge to extend blade life, given the abrasive nature of glass.

After the long sides of the laminate are trimmed, the belt conveyors run at high speed to remove any material that may fall on them during trimming. When all four sides are trimmed, the lift vacuum is turned off and the module lift moves down to place the module on the conveyor. If the output roller conveyor is empty, the belt conveyors and the output roller conveyor turn on to transport the module from the trimming station to the output conveyor to clear the trimming area for the next module. When the downstream process signals that it is ready to receive a module, the output conveyor turns on to transport the module out of the trimmer.

A detailed process sequence and a process flow chart were written for edge trimming. These documents were used as the basis for specifying sensors and controls and for developing the operating software. A summary of the process sequence follows:

1. Transport a module into the trimmer on a roller conveyor and do a coarse alignment.
2. Transport the module onto a pair of belt conveyors and stop at the trim position.
3. Grip and raise the module up above the belt conveyors with a vacuum lift.
4. Sense the glass edges with a pair of optical sensors and calculate the location of the glass perimeter.
5. Trim the module edges with a hot knife.
6. Empty the belts of cut material.
7. Lower the module onto the belts.
8. Transport the module out of the trimming area.

The robot end-effector was designed with several improvements over the system used for process development in Phase 1:

- a second fiber optic sensor was added to reduce sensing time. With two sensors, the end-effector can detect two edge points on adjacent sides of a module in one scan, by scanning each corner at a 45° angle. This reduces the number of slow-speed edge scans from eight to four, while still detecting eight edge points.
- the two fiber optic sensors are mounted on the opposite side of the robot's rotation axis from the hot knife, to prevent trimmed material from falling onto the sensors.
- a thermocouple was added to monitor the knife temperature.
- a mechanical clutch was added between the end-effector and the robot. The clutch protects the robot from damage in the event of a collision.

The clutch holds the end-effector rigidly in position under normal conditions. In the event that a torque threshold is exceeded in the x, y, or z direction, the bottom part of the clutch pivots and a limit switch opens. The limit switch is wired to the robot motor controller, which immediately stops the robot's motion in all four axes. The bottom part of the clutch remains captive in the top part, so the end-effector remains attached to the robot arm.

While the clutch provides protection for the robot and its end-effector, it is not sufficient to ensure the safety of personnel from possible injury from the hot knife or the moving robot arm, which present cutting and crushing hazards. Light curtains and mechanical guards were considered for operator protection. While either approach can provide the necessary level of safety, the use of mechanical guards was selected because it results in a smaller machine footprint, while reducing the chance of accidentally interrupting machine operation.

Clear acrylic sliding doors are provided above the conveyor to allow the machine to be observed during operation and to provide access for set-up or maintenance. Hinged doors below the conveyor allow trimmed scrap material to be cleaned out periodically. All doors are electrically interlocked for safety. Emergency stop buttons are installed at each corner of the machine.

A light tower with red, yellow and green lights is provided to indicate machine status. The trimmer has six states: run, reset, automatic pause, manual pause, error, and emergency stop. Colors were assigned for each state, using the same conventions used for the module buffer, listed previously in Table 5. The light tower is mounted at the highest point of the machine, on top of the main frame, for visibility in the factory.

Two electronics bays are provided, one in the front and one in the back of the machine. The bays' frames were designed to hold standard 19-inch rack mount equipment. A rack mount PC, a touch screen monitor, and a sliding keyboard shelf are mounted in the front bay for machine control and user interface functions.

A control system block diagram for the trimmer is provided in Figure 21. The main controller is an industrial PC running a Microsoft Windows NT operating system. An Ethernet connection links the PC with a process controller for servomotor control and handling digital input/output (I/O). A serial (RS232) port connects the PC to a thermocouple converter for monitoring the temperature of the hot knife.

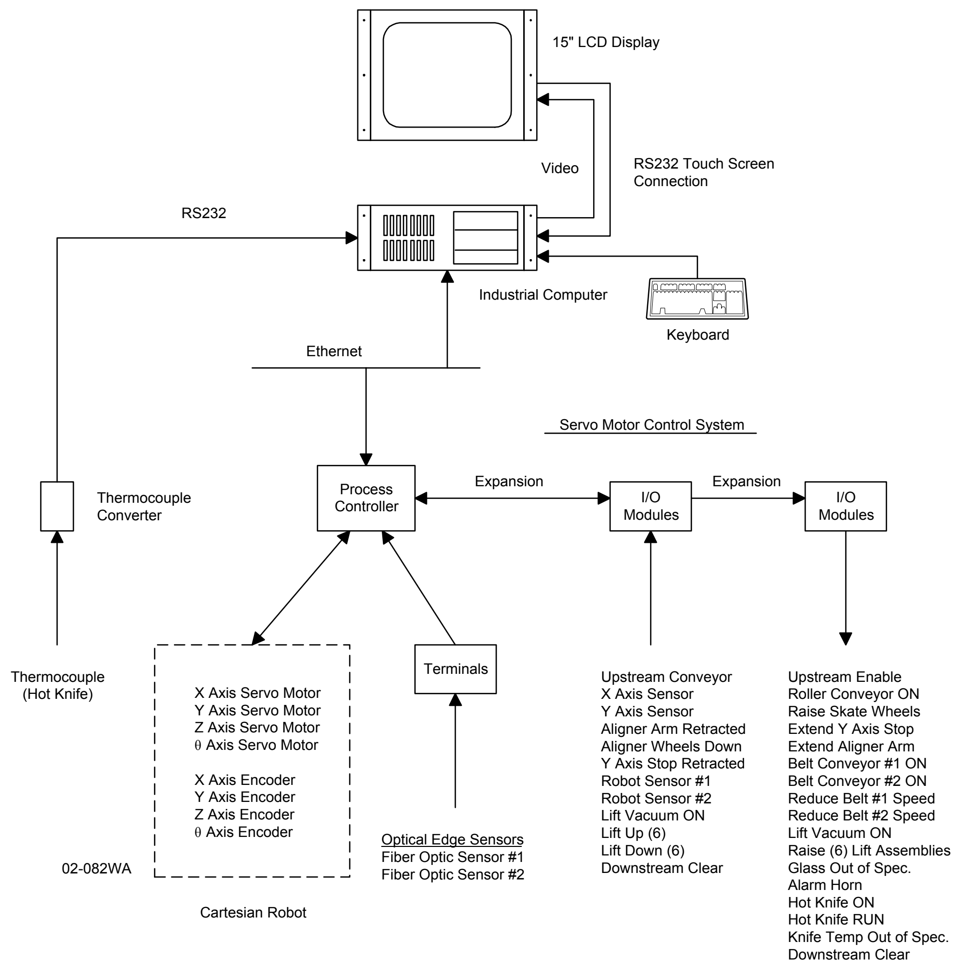

Figure 21 Trimmer control system block diagram.

The SMEMA electrical interface standard[8] was selected for trimmer communications with upstream and downstream automation. The SMEMA standard defines a protocol for electrical signals used for transferring product between machines. This standard is used in all of the automated systems developed in this program.

Spire's engineering group created 3-D design models for the mechanical assemblies using Autodesk Mechanical Desktop solid modeling software. From these models, detail drawings were produced for fabricating parts and mechanical assembly drawings were produced to assist the manufacturing group with assembly. A pneumatic schematic was created to document the compressed air and vacuum systems. Electrical wiring drawings and electrical panel layout drawings were created.

The machine control and user interface software was written in Visual Basic. A touch screen, rack mounted in the main frame, provides the main operator interface. The main operating window is shown in Figure 22. Process parameters are set on a separate window, shown in Figure 23.

A system parameters screen is provided to set the Cartesian robot parameters, such as acceleration, velocity, and home positions, for each of four axes. Diagnostics screens were also developed to view the status of inputs and outputs. The diagnostics screens allow the outputs to be operated manually (by pressing buttons on the touch screen) to test them for proper operation or to make adjustments for setup or maintenance purposes.

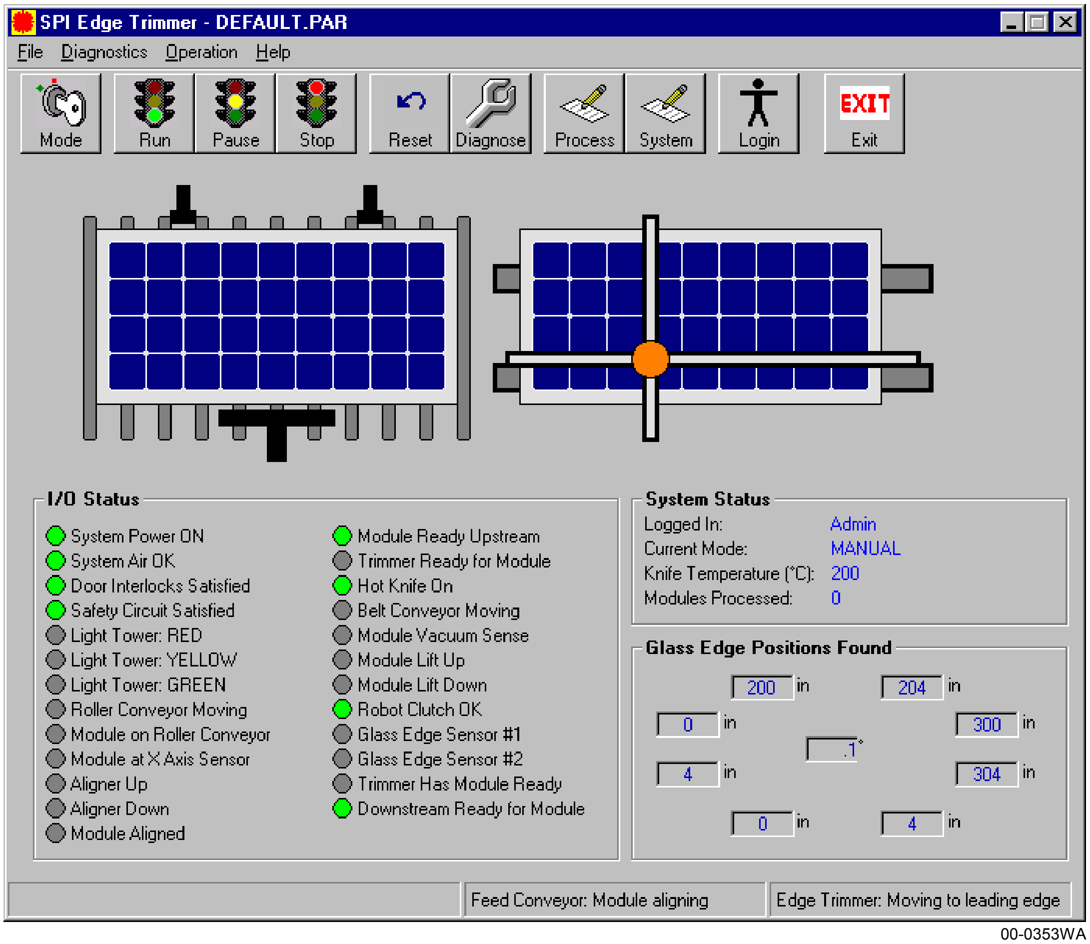

Figure 22 Main operating window, edge trimmer.

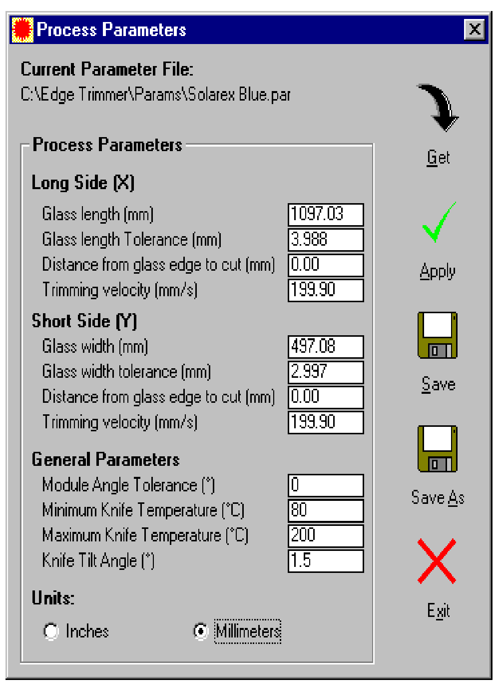

Figure 23 Process parameters window, edge trimmer.

2.5.2 Design Edge Sealing and Framing System

A detailed design was developed for a prototype automated module edge sealing and framing system, designated the SPI-FRAME™ 350. The edge sealer and framer's main components include module transport conveyors, a module aligner, a module lift, a robotic frame transport, a long frame feeder, a short frame feeder, corner key feeders, corner key presses, and a two-axis frame press. The design is shown in Figure 24, with panels removed to show the system's functional elements.

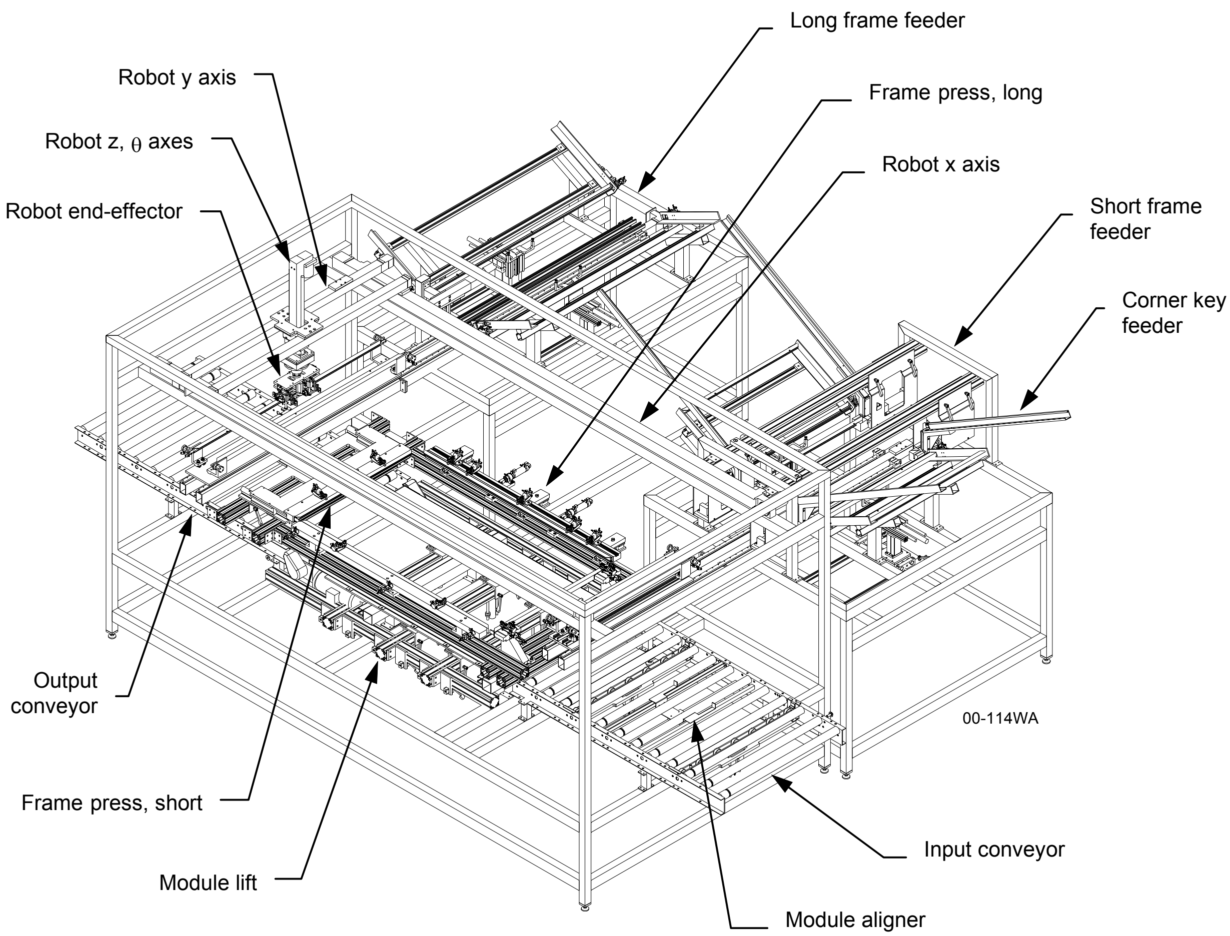

Figure 24 Edge sealing and framing system; panels, doors and controls not shown.

The conveyor system has three sections: input, framing, and output. The conveyors are similar to those used in the trimmer. Motor driven rollers transport modules on the input and output conveyors. The rollers are covered with urethane to provide traction and prevent damage to modules with glass surfaces. A pair of motor-driven belt conveyors is used to transport modules in the center framing section. The belt conveyors provide clearance for positioning the module lift assemblies.

When the upstream process signals that it is ready to send a module, the input conveyor turns on and transports the module into the aligner section of the machine. The conveyor turns off when the leading edge of the module breaks an infrared beam. The aligner design is similar to the aligner in the edge trimming system. Modules are lifted up above the conveyor by two sets of wheels that are perpendicular to the roller direction, and an arm driven by an air cylinder gently pushes the module against a pair of stops on the opposite edge of the conveyor.

When an optical sensor detects that the module reaches the stops, the two cross roller assemblies retract, placing the module back on the conveyor rollers. First the aligner arm and then the module stops retract away from the module. The module is now ready to enter the framing area. In production, the aligned module typically will wait on the input conveyor until the framing process is completed on the previous module, since the alignment process is faster than the framing process.

After alignment, the module is transported into the framing section on two belt conveyors. Seven guided air cylinders, two with large rubber vacuum cups to grip the module and five with plastic pads to support the module, raise up to lift the module above the belt surface to the level of the frame press. These lift assemblies are mounted on rails with quick release clamps that allow the lift locations to be adjusted in x and y directions, to accommodate various size modules. The two conveyor belts are also mounted with quick release clamps to allow the belt positions to be adjusted as needed for various width modules. The lift and conveyor belt assemblies are similar to those used in the trimming system.

Once the module is raised up on the lift, the two vacuum cups are vented and retracted, leaving the module supported on the five plastic pads, arranged with one near each corner of the module and one at the center. These pads allow the module to slide horizontally when the frame members are pressed onto the module edges.

The long frame feeder subassembly automatically dispenses long frame members from trays and places them on a carriage. The long frame feeder consists of two trays with feed index mechanisms for dispensing frames and two frame pick-and-place mechanisms for transferring frames from the trays to a carriage for sealant dispensing.

Frame feed mechanisms at the bottom of each tray hand off one frame member at a time to a pneumatic pick-and-place mechanism. A side view of the frame tray and feed index mechanism is provided in Figure 25.

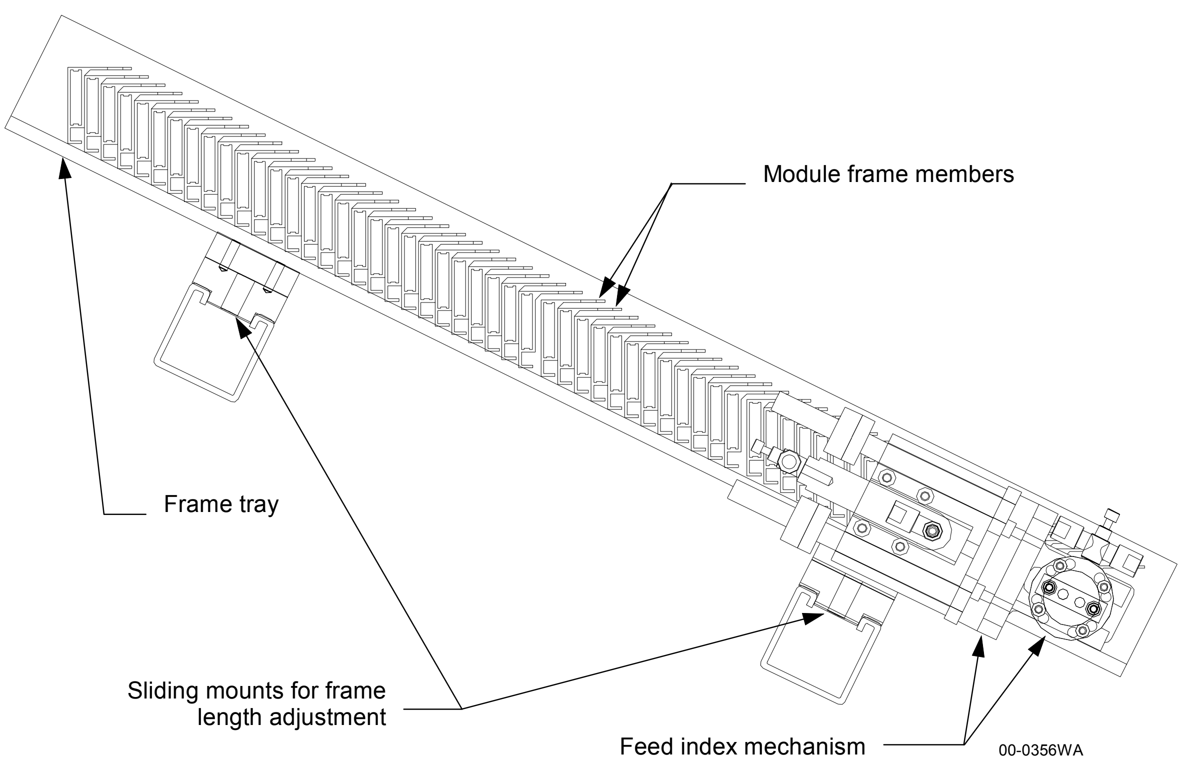

Figure 25 Side view of the frame feeder, shown loaded with 60 frame members.

The index mechanism inserts a pin in the rectangular hole in the bottom frame member in the tray to hold the stack in place. Mirror image assemblies were designed to hold both ends of the frame member. When the pick-and-place mechanism acquires the bottom frame member with its vacuum hand, the pins are retracted from the ends of the frame member and the pins are indexed up and inserted into the next frame member on the tray. The pick-and-place mechanism removes the bottom frame from the tray, and the pins index down to reposition the stack for the next hand-off.

A mock-up of the frame tray was fabricated to test the gravity-feeding concept with 147 cm (58") long frame members provided by AstroPower. These frame members form a 24° angle with the horizontal when stacked in a nested manner, as shown in Figure 25.

A stack of frame members was placed on aluminum angles mounted at a 24° angle to see if the frames will slide down the tray under their own weight when frames are dispensed from the bottom of the stack. The frame members tended to stick to the aluminum angles, so strips of Delrin,[12] a hard plastic, were attached to the side and bottom surfaces of the angles to reduce friction. With these strips in place, the frames fed smoothly, for both small and large quantities of frames. Thus no pushing mechanism or additional weight is needed. The nested frame stack was found to be stable on the support angles and the frames did not jam inside the tray. As a result, Delrin strips were added to the frame tray design to ensure smooth operation.

Two pneumatic pick-and-place assemblies, each with three actuators and a vacuum hand assembly, grip frame members and transport them from the two trays to a carriage for sealant dispensing. Each pick-and-place mechanism has one horizontal and two vertical guided cylinders. A plate mounted on channels with quick-release clamps allows the mechanism to be positioned as required for frame members ranging from 91 cm to 162 cm (36" to 64") long.

A vacuum hand assembly was designed for gripping frame members. Four of these subassemblies are used, two in the short frame feeder and two in the long frame feeder. Each vacuum cup is independently mounted on center-loaded linear ball bushings for compliance when picking or placing a frame member. Independent spring loading of each vacuum cup relaxes the parallelism tolerance for the assemblies that hold the frames at the pick up and placement locations.

The long frame carriage drives two long frame members at constant velocity past two hot melt sealant nozzles which dispense a bead of sealant into a channel in each frame member. The frame members are then picked up by the robot and transported to the long frame press. The maximum frame member length is 162 cm (64 inch).

The short frame feeder subassembly automatically dispenses short frame members from trays, places them in key presses to install corner keys, and places them on a carriage for sealant dispensing. The short frame feeder consists of two trays with feed index mechanisms for dispensing frames, two frame pick-and-place mechanisms for transferring frames from the trays to the key presses and to a carriage, and four key presses with removable key magazines.

The short frame feeder trays and index mechanisms are similar to those in the long frame feeder assembly. A four-axis pneumatic pick-and-place mechanism was designed for dispensing short frame members. The vacuum hand assembly described previously is mounted on each pick-and-place mechanism for gripping frame members. Two horizontal and two vertical guided cylinders transport frame members from the feed tray to a key press, where corner keys are inserted in both ends of the frame, and from the key press to a carriage for sealant dispensing. Plates mounted on channels with quick-release clamps allows the pick-and-place mechanism to be positioned as needed for frame members ranging from 30 cm to 102 cm (12" to 40") long.

Four corner key feeders and four key presses are provided to dispense L-shaped corner keys and press them into both ends of two short frame members. A gravity-feed concept for dispensing corner keys was developed. The system uses a sloped channel to dispense corner keys directly into each corner key press. This design greatly simplifies the original key feeder concept by eliminating two pneumatic three-link (x-z-θ) pick-and-place mechanisms, two pairs of retracting pins for releasing keys, and two push bars for moving keys to the front of the feeders.

A prototype corner key feeder was fabricated during the design phase to evaluate the gravity feed concept. The feeder was tested with corner keys provided by AstroPower. The tests were successful in proving the basic concept, but also identified some aspects of the design that needed improvement. As a result, the design was modified for easier loading and smoother operation.

Each key feeder includes a key tray that holds up to 60 corner keys, approximately a one-hour supply. The tray can be removed from the feeder to simplify key loading. The tray is designed to slide into the tray support so it can be removed and replaced without tools. A "keys low" optical sensor detects when the last key slides out of the tray, at which point the operator is alerted to fill the tray. The machine will continue to run for several minutes, since there are still several keys in the vertical section of the feeder. This allows time for the operator to refill the tray or insert another pre-filled tray. A "keys empty" sensor detects when the feeder has only two keys left in the vertical section, which stops the key press operation and alerts the operator that the press is out of keys.

Quick-release clamps attach two key press subassemblies to a common extruded aluminum structural support. The presses can be positioned anywhere on the support to suit the length of the module frame member.

Short frame members are transported by the pick-and-place mechanism from a frame feeder and placed on two key presses. Each end of the frame member sits on a support block in the frame press. A proximity sensor in each block detects when the frame is loaded, and the two key press cylinders push corner keys into both ends of the frame member.

Each press has a block attached to the cylinder rod that presses the key into the frame. The block is designed to hold the stack of keys up while pressing. When the cylinder retracts, gravity causes the stack to fall, automatically loading the next key in the press.

The short frame feeder subassembly includes a carriage and hot melt sealant dispensers that are similar to those used in the long frame feeder. Once the keys are pressed into the ends of the frame members, the pick-and-place mechanisms transport the frames from the key presses to the carriage for sealant dispensing. The carriage assembly has two pairs of pneumatic clamps to hold two frame members in place. The clamps mount on rails that allow adjustment to match the length of the frame member.

The carriage slides on linear ball bushings on precision shafts, powered by a servomotor-driven belt. The carriage moves two short frame members at constant velocity past two nozzles that dispense a bead of hot melt sealant into a channel in each frame member. Adjustments are provided for nozzle angle, horizontal (x and y) and vertical positions.

The hot-melt sealant dispensing system includes a heated tank, a sealant pump, two dispensing nozzles with valves, and two heated hoses to deliver sealant from the tank to the nozzles. The tank has a capacity of 22.7 kg (50 lbs) of sealant. Sealant low and empty sensors were added to the tank. If the sealant level drops to the low sensor position, the operator is alerted to add more sealant to the tank, although the machine continues without interruption. If the sealant level reaches the empty sensor position, the operator is alerted and the machine stops until the sealant tank is refilled.

After sealant is dispensed, each carriage hands off two frame members to the Cartesian robot for transport to the frame press. The four-axis (x, y, z, and θ) robot transports an end-effector with four mechanical grippers that hold two frame members. Frame members are picked up from either the long or short frame carriage and placed in one of four positions in the frame press: the moving and stationary sides of the long frame press, and the moving and stationary sides of the short frame press. Long frame members are rotated 90° before placement in the press.

Vertical and horizontal compliance was designed into the robot end-effector to relax tolerance requirements and provide gentle parts handling when placing frames in the press. A mechanical clutch is installed between the end-effector and the robot to protect the robot from damage should a collision occur.

The end-effector design was modified to enable process improvements identified when process flow charts were developed. A vertical linkage was designed for each pair of grippers, driven by a pneumatic cylinder. This allows the robot to place one frame member at a time in the frame press, even if a module is lifted up into the press. This allows two long frame members to be pressed onto a module before two short frame members are loaded into the press, thereby reducing the time that the hot melt sealant cools in the long frame members before pressing. In addition, the machine cycle time is reduced, since the long frame members can be pressed while the robot retrieves two short frame members from the short frame carriage.

The end-effector has a pair of horizontal slides, which allow the frame sections to be gently placed into position in the frame press. The slides also correct for any small rotational errors. This horizontal motion was maintained after the two vertical linkages were added to the end-effector by coupling the piston ends of the cylinders to the grippers with rollers that ride in tracks on the gripper support brackets.

The frame press design in shown in Figure 26. As the robot places each frame member in the press, air actuated clamps close to hold the frame member in place. Pneumatic cylinders extend to press the frame members up against the edges of the module laminate. Ball bushing slides provide support and prevent the press from racking as it moves. A higher force cylinder is used for the short frame members because it also presses the corner keys attached to the short frame members into the ends of the long frame members.

Regardless of module size, the module is always aligned in one corner of the press, near the point where the moving side of the short press meets the stationary side of the long press. The three frame support blocks on each side of the short frame press are mounted on rails so their positions can adjusted to suit the length of the short frame member. The long frame press has frame member supports that do not need adjustment to accommodate different size frame members, although the positions of the frame clamps can be adjusted. The positions of the support rails for the stationary side of the short press and the moving side of the long press are adjustable, to suit the lengths of the long and short frame members.

After the long and short frame members are pressed onto the module, the two moving sides of the press retract and ejection pins push the module away from the frame supports at the two stationary sides of the press. The module is now free to be lowered down onto the belt conveyors when the five lift cylinders retract. If the downstream process is ready to receive a module, as indicated by a SMEMA interface signal, the belt conveyors and the output roller conveyor are turned on to transport the module out of the trimming station.

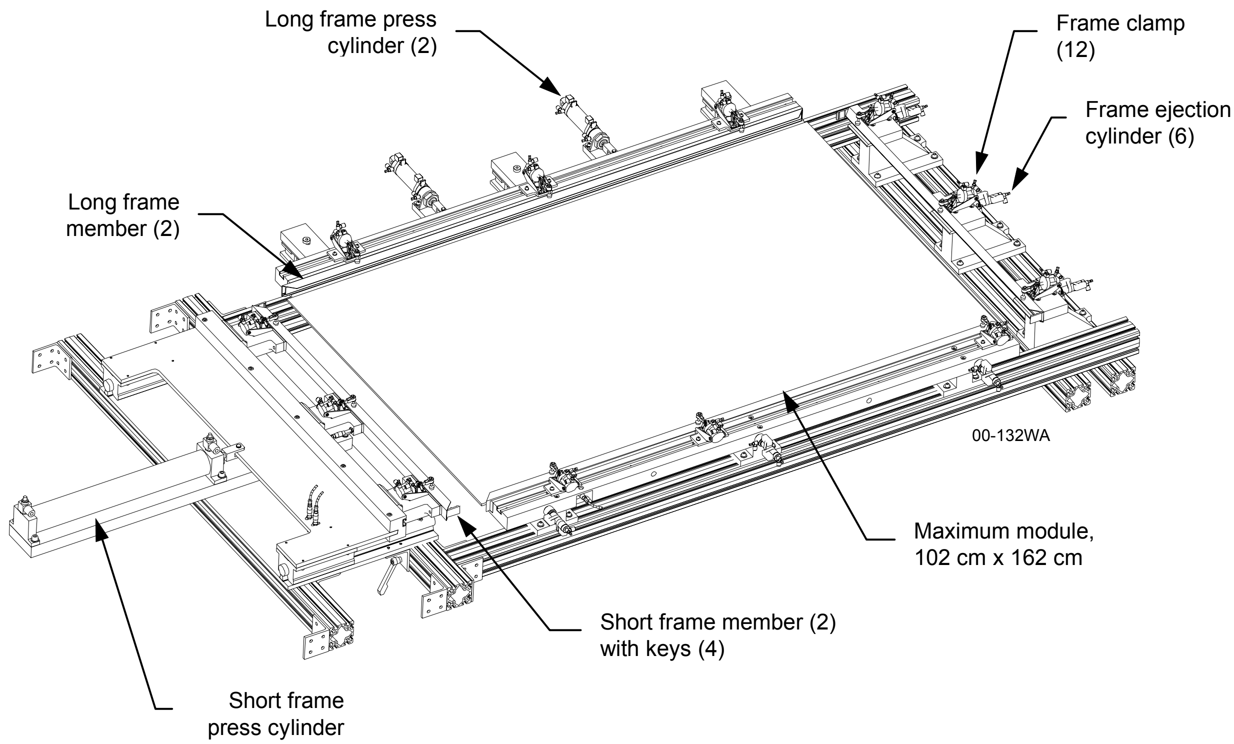

Figure 26 Two-axis frame press subassembly.

The sealing and framing machine can be divided into four interdependent subsystems that function in parallel: the short frame subsystem, the long frame subsystem, the Cartesian robot, and the conveyors and frame press subsystem. A top-level flow chart for these processes is provided in Figure 27. Detailed flow charts were also developed for each of these four subsystems. These flow charts were used as the basis for specifying sensors and controls and for developing the operating software.

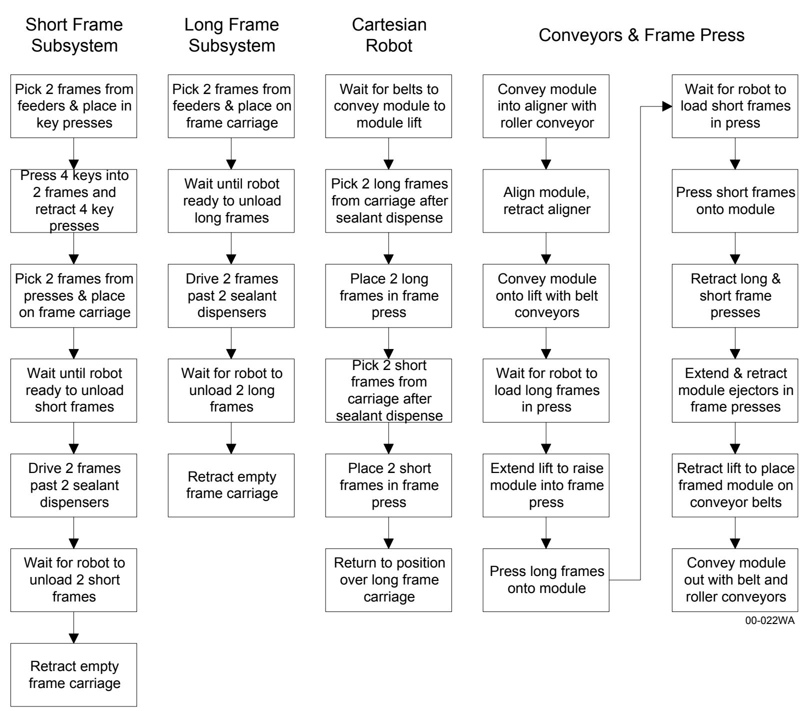

Figure 27 Top-level process flow chart for the module framing system.

A control system block diagram for the framer is provided in Figure 28. The main controller is an industrial PC running a Microsoft Windows NT operating system. An Ethernet connection links the PC with two process controllers for servo motor control and handling digital I/O. Like the trimming system, the framer uses the SMEMA electrical interface to communicate with upstream and downstream automation.

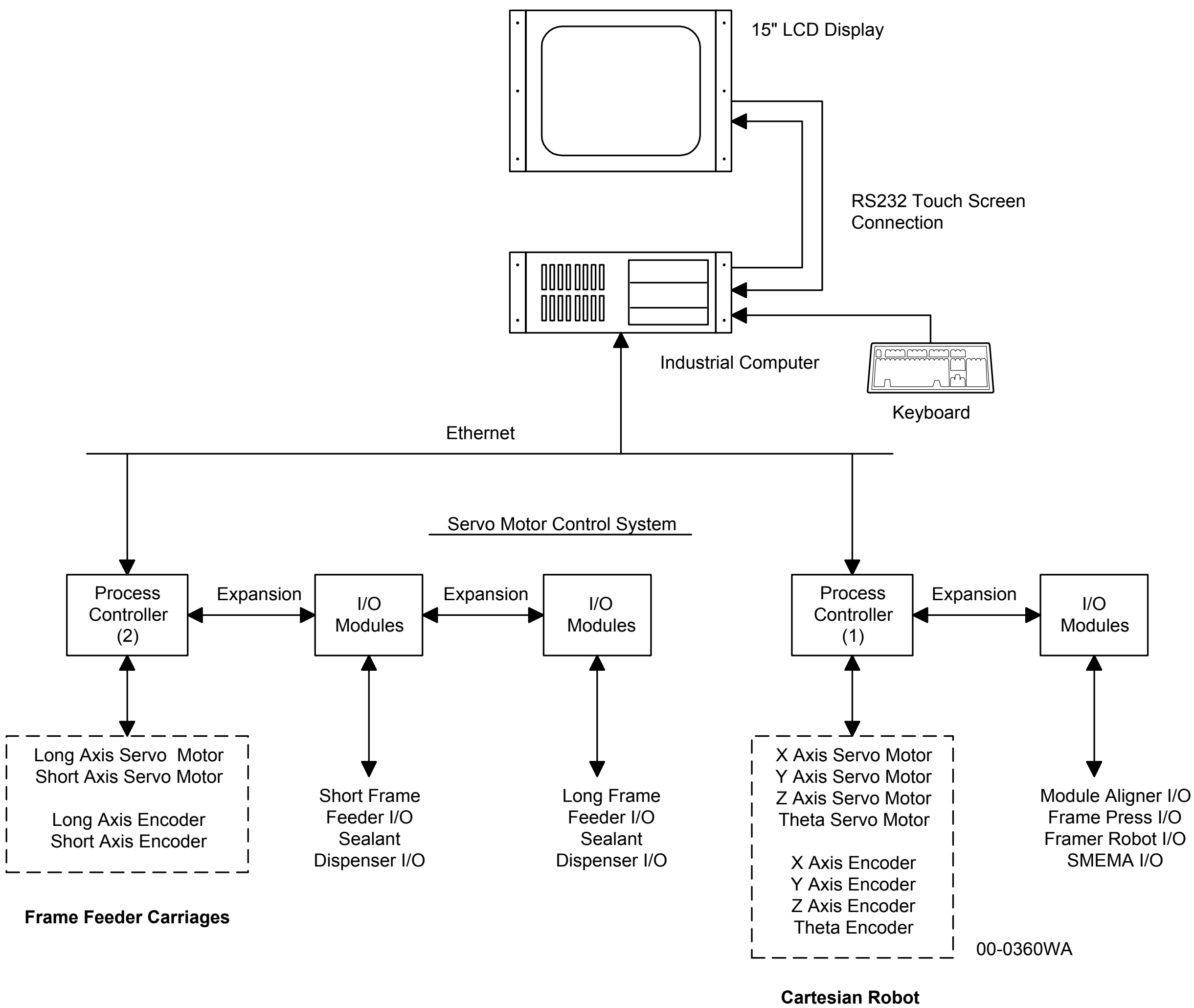

Figure 28 Framer control system block diagram.

The main structural frame is enclosed with panels and doors that are electrically interlocked to protect personnel from crushing hazards due to the robot and its end-effector. Transparent acrylic panels are provided in key locations to allow the machine to be observed in operation. Safety guards and devices are also provided to protect personnel from pinch points in the long and short frame loader, key press, and frame carriage areas. Emergency stop buttons are installed around the perimeter of the machine.

A light tower with red, yellow, and green lights indicates the machine status, as described previously in Table 5. The light tower is mounted at the highest point of the machine, on top of the robot frame, for visibility in the factory.

Spire's engineering group created 3-D design models for the mechanical assemblies using Autodesk's Mechanical Desktop solid modeling software. From these models, detail drawings were produced for fabricating parts and mechanical assembly drawings were produced to direct the manufacturing group during assembly. A pneumatic schematic was created to document the compressed air and vacuum systems. Electrical wiring drawings and electrical panel layout drawings were created.

The machine control and user interface software was written in Visual Basic. A touch screen provides the main operator interface. The main operating window is shown in Figure 29. Process parameters are set on a separate screen, shown in Figure 30.

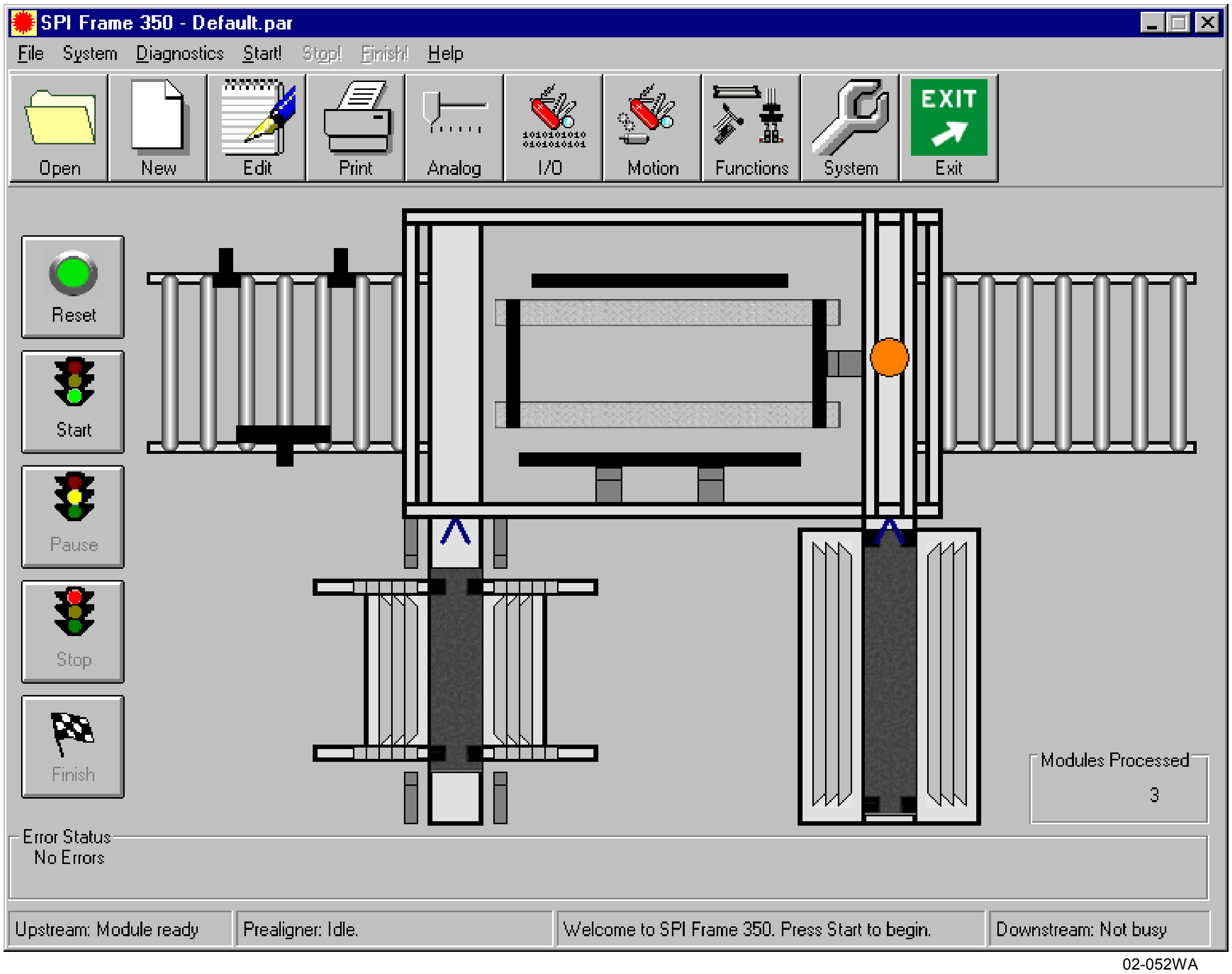

Figure 29 Main operating window, framer.

A system parameters window is provided to set servo motor parameters, such as acceleration, velocity, and home positions, for each of the four Cartesian robot axes and the two frame carriage drive motors. Diagnostics screens were also created to view the status of inputs and outputs. The diagnostics screens allow the outputs to be operated manually (by pressing buttons on the touch screen) to test them for proper operation or to make adjustments for setup or maintenance purposes.

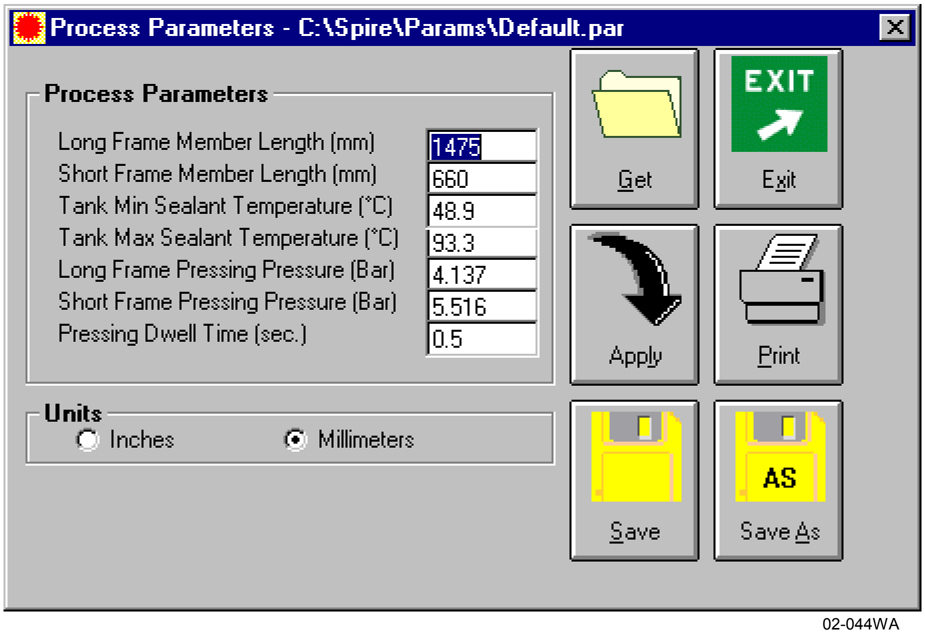

Figure 30   Process parameters window, framer.

2.6 Task 6 - Initial Fabrication of Edge Process System

The automated module edge process system consists of both the trimming system and the edge sealing and framing system. The trimming system was fabricated under Task 6 in Phase 2 of this program, while the edge sealing and framing system was fabricated under Task 7 in Phase 3.

The module trimming system consists of a number of subassemblies. When the design of each subassembly was completed, a bill of materials was created and the parts were released for fabrication and procurement. Parts were received, inspected, kitted, and issued to manufacturing for assembly. Mechanical, electrical, and pneumatic systems were assembled and tested. Software was installed and the control system was debugged. Once operational, the trimming process was developed and evaluated with laminates from several PV manufacturers.

The completed automated trimming system, designated the SPI-TRIM™ 350, is shown in Figure 31. Major components of the system include conveyors for module transport, a module aligner, a module lift, and a 4-axis (x, y, z, θ) Cartesian robot with an end-effector for module edge sensing and trimming. The system can process module sizes ranging from 30 cm x 91 cm up to 102 cm x 162 cm.

The input conveyor and aligner are shown in Figure 32. The module lift system and the robot end-effector are shown in Figures 33 and 34.

00-0713WA

Figure 31 SPI-TRIM 350 automated module edge trimmer, with module laminate at aligner on in-feed conveyor.

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Figure 32 Input conveyor and aligner.

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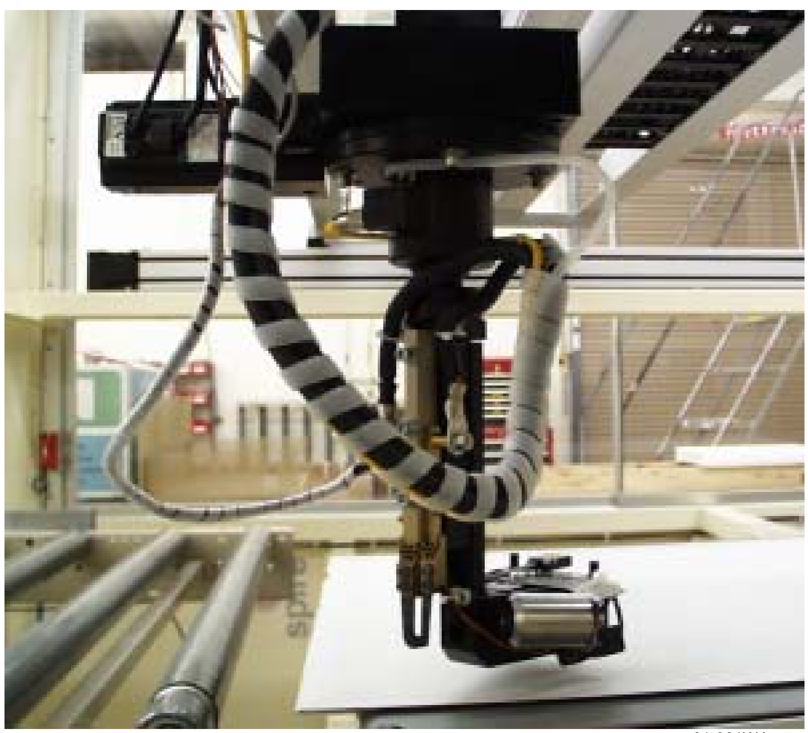
Figure 33 Module vacuum lift, retracted under belt conveyors.



01-061WA

Figure 34 Edge trimmer robot end-effector.

Significant work was done on software testing and trimmer process development using laminates made at Spire and others provided by AstroPower (Newark, DE), BP Solar (Frederick, MD) and Siemens Solar Industries (Camarillo, CA). Several improvements were made to the robot end-effector as a result of this testing:

- The plate that holds the fiber optic sensors was redesigned to spread the fibers apart from each other and move them further from the end-effector's axis of rotation. The new arrangement was found to be more reliable in sensing glass edges.
- The optical fibers used for edge sensing hang below the sensor bracket and, during tests, they caught on a module corner and broke. A protective cover was designed, fabricated and installed on the end-effector to prevent this damage.
- The thermocouple used to sense hot knife temperature did not provide an accurate reading of the temperature on the blade's cutting surface. The thermocouple was attached to one of the blade mounting screws, but the mounting point is significantly cooler than the cutting surface. Since the thermocouple could not be mounted closer to the blade without interfering with the cutting process, a non-contact infrared sensor was installed on the end-effector to monitor the blade temperature.
- Variations in laminate flatness cause the light from the optical sensors to defocus, which reduces edge detection accuracy. New lenses for the fiber optics were obtained with a longer usable range to reduce this effect. In addition, a capacitive proximity sensor was installed that provides a non-contact means to sense the glass height at each edge sensing location. This allows the robot to automatically compensate for laminate flatness variations, but the added sensing step increases the process time.

Figure 35 is a photograph of two BP Solar laminates, one before and one after edge trimming. The laminates are made with 3.2 mm thick x 497 mm x 1097 mm tempered glass, EVA encapsulant, and a thin (38 μm) blue Tedlar[9] back sheet. No solar cells were included in the laminates, but otherwise the materials and processes used to fabricate them were identical to production modules. The edges of the laminate at the left are typical for these modules after lamination and prior to edge trimming. Note the back sheet and encapsulant that extend beyond the glass edges. The edges of the laminate on the right have been trimmed on the SPI-TRIM 350. A 1 to 2 mm border of encapsulant and back sheet remain on the glass edges after trimming.

Figure 35 BP Solar laminates before (left) and after (right) trimming with SPI-TRIM 350.

The SPI-TRIM 350 was videotaped as it automatically trimmed several 432 mm by 972 mm laminates. The cycle time was consistently measured at 1 minute 42 seconds. The process was divided into five steps, listed in Table 11. Process A is the baseline process we measured. If step 4, transport module out of the trimming zone, is done concurrently with step 5, transport module in and raise up on lift, there is an immediate 8 second reduction. In addition, if height sensing is eliminated, the time for step 1 decreases, resulting in a 1 minute 19 second cycle time, shown as process B in Table 11.

Table 11 Trimmer cycle time for four processes.

Step No.	Description	Process Time (min:sec) A	B	C	D
1	Sense four edges	0:43	0:28	0:08	0:00
2	Trim four edges	0:30	0:30	0:30	0:40
3	Module down on conveyor	0:04	0:04	0:04	0:04
4	Module out	0:08	0:00	0:00	0:00
5	Module in & up on lift	0:17	0:17	0:17	0:17
	Total cycle time	1:42	1:19	0:59	1:01

If four sensing heads are mounted on the machine, one near each corner of the laminate, the robot will not need to travel around the module for edge sensing, so the time for step 1 is further reduced. This is process C, which has a 59 second cycle time. Finally, if no edge sensing is done and the hot knife is allowed to cut the laminate along the glass edge, the cycle time is estimated at 1 minute 1 second (process D). The cycle and step times are shown graphically in Figure 36.

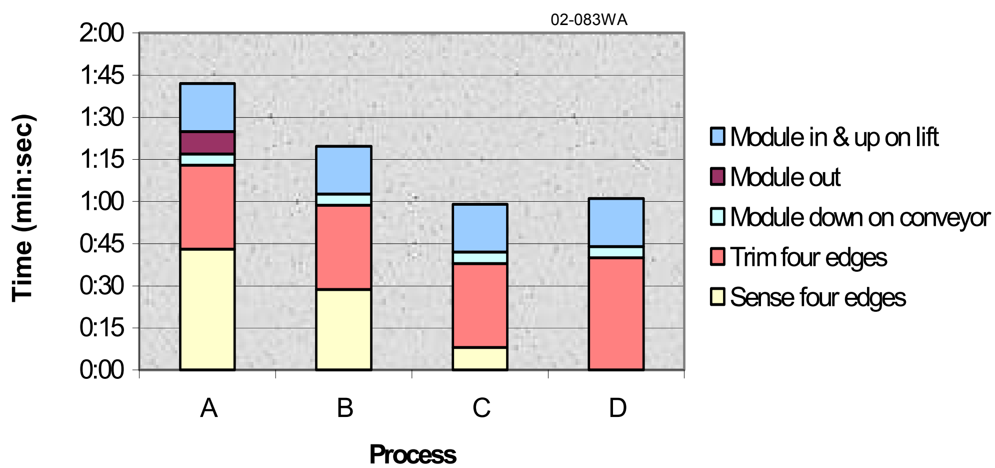


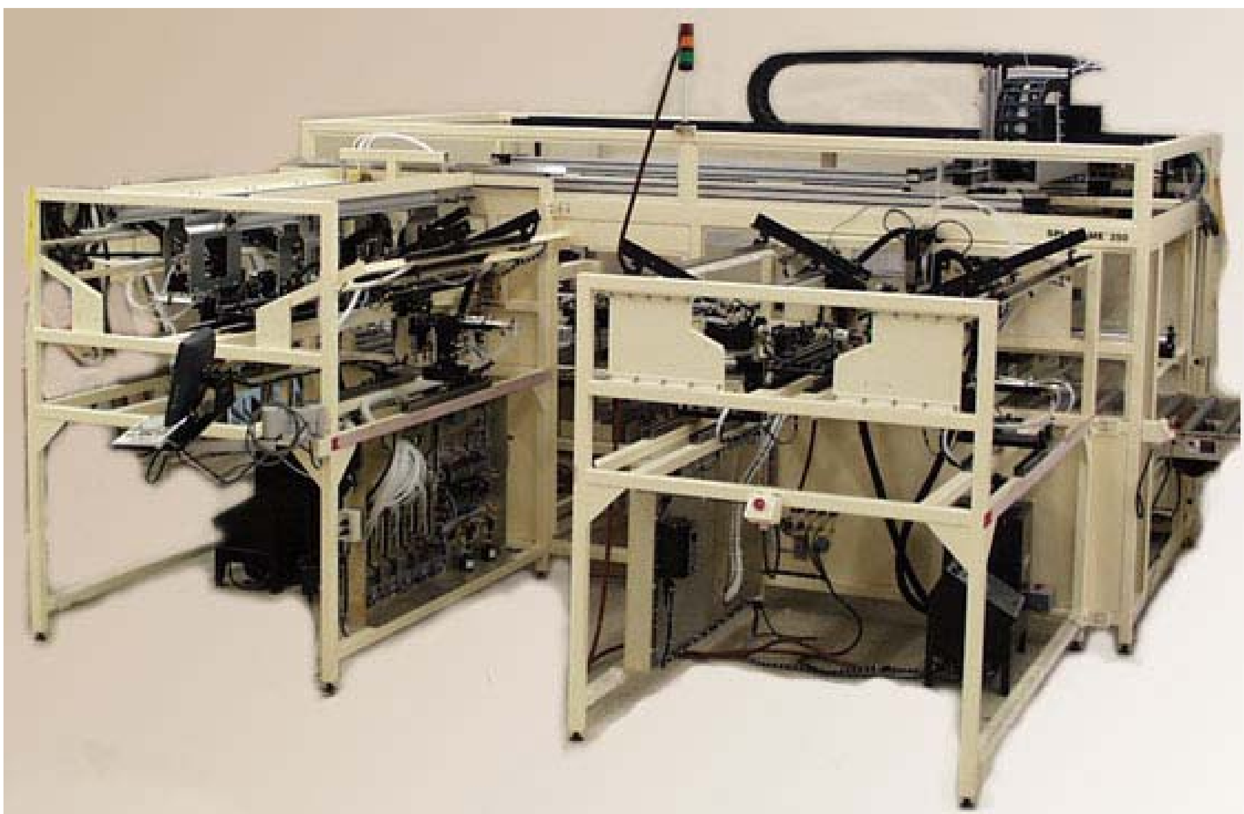
Figure 36 Trimmer process cycle time for four processes.

Process D would require a redesign of the end-effector to allow compliant side loading of the blade. This approach was considered early in the trimming system design task, but it was rejected because cutting against a glass edge causes rapid blade wear, requiring frequent blade changes. Two cuts are required for each side, because the edge location is not known until the blade becomes side loaded. This increases the trimming time compared to the other three processes. Process D could be more robust than the other processes, since the optical edge sensing is eliminated. It is likely that automated blade changing would have to be developed, to prevent excessive downtime.

2.7 Task 7 – Fabricate and Integrate Edge Framer System

An automated module edge sealing and framing system was fabricated under Task 7 in Phase 3. The edge sealing and framing system consists of a number of subassemblies. When the design of each subassembly was completed, parts were fabricated, procured and inspected. Mechanical, electrical, and pneumatic systems were assembled and tested. Software was installed and the control system was debugged. Once operational, the edge sealing and framing processes were developed and evaluated.

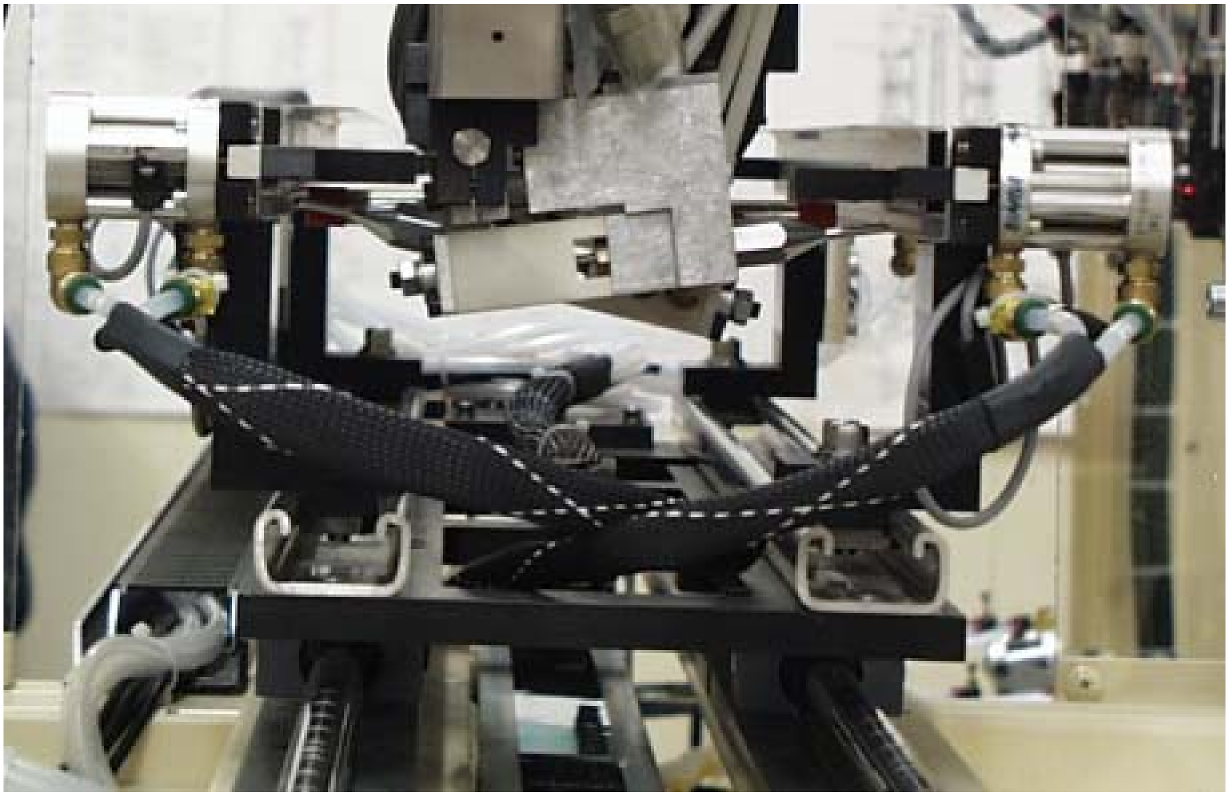
The completed edge sealing and framing system, designated the SPI-FRAME™ 350, is shown in Figure 37. The system includes a conveyor system and lift for module transport, a module aligner, automatic feeders for short and long frame sections, corner key feeders, corner key presses, hot melt sealant dispensing systems, a two-axis pneumatic frame press, and a four-axis (x, y, z, θ) Cartesian robot for transporting frame members to the press. The system can process module sizes ranging from 30 cm by 91 cm (12 inch by 36 inch) up to 102 cm by 162 cm (40 inch by 64 inch).



02-043WA

Figure 37 SPI-FRAME 350 automated module edge sealer and framer.

The hot melt sealant nozzles for the short frame sections are shown in Figure 38. The frame press is shown in Figure 39 and the robot end-effector is shown in Figure 40.



02-084WA

Figure 38 Sealant dispense nozzles over short frame carriage.

02-085WA

Figure 39 Two-axis frame press.

02-072WA

Figure 40 Framer robot end-effector.

System tests and process evaluations resulted in a number of improvements made to the system:

- Frames slipped in the robot grippers when the robot transported and rotated the long frames. The problem was solved by enlarging the gripper contact area and covering it with a high-friction material (silicone rubber).
- The weight of the stack of frames in the frame feeders applied a side load on the vacuum transport arm that was sufficient to bend the vacuum cups, causing the automatic frame feeding process to fail. Retractable stack stops were designed to prevent this problem.
- The sealant dispensing nozzles were unable to apply enough sealant volume into the frame sections in the required time, so a new set of nozzles was obtained that increased the orifice diameter from 1.3 mm (0.050”) to 2.3 mm (0.090”). The larger nozzles allowed the desired sealant volumes to be dispensed in the frames at a reasonable shuttle velocity.

Significant work was done to adjust the machine mechanically and in software for proper parts alignment during pressing. The module laminate alignment system was tested and found to be sufficiently accurate for locating the laminate in the press. This system includes a mechanical aligner for the laminate’s long axis and rotation, and a two-step optical sensing method that works with a two-speed conveyor belt control to align the laminate’s short axis.

The software window used to select process parameters for sealing and framing laminates is shown in Figure 30. A parameter file is created to save the parameters used to process each type of module. The process parameters include:

- Long and short frame member lengths, used for synchronizing the sealant dispensing valves with the motions of the long and short frame carriages, and used when calculating robot positions for picking up and placing frame members.
- Minimum and maximum sealant temperature values, used by the operator to set up the two hot melt sealant dispensing units.
- Long and short frame pressing pressures, used as a reference by the operator to setup the corresponding air pressure regulators.
- Pressing dwell time, the amount of time the press cylinders stay in their extended positions before retracting.

Sealant dispensing process development was done for injecting a bead of sealant in a channel in the short and long frame sections. Process parameters include the temperatures of the sealant tanks, hoses and dispensing valves, the valve pressure, the sealant pump speed, the sealant nozzle diameter, the nozzle position (height, distance, and angle) with respect to the frame, and the frame shuttle velocity. Each of the sealant tanks was filled with several 2.3-kg (5-lb) blocks of Q-17, a hot-melt glazing material from Q'So, Inc. (Saginaw, TX).

The temperature of the two tanks and four hoses was set to 177°C. The temperature of the four dispensing valves was increased from 177°C (350°F) to 193°C (380°F) to prevent "stringing," the formation of thin strands of sealant between the nozzle and the frame section after the valve closes. The nozzles were installed at an upward angle, approximately 30° above horizontal, to prevent sealant from dripping when the valves are closed. Once consistent sealant dispensing was achieved at the nozzles, sealant valve openings and closings were synchronized with the leading and trailing edges of each of the four frame members, as the long and short frame shuttles move the frames past the nozzles. Figure 41 shows a short frame section that had corner keys pressed and sealant applied automatically.

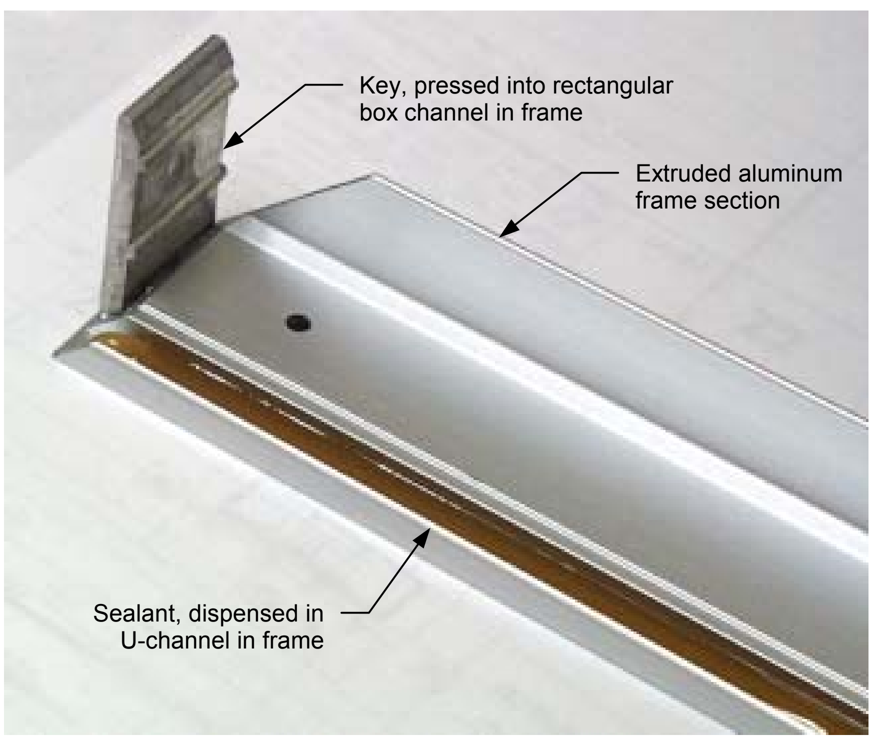


Figure 41 Short frame section with corner key inserted and hot-melt sealant dispensed automatically by the SPI-FRAME 350.

A simple but effective test was done to determine how long it takes for the hot-melt sealant to cool and become too viscous to form around the laminate edges during frame pressing. Sealant was dispensed into a frame section and the sealant was probed repeatedly with a small wooden rod until the sealant became too hard to deform easily. By this method we determined that we have 30 to 35 seconds from the time the sealant is dispensed to the time when the frame sections must be pressed onto the laminate. Subsequent evaluations of the automated process showed that both the long and short frames are pressed onto the laminate within this time window.

Several modules were sealed and framed automatically by the SPI-FRAME 350. AstroPower provided module laminates, short and long frame sections, and corner keys for use in the edge sealing and framing process evaluations. Each laminate consists of 36 solar cells, 155 mm square, laminated between tempered glass and plastic back sheet with ethylene vinyl acetate (EVA) encapsulant. The module size after framing is 659 mm x 1475 mm (25.94 inch x 58.06 inch).

One of these modules is shown on the output conveyor in Figure 42. The system frames the module facedown, as shown in the left photo in Figure 42. A front view of the same module is shown in the right photo in Figure 42. Close-up views of framed module corners are shown in Figure 43. The machine cycle time is approximately 90 to 105 seconds per module, although the sequence was not yet fully optimized.

02-047WA

Figure 42 Module sealed and framed automatically, on the output conveyor of the SPI-FRAME 350. Module is processed facedown, as shown at left. Module is shown face-up at right.

02-048WA

Figure 43 Framed module corners, front (left) and rear (right) views.

2.8 Task 8 – Junction Box Process Development

The electrical junction box (J-box) provides a means for connecting a module to external system wiring and optionally provides a place for installing one or more by-pass diodes for reverse bias protection. PV module manufacturers typically design custom J-boxes for their own use. The J-box must conform to Underwriters Laboratory (UL) requirements if the module is to be UL listed.[5] Multi-Contact, an electrical connector manufacturer, produces a J-box for PV modules that is UL listed: model PV-JB/2-UR. A photo of this box is shown in Figure 44. Spire selected this box for use in Tasks 8 and 9 because it is the only commercially available UL listed junction box.

00-0611WA

Figure 44 Multi-Contact junction box, model PV-JB/2-UR, with cover open (scale is in cm).

ARRI, under subcontract to Spire Corporation, assisted in the design and development of an automated work cell for the installation of a J-box on the back surface of a solar module. ARRI developed prototype J-box installation processes on an AdeptOne (SCARA) robot platform. These processes include module surface preparation, module connector tab lift up, sealant bead dispense, and J-box placement on top of the sealant bead.

Installation of diodes in the J-box was beyond the scope of this work. Equipment for feeding, forming, and inserting diodes is commercially available for the electronics industry. This equipment could be used to install diodes in J-boxes prior to the J-box installation step.

The J-box cover was not installed as part of this process. While it would be a relatively simple task for the robot, an installed cover would interfere with final electrical testing (for electrical isolation and module performance) and final visual inspection.

2.8.1 Surface Preparation

A robotic alcohol dispensing process was developed for a wet brush to clean the module back surface in preparation for adhesive dispensing. An alcohol dispense robot end-effector was designed and fabricated, as shown in Figure 45. The end-effector includes a quick-change tool plate, a diaphragm valve, a valve bracket and a dispensing tube with a soft bristle tip. The quick-change tool plate allows the robot to select from a variety of different end-effectors, as needed. Each end-effector is mounted on a tool rest when not in use.

Isopropyl alcohol is supplied to the valve from a reservoir that is slightly pressurized (3 to 5 psig). At this pressure, the alcohol is dispensed at the proper rate, which is approximately one drop every five seconds. A robot software routine was written such that alcohol is dispensed during only the first of three brush passes on the target surface. On each pass, the brush follows the same path where the sealant will be dispensed.

02-086WA

Figure 45 Alcohol dispense end-effector.

2.8.2 Sealant Dispensing

A silicone sealant dispensing process was developed to apply sealant to the back surface of a module, for attaching and sealing a J-box. A sealant dispense robot end-effector was designed and fabricated, as shown in Figure 46. The end-effector includes a quick-change tool plate, a piston valve, a valve bracket and a tapered dispensing tip.

02-087WA

Figure 46 Sealant dispense end-effector.

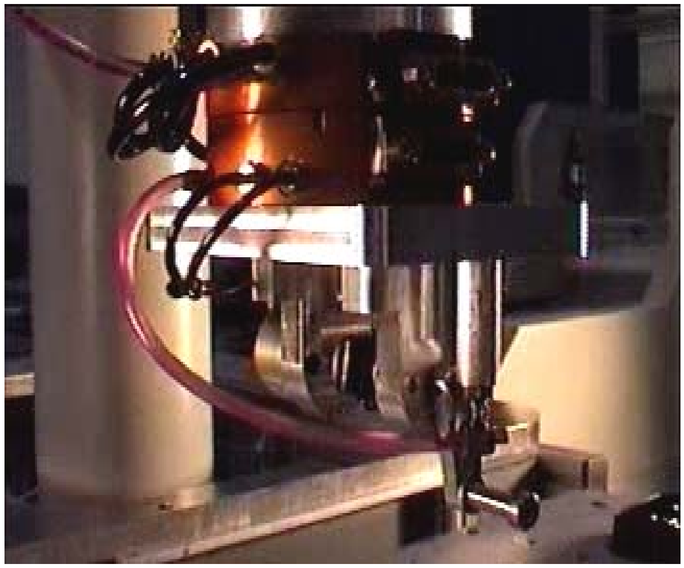
Through a series of experimental tests, optimal parameters for the dispensing operation were determined to provide proper sealing between the J-box and the module. The objective is to obtain a good seal while minimizing material consumption. Sealing quality is controlled by the size of the silicone bead and the amount of pressure applied to the J-box during placement on the module. The required bead size can be achieved by controlling the sealant supply pressure, tip speed, distance to target and angle of inclination. A constant-force feature was designed into the pick-and-place end-effector to control the pressure on the J-box.

A robot software routine was written to dispense sealant in a pattern to match the Multi-Contact J-box. Several beads of sealant ranging in diameter from 1 mm to 5 mm were dispensed onto a glass plate. J-boxes were placed on top of the beads and subjected to varying degrees of pressure. The 4 mm and 5 mm beads produced proper seals with a 0.45 kg (1 lb) load; however, excessive sealant flow occurred in both cases. The 3 mm bead yielded reduced flow, yet still provided a sufficient seal and a visible, consistent bead around the box perimeter. Therefore a 3 mm bead was recommended with a 0.45 kg (1 lb) load on the J-box. This combination will provide an adequate seal with minimal material waste. Once the J-box has been pressed onto the silicone bead, moderate material handling of the module will not disturb the location of the J-box.

ARRI used syringes and cartridges for the sealant dispense prototype development. Although the results are adequate and confirm the viability of the process, these reservoirs have insufficient volume to support the unattended production runs required for factory use. ARRI recommended the use of dispensing equipment with much larger reservoirs, such as 18.9 l (5 gallon) pails.

2.8.3 Contact Tab Lift

A process was developed to lift up module contact tabs from an as-laminated (horizontal) position to an upright (vertical) position. A tab lift robot end-effector was designed and fabricated, as shown in Figure 47. The end-effector includes a quick-change tool plate, a small 90° pneumatic rotary actuator, a swing arm and a spring-loaded vacuum cup.



02-088WA

Figure 47 Tab lift end-effector, with swing arm in down position.

Spire produced several module laminates with contact tabs extending through slits in the back sheet, and provided them to ARRI for process tests. The tabs were left flat after lamination. ARRI wrote robot software and successfully demonstrated the tab lift process. With the swing arm set to its up position, the robot places the vacuum cup on one of the module tabs, near the loose end of the tab. Vacuum is turned on and the tab is lifted a short distance (approximately 1 cm) above the module surface. The swing arm rotates 90° to its down position, which positions a metal rod under the tab, just above the module surface. The vacuum is released, allowing the tab to rest on the rod, and the robot moves the rod towards the place where the tab extends out from the module. This motion causes the rod to bend the tab to an upright position.

2.8.4 J-box Pick-and-Place

A process was developed to pick up a J-box, move it to the proper location over the module and place it with controlled force for a selected time for proper sealant flow. A J-box pick-and-place robot end-effector was designed and fabricated, as shown in Figure 48. The end-effector includes a quick-change tool plate and a parallel gripper mounted on a linear slide.

02-089WA

Figure 48 J-box pick-and-place end-effector.

A bracket holds the stationary side of the linear slide in a vertical position. The moving side is attached to the parallel gripper with two blocks that provide the dead weight required for sealant flow. The gripper fingers are sized to provide an interference fit for an inside grip of the J-box when fully extended. Horizontal compliance is provided by the compression of rubber pads on the gripper fingers and a slight outward deflection of the J-box walls.

A robot software routine was written to implement the J-box pick-and-place process. The process was successfully demonstrated with Multi-Contact J-boxes.

2.8.5 J-box Redesign for Robotic Assembly

A review of the current method of module contact tab attachment to the Multi-Contact J-box has established that it is unsuitable for automation. However, any changes to the J-box are constrained by the fact that (1) the J-box is already UL recognized in its present form, and (2) the changes must be justified based on potential sales orders.

In the present design, a tool must be inserted in the connector block to open each contact while a ribbon is inserted into the contact. A new idea proposed by Multi-Contact would allow the connector blocks to mate with the module tabs through a special contact strip without tool or ribbon insertion. In this scheme, the module tabs would not have to be lifted, and the J-box installation would be accomplished via simple top-down placement.

This solution is highly compatible with automation. In this case, the automation process would have to apply sufficient contact pressure between the terminal contact strip and the module tabs. This might involve the use of fast-curing adhesives or a method of providing pressure while curing takes place, such as a weight, a clamp, or a primary, but not long-term, adhesive.

2.9 Task 9 - Develop Junction Box Installation System

The design concepts and prototype processes developed in Task 8 provided the basis for the design and fabrication of a production-scale automated junction box installation system in Task 9. Spire incorporated the four end-effector design concepts provided by ARRI (described in Task 8) along with subassemblies for module transport, module alignment, J-box dispensing, and a robotic arm to produce an overall design for the J-box installation system. A safety enclosure and electrical and pneumatic controls were also designed. The junction box installation system design is shown in Figure 49.

Design work was completed for all mechanical subassemblies. Components were fabricated, procured and assembled. Process flow charts were created for the main system (Figure 50) and the J-box feeders, to guide the development of software and electrical controls. Electrical and pneumatic designs were completed, and assembly of these systems is nearly complete. A photo of the system, designated the SPI-BOXER™ 350, is provided in Figure 51. Task remaining to complete the J-box installation system are software for machine control and user interface, final electrical and pneumatic assembly, power-up, test, and process evaluations.

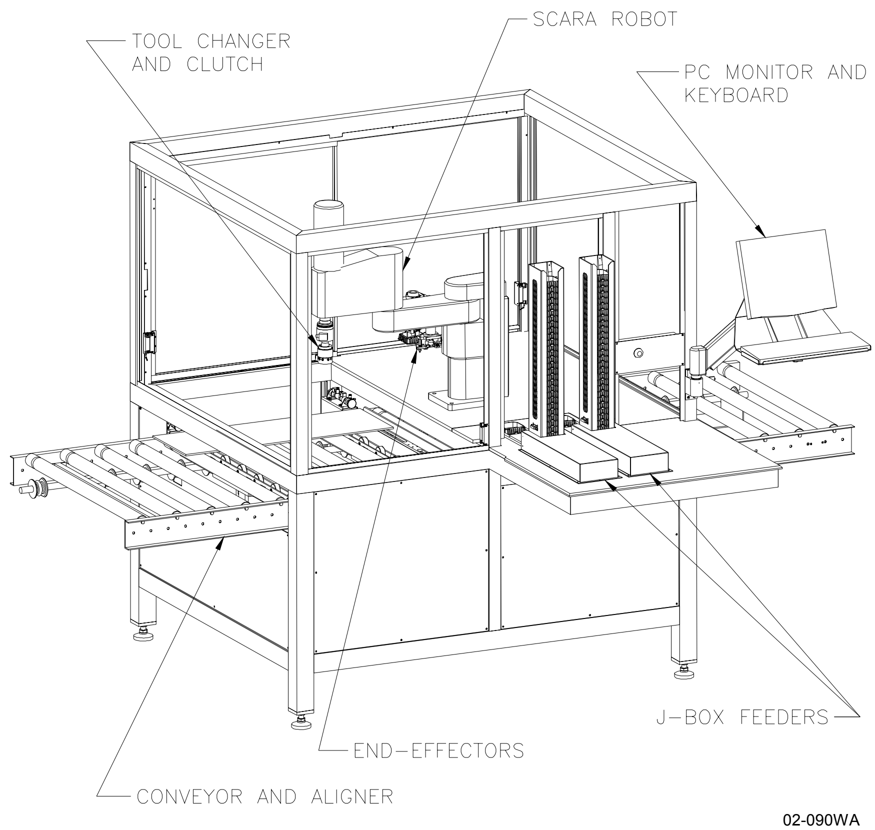


Figure 49 Junction box installation system design.

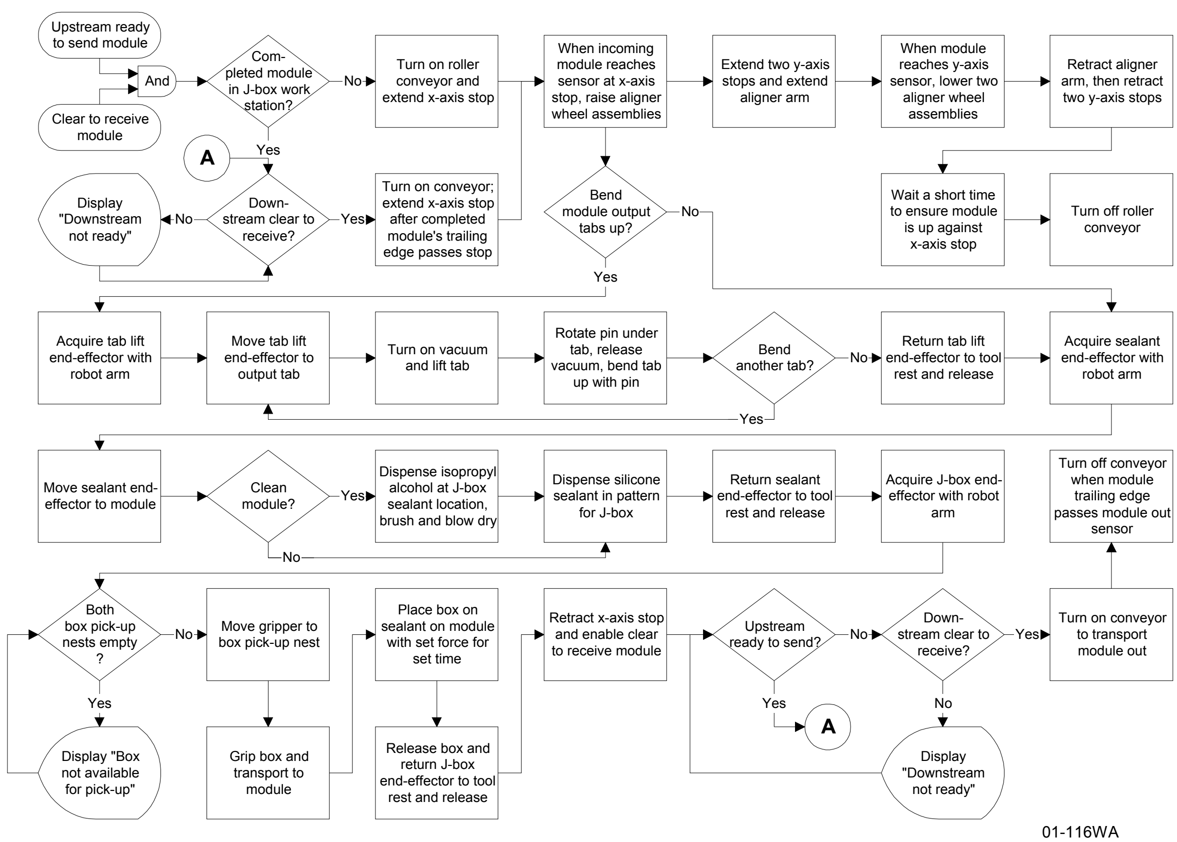


Figure 50 Main process sequence, J-box installation system.

02-073WA

Figure 51 SPI-BOXER 350 J-box installation system.

2.9.1 Junction Box Feeder

The original plan for dispensing junction boxes was to use a simple gravity feeder with a plunger that pushes out the bottom box in a stack. However, discussions with Multi-Contact indicated that there could be a box redesign in which a contact strip extends slightly below the bottom of the box. This contact strip would catch on the side of the box if dispensed using the original concept. An escapement mechanism was added to the gravity feeder to solve this problem. The escapement has a pair of opposing fingers that hold the stack of boxes up when a box is dispensed to the robot pick-up location.

The feeder design is shown in Figure 52. The operator loads boxes into a stack holder that has stack low and stack empty optical sensors. An air cylinder mounted under the tabletop drives a plunger. The escapement is also air operated. A protective cover was designed to shield personnel from exposure to pinch points caused by the plunger and the escapement mechanisms.

The J-box feeder process is as follows:

1. A plunger pushes a box from the bottom of the stack to a nest for robot pick up.
2. The escapement fingers open to drop the stack of boxes onto the plunger body.
3. The escapement closes to grip the second box from the bottom of the stack.
4. The plunger retracts, allowing only the bottom box to drop down to the tabletop, in the position required for step 1.

Given the throughput goal of one box per minute for the system and the desire to limit the frequency of loading to once per hour, the feeder must have a capacity of 60 J-boxes. However, since the Multi-Contact J-box is 24 mm high, the top of a stack of 60 boxes would be too high for an operator to reach: approximately 251 cm (8 ft 3 inch) above the floor. Therefore, two box feeders were included to reduce the top of the stack to a manageable 179 cm (5 ft 10 inch) above the floor.

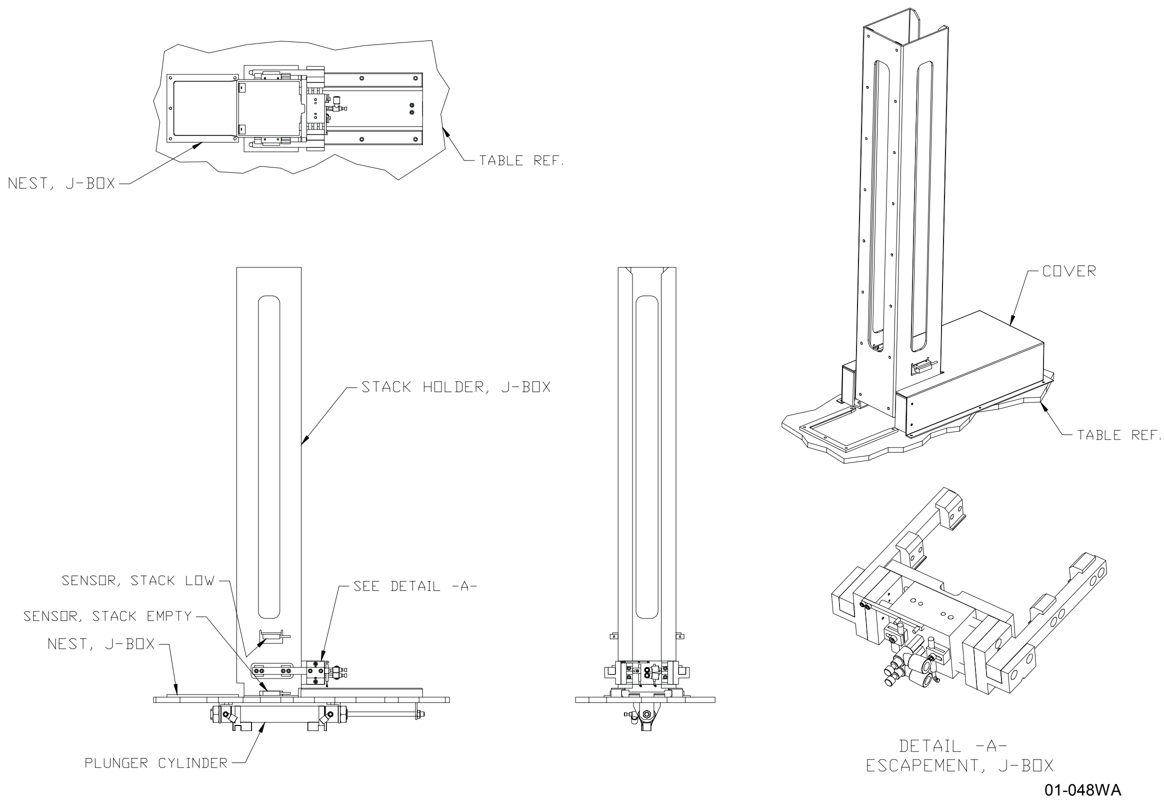


Figure 52 Junction box feeder assembly design.

2.9.2 Clean and Dispense End-effector

The clean and dispense end-effector applies alcohol with a soft brush to clean the area where sealant will be dispensed, and then dispenses a bead of sealant on the module to attach and seal the junction box. The end-effector design is shown in Figure 53.

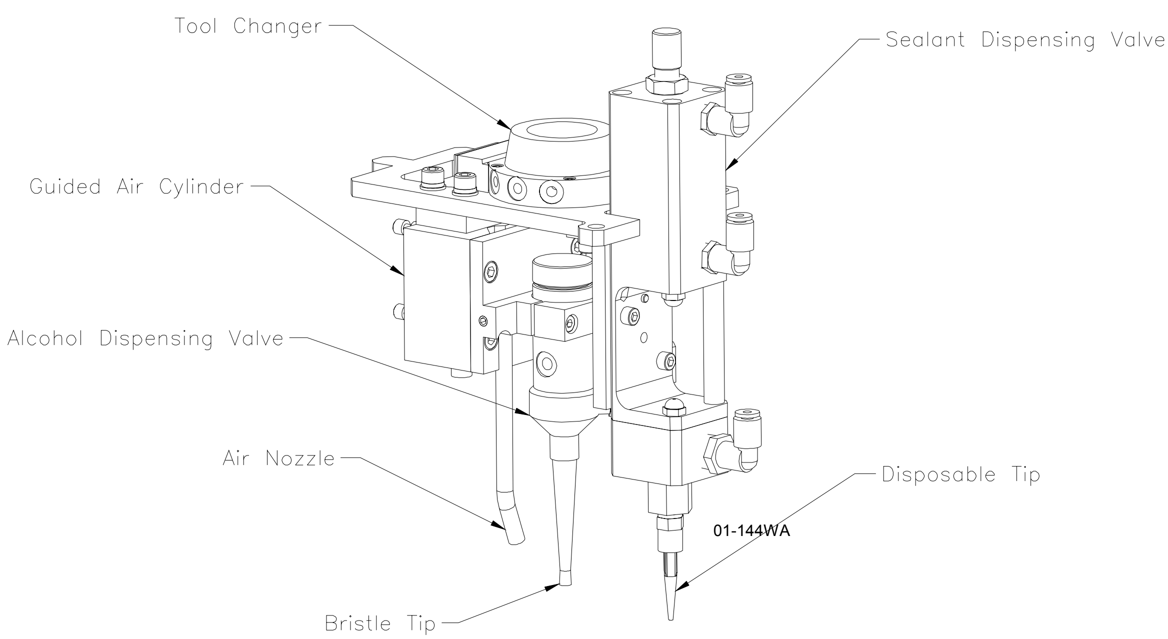


Figure 53 Robot end-effector design for cleaning and sealant dispensing.

ARRI used two separate end-effectors, one for cleaning and one for sealant dispensing, in its process development work. Since both operations require a tethered fluid supply, Spire combined them into a single end-effector with a common tether, to eliminate the possibility of fluid line entanglement. This dual-purpose end-effector will also reduce cycle time, since there is no need for a tool change between the cleaning and sealant dispensing operations. An air nozzle was added so that compressed air can be used to dry the alcohol quickly after cleaning. The end-effector is shown in Figure 54.

Figure 54 Robot end-effector for cleaning and sealant dispensing.

The alcohol dispensing components include a one-liter pressurized reservoir, diaphragm dispensing valve, and soft bristle tip. The reservoir was modified to add a float switch that automatically detects when the alcohol supply is low. The dispensing valve is mounted on a guided cylinder that is extended (down) during cleaning and retracted (up) during sealant dispensing.

The prototype sealant dispensing process demonstrated by ARRI used a sealant cartridge mounted on the end-effector. While this approach was acceptable for demonstration purposes, there are two drawbacks in production: the limited sealant supply requires frequent reloading, and the robot must be disabled during reloading to prevent injury.

The volume of sealant in a standard 305 ml (10.3 fl. oz.) cartridge is sufficient to mount approximately 120 J-boxes, assuming a 3 mm diameter bead and a 36 cm box perimeter (Multi-Contact PV-JB/2-UR box). At a system throughput of one module per minute, cartridges have to be replaced after every 2 hours of operation. Sealant is also available in 18.9 liter (5 gallon) pails. These pails contain enough sealant to mount approximately 7400 J-boxes, equivalent to 123 hours of operation, under the same process conditions listed for the cartridges.

A commercially available sealant pumping systems was identified for dispensing silicone directly from a 5-gallon pail. The pail and the pumping system are located outside the safety-guarded area for the robot, so replacing the pail can be done without stopping the robot. The sealant is transferred from the pump to the valve on the end-effector through a tethered hose.

2.9.3 Tab Lift End-effector

The tab lift end-effector design is shown in Figure 55. This design is similar to the ARRI prototype design, except for the addition of a pin position sensor and an extension to allow the robot to reach down to the level of the module on the conveyor.

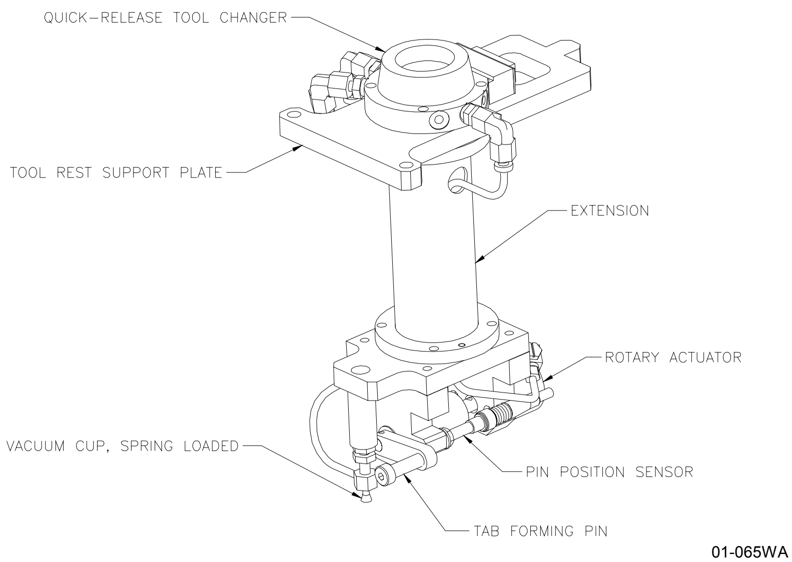


Figure 55 Tab lift end-effector design.

The robot acquires the end-effector with its quick-release tool changer, lifts the end-effector up from its tool rest, positions the spring-loaded vacuum cup on top of a module output tab, and lifts the tab up a small distance from the back surface of the module. A swing arm rotates 90° to position a tab forming pin under the tab. The vacuum is released and the robot moves the pin towards the spot where the tab extends through the module back sheet. This motion causes the tab to bend up approximately 90° from the surface of the module. The process is repeated for the remaining tab(s). The robot then carries the end-effector back to its tool rest where it is released. The end-effector is shown in Figure 56.

02-092WA

Figure 56 Tab lift end-effector.

2.9.4 Junction Box End-effector

The junction box gripper end-effector design is shown in Figure 57. The tool changer, tool rest, and gripper are similar to ARRI's prototype design. However, the weighted ball slide used to apply pressure to the sealant was replaced with a guided air cylinder. This design makes it easy to adjust the amount of pressure applied to the box by adjusting an air pressure regulator.

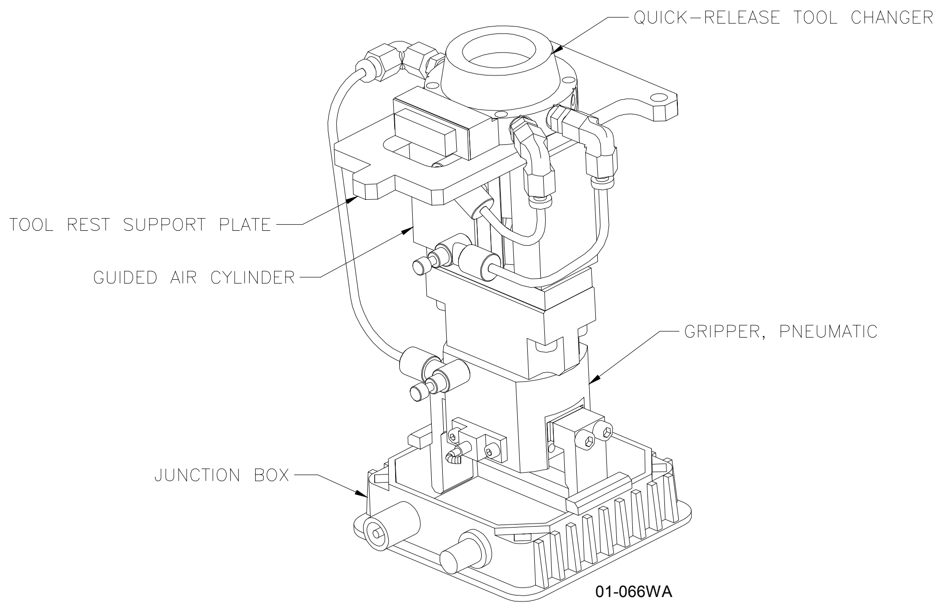


Figure 57 Junction box gripper end-effector design.

In operation, the robot acquires the end-effector with its tool changer, lifts the end-effector up from its tool rest, and positions the gripper inside a junction box located at the output of one of two box feeders. The gripper has two fingers that spread apart when air is applied to grip the box by opposing inside edges. The robot lifts the box out of the feeder and positions it over the module, directly above a bead of sealant that was dispensed on the module's back sheet. The guided air cylinder actuates to press the box down onto the sealant, which attaches and seals the box to the module. After a short press time, which gives the viscous sealant time to flow, the grippers retract, the guided cylinder retracts, and the robot carries the end-effector back to its tool rest where it is released. The end-effector is shown with a junction box in Figure 58.

2.9.5 Robot and Tool Rests

A mounting assembly for the robot and tool rests for its three end-effectors were designed, as shown in Figure 59. Each end-effector has a flat plate designed to sit on a three-point tool rest when the end-effector is not in use. Each tool rest has a flat post at the back and two pins at the front that line up with two holes in the end-effector plate. The pins provide the alignment needed for the robot arm to acquire the end-effector reliably. The pins are mounted on cantilevered posts that allow clearance for removing and replacing the end-effector.

Figure 58 Junction box gripper end-effector with a Multi-Contact J-box.

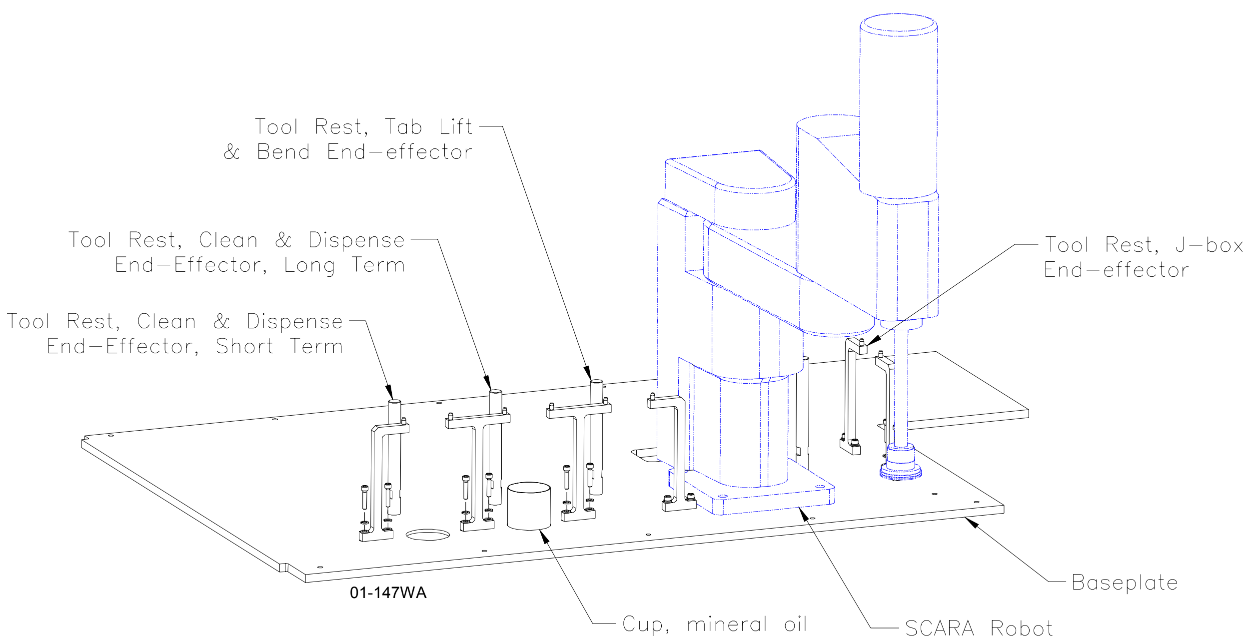


Figure 59 Robot and end-effector tool rest assembly.

The sealant dispensing end-effector has two tool rests. One, labeled "short term" in Figure 59, is used in normal production. If production is interrupted for periods of 30 minutes or more, the silicone sealant will begin to harden at the end of the dispensing tip due to exposure to ambient air. Before this occurs, the robot will be programmed to move the end-effector to the "long term" tool rest. At this position, the sealant-dispensing tip will be inserted in a cup containing mineral oil to prevent the silicone from hardening. Mineral oil is not used at the short term position because the oil must be wiped from the tip before it can be used to dispense sealant, since the oil can interfere with sealant bonding.

The four-axis SCARA robot system is shown in Figure 60. The robot controller is mounted in the electrical cabinet at the rear of the system. The controller interface panel, which includes an emergency stop button, is mounted on the frame at the front of the system. A tethered pendant plugs into the controller interface panel.

Figure 60 Four-axis SCARA robot for the J-box installation system. The robot controller is shown at right; the controller interface panel is at left.

The robot clutch and tool changer assembly design is shown in Figure 61. An adapter plate was designed to attach the assembly to the quill on the robot arm. The clutch protects the robot from damage in the event of a collision. This is the same type of clutch used to protect the Cartesian robots in the automated edge trimming and framing systems. If an end-effector strikes an object, the bottom half of the clutch pivots away from its normal position and a limit switch signals the robot to stop.

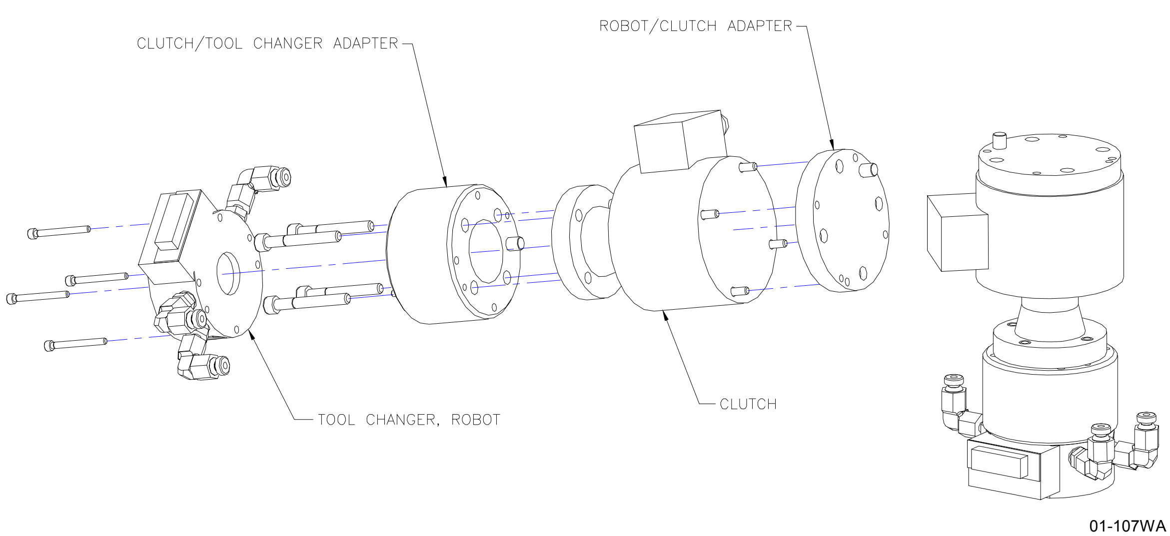


Figure 61 Robot clutch and tool changer assembly design.

An adapter ring was designed to attach the tool changer to the clutch. The tool changer consists of two parts, one part on this assembly and another mating part on each end-effector. The tool changer has a pneumatic mechanism for clamping the two parts together as well as electrical and compressed air line connections for the end-effectors.

2.9.6 Module Transport and Alignment

Subassemblies for module transport and alignment were released and fabricated with only minor modifications from previous designs developed in this program. For example, the conveyor and aligner assemblies are similar to those used in the module trimming and framing systems, while the module stop assembly was used in the module buffer system. The SMEMA handshake protocol was incorporated for communicating with upstream and downstream automation.[8]

3 CONCLUSIONS

Spire Corporation developed automated systems for PV module assembly and testing processes after lamination. These processes are applicable to a broad range of module types, including those made with wafer-based and thin-film solar cells. No off-the-shelf automation was available for these processes prior to this program.

Spire conducted a survey of PV module manufacturers that identified industry practices and determined the requirements for the automated systems developed in this program. Survey data and input from module manufacturers gathered during site visits was used to define system capabilities and process specifications.

Module edge trimming, edge sealing, framing and junction box installation processes that are suitable for automation were developed and demonstrated by Spire's subcontractor, ARRI. Spire and ARRI collaborated to define concepts for implementing these processes in production. These concepts formed the basis for developing production scale systems.

Prototype production systems that can process modules up to 102 cm by 162 cm (40" by 64") were developed. Spire completed mechanical, electrical and software engineering for four automation systems: a module edge trimming system, the SPI-TRIM 350; an edge sealing and framing system, the SPI-FRAMER 350; an integrated module testing system, the SPI-MODULE QA 350; and a module buffer storage system, the SPI-BUFFER 350. These systems were fabricated, tested, and evaluated with module components from several module manufacturers. A fifth system, for junction box installation, was designed and assembly was nearly completed during the program. Spire expects to complete this system, the SPI-BOXER 350, when additional funding becomes available.

A new size solar simulator, the SPI-SUN SIMULATOR 350i, was designed as part of the SPI-MODULE QA 350. This simulator occupies minimal production floor space, while its test area is large enough to handle most production modules. This unit has become a successful product for Spire, with thirty machines built and delivered to PV module manufacturers.

The automated systems developed in this program are designed for integration to create automated production lines. Modules are transported by conveyors and processed face down in all systems. All systems use the same standard handshake protocol to communicate with upstream and downstream automation. The processes are modular, so they can be arranged in the order desired by the module manufacturer. The use of networked controllers, as shown in Figure 62, allows real time product tracking and test data acquisition. Bar codes on the backs of modules can be used with scanners to track and assign data to individual modules by serial number.

A cost study was done by ARRI to determine the level of investment that can be justified by implementing automation for post-lamination assembly and testing processes. The study concluded that a module production line operating two shifts per day and producing 10 MW of modules per year can justify $2.37 million in capital equipment, assuming a 5-year pay back period.

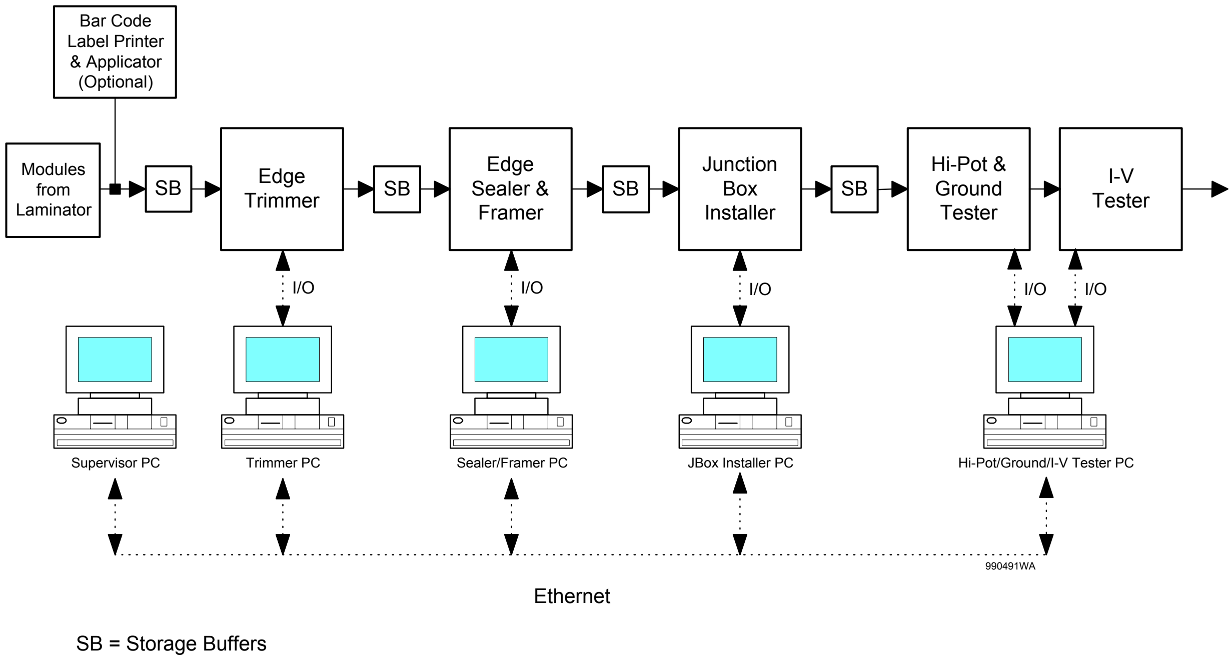


Figure 62 **An example of an automated module production line with a network for product tracking and data acquisition.**

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5 REFERENCES

1. M. J. Nowlan and W. G. Kurth, "Design Definition for Post-Lamination Process Automation for Photovoltaic Modules," Spire document No. Design-10182, October, 1998, deliverable No. D-1.2.2.

2. Maycock, P. D., *PV News*, **17**, No. 2 (1998) 2.

3. M. J. Nowlan, "Results of a Photovoltaic Industry Survey on Post-Lamination Module Assembly and Testing," Spire document No. Survey-10182, September, 1998, deliverable No. D-1.2.1.

4. M. J. Nowlan, W. G. Kurth, T. D. Harmon, T. W. McCormick, J. M. Murach, W. F. Breen, S. J. Hogan, M.R. Diver, M. I. Symko, and S. R. Rummel, "A Photovoltaic Industry Survey on Post-Lamination Module Manufacturing," *NCPV Photovoltaics Program Review; Proceedings of the 15th Conference,* Denver, CO, September, 1998; AIP Conference Proceedings 462 (1999) 725.

5. UL 1703 Standard for Safety, "Flat-Plate Photovoltaic Modules and Panels," Northbrook, IL, Underwriters Laboratory, Inc., 1993.

6. M. R. Diver, "A Cost Comparison of Manual vs. Automated Methods for PV Module Lamination, Trimming, Framing, and Testing," UTA ARRI report, January 24, 1999; program deliverable No. D-1.3.5.

7. European Standard EN 60204-1, "Safety of Machinery - Electrical Equipment of Machines, Part 1: General Requirements," European Committee for Electrotechnical Standardization (1992).

8. SMEMA Interface Standard 1.2, Surface Mount Equipment Manufacturers Association, Lafayette Hill, PA (1993).

9. Tedlar is a registered trademark of DuPont for its polyvinyl fluoride (PVF) film.

10. ASTM E 927, "Standard Specification for Solar Simulation for Terrestrial Photovoltaic Testing," Annual Book of ASTM Standards, Vol. 12.02, American Society for Testing and Materials (1997) 501.

11. ASTM E 1462, "Standard Test Methods for Insulation Integrity and Ground Path Continuity of Photovoltaic Modules," Annual Book of ASTM Standards, Vol. 12.02, American Society for Testing and Materials (1997) 751.

12. Delrin is a registered trademark of DuPont for the acetal homopolymer polyoxymethylene.

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M.J. Nowlan, J.M. Murach, S.F. Sutherland, D.C. Miller, S.B. Moore, and S.J. Hogan

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Spire Corporation
One Patriots Park
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13. ABSTRACT *(Maximum 200 words)* This report describes the automated systems developed for PV module assembly and testing processes after lamination. These processes are applicable to a broad range of module types, including those made with wafer-based and thin-film solar cells. Survey data and input from module manufacturers gathered during site visits were used to define system capabilities and process specifications. Spire completed mechanical, electrical, and software engineering for four automation systems: a module edge trimming system, the SPI-TRIM 350; an edge sealing and framing system, the SPI-FRAMER 350; an integrated module testing system, the SPI-MODULE QA 350; and a module buffer storage system, the SPI-BUFFER 350. A fifth system for junction-box installation, the SPI-BOXER 350, was nearly completed during the program. A new-size solar simulator, the SPI-SUN SIMULATOR 350i, was designed as part of the SPI-MODULE QA 350. This simulator occupies minimal production floor space, and its test area is large enough to handle most production modules. The automated systems developed in this program are designed for integration to create automated production lines.

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