



Development of Automated Processes for Large Area Photovoltaic Module Production

DOE Solar Energy Technologies Program Peer Review

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Relevance/Objectives



DOE/NREL PV Manufacturing R&D Project

▶ Objectives

- Improve PV manufacturing processes and products while reducing costs
- Develop a technology foundation that supports significant manufacturing scale-up

▶ Approach

- Develop manufacturing techniques and automation to produce large area modules for utility-scale arrays in high volume production
- Produce automated production tools for the PV industry

Program Objectives



- ▶ Design large area module for utility applications
 - Multi-megawatt grid-connected arrays
 - Minimize PV system cost (\$/W)

- ▶ Develop automated processes & equipment for large area module production
 - Thin cell soldering
 - String inspection
 - String busing
 - Materials lay-up
 - Lamination
 - Module performance testing
 - Production line SCADA system

Summary of Activities

Phase III – October 2005 to March 2007

- ▶ Task 14 – Fabricate and Test Large Area Solar Simulator
- ▶ Task 15 – Develop Computer Integrated System for Module Manufacturing
 - Subcontractor: Automation & Robotics Research Institute at the University of Texas at Arlington
- ▶ Task 16 – Development of Low-stress Cell String Assembly Processes
 - This task added at Spire's request to address industry trend towards thin ($\sim 200 \mu\text{m}$) crystalline silicon cells
 - Funding for this work diverted from Tasks 12 and 13
 - Task 12 – Fabricate and Test Advanced Laminator
 - Task 13 – Fabricate and Test Lamination Automation
 - Work terminated on Tasks 12 & 13 in March 2006



Task 14 – Large Area Solar Simulator



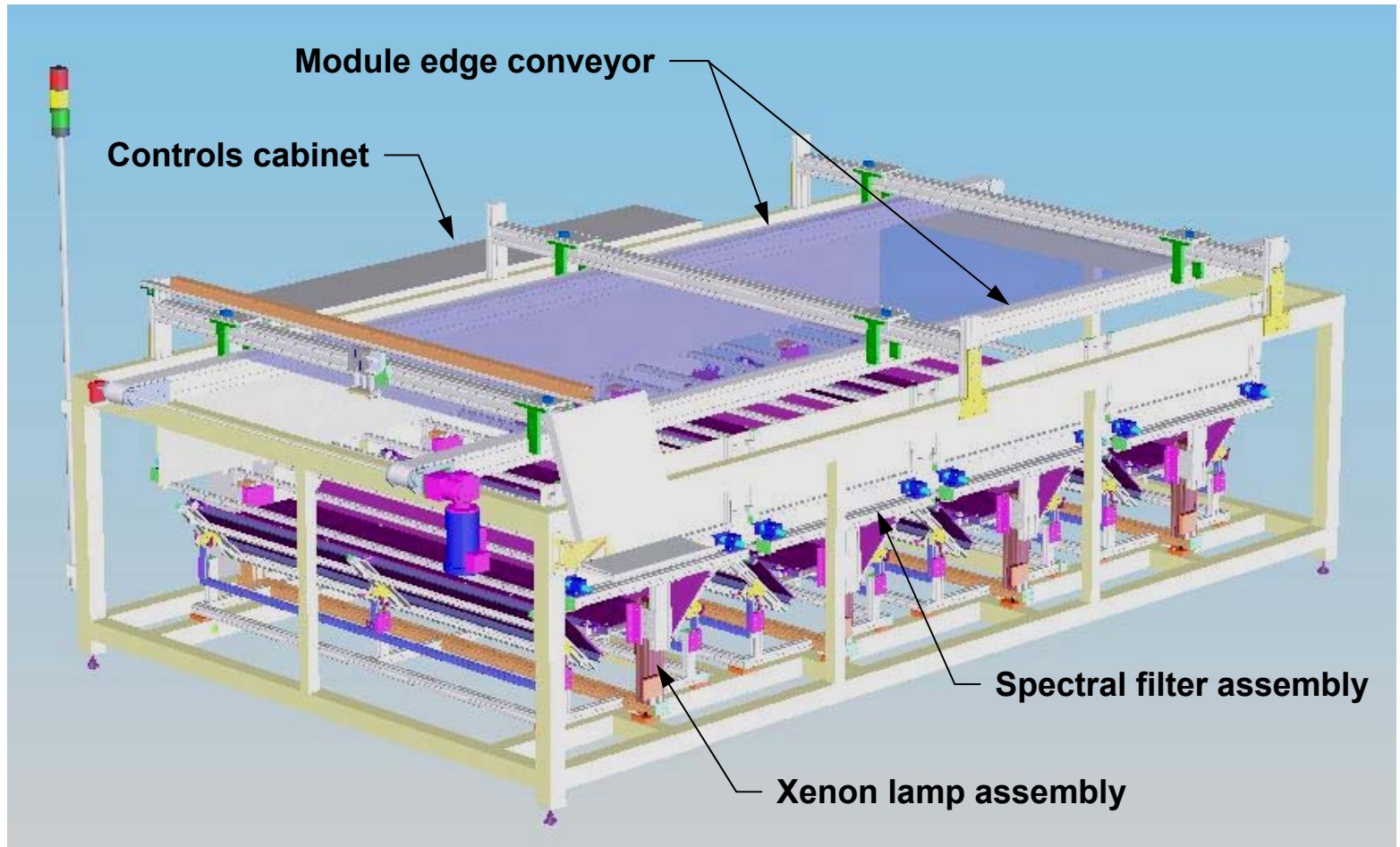
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- ▶ Capable of handling and testing 2 m x 4 m “utility scale” modules
 - Nearly 3X the size of Spire’s largest simulator (1.4 m x 2.0 m)
- ▶ Inverted design
 - Simplifies module transport automation
- ▶ Modular illumination approach
 - Single xenon lamp illuminates 2 m x 1 m test plane
 - 4 lamps → 2 m x 4 m test plane
- ▶ New reflective optics for spatial uniformity of irradiance
 - Meets Class A non-uniformity of irradiance: $\leq 2\%^*$
- ▶ Custom optical filtering for Class A spectrum*
 - NREL support for spectral measurements

**per IEC 60904-9, Photovoltaic devices - Part 9: Solar simulator performance requirements*

Large Area Solar Simulator Design

2 m x 4 m Test Area – Spi-Sun Simulator 2040 SLP



Side panels removed to show internal components

Large Area Solar Simulator

2 m x 4 m Test Area – Spi-Sun Simulator 2040 SLP



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Single Long Pulse (SLP) Solar Simulator



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- ▶ Developed new single-flash long pulse simulator
 - Previous method: multiple short (1 ms) pulses, one I-V data point per pulse, 50 to 200 pulses typical
- ▶ Full I-V curve taken in one flash, up to 100 ms long
 - Hundreds of IV data points recorded per flash
 - Curve smoothing not needed at P_{\max} for $n > 400$ points
- ▶ Measurement time reduced from ~ 20 s to < 1 s
 - Capacitor charge time is ~ 5 s
 - Charge during module load/unload
- ▶ Lamp lifetime exceeds 100,000 flash goal
 - Lamp survives 164,000 flashes in life test

Single Long Pulse (SLP) Solar Simulator



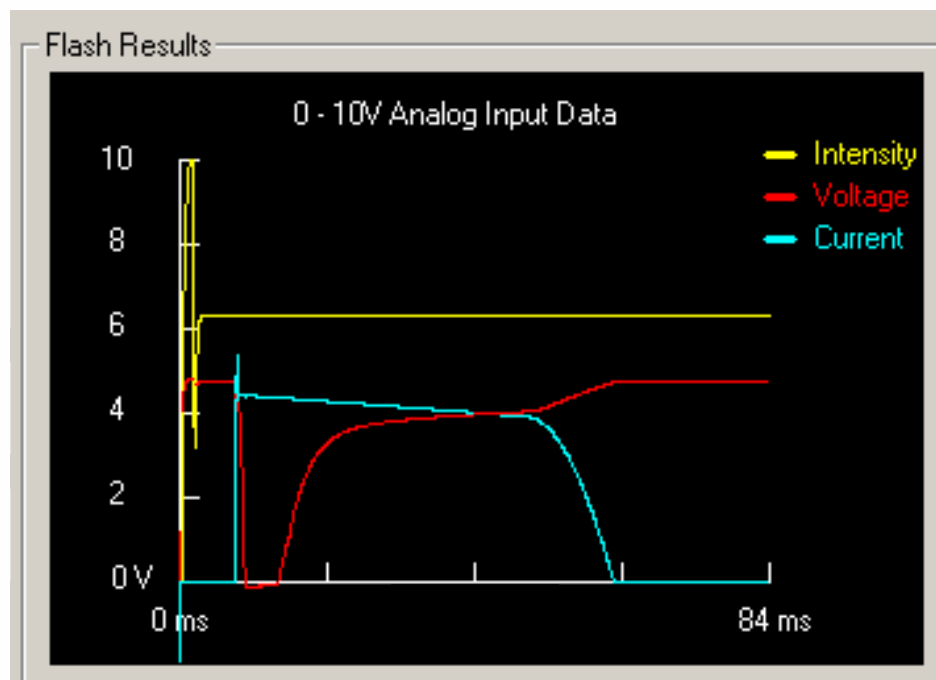
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- ▶ Closed-loop lamp intensity control developed
 - Reference cell feedback for each lamp
 - Temporal instability of irradiance $T_{IE} = \pm 0.1\%$ typical
 - Exceeds IEC Class A requirements of $\leq \pm 2\%^*$
 - Option to measure 2 I-V curves at 2 intensities in 1 flash
 - Accurate series resistance measurements, per IEC 60891
- ▶ New electronic load & measurement board developed
 - Higher power for large area modules
 - Modified for SLP operation

**IEC 60904-9, Photovoltaic devices - Part 9: Solar simulator performance requirements*

Lamp Flash with Active Intensity Control

2 m Xenon Lamp, Reference Cell Feedback



Measured lamp intensity, module voltage, module current

- 100 ms flat pulse, 1000 W/m² irradiance
- Temporal instability of irradiance $T_{IE} = 0.1\%$

Single Long Pulse (SLP) Solar Simulator

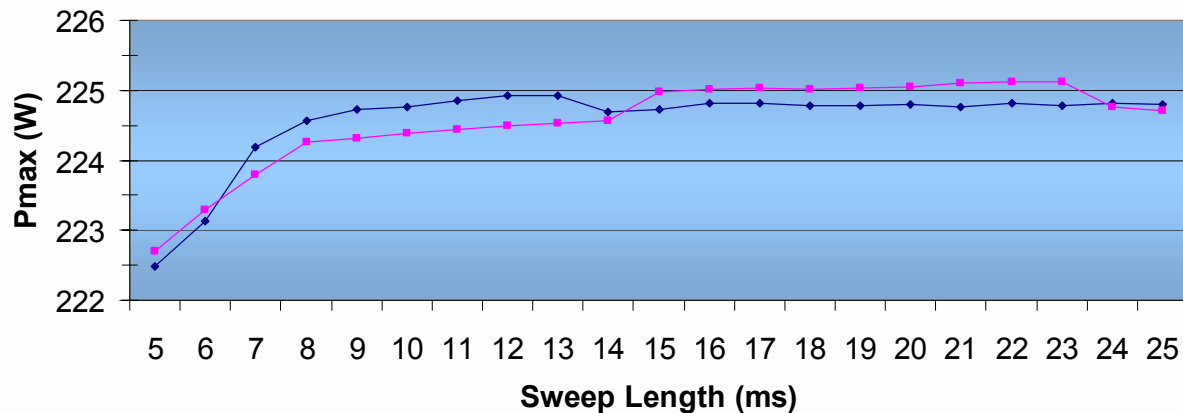
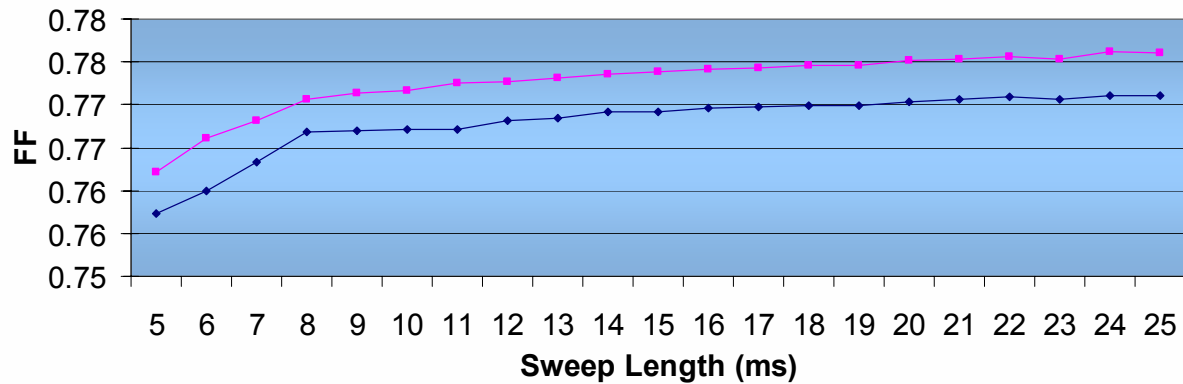


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- ▶ Thin film and high-efficiency silicon modules can exhibit artificially low fill factors when tested with short flashes
- ▶ Spire multi-pulse Simulator minimizes but does not eliminate this effect, by using slow dV/dt during I-V curve
- ▶ SLP simulator shows higher FF and P_{\max} at longer I-V sweep times

Module Performance vs. I-V Curve Sweep Time

- ▶ High efficiency crystalline Si cell modules ($\eta_{\text{cell}} = 21\%$)
- ▶ Fill factor and peak power increase with sweep time
 - Data from two modules shown



Task 15 – Computer Integrated System for Module Manufacturing



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- ▶ Develop and demonstrate Supervisory Control and Data Acquisition (SCADA) software
 - Monitoring module manufacturing processes
 - Acquiring process and test data
 - Tracking cells & modules through the production line
- ▶ Subcontractor: Automation & Robotics Research Institute (ARRI) at the University of Texas at Arlington

Major SCADA Project Subtasks



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- ▶ Analysis of typical Spire PV module production line
Glass feeder→Glass washer→EVA place→Cell string Assembler→
Busing→EVA & back sheet place→Laminator→Framer→Boxer→
Sun Simulator→Hi-pot tester→Buffer
- ▶ Survey and assessment of SCADA market
- ▶ ID key technologies and evaluate candidate industrial platforms
- ▶ Develop and demonstrate a SCADA prototype

Spire Machine Controls



- ▶ Complex machines controlled by PC with VisualBasic
 - Cell sorter, cell string assembler, etc.
 - High-quality interface designed for stand-alone operation – no standard connectivity
- ▶ PLCs used to control more traditional equipment
 - Glass washer, EVA sheeter, buffer, etc.
- ▶ Operators needed for manual steps
 - No formal data collection
- ▶ SCADA provides opportunity for line monitoring, data acquisition, databasing and control
 - Key component: providing VB variable exposure with minimal modifications to existing software

SCADA Survey Results



- ▶ May be segmented according to project size
 - Enterprise-level (large process industries): iFix, Wonderware, WinCC, RSVIEW
 - Mid-range applications: National Instruments, Parker CPC
- ▶ Equivalent functionality offered by virtually all packages
- ▶ Heavy reliance on OLE for Process Control (OPC)
 - OPC is the industry standard for Windows-based inter-process communications
- ▶ National Instruments LabVIEW with Data logging and Supervisory Control (DSC) module selected for demonstration

SCADA Prototype



- ▶ Two main development tasks
 1. Identify, learn and use toolkit to implement OPC connectivity within VisualBasic environment
 2. Develop typical (prototype) SCADA application using LabVIEW DSC with simulated machine server
- ▶ Development targeted at Spire's Cell Sorter automated solar cell tester/sorter
 - Same principles scaleable to full PV module production line

LabVIEW SCADA Demonstration



- ▶ SCADA application prototyped in LabVIEW, demonstrating access to the Spi-Cell Sorter
 - Implemented a realtime view of the Cell Sorter for basic production monitoring, alarming, safety, and control
 - Data exchanged between LabVIEW and the Cell Sorter
- ▶ Complete interface is a suite of “views”
 - Process view – manufacturing effectiveness of system
 - Throughput, utilization, downtime, events and alarms
 - Product view – manufactured product characteristics
 - Cell quantity/quality, correlation with equipment performance
 - Maintenance view – machine health monitoring, predictive maintenance

LabVIEW SCADA Demonstration



SPI-CELL TEST 1000 Supervisory Controller

Start
Stop
Calibrate

Power
Air
High Voltage

EMPTY

SAFETY (CURTAIN)

Cell count: 0

SAFETY (MAT)

Alarm & Event Display

Object Name	Set Time	Set User

Process View
Product View
Maintenance View

Main LabVIEW Development Window

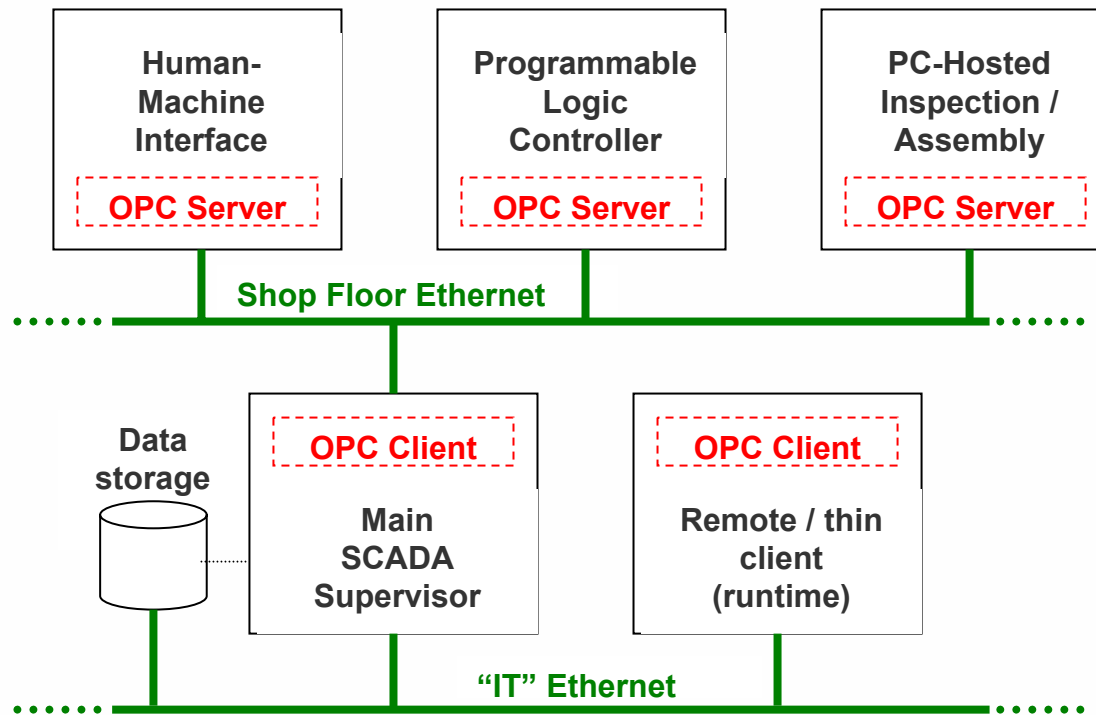
Multi-server / Multi-client SCADA

PV Module Manufacturing Line

- Glass inspection
- Ribbon feed
- Dark I/V
- Inspection/lift
- Frame press
- Lead attach

- Glass washer
- Conveyor handling
- Module buffer
- EVA cut & place
- Label printer

- Cell tester-sorter
- Assembler
- String lay-up
- Laminator
- Robotic j-box attach
- Sun Simulator



Task 16 - Low-stress Cell String Assembly



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- ▶ Develop low-stress high-throughput cell string assembly processes
 - Thin cells: 150 to 200 μm
 - High yields: $\geq 99.5\%$
 - High speeds: ≥ 1000 cells per hour
 - Cells up to 210 mm square
 - Strings up to 2500 mm long
- ▶ Develop a concept for stringing back-contact cells

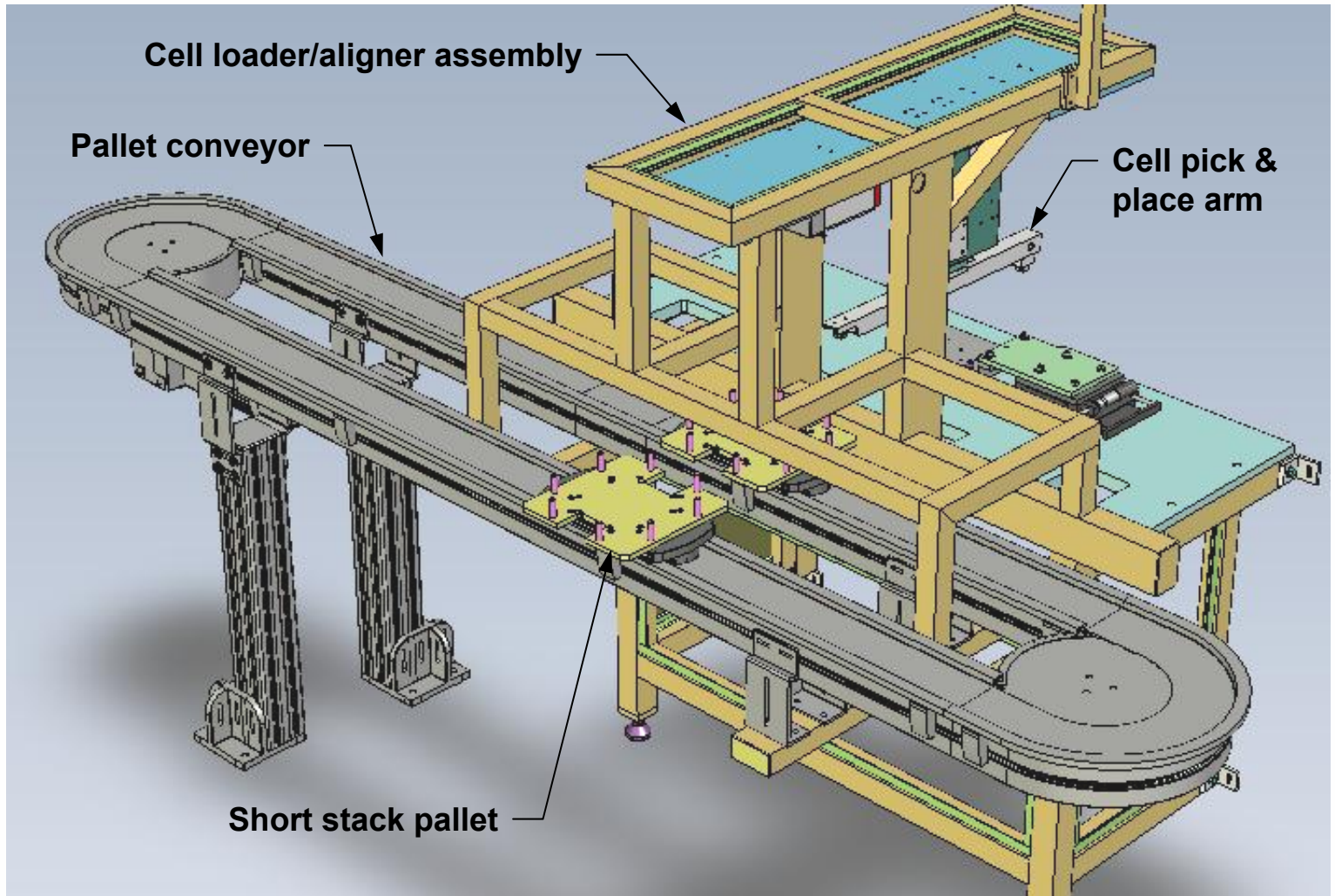
Low-stress Cell String Assembly Processes



- ▶ New cell loading assemblies designed
 - Short cell stack pallets replace tall stack cassettes
 - Stack height reduced from 150 mm to 25 mm to reduce weight on cells
 - Vertical side walls replaced with tapered pins to eliminate edge rubbing when lifting cells from stack
 - Pallet conveyor replaces tall stack shuttle
 - Provides large load capacity with short stacks
 - Compliant vacuum hand with air jets and cell flexer
 - Height compliance eliminates stack elevator
 - Air jet switching eliminates cell flutter prior to pick up
 - Jets on hand provides more reliable single-cell separation from stack
- ▶ These assemblies are being incorporated into Spire's commercial cell stringing equipment

Thin Cell Handling

Short Stack Cell Loader on Spi-Assembler 6000

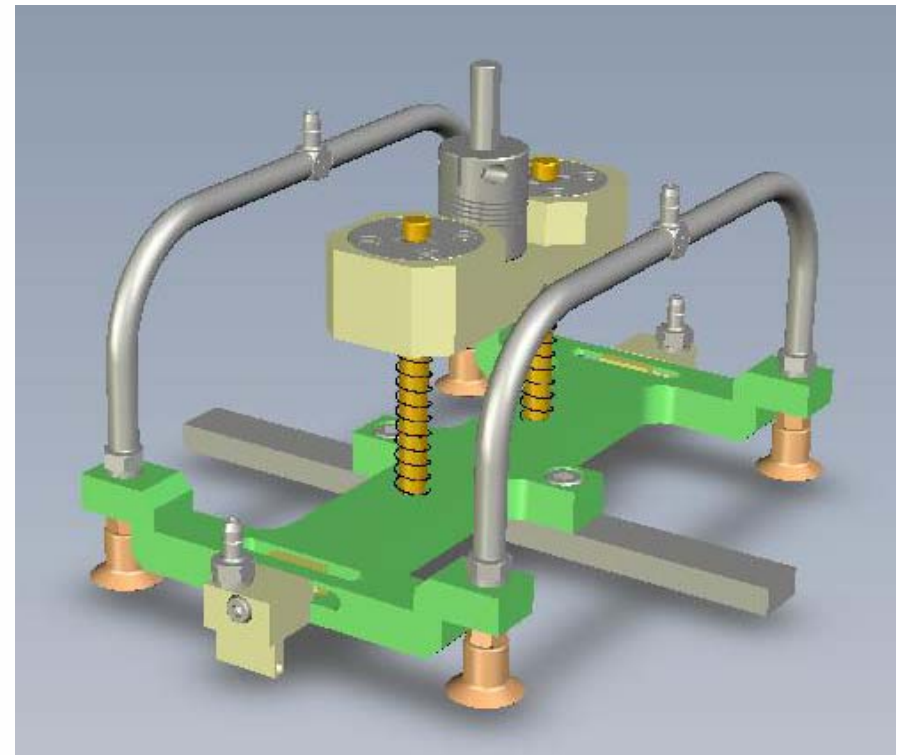
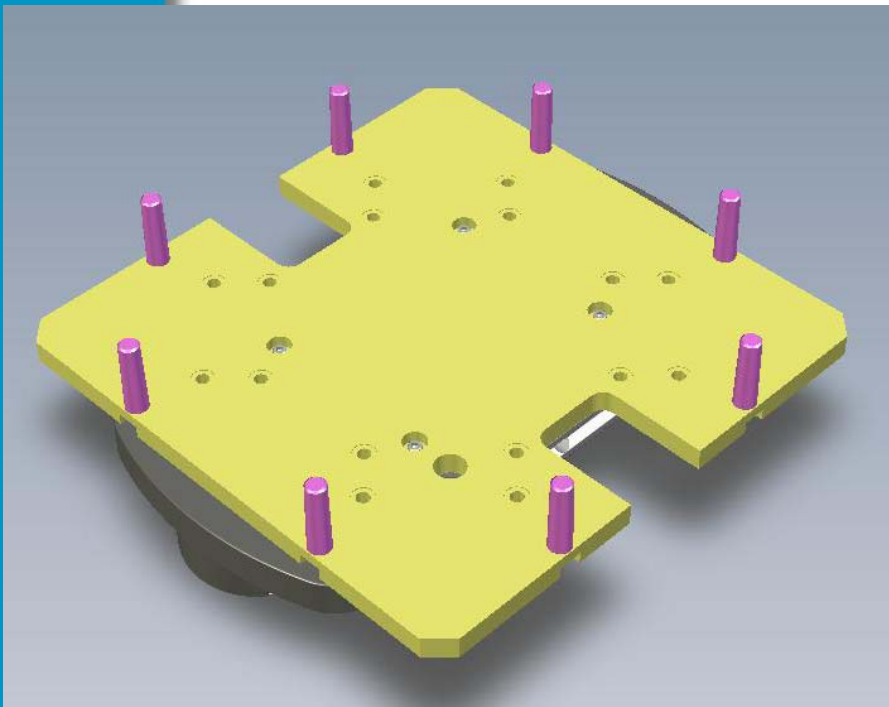


Thin Cell Handling



Pallet for short cell stacks

- Fits standard pallet conveyor
- Holds 125, 156 or 210 mm cells



Vacuum pick-up hand

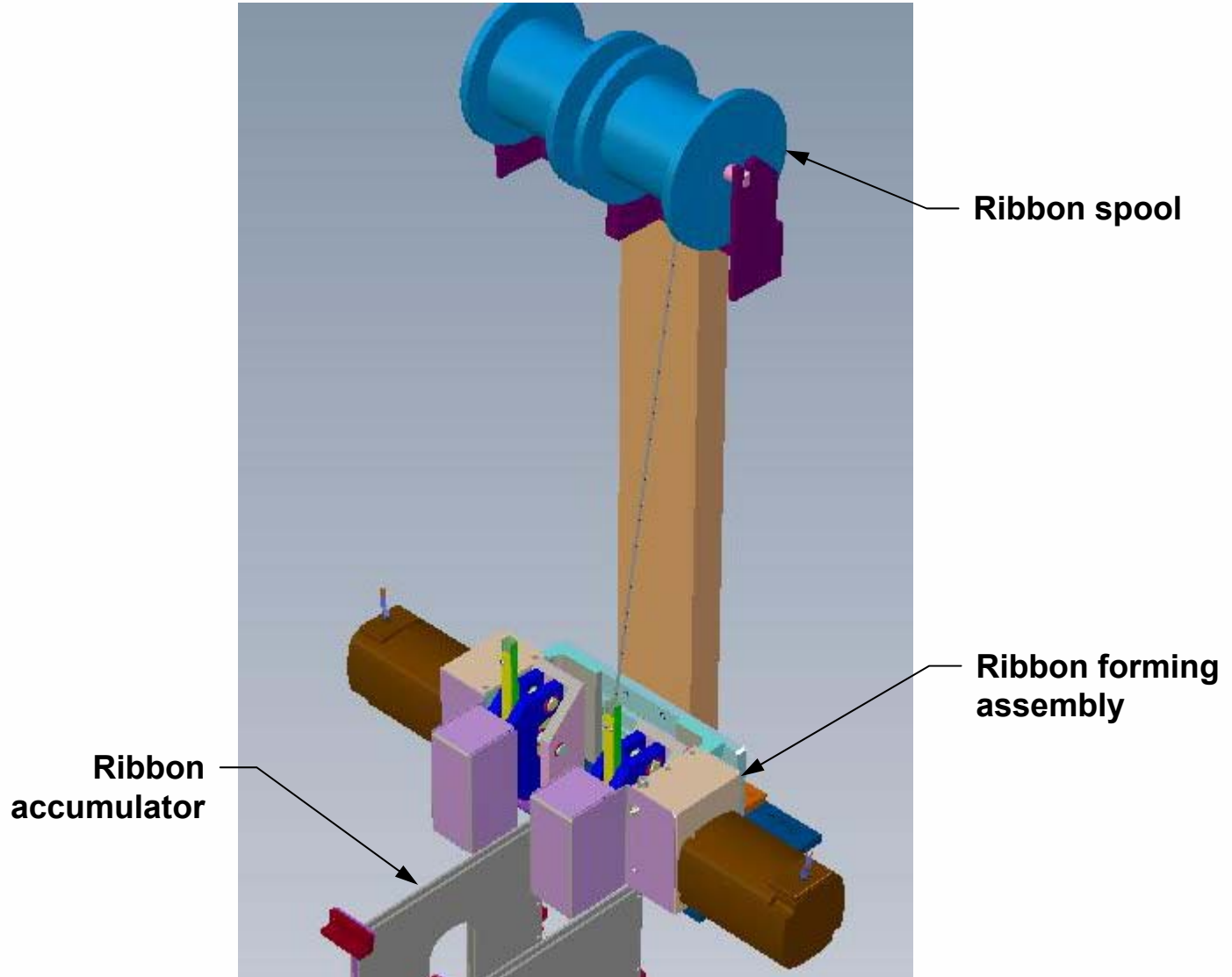
- Vertical and angular compliance
- Air jets and slight flex for separation

Low-stress Cell String Assembly Processes

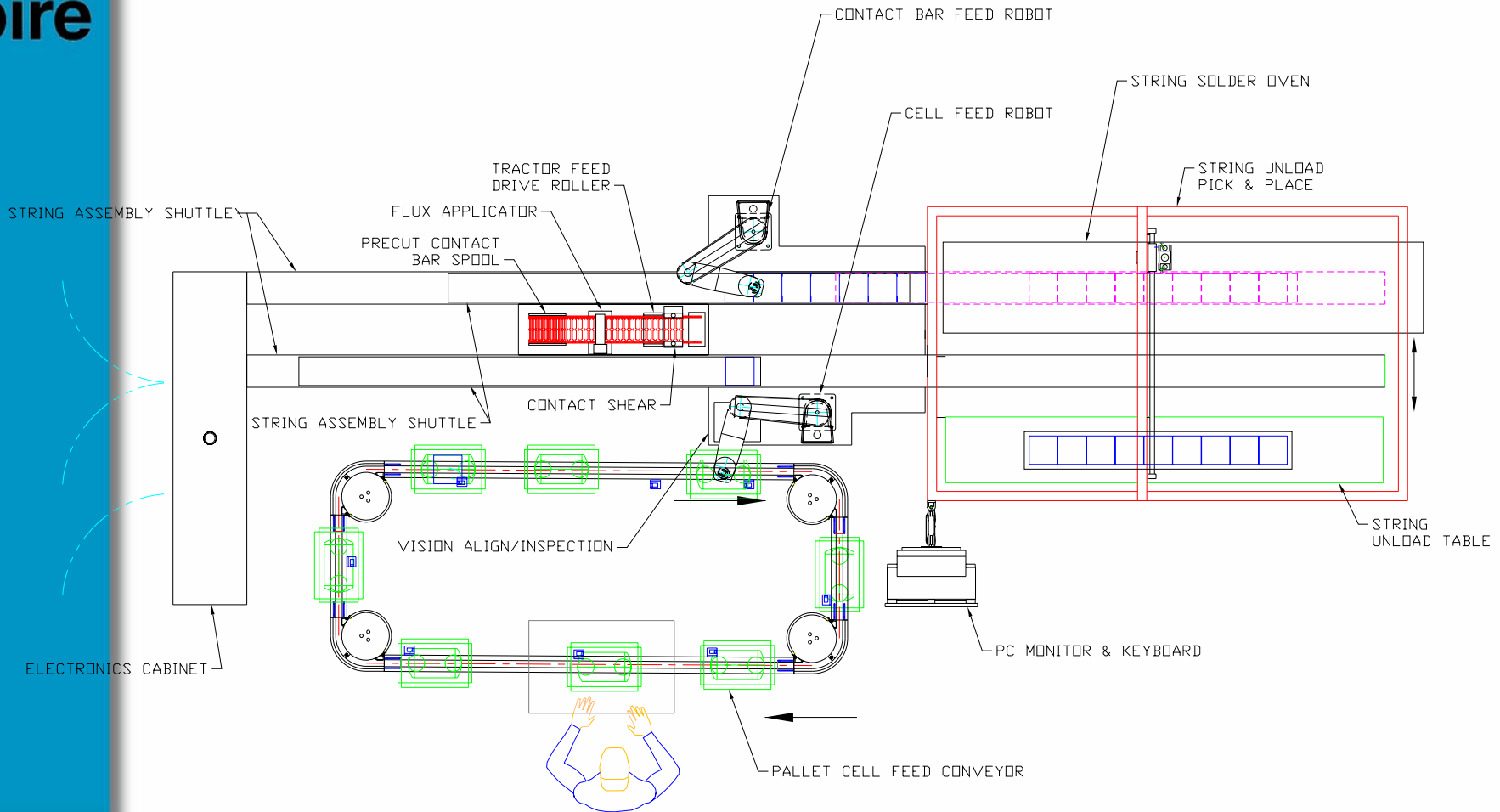


- ▶ Cell handling
 - SCARA robot for high speed loading
 - Remove cell from pallet, move to aligner, place in string
- ▶ Cell alignment
 - Non-contact machine vision, on the fly
- ▶ Cell soldering
 - Ribbon forming assembly designed, built & tested
 - Reduces stress due to thermal expansion mismatch between Si and Cu
 - Tests show reduced stress in cell strings – less bow, less breakage
 - Batch string soldering in uniform IR “oven”
 - Uniform temperature for soldering process control
 - Batch soldering for high throughput
 - Prototype 1 m long oven being assembled for process evaluations

Ribbon Forming Assemblies



Automated Stringing Concept for Back-contact Cells



Budget History

Phase	Project Task		Total Value
I Jun 03 to Jun 04	1	Design Brightfield Module and Module Production Line	430,700
	2	Develop Cell String Inspection Process	367,193
	3	Develop Advanced Lamination Process	220,011
	4	Design Module Lay-up System	405,665
	5	Design String Busing System	463,922
II Jul 04 to Oct 05	6	Fabricate and Test Module Lay-up System	326,395
	7	Fabricate and Test String Busing System	335,420
	8	Design Advanced Lamination Process Tool	473,065
	9	Design Lamination Automation	470,827
	10	Design Large Area Solar Simulator	320,598
	11	Develop Soldering Process for Thin Solar Cells	34,444
III Oct 05 to Mar 07	12*	Fabricate and Test Advanced Laminator	22,135
	13*	Fabricate and Test Lamination Automation	0
	14	Fabricate and Test Large Area Solar Simulator	327,988
	15	Develop Computer Integrated System for Module Mfg.	290,725
	16	Develop Low-stress Cell String Assembly Process	638,334
Grand Total		5,127,422	

**Tasks 12 & 13 were replaced by Task 16*



Accomplishments



- ▶ Large area solar simulator designed
 - 2 m x 4 m test plane
 - New optics for uniform illumination of large areas
 - Fabrication underway
- ▶ New single long pulse (SLP) technology developed
 - 100 ms long pulses with active lamp control
 - Highly stable irradiance
 - More accurate testing of thin film and high efficiency cells
 - New product offering – over 10 SLP Simulators sold to PV manufacturers and test laboratories

Accomplishments



- ▶ Strategy developed for module line SCADA control and monitoring
- ▶ Connectivity upgrade identified for Spire equipment
 - Minimal impact on existing VisualBasic machine software investment
 - VisualBasic variables exposed via OPC
- ▶ SCADA demonstrated by linking LabVIEW/DSC executive software with machine control software via OPC

Accomplishments



- ▶ Low-stress cell string assembly processes designed for thin cells
 - Cell loading, handling, and alignment
 - Uniform batch soldering of cell strings
 - Some designs incorporated into our commercial stringing equipment (Spi-Assembler 6000)
 - Short cell stack pallets and pallet conveyor
 - Compliant vacuum hand with integrated air jets and flexer
 - Ribbon forming assembly
- ▶ Concept developed for low-stress stringing of back contact cells

Schedule of Major Events/Milestones



- ▶ October 2005 – Start of Phase III
 - Activity began on Task 14 - Large Area Solar Simulator
- ▶ November 2005 – Annual Technical Progress Report submitted to NREL for Phase II
- ▶ December 2005 – NREL directs Spire to reduce spending rate and extend program by 4 months, due to FY2006 budget
- ▶ January 2006 – work began on Task 12 – Fabricate and Test Advanced Laminator
- ▶ February 2006 – lower-tier subcontract implemented with UTA/ARRI
 - Work began on Task 15, Develop Computer Integrated System for Module Manufacturing
- ▶ March 2006 – Class A spatial uniformity achieved with new lamp optics over 1 m x 2 m test area
- ▶ March 2006 – Spire requests change of scope to investigate low-stress stringing processes for thin cell
 - Work stopped on Tasks 12 & 13

Schedule of Major Events/Milestones



- ▶ April 2006 – Completed the definition of computer integrated manufacturing (CIM) system
- ▶ July 2006 – Change of scope implemented
 - Tasks 12 & 13 replaced with new Task 16 - Development of Low-stress Cell String Assembly Processes
- ▶ July 2006 – mechanical detail drawings completed for large area solar simulator
- ▶ August 2006 – work began on Task 16 - Development of Low-stress Cell String Assembly Processes
 - Preliminary concept devised for high-speed low-stress string assembly
- ▶ October 2006 – SLP lamp survives 164,000 flashes, exceeding design goal of 100,000 flashes
- ▶ December 2006 – Completed investigation of back contact cell stringing methods
 - Delivered concept drawing for automated stringing machine for back contact cells

Schedule of Major Events/Milestones



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- ▶ January 2007 – Completed development of CIM system
 - Delivered summary report for CIM system development
- ▶ April 2007 – complete assembly of large area solar simulator
- ▶ June 2007 – complete investigation of thin cell soldering
- ▶ June 2007 – complete testing of large area solar simulator
 - Deliver evaluation report of large area solar simulator
- ▶ June 2007 – complete design of low-stress high-speed cell stringing machine
 - Deliver assembly drawing of high throughput stringing machine
- ▶ July 2007 – submit Final Technical Report to NREL

Future Directions



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- ▶ Complete fabrication and test of large area 2 m x 4 m simulator (Spi-Sun Simulator 2040 SLP)
- ▶ Evaluate high-speed low-stress batch soldering process with prototype oven
- ▶ Complete detailed design for next-generation cell stringing machine (Spi-Assembler 12K)
 - Incorporate low-stress high-speed techniques

Future Directions

Monitor performance and support initial product launches for new technologies developed under this program:

- ▶ Single Long Pulse simulators
 - Spi-Sun Simulators 3500 SLP and 4600 SLP
 - Active lamp controls
 - Electronic load & measurement electronics
- ▶ New low-stress cell handling assemblies
 - Spi-Assembler 6000
 - Short cell stack pallets and pallet conveyor
 - Compliant vacuum hand
 - Ribbon forming assembly
- ▶ Cell string vision inspection systems
 - Spi-Assembler 6000



Acknowledgements and Partners



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- ▶ ARRI (Automation & Robotics Research Institute, U. of Texas Arlington)
 - Raul Fernandez