

Commercial Production of Thin-Film CdTe Photovoltaic Modules

Final Report

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1996 Annual Report

General Overview of Progress

In January 1996 GPI was producing photovoltaic modules with an average output of 20 watts at a rate of approximately 1200 modules/month with a total process yield of 50%. Over the next 6 months several critical operating changes were employed:

- Implementation of a Statistical Process Control plan identified numerous areas of process variability. Through more rigorous process measurement, specification analysis and subsequent specification changes, machine modifications and process changes directly led to yield improvements in our cell division operations and module output and total process yield improvements.
- A complete redesign of our encapsulation scheme resulted in major raw materials and labor savings.
- Implementation of Incoming Raw Material and Pre-Qualification procedures, plus improvements to operating procedures in our spray deposition furnace lines also added to GPI's overall performance improvement.

By June 1996 the average module output increased to 25.5 watts, our productivity increased to 1,900 modules/month, our yield increased to 76% and our module cost decreased by 20%. Although these milestones were impressive, excessive module degradation continued to be a major obstacle and greatly extended our liability for continued production.

In July 1996 the decision to scale back manufacturing was due primarily to our inability to consistently produce stable photovoltaic modules. After restructuring, GPI developed an improved methodology for rapidly and reliably progressing through improved understanding of processing and materials issues. The result of these intellectual discoveries and process changes led to the following achievements in the production of photovoltaic modules.

First, extensive examination of the CdS and CdTe films as well as the interface between the CdS and CdTe films revealed; 1) concerns as to the sufficiency of the CdTe film, and 2) a mechanistic model of the growth of the CdTe layer during processing. These two findings led to a process change to achieve the desired CdTe film microstructure, improving stability and efficiency.

Furthermore, efforts led to the following results/milestones:

- Improved incorporation of oxygen into the process to improve stability,

- The major sensitivities of all the critical process steps have been evaluated with parametric studies.
- Development of a new CdS thickness measurement capability resulting in a new ability to monitor and control the thickness of this film and the Quantum Efficiency.

Through these improved measurement capabilities, changes to our fluid delivery system, new nozzles, a modified exhaust system, heated air inlets, better furnace maintenance, and the ability to adjust belt speed in the furnaces during the process, we now have the capability of adjusting CdS thickness by design as well as improving our yield through both the CdS and HRT furnaces to almost 99%.

By employing new designs and concepts into a test on the standard processing line, GPI has achieved a world record small cell efficiency on soda-lime glass. The National Renewable Energy Laboratory (NREL) confirmed up to 14.7% efficiencies on GPI devices having ~0.3 cm² areas. GPI is now finalizing how these process improvements will be mechanically implemented into the module manufacturing line, so that manufacture and outdoor testing of these next-generation modules can begin.

Prior to the above mentioned improvements GPI has demonstrated the capability to manufacture photovoltaic modules with a wattage of 29.3 watts as measured by NREL after 2 months exposure in the field. Recently, world records have been verified by NREL for module aperture area efficiency (9.2%) and module active area efficiency (10.8%) on soda-lime glass substrates. Repeatable prototype quantities of modules with 30-31 watt outputs have been demonstrated and pathways have been identified to achieve 45-50 watt modules. GPI has demonstrated short-term module stability with less than 5% degradation for several batches of modules.

Manpower Status

Staffing in January 1996 included approximately 9-10 operators per shift. The operations department started with 45 full-time employees. The Engineering department had five (5) full-time employees and 5 contract/part-time employees. The Research and Development employed 7 scientists and technicians.

This staffing level remained essentially constant throughout the first half of 1996 even though production throughput increased by approximately 50% in June compared to our production output in January.

As discussed above, in July the decision to scale back manufacturing was due primarily to our inability to consistently produce stable photovoltaic modules.

The restructured GPI employed approximately 21 people, including manufacturing, engineering and research and development.

Ongoing safety and environmental issues requiring auditing and/or external advisement continue to be handled through the GTC Environmental, Health and Safety (EHS) Manager with the assistance of one internal Safety manager.

Despite the staff reduction, three key positions were filled during the year. The initial position filled was Process Engineering/Quality Control Manager and was created to assist operations in optimizing process control. A plant maintenance manager was hired in May. In June, a distinguished scientist was hired to augment our Research and Development department.

Status of Subcontractor Progress

Task 12: Engineering Design

This past year was one of process refinements and process improvements for Golden Photon, Inc. The overall process was fairly defined by the end of 1995 and had been operating long enough for problem areas to surface and be identified.

Film Application Process Improvements

GPI started out 1996 by concentrating on improving the repeatability of our process films. We accomplished this with redesigned spray nozzles, reprogramming the traverses for a more uniform profile, new exhaust system for better flow, and redesigning the spray tanks and pumps for reduced aeration. We now have a more uniform spray, more uniform films, a reduction in film voids, and improved capture efficiencies.

Reduction in CdTe Waste and Improved Repeatability

GPI installed a new linear traverse with programmable limits and accelerations curves. We also purchased a Spray Systems nozzle that can be cycled on and off and is capable of spraying in an oval pattern compared to our present circular pattern. Both the new linear traverse and the Spray Systems nozzle shall reduce our CdTe overspray which in turn shall reduce the overall amount of CdTe waste. A newly designed capture vessel was added to the CdTe exhaust system. This system has reduced the buildup in our CdTe exhaust system. The mixing tank and plumbing were reworked on the CdTe line for reduced aeration and gauges were added for improved repeatability of spray settings.

Compression

We replaced the table surface with a hardened surface table. This has significantly reduced our breakage rate on the compression machine. We also implemented newly designed 85 RWC hardened compression wheels. These perform better with respect to the finish after compression. They are less susceptible to marring and scratching.

Regrowth Oven

New cooling coil and seals were installed after the previous coil leaked. The oxygen analyzer was rebuilt improving the accuracy of the process.

Etch

The Etch/Washer/Rinser had new positive displacement pumps installed to improve the repeatability of the flow rates to the spray nozzles.

Division

During the interim period of the malfunctioning laser and rebuild we were able to develop an alternative method for our initial division process. We used alumina to cut through the tin oxide layer after first sand blasting the division line. We have not observed any differences in panel performance between the alumina and laser methods.

Tin Evaporation

A new and improved panel installation/removal brackets were installed on the carousel. This new design has significantly reduced the cycle time for the tin evaporation process step.

Post Tin Evaporation Division

The programming was modified on the second division process so that both our division processes can be run on the same machines.

Edge Delete

A combination of both wire brushes and grinding wheels was designed and tested for the edge delete process. By first removing most of the film layers with a wire brush followed by the use of grinding wheels we have extended the life of our expensive diamond coated grinding wheels by a factor of four.

Border Isolation

We moved the border isolation process off the laser to an inline second division machine after edge deletion. We are using alumina as our blast media for border isolation. This improved productivity and reduced our dependency on the laser.

Task 13: Process Improvement and Development

During 1996, considerable emphasis was placed on process measurement. Operations and Research and Development targeted key areas in the process and determined the extent of measurement that was occurring or needed to be developed. The outcome of this has been implementation of Statistical Process Control charting and logging of data throughout the process. Areas for emphasis have been focused in the cell interconnection steps including pre-resist application, compression, and cell division. Other areas of interest during this time period were employee training and process improvements and modifications.

As part of the need for measurement, Operations implemented Statistical Process Control (SPC) at key stages in the process. Some of these SPC measurements in the process were performed and charted manually while others were performed using an automated visual inspection station. This process monitoring was able to identify the capabilities of each process, tighten specifications where appropriate, and determine when the process was not in control. Implementation of the SPC plan identified numerous areas of process variability. Through more rigorous process measurement, specification analysis and subsequent specification changes, machine modifications and process changes directly led to yield improvements in GPI's cell interconnection operation as well as improvements in module output and total process yield.

Research and Development completed and implemented a means to measure Cadmium Sulfide film thickness in an on-line fashion. The technique borrows from previous work completed at the National Renewable Energy Laboratory, but uses a monochromatic light source in place of a laser. Operations has used this technique to monitor and control Cadmium Sulfide film thickness to $5150 \text{ \AA} \pm 350 \text{ \AA}$. The thickness was measured using the non-destructive optical transmission technique developed at NREL and allows for rapid turnaround of thickness data. Film thickness was controlled by varying the solution concentration and furnace belt speed with every fifth panel measured.

Multiple process improvements were also implemented during the past year. Several noteworthy examples are listed below.

1. NREL measured a Golden Photon module at 29.3 watts output. This module had previously been subjected to lengthy outdoor exposure and provides evidence of GPI product stability.
2. GPI showed considerable improvement in wattage output throughout the year. The average wattage was observed to increase from approximately 21 watts at the beginning of the year to the current standard of 25-26 watts on average. This increase in wattage was attributed to various processing improvements.
3. Operations installed new spray nozzles and material delivery systems on the Tin Oxide, Cadmium Sulfide, and Cadmium Telluride deposition lines. This new nozzle requires less maintenance and produces a more consistent spray pattern than the previous design and should produce more consistent coatings. The modified material delivery system provides more consistent flow rates to the nozzles and should enable better control of film thickness with time.
4. Operations completed installation of a heating system above the Cadmium Sulfide furnace to provide a more controlled environment around this furnace. This has resulted in more consistent yields for this furnace. A similar unit installed above the Tin Oxide line resulted in yields increasing from 55% to greater than 90%. Timely cleaning and maintenance have also contributed to the increased yields for both furnaces.
5. The Cadmium Telluride Regrowth profile was modified based on analyses of the Cadmium Telluride microstructure from Scanning Electron microscopy. The initial microstructure displayed considerable variation across individual panels whereas the new re-crystallization profile yielded a more consistent morphology. This improvement has resulted in both gains to initial wattage and module stability.
6. Operations identified key variables that produced changes in the Cadmium Telluride morphology. These included amount of flux loading and oxygen level after gettering. Oxygen level is now monitored on each batch of Cadmium Telluride as part of measuring the capabilities of the gettering process.
7. Operations implemented an improved means for the border isolation process. The new technique uses aluminum oxide powder in place of a laser. This improved technique was also utilized for cell interconnection process after laser equipment failure.
8. Operations and Research and Development tested and implemented a new Cadmium Telluride dopant application process into production. This new material, delivery system, and thermal profile have resulted in a marked gain in wattage on finished panels and reduced efficiency variation across a panel and between batches.
9. Operations increased the batch size during the year from 55 panels per batch to 75 panels per batch. This required modifications to the Cadmium Sulfide and Cadmium Telluride batch size to accommodate this change.

Changes in priorities, however, necessitated that this be decreased to 25 panels per batch.

10. During April, a material contamination problem caused the average panel output to drop considerably. Because of this, Process Engineering implemented a raw material characterization and qualification plan to screen all incoming raw materials before they are used in production.

Task 14: Cost Improvement of Raw Materials

Raw material pricing and quality continued to be a primary focus for Golden Photon, Inc., in the first half of 1996. All major raw materials have been fully qualified for use in production, and stable sources of supply have been established. Quality assurance procedures and standards have been established and communicated to GPI's suppliers to ensure quality standards are met and material rejections are minimized. Highlights from 1996 are listed below.

- The new encapsulation scheme was fully implemented in 1996. The new design has allowed significant reductions in raw materials costs and encapsulation labor compared to our previous design. In addition, the new design and encapsulation process makes it easier to encapsulate a module, reduces our module weight and shipping costs, and allows more efficient module packaging.
- Purchasing activities in the latter part of 1996 were minimized due to a re-alignment of focus at GPI. Stock levels are routinely monitored to ensure adequate inventory levels to maintain current production rates.
- GPI's raw material inventories were maintained at adequate levels during process scaling early in 1996 to allow production ample time for material qualification in production. Similarly, the costs associated with many of these materials decreased as the order quantity increased.

Key areas for further raw materials cost reduction that have been targeted include additional refinements to our encapsulation design and process, in-house capability and implementation of applying low-resistance tin oxide to sheet glass as opposed to purchasing this product, and continued effort towards more efficient and economical purchasing procedures.

Task 15: Environment, Safety and Health

Compliance

The OSHA Cadmium Standard is utilized at the facility to steer all environmental, safety, and health work. The facility passed inspection by the Jefferson County Department Of Environment and Health for compliance to our air emission

permit requirements. Periodic plant inspections by an independent consultant helps us to ensure compliance with federal, state, and local requirements.

Employee Exposure

An alarm system was installed, tested, and is currently operating to give maximum warning to the employees in the case of a dust collection failure. Interlocks are being installed on cadmium processing equipment to automatically shutdown operations in the case of reduced dust collection flow. We are continuing to take air and wipe samples to ensure that all exposure levels are below the acceptable OSHA and internal action levels. Medical and cadmium sampling records are being recorded with the hope that trending and analysis can help to clarify the toxicity risks of working with cadmium and possibly other hazardous materials.

Waste Minimization

A waste plan is in place to provide procedures and training for accumulating, permitted compacting, stabilization, temporary storage, and disposal of all waste streams generated at the facility. The plan is continually evaluated and updated as new methods and sources come about for reduction and recycling. Jefferson County is helping GPI to locate technical methods for converting some of our waste streams to recycle or reuse materials. We are currently discussing the opportunities to join the DOE Climate Wise group. GPI is expecting the work with these groups to move us in the direction of reduced waste, increased recycling, and a better utilization of energy and materials.

Task 16: Manufacturing Cost and Productivity Optimization

For 1996, the power average for 24"x 24" PV modules has increased from approximately 21 watts/panel to over 25 watts/panel. The highest power attained was in excess of 30 watts showing an improvement from 1995's high of 26.6 watts. This increase has been attributed primarily to 1) an improved and more uniform Cadmium Telluride morphology, and 2) an improved method of applying the Cadmium Telluride dopant.

Several factors continued to drive down the price per watt of output power. Foremost, the power per module continues to show an increasing trend from 1995. The average wattage on modules has increased by approximately 25%. This sizable increase can be attributed in part to implementing a method to measure and monitor key attributes in the process and implementation of multiple process improvements. Additionally, furnace yields have maintained high levels from the previous year and are typically at levels approaching 96-

98%. During 1996, GPI has demonstrated the capability to process up to 1200 panels per week and maintain through process yields up to 75%. Operations has since increased the throughput rate to the Cadmium Sulfide line by 50% which does not impact film quality or the furnace yields. This increase will be advantageous for process scale-up.

At 1996 year-end, the following table summarizes the status of the PV program relative to measurable process values of continuing interest to management.

<u>ATTRIBUTE</u>	<u>VALUE</u>
Power Output (Average)	~ 26 watts/panel
Tin Oxide Yields	~ 95%
Cadmium Sulfide Yields	~ 95%
Production Throughput Yields	~ 70-75%
Production Throughput	Up to 1200 panels/week

MILESTONES

End of the First Quarter

- m-1.1.1** Complete design and debug of in-house designed equipment.
(Task 1)
Status: This milestone was completed in June 1994.
- m-1.1.2** Complete development of installation procedures for equipment on
2 MW manufacturing line. (Task 1)
Status: This milestone was completed in June 1994.
- m-1.1.3** Improve equipment designs for the division (cell separation) steps
shown feasible. (Task 2)
Status: This milestone was completed in June 1994.
- m-1.1.4** Complete development of procurement/contracting Program for
qualified raw materials and associated suppliers. (Task 3)
Status: This milestone was completed in June 1994.
- m-1.1.5** Complete processing of all required permits. (Task 4)
Status: This milestone was completed in June 1994.
- m-1.1.6** Complete the development, documentation, and implementation of
Environmental, Health, and Safety Plan for the 2 MW line. (Task 5)
Status: This milestone was completed in June 1994.
- m-1.1.7** Complete the development, documentation, and implementation of
Employee Exposure Monitoring Plan. (Task 5)
Status: This milestone was completed in June 1994.
- m-1.1.8** Demonstrate increased yields to 99% for glass preparation steps
on 340 consecutive substrates. (Task 6)
Status: This milestone was completed in November 1994.
- m-1.1.9** Demonstrate tin oxide deposition rates that are three times that of
the "original rate". (Task 6)
Status: This milestone was completed in November 1994.
- m-1.1.10** Demonstrate CdS deposition rates that are four times that of the
"original rates". (Task 6)
Status: This milestone was completed in July 1994.

End of the Second Quarter

- m-1.2.1** Initiate manufacturing equipment start-up and evaluate for process suitability. (Task 1)
Status: This milestone was completed in July 1994.
- m-1.2.2** Demonstrate CdTe module production at 80 modules/week rate. (Task 1)
Status: This milestone was completed in July 1994.
- m-1.2.3** Complete non-optimized module utilizing 2nd generation methods (Task 2)
Status: This milestone was completed in July 1994.
- m-1.2.4** Complete analysis of baseline first quarter data per Employee Exposure Monitoring Plan and types and volumes of first quarter waste generated from GPI module manufacturing process. (Task 5)
Status: This milestone was completed in July 1994.
- m-1.2.5** Demonstrate improved thickness uniformity for CdS step to <5% across a 24" x 24" substrate. (Task 6)
Status: This milestone was completed in October 1994.
- m-1.2.6** Demonstrate increased yields to 99% for CdTe deposition and recrystallization steps on 340 consecutive substrates. (Task 6)
Status: This milestone was completed in December 1994.
- m-1.2.7** Demonstrate rates for interconnection steps that are approximately four times that of the "original rates". (Task 6)
Status: This milestone was completed in June 1994.

End of the Third Quarter

- m-1.3.1** Complete investigation of material handling techniques related to automation. (Task 1)
Status: This milestone was completed in September 1994.
- m-1.3.2** Demonstrate CdTe module production at 160 modules/week rate. (Task 1)
Status: This milestone was completed in September 1994.

- m-1.3.3** Demonstrate 24 watt (average) modules, from a batch of at least >50 consecutive modules, with a batch standard deviation of <5% for the output distribution and a total process yield of >85% (Task 2)
Status: This milestone was completed in April 1996.
- m-1.3.4** Complete revised IEEE21 qualification tests on GPI modules from production test runs. (Task 2)
Status: Engineering completed the execution of this qualification test in the third quarter of 1995.
- m-1.3.5** Complete review and update Employee Exposure Monitoring Plan and types and volumes of second quarter waste generated from GPI module manufacturing process. (Task 5)
Status: This milestone was completed in September 1994.
- m-1.3.6** Demonstrate increased yields to 99% for CdS deposition steps on 340 consecutive substrates that provide average module outputs at the 24 watt level. (Task 6)
Status: This milestone was completed in November 1996.
- m-1.3.7** Demonstrate increased yields to 98% for tin oxide deposition steps on 340 consecutive substrates (Task 6)
Status: This milestone was completed in April 1996.
- m-1.3.8** Demonstrate increased yields to 99% for interconnection steps on 340 consecutive substrates that provide average module outputs at the 24 watt level. (Task 6)
Status: This milestone was completed in November 1996.

End of the Fourth Quarter

- m-1.4.1** Demonstrate CdTe module production at 320 modules/week rate. (Task 1)
Status: This milestone was completed in October 1994.
- m-1.4.2** Complete the Phase 1 portion of the effort under Task 1. (Task 1)
Status: This milestone was completed in December 1994.
- m-1.4.3** Complete the QA/QC documentation for 28 watt modules with standard deviation of <5% for the module batch output distribution and a total expected process yield of >90%. (Task 2)
Status: This milestone was completed in December 1994.

- m-1.4.4** Demonstrate prototype quantities of modules at the 28 watt average output level. (Task 2)
Status: This milestone was completed in October 1994.
- m-1.4.5** Complete the Phase 1 portion of the effort under Task 2. (Task 2)
Status: This milestone was completed in December 1994.
- m-1.4.6** Complete integration of qualified supplies with the Quality Assurance Program. (Task 3)
Status: This milestone was completed in October 1994.
- m-1.4.7** Complete analysis of monthly averages of relative material costs per watt produced (Task 3)
Status: This milestone was completed in December 1994.
- m-1.4.8** Complete the Phase 1 portion of the effort under Task 3. (Task 3)
Status: This milestone was completed in December 1994.
- m-1.4.9** Complete all permitting and planning for proposed 10 MW site. (Task 4)
Status: All permits at the current facility allow expansion to 10MW total capacity. The only exception is the air permit which requires revisions based on projected emissions net of expanded air treatment facilities. This milestone was completed in June 1995.
- m-1.4.10** Complete the Phase 1 portion of the effort under Task 4. (Task 4)
Status: This milestone was completed in December 1994.
- m-1.4.11** Complete review and update of Employee Exposure Monitoring Plan and types and volumes of third quarter waste generated from GPI module manufacturing process. (Task 5)
Status: This milestone was completed in October 1994.
- m-1.4.12** Complete development of 2nd generation program for waste minimization. (Task 5)
Status: This milestone was completed in December 1994.
- m-1.4.13** Complete cost analysis of additional costs to be gained through the 2nd generation waste minimization program. (Task 5)
Status: This milestone was completed in December 1994.
- m-1.4.14** Complete the Phase 1 portion of the effort under Task 5. (Task 5)
Status: This milestone was completed in December 1994.

- m-1.4.15** Complete design for Pinhole plugging and Buss Bar Application steps. (Task 6)
Status: This milestone was completed in March 1994.
- m.1.4.16** Complete implementation of improved equipment designs for packaging steps. (Task 6)
Status: This milestone was completed in October 1994.
- m-1.4.17** Demonstrate increased yields to 99% for the encapsulation steps on 340 consecutive substrates. (Task 6)
Status: This milestone was completed in April 1995.
- m-1.4.18** Complete analysis of monthly averages of total process yield for modules produced within 5% of the 24 watt average output level. (Task 6)
Status: This milestone was completed in April 1995.
- m-1.4.19** Complete analysis of monthly averages of relative labor costs per watt produced. (Task 6)
Status: This milestone was completed in December 1994.
- m-1.4.20** Demonstrate 24 watt output GPI modules to be outdoor life tested at NREL. (Task 6)
Status: Panels were delivered to NREL for life testing in April 1995.
- m-1.4.21** Complete the Phase 1 portion of the effort under Task 6. (Task 6)
Status: This milestone was completed in July 1995.

PHASE 2

End of the Fifth Quarter

- m-2.1.2** Initiate design/re-design of specialty equipment for next 4 MW addition to the GPI manufacturing line. (Task 7)
Status: An extensive evaluation of equipment, facilities and support utilities required for the 10 MW expansion facility was completed in February 1995.
- m-2.1.3** Demonstrate 2:2 watt modules with a total post CdTe process yield of >95%. (Task 8)
Status: This milestone was completed in April 1995.

- m-1.3.3a** Demonstrate 22 watt (average) modules, from a batch of at least >50 consecutive modules, with a batch standard deviation of <5% for the output distribution and a total post CdS process yield of >85%. (Task 8)
Status: This milestone was completed in June 1995.
- m-1.4.3a** Complete the QA/QC documentation for 24 watt modules with standard deviation of <5% for the module batch output distribution and a total expected post CdS process yield of >85% (Task 8)
Status: This milestone was completed in March 1996.
- m-1.4.4a** Demonstrate prototype quantities of modules at the 26 watt average output level. (Task 8)
Status: This milestone was completed in March 1996.
- m-2.2.x** Complete initial review of Phase I Environmental, Health and Safety and Employee Exposure Monitoring Plans. (Task 9)
Status: This milestone was completed in February 1995.
- m-1.3.6a** Demonstrate increased yields to 90% for CdS deposition steps on >50 consecutive substrates that provide average module outputs at the 22 watt level. (Task 11)
Status: This milestone was completed in March 1996.
- m-1.3.7a** Demonstrate increased yields to >85% for tin oxide deposition steps on >50 consecutive substrates. (Task 11)
Status: This milestone was completed in March 1996.
- m-1.3.8a** Demonstrate increased yields to 99% for interconnection steps on >50 consecutive substrates that provide average module outputs at the 22 watt level. (Task 1)
Status: This milestone was completed in March 1996.
- m-1.4.16** Complete implementation of improved equipment designs for packaging steps. (Task 11)
Status: This milestone was completed in June 1996.
- m-1.4.17** Demonstrate increased yields to 99% for the encapsulation steps on >50 consecutive substrates. (Task 11)
Status: This milestone was completed in February 1995.
- m-2.3.8** Complete the optimization of the next generation of Encapsulation and Packaging steps. (Task 11)
Status: This milestone was completed in July 1996.

End of the Sixth Quarter

- m-2.1.1** Initiate preparation of equipment specifications and send specifications to vendors for quotes. (Task 7)
Status: An extensive evaluation of equipment, facilities, and support utilities required for the 10MW expansion facility was completed in the second quarter of 1996.
- m-2.1.3b** Demonstrate 24 watt modules with a total post CdTe process yield of >95%. (Task 8)
Status: This milestone was completed in April 1996.
- m-2.2.1** Demonstrate 24 watt modules, from a batch of at least >50 consecutive modules, with a batch standard deviation of <5% for the output distribution and a total post CdTe process yield of >95%. (Task 8)
Status: This milestone was completed in April 1996.
- m-1.3.3b** Demonstrate 24 watt (average) modules, from a batch of at least >50 consecutive modules, with a batch standard deviation of <5% for the output distribution and a total post CdS process yield of >90%. (Task 8)
Status: This milestone was completed in April 1996.
- m-1.4.3b** Complete the QA/QC documentation for 26 watt modules with standard deviation of <5% for the module batch output distribution and a total expected post CdS process yield of >85%. (Task 8)
Status: This milestone was completed in the third quarter of 1995.
- m-1.4.4b** Demonstrate prototype quantities of modules at the 28 watt average output level. (Task 8)
Status: This milestone was completed in August 1996.
- m-1.3.4** Complete revised NREL TP-213-3624 qualification tests on GPI module manufacturing Process. (Task 8)
Status: This milestone was completed in the second quarter of 1996.
- m-2.2.2** Complete review, update documentation, and implement of both the Environmental, Health, and Safety and Employee Exposure Monitoring Plans. (Task 9)
Status: This milestone was completed in December 1995.

- m-1.3.6b** Demonstrate increased yields to >98% for CdS deposition steps on >50 consecutive substrates that provide average module outputs at the 24 watt level. (Task 11)
Status: This milestone was completed in April 1996.
- m-1.3.7b** Demonstrate increased yields to 90% for tin oxide deposition steps on >50 consecutive substrates. (Task 11)
Status: This milestone was completed in March 1996.
- m-1.3.8b** Demonstrate increased yields of 99% for interconnection steps on >50 consecutive substrates that provide average module outputs at the 24 watt level. (Task 11)
Status: This milestone was completed in April 1996.
- m-1.4.18** Complete analysis of monthly averages of total post CdS process yield for modules produced within 5% of the 24 watt average output level. (Task 11)
Status: This milestone was completed in April 1996.
- m-1.4.20** Demonstrate 24 watt output GPI modules to be outdoor life tested at NREL. (Task 11)
Status: Modules were sent to NREL for outdoor life testing in the second quarter of 1996.

End of the Seventh Quarter

- m-2.3.1** Complete development of installation procedures for equipment next 4 MW of the GPI manufacturing line. (Task 7)
Status: This milestone was completed in the third quarter of 1995.
- m-2.3.2** Demonstrate 28 watt (average) modules for a batch of at least 50 consecutive modules with a batch standard deviation of <5% for the output distribution and a total post CdTe process yield of at least 85%. (Task 8)
Status: GPI has been successful in producing 28 watt average modules for a batch of 20 modules with a batch standard deviation of <5% for the output distribution and a total post CdTe process yield of at least 85%. This milestone was completed in December 1996.
- m-1.4.3b** Complete the QA/QC documentation for 28 watt modules with standard deviation of <5% for the module batch output distribution and a total expected post CdS process yield of >85%. (Task 8)

- Status:** Operations has produced 26 watt modules within a batch with < 5% deviation and a total post CdS process yield of > 85%. This milestone was completed in December 1996.
- m-1.4.9a** Complete all permitting and planning for proposed additional 4 MW site. (Task 8)
- Status:** All permits at the current facility allow expansion to 10 MW total capacity. The only exception is the air permit which requires revisions based on projected emissions net of expanded air treatment facilities. This milestone was completed in the third quarter of 1995.
- m-2.3.3** Initiate integration of qualified raw materials with the revised Quality Assurance Program. (Task 9)
- Status:** This milestone was completed in the fourth quarter of 1995.
- m-2.3.4** Complete development of a 3rd generation program for waste minimization. (Task 10)
- Status:** This milestone was completed in March 1996.
- m-2.3.5** Demonstrate increased yields for the critical deposition steps that can allow the total post CdS process yields to achieve 80% at the 28 watt average module level. (Task 11)
- Status:** This milestone has been completed for a post CdS yield of 80% and a 28 watt average module level. Milestone was completed in December in 1996.
- m-2.3.6** Demonstrate a 600% increase in rate of the interconnection steps over that of the original rates. (Task 11)
- Status:** This milestone was completed in September 1995.
- m-2.3.7** Demonstrate increased yields to 99% for the interconnection steps at the 28 watt average module level. (Task 11)
- Status:** GPI has demonstrated greater than 99% yield for the interconnection steps at the 28 watt average module level for a batch greater than 20 panels but less than 50 panels. This milestone was completed in December 1996.
- m-2.3.8** Complete the optimization of the next generation of Encapsulation and Packaging steps. (Task 11)
- Status:** This milestone was completed in September 1995.

End of the Eighth Quarter

- m-2.4.1** Complete the evaluation of the process suitability of the next generation machinery. (Task 7)
Status: An extensive evaluation of equipment, facilities and support utilities required for the 10MW expansion facility has been completed. The majority of the equipment for the expansion is a replication of existing equipment and has passed the suitability test. This milestone was completed in the second quarter of 1996.
- m-2.4.2** Complete preparations for equipment readiness and move-in plans for the next 4 MW of production at the new facility. (Task 7)
Status: This milestone was completed in March 1996.
- m-2.4.3** Demonstrate CdTe module production at 960 modules/week rate. (Task 7)
Status: Maximum production levels achieved were 700 modules/week.
- m-2.4.4** Complete the Phase 2 portion of the effort under Task 7. (Task 7)
Status: This milestone has been completed.
- m-2.4.5** Demonstrate prototype quantities of modules at the 30 watt average output level. (Task 8)
Status: This milestone was completed in January 1997. Completion of batch 662 produced 8 of 11 modules with an average output greater than 30 watts.
- m-2.4.6** Complete the QA/QC documentation for 30 watt modules with standard deviation of <10% for the module batch output distribution and a total expected post CdTe process yield of >90%. (Task 8)
Status: The QA/QC documentation of batch 662 was completed. The average wattage of entire batch was 29.7 watts with a standard deviation of less than 2.5%.
- m-2.4.7** Complete the Phase 2 portion of the effort under Task 8. (Task 8)
Status: This milestone has been completed.
- m-2.4.8** Complete the integration of qualified suppliers with the revised Quality Assurance Program. (Task 9)
Status: This milestone has been completed.
- m-2.4.9** Complete analysis of monthly averages of relative material costs per watt produced to indicate reduction of materials costs over time. (Task 9)
Status: This milestone was completed in July 1996.

- m-2.4.10** Complete the Phase 2 portion of the effort under Task 9. (Task 9)
Status: This milestone has been completed.
- m-2.4.11** Complete development of 3rd generation program for waste minimization. (Task 10)
Status: This milestone has been completed.
- m-2.4.12** Complete cost analysis of additional costs to be gained through the 3rd generation waste minimization program. (Task 10)
Status: This milestone was completed in April 1996.
- m-2.4.13** Complete the Phase 2 portion of the effort under Task 10. (Task 10)
Status: This milestone has been completed.
- m-2.4.14** Complete analysis of monthly averages of total post CdS process yield for modules produced within 10% of the 28 watt average output level. (Task 11)
Status: This analysis has been completed for a batch size of less than 50 panels. The total post CdS process yields was greater than 85%. Milestone was completed in December 1996.
- m-2.4.15** Complete analysis of monthly averages of relative labor costs per watt produced. (Task 11)
Status: This milestone has been completed.
- m-2.4.16** Demonstrate 28 watt output GPI modules to be outdoor life tested at NREL. (Task 11)
Status: Panels have been delivered to NREL for testing. GPI is awaiting test results. This milestone was completed in the second quarter of 1996.
- m-2.4.17** Demonstrate increased yield for the critical deposition steps to allow the total process yields of those particular steps to achieve 85% at the 28 watt average module level. (Task 11)
Status: This milestone was completed in December 1996.
- m-2.4.18** Complete the Phase 2 portion of the effort under Task 11. (Task 11)
Status: GPI has produced 28 watt modules at relatively high yields and 30 watt modules at low yields by optimizing and increasing yields in our film deposition processes, interconnection processes and by

improving our encapsulation design and procedures. Costs, yields and throughput rates have been documented completely.

PHASE 3

End of the Ninth Quarter

m-3.1.1 Complete documentation of employee safety and effluent testing. (Task 10)

Status: This milestone was completed in June 1996.

m-3.1.2 Determine equipment specifications and request vendor quotes. (Task 12)

Status: This milestone was completed in August 1995.

m-3.1.3 Complete vendor selection. (Task 12)

Status: This milestone was completed in August 1995.

m-3.1.4 Complete design/redesign of specialty equipment. (Task 12)

Status: This milestone was completed in August 1995.

m-3.1.5 Complete identification of encapsulation options for GPI module fabrication. (Task 13)

Status: This milestone was completed in July 1996.

m-2.4.5a Demonstrate prototype quantities of modules at the 32 watt average output level. (Task 13)

Status: The maximum wattage attained at GPI (and confirmed at NREL) was 31.0 watts. The maximum average wattage for greater than 6 modules in one batch was 30.0 watts.

m-2.4.6a Complete the QA/QC documentation for 32 watt modules with standard deviation of <10% for the module batch output distribution and a total expected post CdS process yield of >90%. (Task 13)

Status: The QA/QC documentation for batch 662 has been completed. The batch average was 29.7 watts with a standard deviation of less than 2.5% and a post CdS process yield greater than 90%.

End of the Tenth Quarter

m-3.2.1 Complete development of installation procedures for equipment on next 4MW of the GPI manufacturing line. (Task 12)

Status: Installation procedures have been developed for the majority of the equipment required for the next 4 MW manufacturing capability.

m-3.2.2 Demonstrate 28 watt (average) modules with a batch standard deviation of <10% for the output distribution and a total post CdTe process yield of >95%. (Task 13)

Status: This milestone was completed in December 1996.

m-3.2.2a Demonstrate 30 watt (average) modules for a batch of >50 consecutive modules with a batch standard deviation of <5% for the output distribution and a total post CdS process yield of >90%. (Task 13)

Status: A 30 watt average and a standard deviation less than 5% was achieved for a batch of modules numbering less than 50.

m-3.2.3 Demonstrate encapsulation process for GPI module fabrication. (Task 13)

Status: This milestone was completed in July 1996.

m-3.2.4 Complete review, update documentation, and implementation of both the Environmental, Health, and Safety and Employee Exposure Monitoring Plans. (Task 15)

Status: This milestone has been completed.

End of the Eleventh Quarter

m-3.3.1 Complete the evaluation of the process suitability of the machinery. (Task 12)

Status: This milestone has been completed.

m-3.3.3 Complete final integration of qualified raw materials with the revised Quality Assurance Program. (Task 14)

Status: This milestone was completed in August 1996.

m-3.3.4 Demonstrate increased yields for the critical deposition steps to allow the total process yields of those particular steps to achieve 90% at the 28 watt average module level. (Task 16)

Status: This milestone was completed in December 1996.

m-3.3.5 Demonstrate tin oxide layers in prototype production with 3×10^{-4} ohm-cm. (Task 16)

Status: GPI demonstrated this on Pyrex substrates. It has not been attempted on soda-lime glass.

m-3.3.6 Demonstrate uniformity over a tin oxide substrate of <5% of the standard error of the distribution. (Task 16)

Status: GPI demonstrated this on Pyrex substrates. It has not been attempted on soda-lime glass.

End of the Twelfth Quarter

m-3.4.1 Demonstrate CdTe module production at 1600 modules/week rate. (Task 12)

Status: The maximum production rate achieved was 700 modules/week.

m-3.4.2 Complete the Phase 3 portion of the effort under Task 12. (Task 12)

Status: Designs and procedures for a 10 MW manufacturing facility have been completed.

m-3.4.3 Demonstrate prototype quantities of modules at the 35 watt average output level. (Task 13)

Status: The maximum wattage attained at GPI (and confirmed at NREL) was 31.0 watts. The maximum average wattage for greater than 6 modules in one batch was 30.0 watts.

m-3.4.4 Complete the QA/QC documentation for 35 watt modules with standard deviation of <5% for the module batch output distribution and a total expected post CdS process yield of >90% (Task 13)

Status: The QA/QC documentation for batch 662 has been completed. The batch average was 29.7 watts with a standard deviation of less than 2.5% and a post CdS process yield greater than 90%.

m-3.3.2 Demonstrate 32 watt (average) modules for a batch of >50 consecutive modules with a batch standard deviation of <10% for the output distribution and a total "post tin oxide" process yield of >90% (Task 13)

Status: The maximum wattage attained at GPI (and confirmed at NREL) was 31.0 watts. The maximum average wattage for greater than 6 modules in one batch was 30.0 watts.

m-3.4.5 Complete the Phase 3 portion of the effort under Task 13. (Task 13)

Status: This milestone has been completed.

m-3.4.6 Complete final integration of qualified suppliers with the revised Quality Assurance Program. (Task 14)

Status: This milestone has been completed.

- m-3.4.7** Complete analysis of monthly averages of relative material costs per watt produced to indicate reduction of materials costs over time. (Task 14)
Status: This milestone was completed in November 1996.
- m-3.4.8** Complete cost analysis of additional costs to be gained through the 4th generation waste minimization program. (Task 14)
Status: This milestone has been completed.
- m-3.4.9** Complete the Phase 3 portion of the effort under Task 14. (Task 14)
Status: This milestone has been completed.
- m-3.4.10** Complete development of 4th generation program for waste minimization. (Task 15)
Status: This milestone has been completed.
- m-3.4.11** Complete final documentation of employee safety and effluent testing. (Task 15)
Status: This milestone has been completed.
- m-3.4.12** Complete the Phase 3 portion of the effort under Task 15. (Task 15)
Status: This milestone has been completed.
- m-3.4.13** Demonstrate increased yields to achieve 85% at the 32 watt average module level. (Task 16)
Status: The maximum monthly yield achieved by GPI was 80% with an average module output of approximately 25.5 watts.
- m-3.4.14** Complete optimization of the next generation of the Interconnection, Encapsulation and Packaging steps. (Task 16)
Status: This milestone has been completed.
- m-3.4.15** Complete analysis of monthly averages of total post CdS process yield for modules produced within <10% of the 32 watt average output level. (Task 16)
Status: The monthly averages of total post CdS process yield has been measured and documented at module outputs less than a 32 watt average.
- m-3.4.16** Complete analysis of monthly averages of relative labor costs per watt produced. (Task 16)
Status: This milestone has been completed.

m-3.4.17 Demonstrate 32 watt output GPI modules to be outdoor life tested at NREL. (Task 16)

Status: Modules with an average output of 30 watts have been delivered to NREL for outdoor life testing.

m-3.4.18 Complete the Phase 3 portion of the effort under Task 16. (Task 16)

Status: This milestone has been completed.

DELIVERABLES

The following deliverables have been submitted to NREL in accordance with the PVMat subcontract.

PHASE 1

No.	Deliverable Description Frequency	Quantity	
D-1.1	Sample of glass substrate from 99% yield on 340 consecutive substrate run for glass preparation step. Delivered July 1994.	1 each	End of 1st Quarter
D-1.2	Sample of tin oxide coated substrate. Delivered July 1994.	1 each	End of 1st Quarter
D-1.3	Sample of CdS coated substrate from deposition run that demonstrate rate four times that of "original rate". Delivered July 1994.	1 each	End of 1st Quarter
D-1.4	Representative sample of GPI CdTe Module from production at rate of 80 modules/week. Delivered July 1994.	1 each	End of 2nd Quarter
D-1.5	Sample of 24" x 24" CdS coated substrate with thickness uniformity <5%. Delivered July 1994.	1 each	End of 2nd Quarter
D-1.6	Sample of CdTe coated substrate from recrystallization step on 340 consecutive substrate run with increased yield. Delivered July 1994.	1 each	End of 2nd Quarter
D-1.7	Sample of GPI module substrate from interconnection step deposition run demonstrating rate four times that of "original rate".	1 each	End of 2nd Quarter

Delivered July 1994.

D-1.8	Representative sample of 24 watt GPI CdTe Module from batch of >50 consecutive modules, with batch standard deviation <5% and total process yield >85%. Delivered October 1994.	1 each	End of 3rd Quarter
D-1.9	Representative sample of 24 watt GPI CdTe Modules from 160 modules/week production rate. Delivered October 1994.	2 each	End of 3rd Quarter
D-1.10	Representative sample of CdS coated substrate from CdS deposition step on 340 consecutive substrate run with 99% yield. Delivered October 1994.	1 each	End of 3rd Quarter
D-1.11	Representative sample substrate from tin oxide deposition step on 340 consecutive substrate run with 98% yield. Delivered October 1994.	1 each	End of 3rd Quarter
D-1.12	Sample module substrate from GPI interconnection step on 340 consecutive substrate run with 99% yield. Delivered October 1994.	1 each	End of 3rd Quarter
D-1.13	Representative sample of 24 watt GPI CdTe Module from 320 modules/week production rate. Delivered April 1995.	1 each	End of 4th Quarter
D-1.14	Representative sample of the GPI module encapsulation from 340 consecutive substrate run with 99% yield. Delivered April 1995.	1 each	End of 4th Quarter

PHASE 2

D-2.1	Representative sample of Pinhole plugging and Buss Bar Application steps. Delivered April 1995.	1 each	End of 5th Quarter
D-2.2	Representative sample of GPI module packaging steps. Delivered April 1995.	1 each	End of 5th Quarter
D-2.3	Representative sample of 22 watt GPI CdTe Module from a batch of at least 50 consecutive modules with a batch standard deviation of <5% for the output distribution and a total post CdS process yield of >85% and a total post CdTe total process yield >95%. Delivered April 1995.	1 each	End of 5th Quarter
D-2.3a	Representative samples of 26 watt GPI CdTe Modules from prototype run. Delivered April 1995.	2 each	End of 5th Quarter
D-2.4	Representative sample of 24 watt GPI CdTe Module from a batch of at least >50 consecutive modules with a batch standard deviation of <5% for the output distribution and a total post CdS process yield of >90% and a total post CdTe process yield >95%. Delivered August 1995.	1 each	End of 6th Quarter
D-2.4a	Representative sample of 28 watt CdTe Modules from prototype run. Delivered August 1995.	2 each	End of 6th Quarter
D-2.5	Representative sample of 28 watt CPI CdTe Module from a batch of at least >50 consecutive modules with a standard deviation of <5% for the output distribution and a total post CdS process yield of >90% and a total post CdTe process yield >85%. Delivered April 1996.	1 each	End of 7th Quarter

D-2.6	Representative sample of 28 watt (average) Module output for an 85% run. Delivered April 1996.	1 each	End of 8th Quarter
D-2.7	Representative sample of 24 watt GPI CdTe Module from production at 960 modules/week rate. Delivered April 1996.	1 each	End of 8th Quarter
D-2.8	Representative samples of 32 watt GPI CdTe Modules from prototype run. Delivered April 1996.	2 each	End of 8th Quarter

PHASE 3

D-3.1	Representative sample 30 watt GPI CdTe Module from a batch of at least >50 consecutive modules with a batch standard deviation of <5% for the output distribution and a total post CdS process yield >90%. Delivered July 1996.	1 each	End of 9th Quarter
D-3.1a	Representative sample of 32 watt GPI CdTe Modules from prototype run. Delivered July 1996.	2 each	End of 9th Quarter
D-3.2	Representative samples 28 watt GPI CdTe Modules with batch standard deviation <10% and total post CdS process yield >95% Delivered July 1996.	2 each	End of 10th Quarter
D-3.3	Representative sample of encapsulation process for GPI module fabrication. Delivered July 1996.	2 each	End of 10th Quarter
D-3.4	Representative samples of 32 watt GPI CdTe Modules with batch standard deviation <5% for batch of >50 consecutive modules and total	2 each	End of 11th Quarter

	post CdS process yield >85%. Delivered April 1997.		
D-3.5	Representative sample of 28 watt GPI CdTe Module with total post CdS process yield >95%. Delivered April 1997.	1 each	End of 11th Quarter
D-3.6	Representative sample of tin oxide coated substrate with resistivity 3×10^{-4} ohm-cm and uniformity <5%. Delivered April 1997.	1 each	End of 11th Quarter
D-3.7	Representative samples of 32 watt GPI CdTe Modules for a batch of >50 consecutive modules with a batch standard deviation of <10% for the output distribution and with >90% total "post tin oxide" process yield and deposited on manufacturing line operating at 1600 modules/week rate. Delivered April 1997.	6 each	End of 12th Quarter
D-3.8	Representative sample of 35 watt GPI CdTe Modules from prototype run. Delivered April 1997.	2 each	End of 12th Quarter