September 2000 • NREL/SR-520-28784

Subcontractor Report

Continuous, Automated Manufacturing of String Ribbon Si PV Modules

Second Annual Report
21 May 1999-20 May 2000

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Waltham, Massachusetts

NREL

National Renewable Energy Laboratory

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Contract No. DE-AC36-99-GO10337

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Prepared under Subcontract No. ZAX-8-17646-07

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EXECUTIVE SUMMARY

Evergreen Solar is a fully integrated PV manufacturer with its own unique technology in silicon ribbon growth, cell making, and module manufacturing. This report describes the activities in manufacturing technology and in silicon ribbon characterization that were completed in the second year of a three-year PVMaT subcontract. The focus in this second year has been on capital cost reduction and automation in silicon ribbon growth, automation and process simplification in the cell area, and some automation in the module area. Evergreen has used the capabilities of the Fraunhofer USA Center for Manufacturing Innovation at Boston University for help in factory layout, process flow, and efficient materials flow. Evergreen will be utilizing this as it prepares to move to a multi-megawatt factory in the latter part of 2000. Silicon ribbon characterization work has been provided for us by researchers at NREL.

A patent has already been filed on this work, and two more are in preparation. Four papers on different aspects of the work have been or will be presented at various conferences here and abroad.

In general, as this report shows, the project is on schedule and the overall goals are being met.

Acknowledgements

Evergreen personnel who have contributed to this work include Rob Janoch, Eric Gabaree, Dr. Andrew Anselmo, Jack McCaffrey, Peter Kane, Chris McLeish, Dr. Andrew Gabor, Mike Ralli, Joe Fava, Bryn Lord and Mark Mrowka. Matthias Grossman has overseen the work done for us by the Fraunhofer Center for Manufacturing Innovation at Boston University. The characterization work was done for us by Dr. John Webb, Lynn Gavrilas and Dr. Bushan Sopori at NREL. Dr. Martha Symko-Davies, our contract monitor, has been very supportive and helpful in this and in all aspects of this subcontract.

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INTRODUCTION

The report describes the second year of work within a three-year PVMaT 5A2 subcontract. Work performed under this subcontract in the first year, and described in the first annual report, laid the groundwork for this second year. This second year (Phase II of the subcontract) had four tasks, all of which are related to manufacturing technology development. In addition, a fifth objective was further characterization of Evergreen's String Ribbon polycrystalline silicon substrate material.

Altogether these tasks or objectives can be listed as follows:

A. Crystal Growth Automation and Technology improvements
B. Cell Manufacturing Automation
C. Module Manufacturing Automation
D. Material Handling and Process Flow Development
E. String Ribbon characterization

The final goal at the end of the three-year project will be a highly automated, nearly continuous manufacturing line for PV modules. As part of attaining this final goal, Evergreen Solar will be moving into a large factory in the latter part of 2000.

Since the inception of this subcontract, there has been some shifting of priorities. The result, especially regarding this report, is that most of the work has been in A, B, D, and E above, and a lesser amount in C.

A. CRYSTAL GROWTH AUTOMATION AND TECHNOLOGY IMPROVEMENTS

<u>Edge Meniscus Control and Crucible Coatings</u>

In the first year of this project Evergreen developed, ahead of schedule, a new string material. The successful deployment of this new string material meant that an earlier goal to investigate crucible coatings as a way of extending crucible life now had less value than first presumed. As a result, the investigation of crucible coatings was suspended indefinitely.

The new string material also required a better control of the meniscus at the edges of the ribbon, close to where the strings were incorporated into the growing ribbon (see the next section and Figure 1). We developed a method for edge meniscus control that provided the result sought and have now filed a patent on this method.

<u>New Furnace Design</u>

Under this task, the specific goals were the redesign of the crystal growth system and general automation of this system. The crystal growth method used by Evergreen is the String Ribbon technique that results in the continuous growth of polycrystalline ribbon. The process utilizes two strings that are wound on spools and continuously fed up through a heated graphite crucible. These serve to stabilize the edges of the growing ribbon (1). Figure 1 illustrates the process.

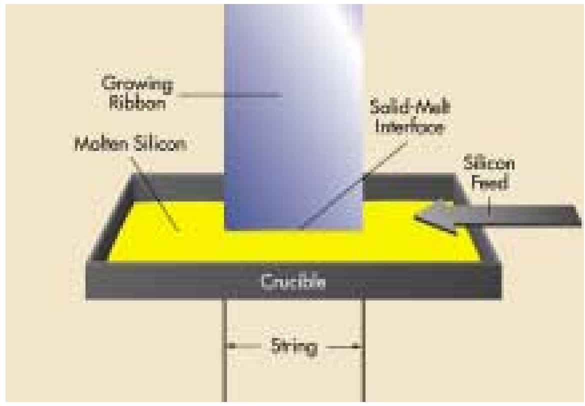


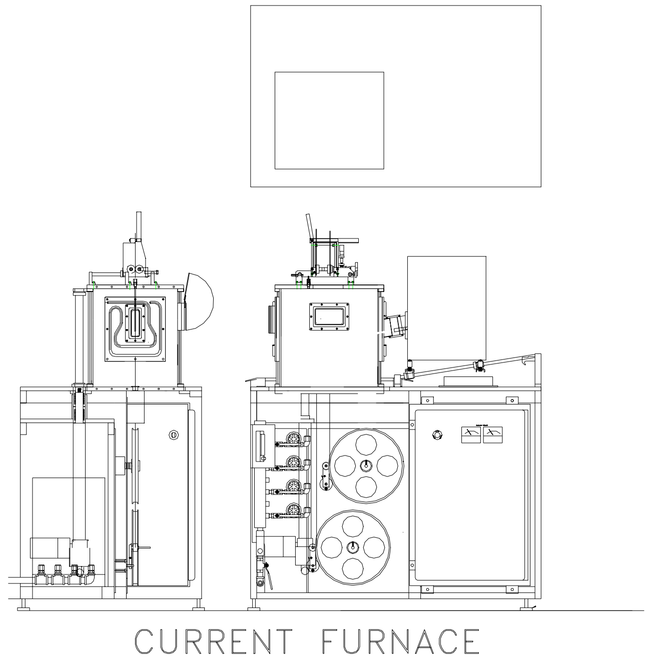
Figure 1 The String Ribbon Crystal Growth Process

The process and machines that Evergreen now employs have been run in a production mode for several years. The PVMaT work is designed to further advance the String Ribbon technology by redesigning the production crystal growth machines. The specific aims of this work were:

1. Improved functionality and reliability.
2. Improved productivity (i.e. labor) and ease of use.
3. Lower cost.
4. Minimal footprint.
5. Sufficient flexibility to accommodate later improvements.

To achieve these goals, the specific areas that were addressed included a redesign and simplification of the water-cooled shell, redesign of the frame, a more compact packaging of the electronics, a tying together of all control functions with one PLC, an overall much better sealed system so as to reduce argon consumption, a more accurate puller design, a redesign of the feeder so as to eliminate any possible source of metallic contamination, a redesign of the method used to deploy the string reels, and a more general base plate design that could easily incorporate further advances such as a lower cost hot zone and the growth of ribbon up to 10 cm in width.

In Figure 2 are shown a schematic drawing of the new furnace design, and for comparison, Evergreen’s present design.



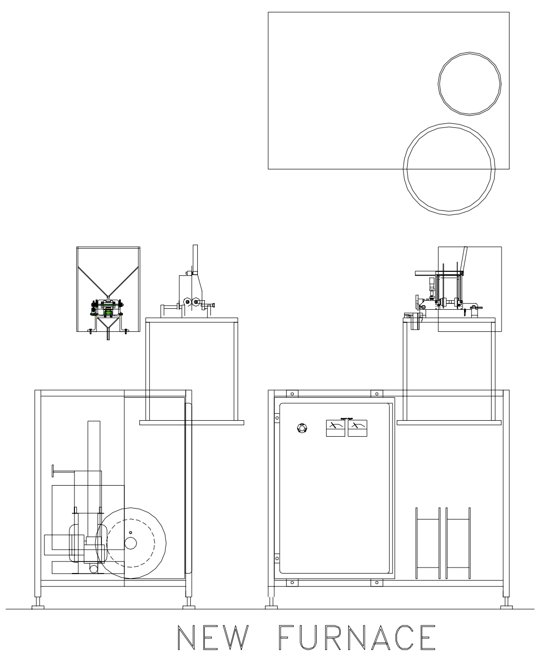


Figure 2 Old and new furnace designs.

Figure 3 is a photograph of the actual system after it was built and debugged. Figure 4 shows a close-up view of the string reels. It should be noted that the new design reduces the frequency with which string reels need to be changed by a factor of at least ten times.

Figure 3 New crystal growth furnace with 5.6 cm wide ribbon growing.

Figure 4 Image of new string reels.

. After running the system in production and completing a number of improvements, it was found that this new system has already satisfied four of the five goals listed above—1, 3, 4, and 5. The second goal, improved productivity (i.e. labor) and ease of use, has already been partially satisfied as the production operators have already noted that the system is easier to use than our earlier systems. Regarding productivity gains, these will be realized in the factory when we have a large number of these machines running.

The successful running of this first machine in production has led to ordering a large number of these machines for our factory. One point in particular is worth emphasizing. The new design has met or exceeded our cost goals and is well within the target cost reduction of at least 20% lower than our earlier machines. For a 10 MW factory we estimate about 120 such crystal growth machines will be needed. So the total capital costs savings here is very considerable.

Automatic Thickness Control

In the String Ribbon crystal growth method, thickness uniformity is achieved by adjustments to the melt temperature along the horizontal width of the growing ribbon. In earlier production systems, ribbon thickness was manually measured by the machine operator as the ribbon exited from the machine. If the thickness measurements warranted any thermal adjustments, they were made by the operator based on a few general rules of thumb. To reach the goal of reduced labor costs and higher productivity, it was clear that an automated method for measuring and controlling thickness would be needed. In the first year of this PVMaT program the basic elements of such a method were studied. In this second year, a complete system with feedback control was designed and built.

The first element developed was the automated measurement of ribbon thickness. A mechanical method was initially tried but found to be too complex, noisy, and unreliable. A non-contact method was then developed that was far simpler and reliable. This measurement method was found to be far more repeatable than operator measurement, with a standard deviation of 0.2 mils versus a standard deviation of 0.75 mils for the manual method. A typical plot of thickness measurement showing the automatic and manual methods below in Figure 5 shows the wide differences in manual measurement among experienced operators, and the repeatability of the automatic method.

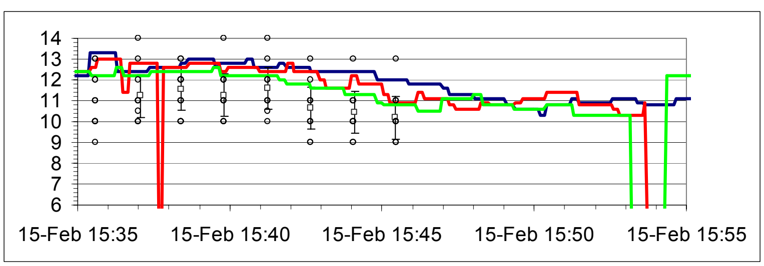


Figure 5 Differences between non-contact and manual thickness measurements. Automatic non-contact measurements are shown as lines, manual measurements are shown as individual data points.

The next element to be developed was a model that could control the ribbon thickness. An objective function was created so that a quantitative measurement of ribbon thickness quality could be determined. The model for the control of ribbon thickness used four control inputs to adjust the thickness of the ribbon, with the objective function as a performance metric. Additional analysis of the process using DOE protocols shows that cross term effects from the inputs can be disregarded for the present. A series of experiments determined the coefficients for the model. Simulations of the control algorithm indicated that even if the calculated control coefficients are off by as much as 50%, there is little effect on the final converged solution.

The ribbon thickness measurement and control system were tied together using an upgraded PLC that was also used to control the rest of the crystal growth machine. Additional hardware was added to the system to detect “freezes” of the ribbon to the growth interface. “Freezes” can be a consequence of both manual and automatic control systems, and must be detectable as soon as possible to minimize process downtime.

Additional options were added to the control system as the system was developed. These options allowed a region of deadband (to prevent over-control), and to allow the modification of certain set control points to avoid oscillations if they were not in a controllable region. Since ribbon thickness is highly dependent on the height of the melt from which the ribbon was grown, steps were taken to ensure that the measurement and control of melt height was stable. Some PID tuning of other control loops was also investigated to eliminate naturally occurring variations in ribbon thickness. Automatic freeze detection was achieved with a low-cost string reel motion detector.

Typical results from the system in automatic mode are shown in the figures below. The control values are given in the first two plots, the thickness values in the third plot, and the objective function in the last plot. The objective function shows how well the system is being controlled as disturbances are introduced into the system (a lower value means the system is closer to optimum). The objective function was defined as = $(T - L)^2 + (T - M)^2 + (T - R)^2$ where T = Target, and L, M, and R are left, middle and right thicknesses.

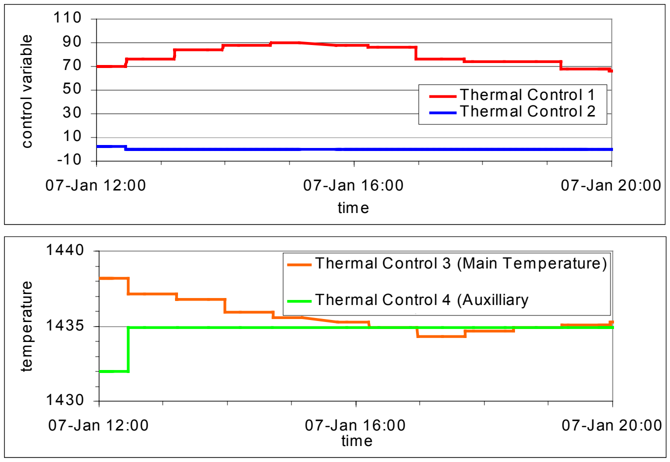


Figure 7 Inputs to the automatic thickness control system.

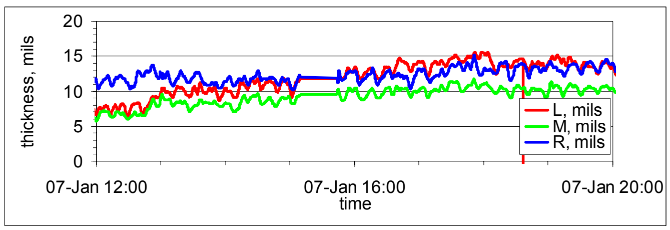


Figure 6 Ribbon thicknesses as a function of time.

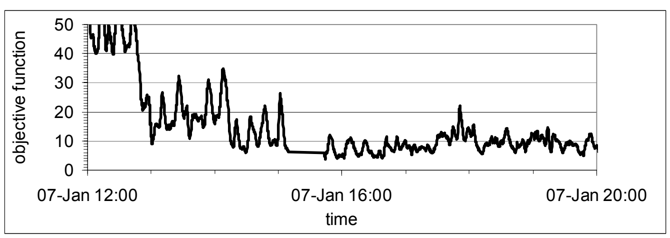


Figure 8 Objective function, showing improvement in the process.

A system has been run in automatic mode for several days without any major problems, and will soon be run continuously by production operators. All the new crystal growth machines will be fitted with automatic thickness control and freeze detection.

Figure 9 shows a close up of the puller head which has the automatic thickness measurement system.

Figure 9 Details of the automatic thickness measurement mechanism on the new furnace.

B. **CELL MANUFACTURING AUTOMATION**

Some General Principles

In the design of the new automated equipment for the factory, certain underlying principles were followed. These included generic PLC's used in every machine. Where rotary tables were employed, these were also all the same. Similar gantry equipment used in various operations and generic vision systems for locating cells were also employed. Also, underlying all this was the effort at designing a high volume automated line with minimal handling and minimal processing steps. A major goal for the last mentioned was the elimination of any pre-diffusion etching—ribbon goes directly from growth into diffusion—and the consequent elimination of the traditional plastic carriers used for acid etching. Instead, the wafers basically stay horizontal as they are made into solar cells.

Transport of Wafers and Wafer Size

As Evergreen prepares for its move into the factory, some significant changes are being implemented. One in particular is the cell size. We are changing from a 5.6 cm x 15 cm cell (area ≈ 84 cm²) to a 8 cm x 15 cm cell (area ≈ 120 cm²). Advances in our crystal growth technology have allowed us to do this with the increased productivity and reduced costs this would bring in its train. Since the conventional plastic carriers have been eliminated, a new method of wafer transport had to be developed. This method embodies the use of plastic boxes designed to hold at least fifty of the 120 cm² area cells or wafers to be easily stacked, to be bar coded so that individual lots of wafers can be traced and to be moved only by robots, conveyors, and the like. An example of these boxes is shown in Figure 10, along with a stack of the 8 cm wide ribbon substrates. This box will represent a volume density saving of about three times over that of the plastic carriers—an important consideration when designing the size needed for a buffer.

Figure 10 Example of storage and handling boxes. 8 cm wide String Ribbon blanks are in the boxes on the left.

Contact Application Machines

Evergreen has its own unique technology for forming contacts on solar cells and has therefore designed machines that are specifically geared to this technology. In particular, three components of contact application have been designed. Two of them were designed and built this second year of the contract and are already in use in our plant site in Waltham. They are working quite well. These are a front contact application machine and a rear contact application machine. The use of these machines alone has contributed to an increase in yield in our cell area on the order of 10%. At present wafers with the front contact applied are then moved into trays, turned over and then fed into the rear contact application machine. For our factory in Marlborough, an additional machine—a so-called accumulator, will be interposed between the front and rear contact machines. The accumulator will have two functions. One will be to turn the cells over, and the other will be to serve as a buffer or storage if and when this is needed. Figure 11 shows the rear contact application machine as it is being deployed. What can be seen in this picture are the 5.6 cm wide blanks being processed.

Figure 11 Rear contact application machine.

In Figure 12 is shown a belt transfer system and a generic gantry system that will be used to take cells from the rear contact application machine and place them on a wide belt that will transfer them to another belt for contact firing.

Figure 12 The belt transfer system and generic gantry system.

Diffusion and Diffusant Glass Etch

In the crystal growth area, strips of String Ribbon on the order of 1.5 m long will be laser scribed into 15 cm blanks and then automatically loaded into the boxes shown in Figure 13.

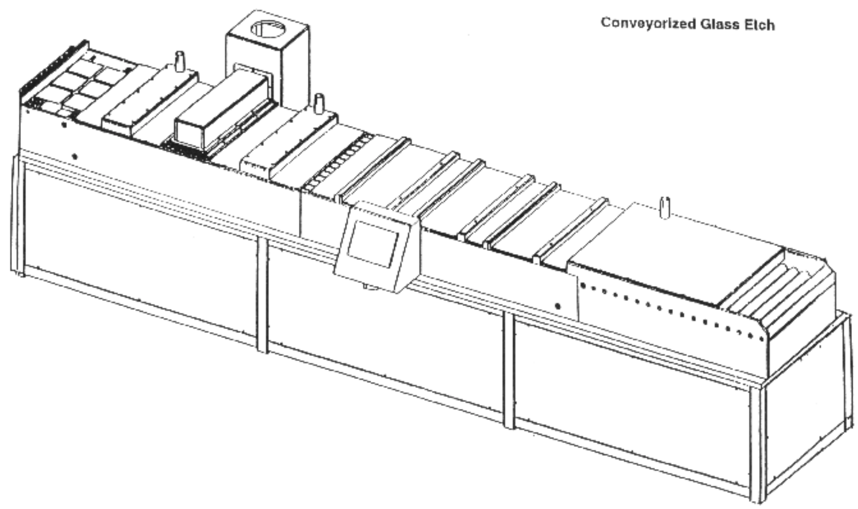


Figure 13 Sketch of glass etch removal machine.

With the elimination of any need for an etch step at this point, these wafers then go directly into diffusion. For diffusion, they will be unloaded from these boxes with a robot and then placed into the diffusion system where the wafers are coated with a phosphorus-containing compound and then fired in a furnace. The robot for loading the wafers at this point is still undergoing design work but is viewed as relatively straightforward and should, in any case, be implemented by the time of the move to the factory. Following diffusion, a method and machine for glass etch removal is now under development (about 90% complete at this time) that will allow the diffused blanks to remain horizontal. Figure 14 shows an image of such a machine. A close-up of the boxes is shown in Figure 15. In actual use, this machine will only be dealing with the white boxes. The green boxes will be used only for metallized cells.

Figure 14 The machine which will take cells from the glass etch machine and then transfer them into plastic boxes.

This box is designed so that a robot can readily transport it and a robot can easily pick out cells or blanks from it. This is expected to produce higher yields in diffusion in particular. Also, the belt-conveyor method for post-diffusion glass etch means that there will be a belt-to-belt transfer between diffusion and glass etch. This then means the elimination of a handling step and some improvements in yield.

The parameters needed for higher throughput in diffusion have been determined

as well, and will be implemented in the factory.

Figure 15 Close-up of the plastic boxes as they move on a belt.

Accumulator and Hydrogen Passivation Load and Unload

Another type of accumulator for buffer storage will be employed following diffusant glass etch. This machine is shown in Figure 14. In this case, the diffused wafers will again be placed in boxes so as to reduce the amount of buffer volume needed.

Hydrogen Passivation

Evergreen is now developing a plasma nitride hydrogen passivation process. The process will have a unique feature in particular in that it will lend itself readily to robotic load and unload of String Ribbon wafers. At the time of this writing the process is still under development and not optimized, but the basic concepts underlying it have already been demonstrated. It has already been shown that efficiency improvements on the order of 25% can be obtained using this process. The best 120 cm^2 cell made this way had the following parameters: J_{sc} = 30.5; V_{oc} = 590; F.F. = .730; Eff = 12.99%. It is clear that there is much room for improvement here.

C. **MODULE MANUFACTURING AUTOMATION**

In-line Tester and Cell Tabber

Using radial tables and a storage area between them, an in-line cell tester and tabber is now being completed in our Waltham facility. Figure 16 shows the setup for the in-line tester that is the foreground. The storage area is above it. Completed cells coming off of the metallization line will be tested and then go into various “bins” according to their peak current. The apparatus for this binning is shown in more detail in

Figure 17. Finally after being stored, the cells are tabbed—that is the front soldered contacts are formed, and this will be done in the equipment shown in Figure 18.

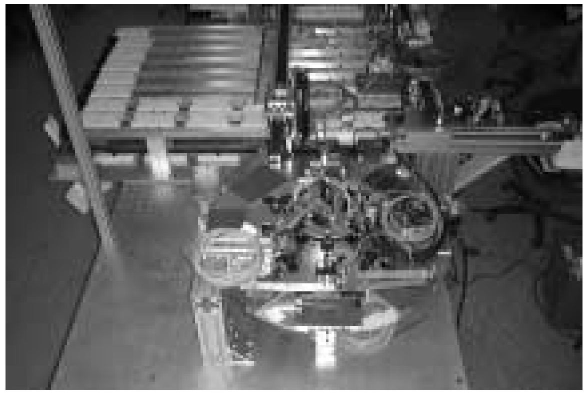


Figure 16 Generic rotary table used for the cell tester.

Figure 17 Binning apparatus.

Figure 18 Tabbing machine with generic rotary table

Improved Soldering Method

The front tabber and the equipment for forming the cells into strings will employ a novel soldering method that has been under development during this second year. A prototype machine for this is shown in Figure 19.

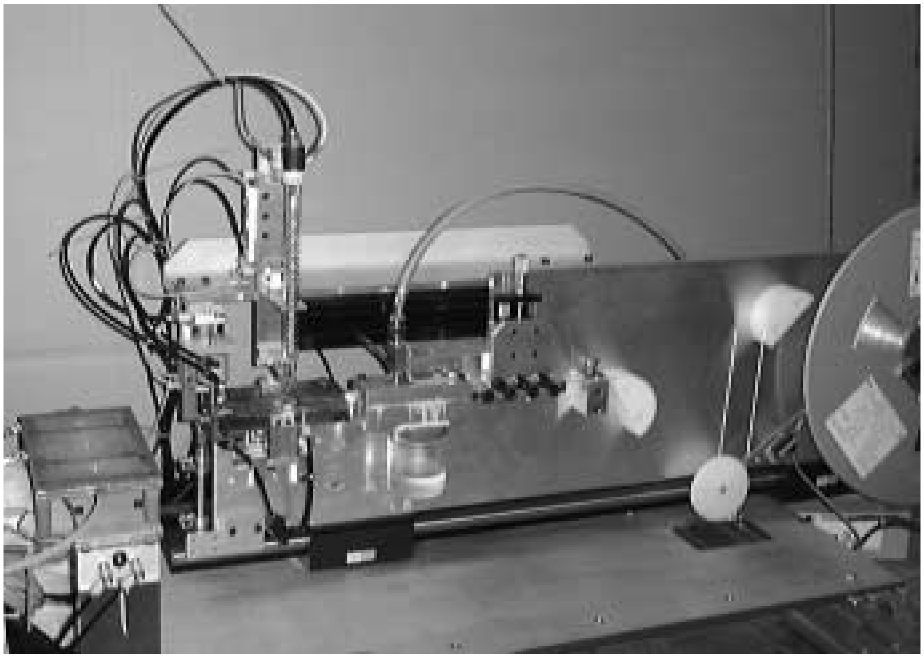


Figure 19 Prototype soldering machine.

D. MATERIAL HANDLING AND PROCESS FLOW DEVELOPMENT

Evergreen's New Factory

Figure 20 shows a picture of the new building Evergreen will be moving into in the fall of 2000 in order to build a multi-megawatt production line. As an important part of our overall PVMaT subcontract objectives, we have enlisted the help of the Fraunhofer USA Center for Manufacturing Innovation at Boston University. This Center is part of the worldwide Fraunhofer Gesellschaft, based in Munich, Germany. The Fraunhofer Center does contract research in manufacturing technology, and Boston University itself offers advanced degrees in this area. A Boston University graduate student spent considerable

Figure 20 Evergreen Solar's new facility.

time doing motion studies on our production line.

As Figure 20 indicates, our new factory has a rectangular shape. Using extensive feedback from virtually all the senior technical personnel at Evergreen, the Fraunhofer group has helped us to lay out a production line with a very efficient factory flow. At one end of the building incoming feedstock silicon is received, and at the other end of the building, finished modules are shipped out to customers. Figure 21 gives a schematic of the building layout.

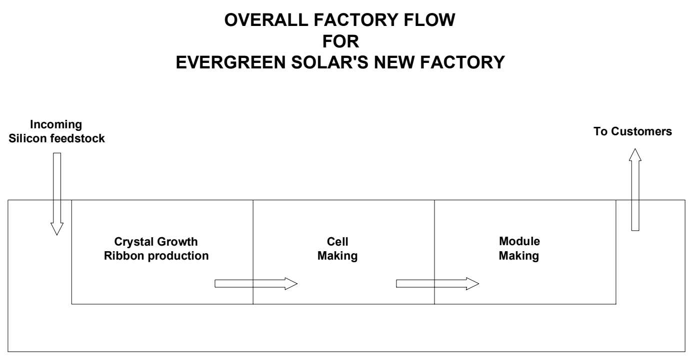


Figure 21 Overall factory flow for new factory.

<u>Plant Layout and Process Flow</u>

The basic model used by the Fraunhofer group is called the Taylor ED Simulation Model. This is a software package that allows for simulating process flow, buffer requirements, downtime, and efficient layout of equipment. The Taylor ED Simulation Model is based on an "Atom Concept." The four dimensions of the atom are x, y, z, and time, t. These atoms can freely communicate with each other, can contain other atoms and be freely created and destroyed. Everything in the simulation package is an atom regardless of whether it is a resource, a product, a model, etc. Following are some important examples of the use of this simulation model in helping us to design the factory.

<u>Power Outages and Continuous Operation</u>

The String Ribbon crystal growth process is one that is designed to run continuously. In fact, the process and the associated crystal growth machines work best run in a fully continuous mode. By continuous here we mean seven days a week, twenty-four hours a day. The only reason for shutting down a furnace is erosion of the graphite crucible. A routine shutdown is schedule for every furnace after a prescribed number of weeks of continuous operation.

Given both the need for, and the desirability of continuous operation, what happens when there is a power outage? An emergency generator large enough to handle the load would be the best answer but the capital investment required here is formidable. So we have had the Fraunhofer group run some simulations of possible downtimes for two outage scenarios, 30 minutes and 24 hours. The idea here was to evaluate where the trade-off would occur for the large capital purchase of an emergency generator versus the lost production due to the outage. An example of the simulation results is shown in Figure 22. From the local utility we obtained historical data on the average times for outages over the last few years. With all this information, it was clear that we could easily afford to defer the purchase of the emergency generator.

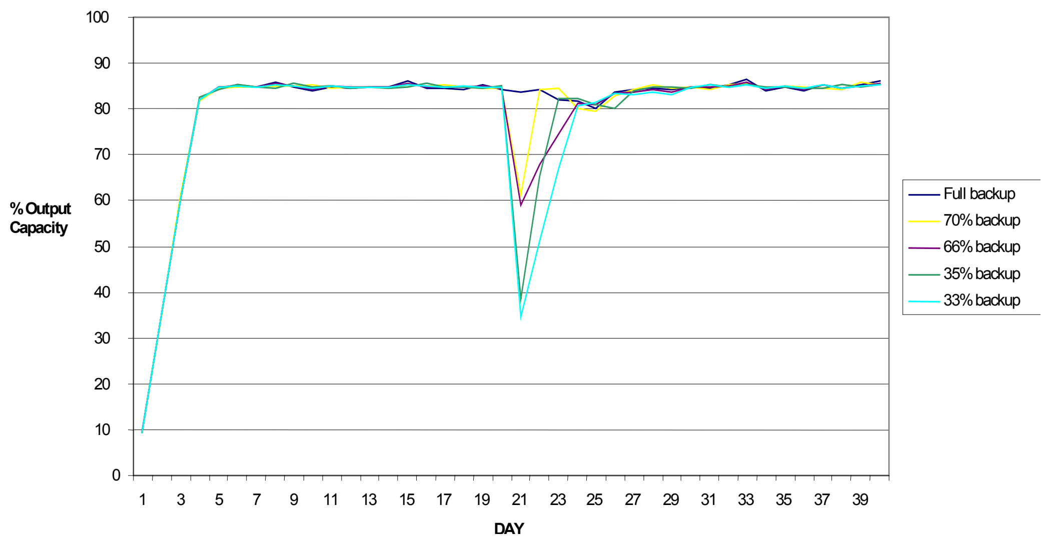


Figure 22 Effect of 1/2 hour power failure on production, as a function of the percentage of crystal growth furnaces on backup power.

<u>Crystal Growth Layout—"Cells"</u>

We anticipate a large number of crystal growth machines for the factory—on the order of 120 for a 10 MW factory. The correct placement of such a large number of crystal growth machines was clearly an important challenge. Again here we first sought feedback from both R&D personnel and production personnel in the crystal growth area. This was then provided to the Fraunhofer people in an iterative process until a mutually satisfactory layout emerged. The result was a layout with a cellular concept. A single such "cell" would contain the number of crystal growth machines that it is expected that a single production operation could run. The cells themselves were in "U" shape. Three such shells are shown in a simulation layout shown in Figure 23 along with the diffusion process line on the right hand side of the diagram.

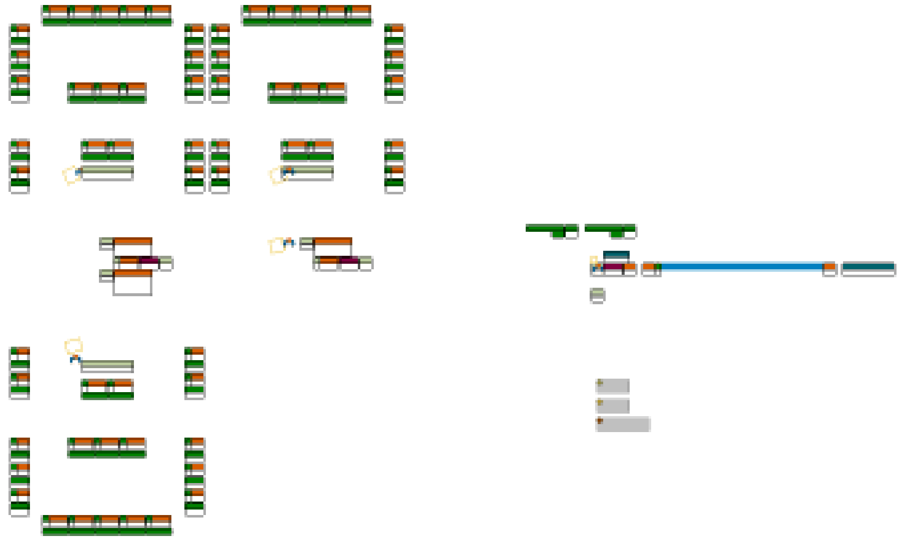


Figure 23 Layout of crystal growth “cells” and diffusion process.

The general process in the crystal growth area is that a strip of ribbon about 1.5M long is grown then scribed without interrupting growth. Then this strip is moved to a laser cutting station and cut into 15 cm long solar cell blanks.

This crystal growth “cell” as it was designed satisfied these requirements: ease of access to both the crystal growth machines and the laser station; ease of access to the crystal growth machine for any facilitation and maintenance needs; ease of moving additional crystal growth machines into the area.

Crystal Growth—Diffusion Buffer

A central issue in any plant layout is that of integrating processes with either very different rates or different modes of operation. This applies particularly to crystal growth and to the next step—p-n junction formation or diffusion. By “crystal growth” here is meant both the growth of the silicon ribbon itself and the laser cutting into 15 cm long blanks. The above difference is very much in evidence in the crystal growth and in the diffusion step. In Figure 19 a cluster or “cell” of crystal growth machines as well as a laser and the diffusion operation are shown in this simulation. Recall that there is no pre-diffusion etching step and that as-grown blanks go directly from laser cutting into diffusion. In such a case, a single diffusion furnace and associated equipment will have a much large capacity even run intermittently, than a large number of crystal growth furnaces, even given the fact that these are run continuously. Hence the need for a buffer between the two operations. An example from the simulation model is shown in Figure 24.

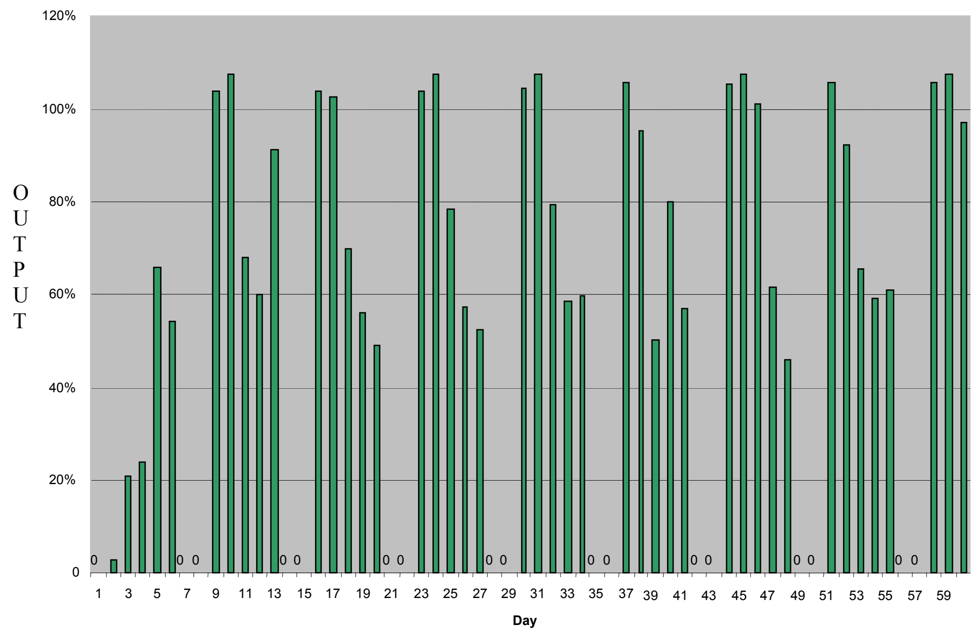


Figure 24 Simulation showing diffusion output.

Process Flow

The cell area is being designed such that a minimal amount of labor will be required and that robotic transfers and gantry cranes as shown in the earlier Figures 11 and 14 will be used to move boxes of cells. Figure 6 showed these boxes. In addition to all this, it is anticipated that carts containing these boxes will be need for, initially at least, manual movement of these carts between some operations. A simulation of the carts and their needs is shown in Figure 25.

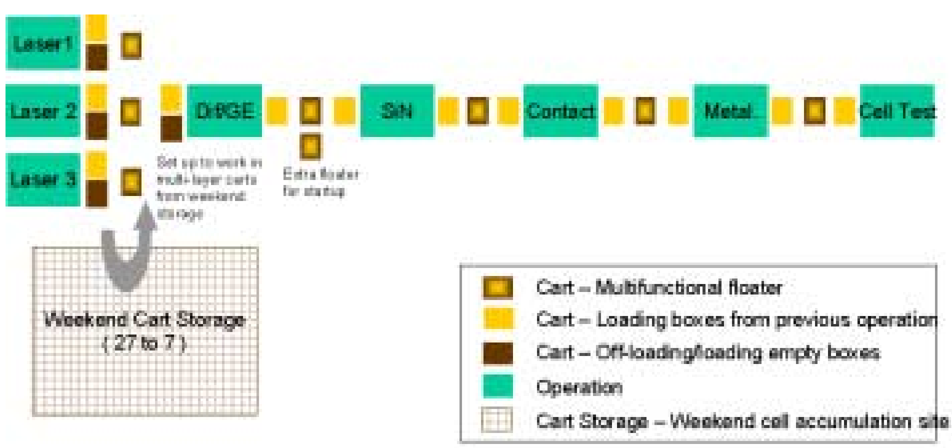


Figure 25 Cart flow simulation and needs.

E. **STRING RIBBON CHARACTERIZATION**

Silicon Ribbon grown with the String Ribbon process is polycrystalline but with its own unique grain structure. The growth geometry imposes much of this structure. The grains are often wide single crystal grains, more or less in the growth direction and bounded by twins or bands of twins similarly oriented. Less frequently, there are grains bounded by high angle boundaries. At the edges of the ribbon, the incorporated strings (see Figure 1) nucleate high angle boundaries and these grow in for a few mm.

Dislocation Distributions

Earlier evidence suggests that a principal limiting defect is that of dislocations. Two other earlier findings are relevant here. One is that String Ribbon responds well to hydrogen passivation and the other is that the starting lifetime in the material varies considerably along the width of the ribbon but does not vary so much in the length (the growth direction). That is, a region that shows a high lifetime continues to do so along the growth direction and vice versa.

Bushan Sopori of NREL has done some dislocation scans on String Ribbon that illustrates the above points rather well. On the left side of Figure 26 is shown a dislocation scan, and on the right side is shown the corresponding distribution. The sample is a 5.6 cm wide piece of ribbon. The scan has gone nearly to the edge of the ribbon. The growth direction is vertically upwards in Figure 26. Note that the overall average of dislocation density is skewed towards the lower end. It should be noted that in all these samples, there was no polishing, the samples were run with as-is surfaces. The lack of a flatter, polished surface precluded an accurate calibration of the dislocation densities, and the numbers shown could be too high by one or two orders of magnitude. Even with this, the comparative mapping here is very instructive. Note, for example, in Figure 26 the wide, range grain that has a very low dislocation density and that runs in a direction close to that of the growth direction. Also, it can be seen that closer to the ribbon edges, the dislocation density is clearly higher. Another sample that has a higher overall dislocation density is shown in Figure 27.

Oxygen and Carbon Concentrations

A set of samples was forwarded to NREL for FTIR analysis. The goal was to determine oxygen and carbon concentrations and how they are distributed in the String Ribbon material as a function of growth system parameters and crystal structure. Analyses were through a 3 mm aperture and by difference—subtracting the spectrum of a float-zoned silicon wafer to yield the impurity absorbance coefficient spectrum of each sample.

The samples included material from a number of growth systems. This included standard production material, material grown at 50% higher speeds, and material from an experimental run that looked at the effects of a reducing ambient in order to suppress silicon oxide and silicon carbide formation and prolong the life of graphite/carbon compounds.

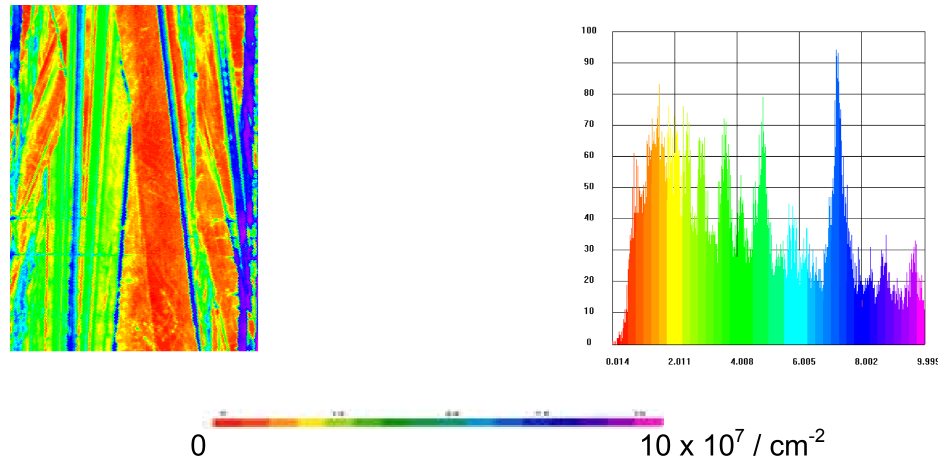


Figure 26 Dislocation map and distribution of a low dislocation sample of string ribbon.

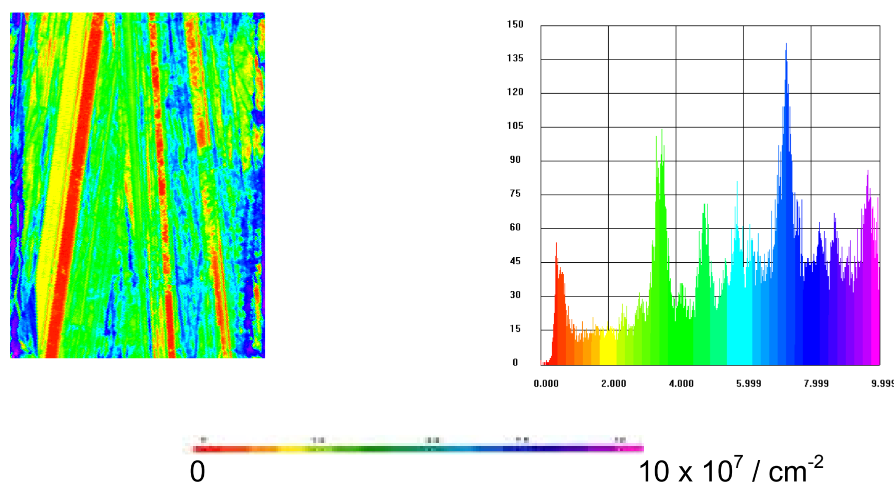


Figure 27 Dislocation map and distribution of a high dislocation sample of string ribbon.

In each case, samples were selected from two of the most commonly occurring grain structures: densely bundled twins covering as much as 1-3 cm across the width of the ribbon, and regions of large single crystal grains that can reach dimensions of 3 x 5 cm.

There are some indications that wafers with mostly densely bundled twins may display superior solar cell performance and that these regions can exhibit low dislocation densities. In the single crystal regions, it was thought that the oxygen and carbon concentrations might give an indication of the degree of dissolution of the graphite crucible and the extent of oxygen contamination. The latter has never been found to be at significant levels in String Ribbon material, at least based on FTIR measurements.

In the reducing ambient experiments the analyses were done to determine whether there were any significant effects on the carbon and oxygen concentrations due to this reducing atmosphere.

These are the general observations:

- Almost no interstitial oxygen was found ($1e^{16}$);
- Substitutional carbon was generally in the mid, $5\text{-}6e^{17}$, range;
- The single crystal grains generally were at the low end of concentration for substitutional carbon; and
- There was no significant difference in interstitial oxygen and substitutional carbon levels for the material grown at 50% higher speed vs. the ribbon grown under our present production speed.

Overall, it is interesting to note that the substitutional carbon levels are lower than that found for EFG. This is generally in the $9e^{17} – 1e^{18}$ range. In general, the present results confirm an earlier analysis of String Ribbon done some four years ago at NREL, except that the carbon level was higher at a value of $7 – 9\ e^{17}$. Since our growth process has changed dramatically since then, it was felt to be worthwhile to again characterize the material and further to see if grain structure differences were measurable. So it may be real that the carbon level is somewhat lower now.

In a later experiment, SIMS was used to measure total carbon and total oxygen. The total [O] concentrations measured using SIMS were at least an order of magnitude higher that the [O_i] measured by FTIR. This must mean that all this oxygen is in the form of precipitates in the ribbon and not as interstitial oxygen. Finally, another interesting phenomenon is that the total carbon measured by these SIMS experiments is similar to that of the $[C]_s$ measured by FTIR indicating that all the carbon present is in the form of substitutional carbon. Also, the carbon level shows a near surface depletion in some cases. A similar effect was observed many years ago in EFG. Its significance is not yet clear.

PAPERS AND PATENTS

Papers

1. A paper on some of this work was given as a poster during the NCPV meeting in March 2000 in Denver, Colorado. Also, a paper on this work has been accepted for the forthcoming PV meeting in Anchorage, Alaska in September 2000.
2. Jack Hanoka presented an invited talk on String Ribbon growth at the recent PVSEC 11 in Sapporo, Japan. Some of the PVMaT sponsored work was described and acknowledged in this talk.
3. Papers on some of the work in this report are to be presented at the forthcoming NREL Defects Workshop in August 2000 in Copper Mountain and at the forthcoming IEEE PVSC in Anchorage, Alaska in September 2000.

Patents—Two patent applications based on the work done this past year are now in preparation, and a patent on edge meniscus control has already been filed.

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REPORT DOCUMENTATION PAGE			*Form Approved* *OMB NO. 0704-0188*

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE September 2000	3. REPORT TYPE AND DATES COVERED Second Annual Report; 21 May 1999-20 May 2000

4. TITLE AND SUBTITLE
Continuous, Automated Manufacturing of String Ribbon Si PV Modules; Second Annual Report; 21 May 1999-20 May 2000

5. FUNDING NUMBERS
C: ZAX-8-17646-07
TA: PV006101

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8. PERFORMING ORGANIZATION REPORT NUMBER

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National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401-3393

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NREL/SR-520-28784

11. SUPPLEMENTARY NOTES
NREL Technical Monitor: M. Symko-Davies

12a. DISTRIBUTION/AVAILABILITY STATEMENT
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)* This report describes the activities in manufacturing technology and in silicon ribbon characterization that were completed in the second year of a three-year PVMaT subcontract. The focus in this second year has been on capital cost reduction and automation in silicon ribbon growth, automation and process simplification in the cell area, and some automation in the module area. Evergreen has used the capabilities of the Fraunhofer USA Center for Manufacturing Innovation at Boston University for help in factory layout, process flow, and efficient materials flow. Evergreen will be utilizing this as it prepares to move to a multi-megawatt factory in the latter part of 2000. Silicon ribbon characterization work has been provided for us by researchers at NREL. A patent has already been filed on this work, and two more are in preparation. Four papers on different aspects of the work have been or will be presented at various conferences here and abroad. In general, as this report shows, the project is on schedule and the overall goals are being met.

14. SUBJECT TERMS
photovoltaics ; crystal growth automation and technology ; cell manufacturing automation ; module manufacturing automation ; material handling and process flow ; string ribbon characterization ; PVMaT

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102