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Thin EFG Octagons

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Summary

The participation of Mobil Solar Energy Corporation in Phase 2A - Process-Specific Issues of the Photovoltaic Manufacturing Technology (PVMaT) Initiative program commenced on April 1, 1992. This effort has as its objective to advance the manufacturing line capabilities in crystal growth and laser cutting of its unique EFG octagon technology and so reduce the manufacturing costs of 10 cm × 10 cm polycrystalline silicon EFG wafers.

This report summarizes the significant technical improvements in EFG technology achieved in the first six months of Phase 2 of this program, and the success in meeting the program milestones. Technical results are reported for each of the three main program areas:

Task 5 - Thin octagon growth (crystal growth) - to reduce the thickness of the octagon to 200 microns.

Task 6 - Laser cutting - to improve the laser cutting process, so as to produce wafers with decreased laser cutting damage at increased wafer throughput rates.

Task 7 - Process control and product specification - to implement advanced strategies in crystal growth process control and productivity designed to increase wafer yields.

Highlights achieved in each task are described briefly in this report.

Task 5 - Crystal growth investigations in the Mobil Solar Phase 1 program were aimed at aiding and accelerating the transition from growth of 400 micron to 300 micron thick octagons in the Mobil Solar pilot line operation, while carrying out the research needed to achieve the Phase 1 interim goal of production of 250 micron thick wafers. We successfully demonstrated the growth of 250 micron thick octagons in Phase 1, with yields of wafers through laser cutting meeting the program targets. Optimization work on finalizing the 250 micron thick material for introduction into the production line is in progress, and similar studies are in progress on 200 micron thick octagons. A transition from 96 × 96 mm^2 to 100 × 100 mm^2 size wafers has been completed to bring the Mobil Solar wafer size in line with the rest of the industry. Design of two new crystal growth furnaces has been started and is proceeding on schedule.

Task 6 - In the laser cutting area, an increased throughput laser station has been designed and a prototype material handling system tested. The laser station is in the final stages of construction and acceptance testing is scheduled for the next quarter. Two new lasers, the dye and the copper vapor laser have demonstrated reduced damage cutting. The cost of the dye laser system deployment is estimated not to be cost effective. The copper vapor laser is closer to commercialization and a more detailed review is under way to evaluate its potential for lower-cost, high speed reduced damage cutting.

Task 7 - On-line deployment studies of several sensor systems have been completed. A buckle monitor, a thickness measurement system and an interface imaging system all show promise as diagnostic tools to help in further development of thin octagon growth. A velocity-based thickness control system has been demonstrated to improve axial thickness uniformity for growth of thinner octagons and will be introduced on-line next quarter.

Introduction

Mobil Solar Energy Corporation currently practices a unique crystal growth technology[1] for producing crystalline silicon sheet, which is then cut with lasers into wafers. The wafers are processed into solar cells and incorporated into modules for photovoltaic applications. The silicon sheet is produced using a method known as Edge-defined Film-fed Growth (EFG), in the form of hollow eight-sided polygons (octagons) with 10 cm faces. These are grown to lengths of 5 meters and thickness of 300 microns, with continuous melt replenishment, in compact furnaces designed to operate at a high sheet area production rate of 135 cm^2/min. Each tube in cut into 10 cm × 10 cm wafers by a high-speed laser, which eliminates the need for slicing or grinding that is wasteful of material.

The present Photovoltaic Manufacturing Technology (PVMaT) three-year program seeks to advance the manufacturing line capabilities of the Mobil Solar crystal growth and cutting technologies. If successful, these advancements will provide significant reductions in already low silicon raw material usage, improve process productivity, laser cutting throughput and yield, and so lower both individual wafer cost and the cost of module production.

Material Requirements

The successful implementation of process technology for the photovoltaic manufacturing program is critically related to a number of EFG material characteristics. First, the mechanical yield of processing wafers into solar cells and encapsulating them into panels depends upon the strength and the flatness of the wafers. Wafer strength is determined by the residual stress in the material, as well as by the length of microcracks created at the wafer edge during laser cutting. Edge cracks can propagate as the wafers are flattened during processing, thus lowering mechanical yield. It is also important to improve wafer flatness during growth in order to facilitate automated wafer transfer between processing steps.

The local electronic characteristics of an EFG solar cell are correlated to the local thickness of the wafer. This results in the conversion efficiency being related to wafer thickness, so variations in thickness uniformity can also affect solar cell efficiency. Hence it is important to control tube thickness uniformity during growth to reduce variations in cell performance and hence raise overall cell efficiency.

Finally, the wafer should contain an optimum level of interstitial oxygen (O_i) for maximum conversion efficiency. Interstitial oxygen is incorporated during crystal growth by adding controlled amounts of carbon monoxide (CO) to the argon ambient. Since the degree of O_i incorporation can vary from run to run, it is necessary to evaluate and modify growth conditions in order to provide a process that will reduce this variation.

Program Goals

The objective of this program is to advance PV manufacturing technology by reducing wafer thickness and cost of crystal growth and laser cutting in Mobil Solar's EFG octagon technology--thereby reducing the cost of module production.

Mobil Solar has undertaken to meet this objective, during a three-year effort, by reducing the EFG wafer thickness by 50%, increasing the throughput of laser cutting of silicon octagon tubes into wafers, increasing the edge strength and thus the yield of wafers, and evaluating integrated computer-aided control programs for the Mobil Solar crystal growth manufacturing line that can enhance productivity.

This report summarizes the significant technical improvements in EFG technology achieved in the first six months of Phase 2 of this program, and the success in meeting program milestones.

Progress in Technology Development

The technical work in this program is structured into three main tasks:

Task 5 - Thin octagon growth (crystal growth)
Task 6 - Laser cutting
Task 7 - Process control and product specification

Program goals for each task are summarized in Fig. 1. Highlights of work performed and results achieved under each task are reviewed in the following sections.

Task 5: Thin EFG Octagon Growth

The EFG process yields a tubular octagon sheet product that eliminates the need for the sawing, grinding, and polishing required to obtain uniform thickness and flat substrates when silicon wafers are produced by conventional processes such as ingot growth or casting.[2] However, the EFG process also requires that stringent measures be taken to control factors--inherent to the crystal growth process--that affect the as-grown material geometry.[3,4]

The following sections describe efforts under each of the Phase 2 subtasks.

Subtask 5.1: Thickness Uniformity

EFG wafer thickness variations originate from a number of sources and are conveniently categorized according to their origins. These are:

1. Transient thickness variations, predominantly associated with changes in the thickness differential between the octagon face center and edge. Typically, the earlier tubes grown tend to have thinner corners, but these corners become thicker as the number of tubes grown increases. These variations are caused by heat transfer nonuniformities in the die and susceptor.

2. Systematic variations around the octagon perimeter which appear to be periodic. These are related to coil placement and the temperature distribution in the melt. Unfavorable combinations of these variables lead to a significant amount of unmelted silicon in the crucible. The resulting temperature nonuniformities are a dominant source of periodic and near-periodic circumferential thickness variations.

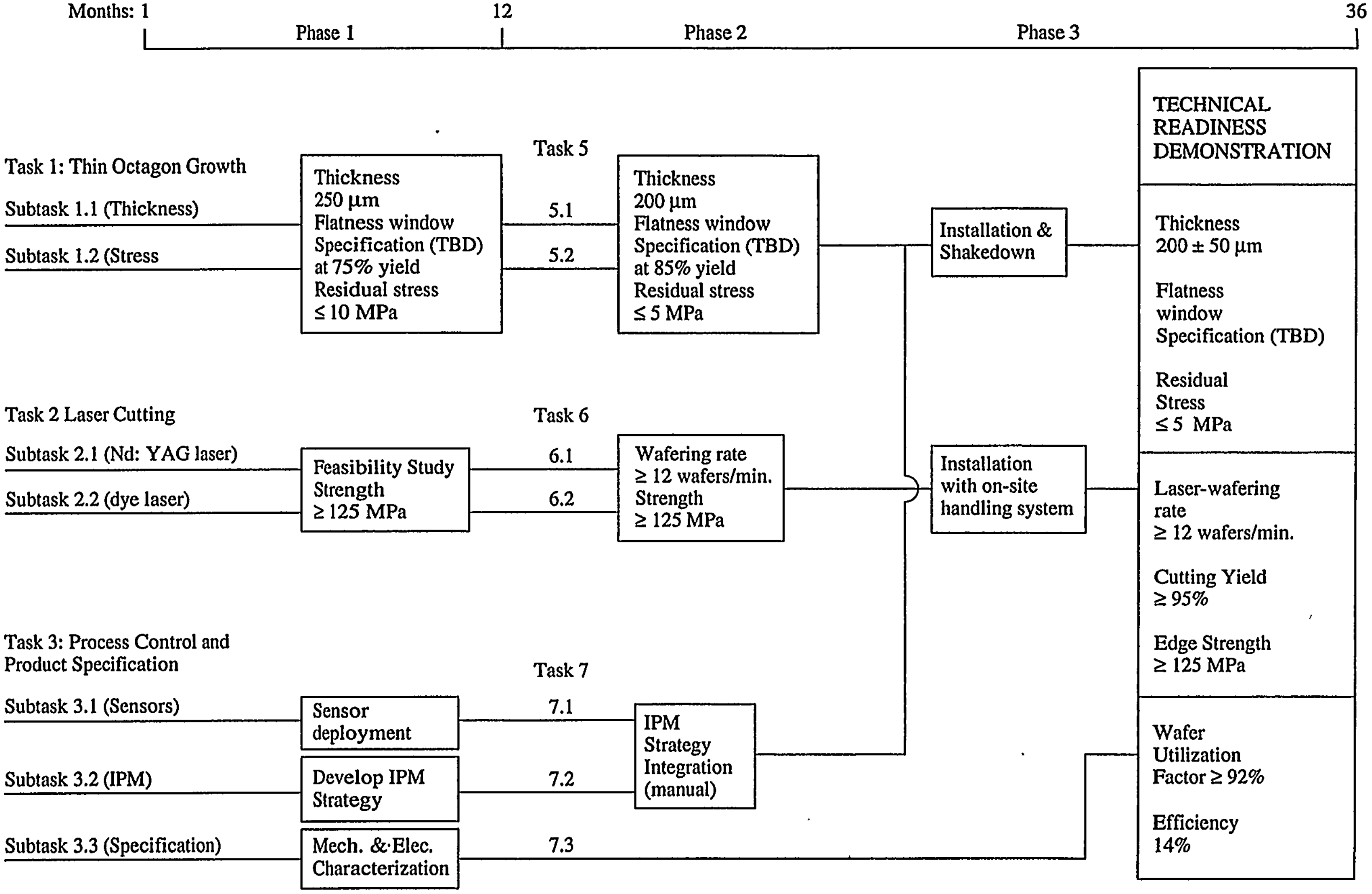

Figure 1. Program Goals Sum of Terms

3. Longitudinal variations along the length of the tube. These are influenced by the melt recharge, temperature and tube weighing control systems associated with the melt replenishment operation.

The computational results that led to the reduction of the thickness variation across the edge of an octagonal face have been reported in a paper.[5] STM consulting conducted an extensive study on the dependence of the three dimensional temperature distribution of the EFG system on the design variables. The results are well documented in the final reports available at Mobil Solar. In Phase 2, the longitudinal thickness variations along the length of the tube, as in item 3 above, were addressed. Details of the work are given under the controls subtask.

Efforts are ongoing to develop specifications for thickness uniformity based on yield requirements as the thickness of the octagon is lowered through the three phases of the program to the target thickness of 200 microns. These specifications will be based on the yield and efficiency response of the thin wafers in processing into modules. A target level of 50 microns for allowable thickness variations has been tentatively set for the 200 micron thick 100 mm × 100 mm wafer to be produced in Phase 3. Subtask 7.3 on product specification will assist in establishing criteria for thickness variations of EFG wafers as thickness is decreased.

A new design of hot zone was introduced in Phase 1 which eliminated the face-center-to-edge thickness variation across the octagon face in the case of 96 mm × 96 mm area wafers which were being produced at that time. In Phase 2, we have been working to introduce a larger size wafer of 100 mm × 100 mm area. This has required some additional modifications in hot zone configuration for growth of 250 micron thick material, and a reoptimization of the furnace design to minimize the thickness variation across the larger octagon face. These studies are nearing completion.

Design tasks for the new EFG crystal growth furnaces have been started. Two separate vendors have been chosen for their expertise in different areas. The two furnaces will incorporate improvements in various aspects of growth process control that are anticipated to lead to increased furnace reliability, up time, and throughput, and improve EFG product (wafer) quality at reduced cost. The two furnace design tasks differ in that one addresses improvements that will consolidate productivity enhancements for growth of 300 micron thick octagons in the Mobil Solar production line, while the second task incorporates advances in crystal growth for growth of thinner octagons. The first task integrates results of design reviews and advancements developed under the PVMaT program crystal growth furnace subtask for growth of 300 micron material into a factory-hardened EFG system. The second furnace design effort addresses a second-generation, advanced EFG growth system. This will incorporate further new concepts not previously tested on a production line to deal with the heightened degree of difficulty present in growth of the thinner material, to address the goals at the end of Phase 3.

In the first project, a central focus is the evaluation of an improved control system. This consists of an industrially hardened controller design that will reduce down time and maintenance, provide increased flexibility for process automation, streamline data collection, and open up possibilities for remote furnace operation. Other furnace improvements designed to consolidate 300 micron thick octagon production line technology include an integrated power supply, an upgraded melt replenishment unit and a new puller configuration. The design phase is scheduled to be completed in the third quarter and the furnace is to be constructed and tested on the Mobil Solar pilot production line during the fourth quarter of Phase 2. The second, advanced concept furnace for 200 micron octagons will test technology for improved growth stability, increased levels of automation, growth ambient control and an increased sensitivity weight sensor for thickness control. The new design concepts are currently being worked out, and a final design review is scheduled for September before construction is authorized. Acceptance tests of the system and growth trials of this furnace are scheduled to take place in the *first and second quarters of* Phase 3.

Subtask 5.2: Stress

Stress within the octagon is caused by nonuniformities and varying high axial gradients (of the order of 1000°C/cm) in the temperature field which create thermal stresses during growth.[4,6] These stresses produce plastic flow and dislocations which then further contribute to residual stresses in the EFG wafer. The most visible manifestation of stress is development of buckles, which are periodic deviations from flatness along an octagon face. These most often have a period of 10 cm and amplitudes that are as large as 2 mm in the extreme. Longer periods are also observed.

Implementation of controls for wafer buckling, as well as improvements in wafer flatness, are closely related to the ability to manipulate the temperature field (more specifically, its second derivative) in the region of greatest plasticity (generally above 1000°C) in post-growth cooling, and in the rate of cooling through the plastic region.[7] This region is located immediately above the die tip. Stress reduction requires detailed information of the temperature fields in close proximity--within about 5 mm--of the growth interface.

The magnetic and thermal models of the EFG system developed at Mobil Solar and the thermocapillary model developed at MIT are being integrated to study the effect of design changes on the temperature field in the growing crystal. It is necessary to include the capillary effect to study the thermal field close to the solid/melt interface.

The residual stress in a growing tube/sheet is computed with the model developed at the University of Florida.[8] The misfit strain concept developed through the model has been helpful in understanding how to design the hot zone to reduce the stress level in the silicon sheets. Some of the results are given in the paper.[8] A final report available at Mobil Solar discusses the formulation of the problem and the final results..The residual stress model uses the temperature field computed from the thermal models as the input.

A buckling analysis will be performed with the computed stress field at the University of Massachusetts at Lowell. With the completion of the buckling analysis, the effect of hot zone design modification on the temperature field, the residual stress level and buckling will be tracked with the integrated models. Note that the models are parametric and therefore the effect of any variable may be modeled readily.

The effect of the transverse temperature field on the residual stress and the buckling of the tubes is being studied experimentally. There has been good success in reducing the stress level and improving the flatness by tailoring the transverse temperature field to be frowning (⌒) isotherms in the solid/melt interface region. This type of transverse isotherm is obtained by modifying the inside afterheater shields, to follow the stress model results of the EFG system.[7]

Flatness specifications on thin EFG wafers that relate to mechanical yields (wafer breakage) will be refined during the remaining phases of the program. The relationship of yield to wafer edge strength, currently limited by the laser cutting process, will be studied as part of the Product Specification task.

Task 5 Highlights

Improvements in EFG crystal growth technology which have demonstrated a potential to increase yields and productivity of 300 and 250 micron thick tubes and wafers are:

- an octagon growth system that produces 96 mm × 96 mm wafers has been successfully replaced by a system that produces 100 mm × 100 mm wafers;
- axial thickness control has been improved by the addition of velocity as a manipulated variable;
- specification of the control system and the mechanical components of a crystal growth system have been completed;
- the transverse temperature profile has been established as one of the significant variables that causes buckles in the octagonal growth system and has been successfully used to improve flatness;
- design work of a resistance heated decagon growth system was initiated.

Task 5 Milestone Status

All the Phase 2 milestones listed for crystal growth in the reporting period were completed.

Task 6: Laser Cutting

The laser cutting work was structured to study the feasibility of attaining program goals by two different routes:

(1) to improve existing cutting technology using Nd:YAG lasers, or
(2) to cut silicon with a new generation of line-focus dye lasers.

These two approaches provide very different options for meeting the cut wafer edge quality (strength) and throughput (wafering rate) objectives of the program shown in Fig. 1.

After feasibility studies and cost evaluation during Phases 1 and 2, the candidate laser technology best suited to meet the program goals and cost objectives will be selected for development and integration with tube-handling concepts in Phase 3.

Commercially available Nd:YAG lasers have the capability of achieving linear traverse speeds of more than 10 cm/s at the power levels necessary to cut through 200–400 micron thick silicon. In principle, this would allow a cut to be made around the perimeter of a 10 cm × 10 cm area in as little as 4 seconds, providing a processing rate of 15 wafers/min. However, maximum rates are not achieved in practice because of the limitations of tube- and wafer-handling mechanisms. Efforts to improve the cutting technology with these lasers thus involves advancing tube- and wafer-handling processes as well as improving the quality of wafer cut edges. This work is described under subtask 6.1 below.

High-power dye lasers have recently become available to allow accessing of new regimes for cutting silicon. These lasers provide the opportunity to work with line-focused beams with sufficient energy to cut through octagons of the target thickness of 200 microns at the rates required. They have the potential to match and to exceed the wafering rates of the Nd:YAG lasers while at the same time improving wafer edge quality. In Phase 1 of this contract, the feasibility of producing low damage line cuts with a dye laser was successfully demonstrated.

Laser cutting goals for the three year program are to demonstrate technology that will increase wafer cutting throughput rates while at the same time also improve the wafer edge strength of the thinner material. To achieve the desired throughput gains requires both improving wafer-handling technology and increasing the cutting speed. These improvements have to be accomplished while at the same time reducing laser damage in the cutting process.

The initial strategy for this task has been twofold: first, to carry out investigations with novel laser systems at lower-tier contractors' facilities in attempts to demonstrate the feasibility of cutting with reduced edge damage in Phase 1; second, to investigate new designs of wafer-handling at Mobil Solar in order to design and evaluate new concepts that will form the basis of throughput upscaling of the laser station to the wafering rates set for the Phase 3 objective, once the laser configurations producing the greatest improvement in edge quality are identified.

The following sections describe efforts under each of the Phase 2 subtasks in the past six months.

Subtask 6.1: Nd:YAG Laser

Lasers have been used for cutting of EFG sheet silicon since 1980. Several types of lasers are currently being evaluated at Mobil Solar for their ability to meet cut quality and throughput objectives for the EFG octagon-based manufacturing technology. Laser system advancement is proceeding in parallel with development of octagon tube- and wafer-handling technology. The objective of this subtask is to determine the limits of cut edge quality and throughput available with new configurations of the Nd:YAG laser technology.

In this subtask we were concerned with:

- design, fabrication and testing of a laser cutting station capable of increasing throughput by a factor of two;
- testing of a different models of Nd:YAG lasers to evaluate their potential for higher speed, reduced damage cutting with lower capital costs.

Subtask 6.2: Dye Laser Feasibility Study

The details of cutting silicon with a dye laser were discussed in a previous report.[9] In Phase 2, we have continued to study the interaction of the dye laser irradiation with the silicon crystal in depth. It was demonstrated that the required cutting speeds of the program could be reached with the operating parameters available with the Textron Defense Systems' (TDS) experimental 100 J dye laser. Cutting damage was very much reduced at the cut edge. Preliminary fracture testing of limited numbers of samples indicated that the edge strength was increased, but that further cutting configuration optimization was required to reach program targets. The results of the studies are available in a final report from the subcontractor.

A cost study was performed by TDS to estimate the design and construction costs of a dye laser system that would satisfy the Phase 3 program goals. This showed that the development, prototype testing and commercialization costs exceeded the allowed budgetary constraints of the PVMaT program. Further work on dye laser cutting of EFG wafers has been discontinued.

Task 6 Highlights

Among the highlights in the Task 6 work in this reporting period are:

- Feasibility studies on reducing damage with a Nd:YAG laser by using a preheat beam have started to show encouraging results. Some cutting conditions have been identified where the microcrack density is reduced. A proposal is being readied by the lower-tier subcontractor for a continuation program.

- A new model Nd:YAG laser has been installed in the production area for on-line testing. This laser has a combination of lower divergence and higher power than the current ones in use, and showed promise that it is capable of reducing damage in cutting in preliminary laboratory tests. The low capital cost of this laser also makes it an attractive candidate for future deployment.

- A new candidate laser has been identified for silicon cutting which has many of the same favorable attributes demonstrated for the dye laser. The copper vapor laser operates at similar wavelengths as the dye laser. Feasibility studies have shown that cutting results are also comparable and show reduced damage. Some models are commercially available and this will considerably reduce the cost of deployment of a cutting system based on the copper vapor laser. A more detailed evaluation of this laser is in progress.

- The fabrication of a higher throughput laser cutting station is proceeding on schedule. Completion of the station and acceptance testing are planned for the next quarter.

Task 6 Milestone Status

Milestone M-1.24 in the laser cutting task was not completed as planned in Phase 1 and shifted to Phase 2. It is currently scheduled to be completed in the next quarter. This is not expected to impact the Phase 3 goals.

Task 7: Process Control and Product Specification

The programs in this task are structured to provide support in areas of sensor development, crystal growth process control improvements, and wafer characterization for the work objectives described above in Tasks 5 and 6 (see Fig. 1). This support is to culminate in implementation of advanced concepts in on-line material property monitoring and crystal growth process control via Intelligent Processing of Materials (IPM) strategies, which lead to increased yield and productivity in fabrication of 200 micron thick EFG wafers in Phase 3.

The following sections describe efforts under each subtask under Task 7 in Phase 2.

Subtask 7.1: Sensor Development

Sensor development programs address feasibility testing and implementation of new approaches to monitor and measure EFG material geometric characteristics and material properties. A number of these will be designed for on-line use in the crystal growth process, among them interface temperature field and meniscus shape measurement, local thickness measurement, and buckle mapping.

Progress made toward these goals is described under Task 7 Highlights later in this section.

Subtask 7.2: Intelligent Processing of Materials (IPM) Strategy

The goal of this subtask is to integrate process models, sensor technology, and process control concepts to develop advanced furnace control elements involving the implementation of IPM strategies for maintaining high yields and productivity in growth of 200 micron thick EFG octagons. A description of the various control elements is given in a previous report.[9] Integration of successful elements into the crystal growth process control structure is currently underway.

Progress made toward these goals is described under Task 7 Highlights later in this section.

Subtask 7.3: Product Specification

As-grown wafer property specifications being addressed in this subtask include: thickness and thickness uniformity, flatness and edge strength, residual stress, and electronic quality.

The program objectives require that EFG wafer electronic quality be sufficient to have the potential to produce 10 cm × 10 cm 14% efficient solar cells. This capability has been demonstrated for a significant number of solar cells on a research level with 300 micron thick octagons.[10] Wafer minority carrier lifetimes are being monitored and small batches of cells made on an experimental basis as material thickness decreases throughout the program to check the impact of crystal growth developments on this material capability. A program was started in Phase 2 to establish as-grown wafer electronic property monitoring and measurement techniques.

Highlights of Task 7 results are described in the following section.

Task 7 Highlights

Sensor Development

Several sensor prototypes have been evaluated for their suitability for on-line operation:

- Buckle patterns were characterized with a projection moire technique, using Fast Fourier Transform Profilometry (FFTP), developed at Texas Tech University. This allows surface deformation on successive full width 10 cm × 10 cm areas of the tube to be mapped on any given face while the tube is growing. The data is digitized and reconstructed to obtain information on the buckle pattern and buckle amplitudes over the entire 5 m length of the tube. The initial application of this technique is intended to be as a diagnostic tool to study buckle behavior as a function of growth conditions such as growth speed, tube thickness and hot zone configuration changes. Correlations of this type allow rapid characterization of the buckles early in the growth process, and permit on-line adjustments to minimize buckling. This will increase the yield of acceptable flatness material and eliminate the need for flatness inspection after cutting.

- We have developed a second buckle mapping system which uses a laser-ranging sensor to measure buckle amplitude continuously while the tube is growing, but only at one point. A full complement of eight sensors, one for each face, has been tested and some refinements in design are being completed before installation and more extensive testing will take place. The single-point information will be used in conjunction with the full buckle shape obtained from the FFTP technique on one face to calibrate the two techniques against one another.

- We are in the process of integrating a velocity-based sensor technique for axial thickness control into the control loop for automated tube growth. This control mechanism greatly reduces excursions of the thickness related to temperature fluctuations and the weight-based sensor noise control loops. These can be an impediment to growth and must be more closely controlled as the octagon wall thickness is reduced because they lead to an unacceptable frequency of voiding and productivity loss in crystal growth. A more detailed account of this approach is found in Appendix A.

- The development of a local thickness measurement technique, also suitable for obtaining octagon thickness while the tube is growing, has been completed at BDM. This utilizes Optical Low Coherence Reflectometry (OLCR). We are proceeding to get a fixed cost estimate for a system that can operate on-line.

- The development of an interface imaging system has been completed at KDY. On-line trials showed that the system was capable of resolving meniscus height during growth, and can be used either as a diagnostic monitor or as a control element for thickness. Temperature measurements were also attempted, but calibration curves could not be established from the preliminary set of data obtained to date, and this area will need additional work.

Intelligent Processing of Materials (IPM)

Several elements which are targeted to be implemented with new control strategies under IPM have been independently tested:

- We are experimenting with a control algorithm for thickness based on velocity manipulation. This may be more advantageous to use for the thinner octagon tubes because of its faster response in comparison to the power level and temperature loop currently employed. Preliminary results have allowed us to start incorporating this control mechanism in control of tube wall thicknesses (see Appendix A).

- A control algorithm has been developed to enable the coil position to be used to automatically manipulate the circumferential thickness and thus minimize nonuniformities during growth. A thin tube face tends to buckle more than a thick face. When buckle amplitude is available from on-line measurements, such as from one of the sensor techniques described above, this information is provided to a coil position manipulation system built to be capable of responding automatically to this input.

- A software program has been written to operate with the velocity-based thickness sensor described above to help in reducing buckling and so to improve the flatness yield. This is done by changing the velocity during growth of particular portions of the tube to reduce the stress, and hence the buckle amplitude.

Product Specification

Highlights of material characterization/specification efforts include:

- Solar cells have been made and characterized for the two different thickness materials, 250 and 300 microns, currently being produced. The results are given in Table 1. Several growth parameters, growth speed, carbon monoxide (CO) level and thickness were investigated. This material was processed without any special effort to optimize processing conditions for the thinner material. We have evidence from other work that the efficiency of 13% currently available is equivalent to 14% with suitable optimization. These results thus demonstrate that the current material quality is sufficient to meet the targets of the program.

- Two 90 cm × 43 cm experimental modules, one containing 250 micron thick wafers and the other 300 thick ones, were fabricated and delivered to NREL. Solar cells before encapsulation averaged about 13.7%. The performance of the two modules were essentially the same.

- New projects at the University of Denver, at the University of California-Berkeley, and at Mobil Solar have been initiated to address the issues of characterization and of material electronic property specification for polycrystalline silicon wafers. The objective is to develop measures of as-grown wafer quality that are predictive of solar cell performance. The work will address the difficulties inherent in characterization of all polycrystalline materials which arise because of inhomogeneities, and because the diffusion length is upgraded to the order of the wafer thickness during solar cell processing, thus complicating quality measurement technique interpretations.

Task 7 Milestone Status

All milestones in Task 7 have been completed.

Cost Elements in EFG Wafer and Module Technology

We have updated our calculation on the cost reduction in EFG wafers and modules that will result from integration into the Mobil Solar production line of the technology improvements anticipated to result from the PVMaT program. These are shown in normalized form in Fig. 2. The normalized cost plotted is the variable, or direct manufacturing cost, excluding capital cost and the cost of money. The individual contribution from a given advance in lowering wafer cost is first broken out separately; then the module cost reduction is calculated to reflect this wafer cost reduction. Each new cost reduction is calculated using the previous improvement as the cost base, so that the final bars represent the cumulative cost reduction when all the advances are fully integrated into the manufacturing line.

Case 1 presents the baseline for 400 micron EFG tubes and wafers. The cases displayed are as follows, with the approximate anticipated time in the PVMaT program that the improvement will be introduced into the line in parentheses:

Table 1
Solar cell parameters for EFG wafers for several growth conditions

IRV: reverse saturation current; VOC: open circuit voltage; ISC: short circuit current; FF: fill factor; PP: efficiency; N: number of cells; STDEV: standard deviation

(a) 250 micron thick material at two growth speeds of slow (1.5 cm/min) and fast (1.75 cm/min)

	Speed	**N**	**Mean**	**Median**	**STDEV**
IRV	Slow	37	0.3414	0.3500	0.1892
	Fast	34	0.2656	0.2100	0.1210
VOC	Slow	37	0.57965	0.58000	0.00278
	Fast	34	0.57965	0.58000	0.00302
ISC	Slow	37	30.045	30.010	0.236
	Fast	34	30.034	30.085	0.300
FF	Slow	37	0.75259	0.75400	0.00879
	Fast	34	0.75194	0.75400	0.00859
PP	Slow	37	13.109	13.060	0.235
	Fast	34	13.090	13.110	0.225

(b) 300 micron thick material with several different oxygen levels varied by increasing carbon monoxide (CO) concentration.

	CO Level (ppm)	**N**	**Mean**	**Median**	**STDEV**
IRV	No CO	47	0.15019	0.14400	0.04718
	500	50	0.2158	0.1940	0.0886
	1000	35	0.16757	0.15200	0.04971
	1500	36	0.1732	0.1540	0.0796
VOC	No CO	47	0.56889	0.57000	0.00701
	500	50	0.58028	0.58050	0.00327
	1000	35	0.58054	0.58000	0.00376
	1500	36	0.57731	0.57700	0.00369
ISC	No CO	47	28.059	28.290	0.780
	500	50	29.049	29.055	0.322
	1000	35	29.342	29.380	0.678
	1500	36	30.043	30.065	0.354
FF	No CO	47	0.74760	0.75100	0.01255
	500	50	0.74712	0.75000	0.01551
	1000	35	0.75371	0.75600	0.01119
	1500	36	0.74733	0.74900	0.01496
PP	NO CO	47	11.938	12.010	0.530
	500	50	12.596	12.640	0.360
	1000	35	12.839	12.920	0.428
	1500	36	12.964	12.985	0.391

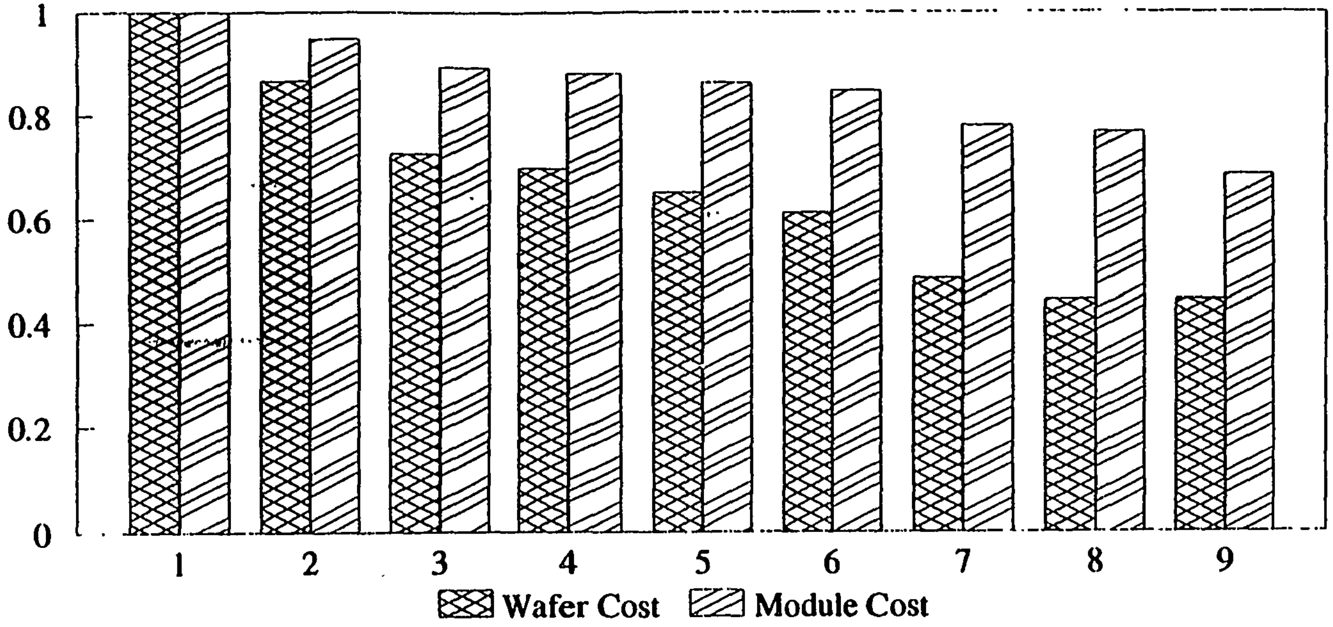

Figure 2 . Variable cost reduction elements for PVMaT program and beyond

Case 2: wafer flatness and cutting yield improvements, productivity increase in crystal growth (Phase 2);
Case 3: crystal growth yield and productivity increases (Phase 2);
Case 4: new furnace and controls upgrading (Phase 2);

Case 5: laser cutting station throughput increase (Phase 2);

Case 6: wafer thickness reduction to 250 microns (Phase 3);

Case 7: advanced laser cutting station with throughput improvement of a factor of three over Case 5 with decreased wafer edge damage, and mechanical yield improvements (post-Phase 3);

Case 8: wafer thickness reduction to 200 microns (post-Phase 3);

Case 9: solar cell efficiency increase from 13 to 15% (not part of PVMaT).

Case 9 reflects the impetus for achieving thinner wafers, which are needed to increase the yield of high efficiency cells. New schemes for solar cell design become accessible when wafer bulk diffusion lengths are consistently maintained of the order of the wafer thickness, and this will increase the percent of cells above a target level and make it possible to achieve the 15% efficiency levels with the new designs.

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Appendix A

Report on Longitudinal Thickness Control Using the Puller Speed

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Introduction

The current method of thickness control in silicon tube growth is based on the manipulation of the die tip temperature. The control algorithm minimizes the thickness error, the difference between the actual and setpoint values, by changing the die tip temperature. Due to the slow thermal response of the system, the current control scheme performs inadequately.

An improved control method has been developed and tested. In this new approach, a second control loop manipulates puller speed as a function of longitudinal thickness error. The principle behind this approach takes advantage of the fact that during growth the longitudinal thickness is inversely related to the puller speed. As puller speed can be changed much more quickly than die tip temperature, the response of this loop is faster, resulting in tighter thickness control. Results have demonstrated up to a 5:1 improvement in longitudinal thickness uniformity as a result of the operation of this added loop. Additionally, die tip temperature is maintained at a more uniform value, as much of the thickness error is corrected by the new speed control loop.

As a consequence of improved thickness control a number of benefits should be realized. Increased uniformity of the die tip temperature, silicon feed rate and melt level should result. It is anticipated that this will help to reduce the number of voids and freezes experienced during growth. Additionally, better thickness uniformity may result in faster laser cutting times. This would result from a reduction in the size and frequency of thick sections of the octagon, and the correspondingly extra time required to laser cut these sections.

A top level diagram describing the present thickness control system and the new approach is depicted in Fig. 1. The region in the dotted box represents the new control loop modification.

Present Approach

The present thickness control approach is accomplished through the variation of die tip temperature as a function of the thickness error between the setpoint and actual values. This error is used to adjust the temperature setpoint of the PID loop controlling the furnace temperature. In this approach, the puller speed is maintained at a constant value.

A block diagram of the complete process is shown in Fig. 1. As indicated in the figure, the puller speed is integrated to yield the growth length of the octagon. This length, in conjunction with the weight of the octagon is used to derive a calculated estimate of the actual octagon thickness. The error between the thickness estimate and the thickness setpoint is used to generate a correction to the temperature setpoint of the furnace hotzone temperature control loop.

OCTAGON THICKNESS CONTROL
BLOCK DIAGRAM

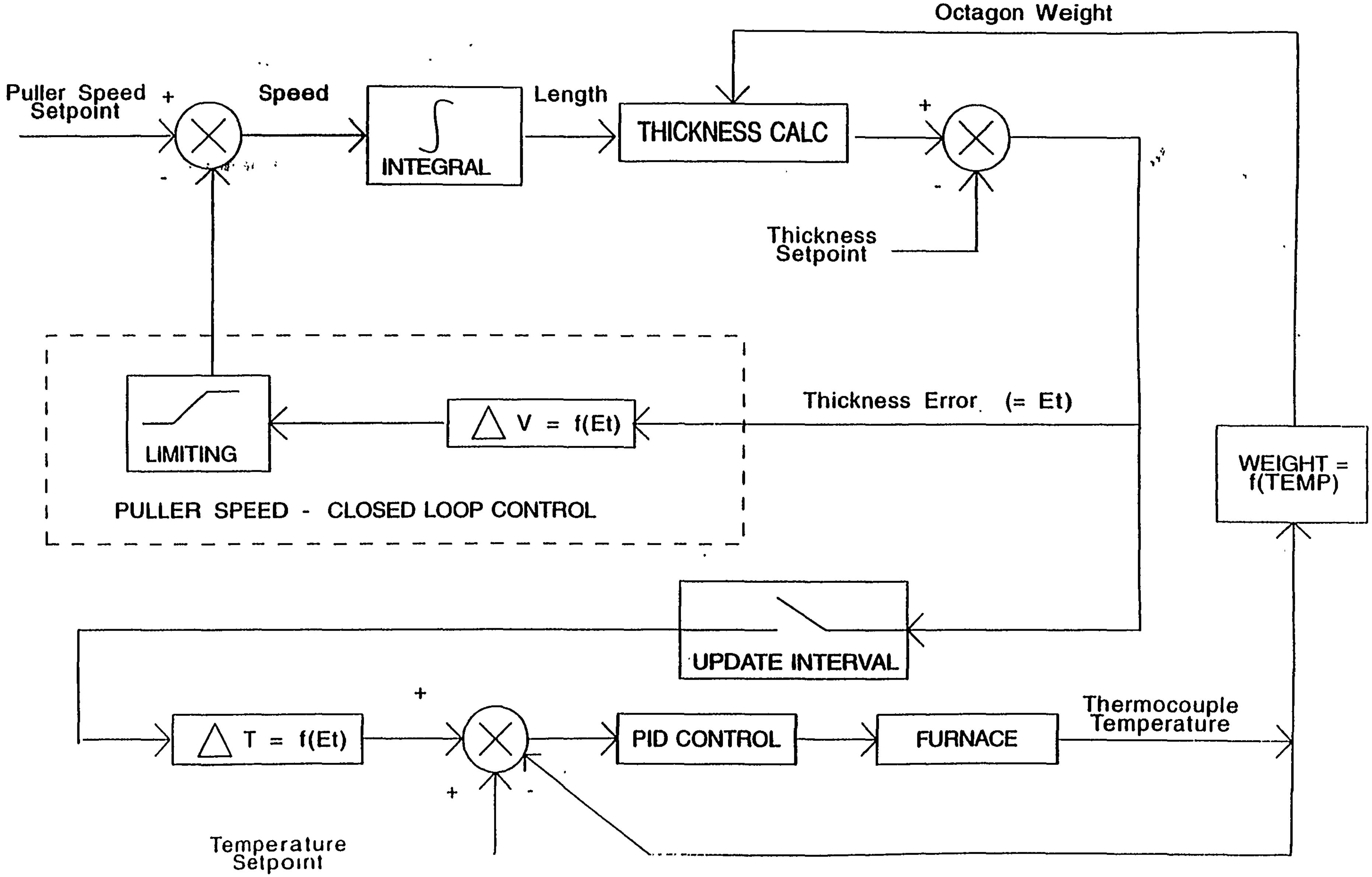


FIGURE 1

PID control of the hotzone temperature is accomplished in hardware, based on the value of the temperature setpoint. Actual hotzone temperature is compared to the setpoint, and the error is used to maintain the temperature at the setpoint value.

The thickness (and therefore the weight) of the growing octagon is dependent on the die tip temperature, which in turn is related to the hotzone temperature. This is depicted in the figure by showing the octagon weight as a function of the furnace hotzone temperature. This weight is then used by the thickness calculation routine to generate a thickness estimate of the growing octagon, thereby closing the loop.

This control loop is relatively sluggish, responding slowly to correct errors in octagon thickness. A principal reason for this is the frequency at which temperature corrections are made to the setpoint of the hotzone temperature control loop. Although thickness errors are updated in the thickness calculation block approximately every 5 seconds, they are used to adjust the temperature setpoint only once every 0.5 inches of growth. At a nominal growth rate of 0.68 in./min, this corresponds to a temperature correction only once every 0.73 minutes.

In addition, the thermal time constant of the hotzone is relatively long. Once a correction has been made to the temperature setpoint, several seconds will elapse before the die tip temperature has achieved the new steady-state temperature.

These factors combine to produce a condition where the temperature correction applied to the PID control loop lags behind the current growth conditions at the die tip. This can result in large errors in thickness.

Tighter thickness control can be realized by reducing the lag time between the initial calculation of a temperature correction and the subsequent change in die tip temperature. However, due to the thermal time constants inherent in the system, there is a limit to how much this lag time can be reduced. An improvement is to add a faster control loop to assist in controlling thickness. This is accomplished by varying the puller speed, as discussed below.

New Approach

The new approach to thickness control incorporates an additional control loop which uses small variations in puller speed to maintain octagon thickness at the setpoint value. This loop is significantly faster than the thermal control loop, resulting in tighter thickness control.

Referring to the dotted block in Fig. 1, the thickness error is passed to an algorithm that computes a change to the present puller speed based on the magnitude of the error. This speed change is then limited if necessary to remain within high and low speed bounds (typically ±0.05 in./min) to ensure that the puller does not attain excessively high or low speeds. This speed change is then summed with the current speed setpoint to generate an updated setpoint value.

As updates to the puller speed setpoint occur every 5 seconds (the update rate of the thickness error calculation), and the electromechanical time constants of the puller motor/drive system are smaller than the thermal time constant hotzone, this loop responds much more quickly to errors in thickness than the temperature control loop. This results in tighter control of thickness.

In this control approach the calculated puller speed correction (which at times might be large to correct large thickness errors), is prevented from exceeding high or low speed limits. This results in the speed control loop functioning to correct small thickness errors quickly, while larger thickness errors are corrected more slowly through a combination of the control actions of both this loop and the thermal control loop. In effect, the thermal and speed control loops function as coarse and fine controls for octagon thickness.

Results

Figures 2 and 3 depict the performance of the speed control loop during two growth runs on Furnace 4. In each run, growth of 12 mil tubes was performed for the first half of the tube using the current (SOP) thickness control approach. In the latter half of the tube, the loop controlling thickness through puller speed was activated.

The resulting improvement in octagon thickness uniformity once the speed control loop is switched on is apparent in the upper graph of each figure. It can be seen that about a 5:1 improvement in thickness uniformity results from the operation of the speed control loop. This result has been consistently demonstrated in the data from several other growth runs.

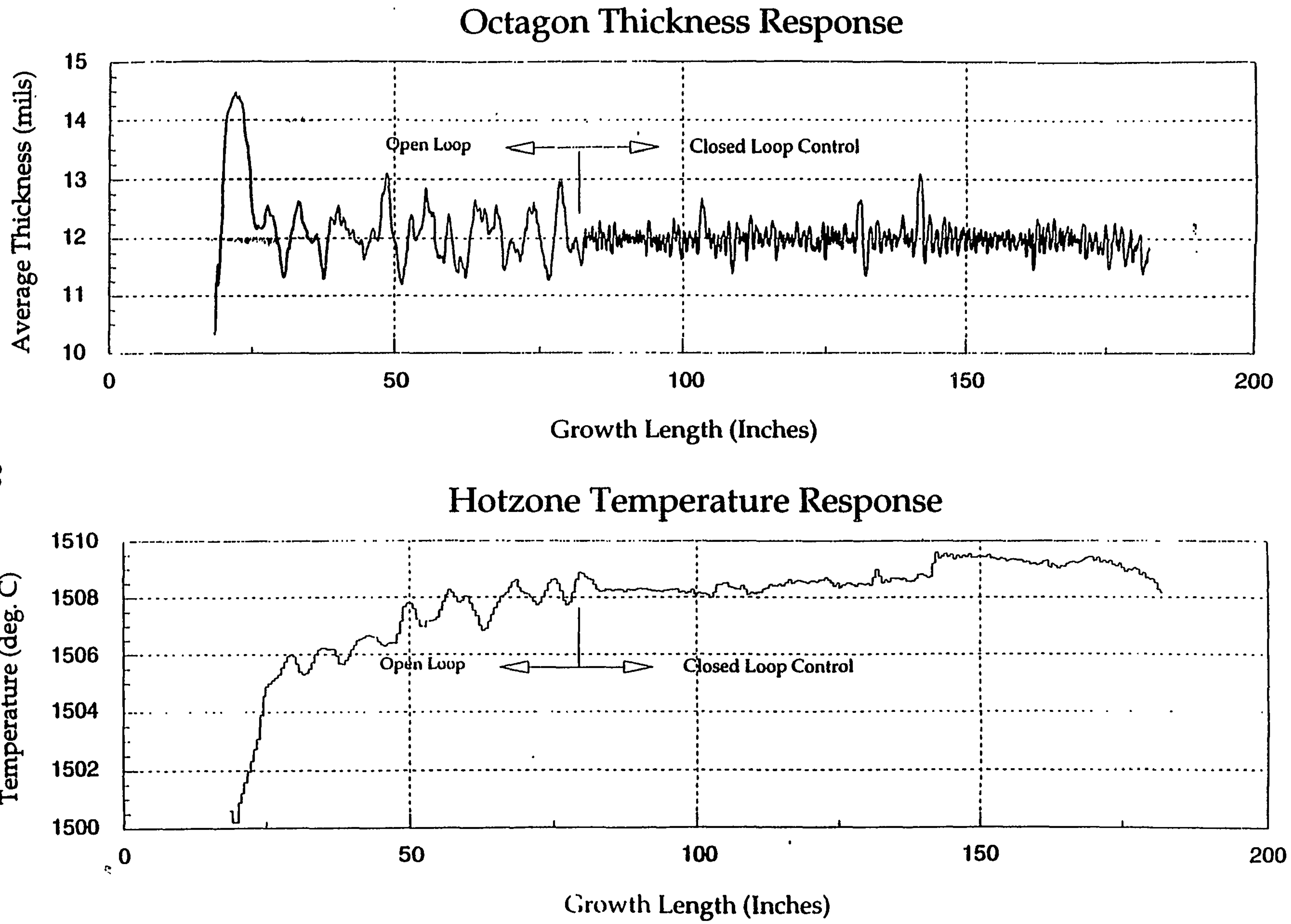
The lower graph in each figure depicts the temperature setpoint of the furnace hotzone PID control loop. Note that the temperature fluctuations around the general temperature trend are smaller once the closed loop speed control is activated. This effect results from smaller thickness errors to be corrected by the temperature control loop, owing to the action of the speed control loop.

One point of interest occurs in Fig. 2 after about 140 inches of growth. At that time, the thickness error suddenly jumps to about 13 mils, due to the effects of some unidentified transient. The speed control loop attempts to correct this thickness error, but due to the limit placed on the maximum puller speed, some residual error remains when the setpoint of the temperature control loop is updated. The step increase in the setpoint temperature in the lower graph reflects the response of the temperature control loop, which acts to increase the hotzone temperature to further reduce the error. At that point, both control loops are working in conjunction to quickly reduce the thickness error.

To study the effect of the interval between updates to the temperature control setpoint on thickness uniformity, the two growth runs in Figs. 2 and 3 were conducted with update intervals of 0.5 and 2.0 inches of growth respectively. (In the latter run, the update interval is 0.5 inch for the first 20 inches of growth, and changes to 2.0 inches for the rest of the run. This can be observed as a change in the length of the small steps which comprise the plot.)

From the figures it can be seen that there is no apparent difference in thickness uniformity between the two growth runs as a function of the different update intervals, either before or after the speed control loop is activated. Further, notice that in Fig. 3, when the update interval in the lower plot changes from 0.5 to 2.0 inches, the thickness control performance in the upper plot does not change. This indicates that the thickness control performance of the temperature control loop is relatively insensitive to the temperature setpoint update interval. Most likely, this is due to large thermal time constants which dominate the lag time of the temperature control loop. Consequently, no significant improvement to thickness uniformity will be realized by more frequent updates.

Thickness Control Performance Comparison (Furnace 4)

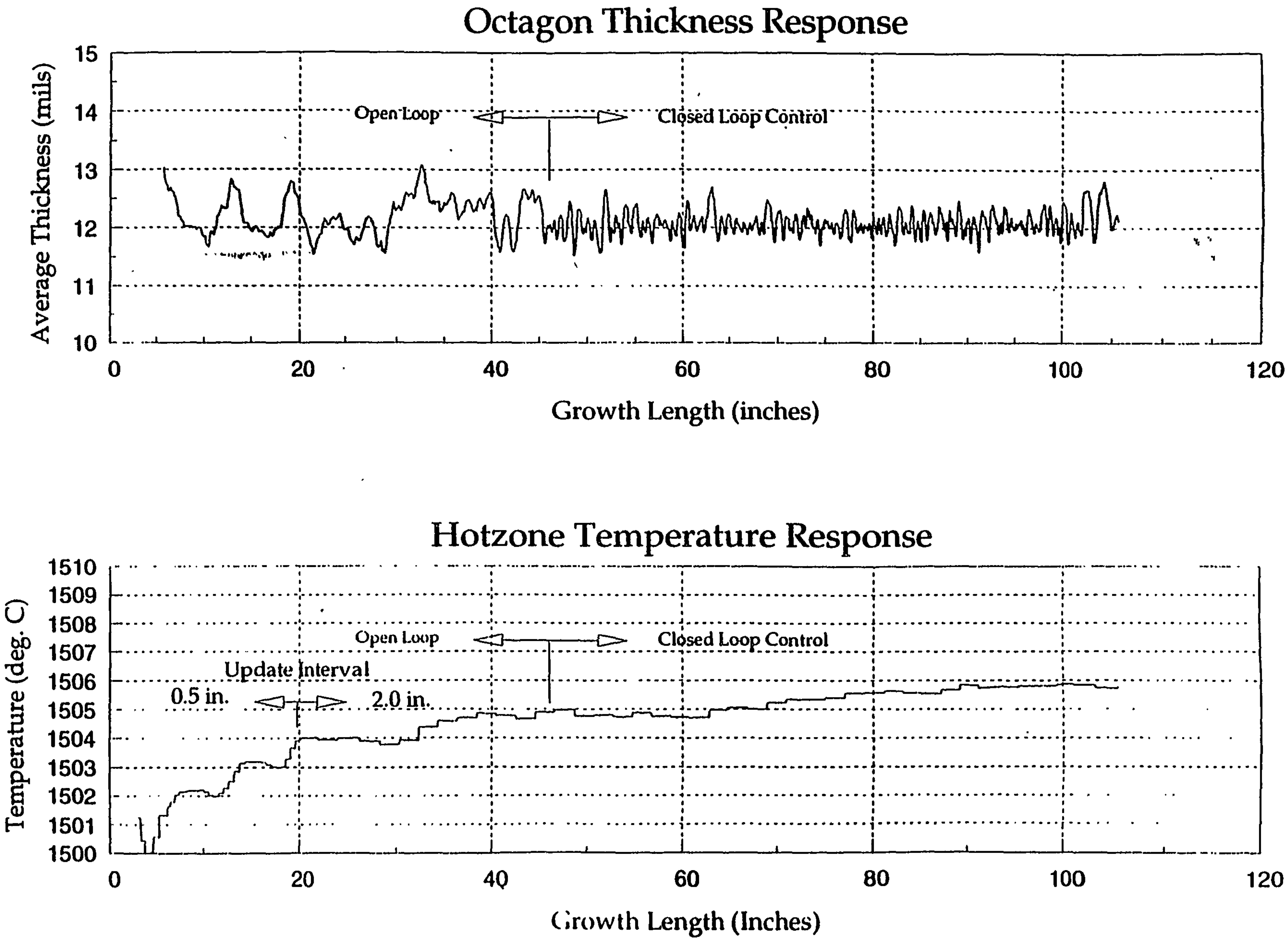

Octagon Thickness Response

Hotzone Temperature Response

Run Date: 09/09/93
Temp Setpoint Update: 0.5 in.

Figure 2

Thickness Control Performance Comparison (Furnace 4)



Run Date: 08/03/93
Temp Setpoint Update: 2.0 in.

Figure 3

The only apparent effect of increasing the temperature setpoint update interval is to smooth out the temperature setpoint profile for the remainder of the growth run. The reduction in temperature fluctuations in the hotzone may have some beneficial effects on crystal growth. Again however, this does not appear to have any significant effect on the ability of the loop to control thickness.

Summary

These test results clearly demonstrate the improvement in longitudinal thickness uniformity possible through introduction of closed loop puller speed control. To evaluate the effects of this approach on material properties and ultimate electrical performance of solar cells, a number of PVMaT wafers will be fully processed and electrically evaluated. Subsequently, with support from production, larger scale experimental runs will be conducted to generate statistical performance data from a larger population. The results from these electrical performance studies in conjunction with the improvement in thickness uniformity would then indicate the viability of introducing this new control approach to production.

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This report describes work to advance the manufacturing line capabilities in crystal growth and laser cutting of Mobil Solar's unique edge-defined film-fed growth (EFG) octagon technology and to reduce the manufacturing costs of 10-cm x 10-cm polycrystalline silicon EFG wafers. The report summarizes the significant technical improvements in EFG technology achieved in the first 6 months of the PVMaT Phase 2 and the success in meeting program milestones. Technical results are reported for each of the three main program areas: Task 5—Thin octagon growth (crystal growth)—to reduce the thickness of the octagon to 200 microns; Task 6—Laser cutting—to improve the laser cutting process so as to produce wafers with decreased laser cutting damage at increased wafer throughput rates; and Task 7—Process control and product specification—to implement advanced strategies in crystal growth process control and productivity designed to increase wafer yields.

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