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Mobil Solar Energy Corporation Thin EFG Octagons

Final Subcontract Report
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Summary

We report here on the Mobil Solar Energy Corporation program in Phase 2A--Process Specific Issues of the Photovoltaic Manufacturing Technology (PVMaT) Initiative. The work was carried on between April 1, 1992, and January 31, 1994. The objective of this program was to advance the manufacturing line capabilities in crystal growth and laser cutting of the Mobil Solar unique EFG octagon technology, and to reduce the manufacturing costs of 100 mm × 100 mm polycrystalline silicon EFG wafers and modules. The cumulative impacts of the EFG technology improvements which have been identified under the program result in 55.7% and 23.4% reductions in EFG wafer and module costs, respectively, when fully integrated into Mobil Solar's production line.

Manufacturing cost decreases which were targeted included a reduction of wafer thickness, hence improving silicon material utilization, improvements in the laser cutting process for EFG wafers, and increases in productivity and yield in crystal growth. In this program, we have designed and tested advanced EFG wafer production techniques which raise yields and productivity at EFG octagon and wafer thicknesses down to 250 μm in the Mobil Solar production line, improve thickness controls, reduce material stress, and raise laser cutting throughput by a factor of two.

We closed out the program with a Technical Readiness Demonstration (TRD) in December, 1993, with production of nominally 250 thick EFG wafers and fabrication of the wafers into solar cells and advanced design non-EVA based 4 foot by 6 foot modules. The TRD produced over 30,000 wafers under various conditions of growth chosen to examine material parameters that influence solar cell efficiency. Solar cell batches, of over 100 cells each, averaging up to 13.7–8% were obtained in the production line from this material, and used to make twelve experimental non-EVA based modules for testing at NREL. Module outputs were in the range from 278 to 290 W. The highest rated module of 290 W represents a record performance for this type of utility-scale EFG module.

The EFG technology improvements which have been fully integrated into the Mobil Solar production line to date have reduced EFG wafer costs by 13.4% and module costs by 5.2%. These include a decrease in wafer thickness from 400 to 300 μm, improved yield and productivity in growth of 300 μm thick octagons, an increase in run length of 28%, and improvements in control of oxygen that enhance solar cell efficiency. EFG technology improvements fully demonstrated and tested on a limited scale, and which are now ready to be introduced into the production line, reduce costs relative to the 400 μm thick wafer baseline by a cumulative amount of 34.9% for wafers and 13.8% for modules. This includes prototype testing and design of production equipment to improve crystal growth furnace controls and for increasing laser cutting station throughput by a factor of two. We have also finished a conversion of EFG wafer size from 96 mm × 96 mm to 100 mm × 100 mm in the production line, and this standardizes EFG wafer dimensions with respect to most of the rest of the industry. The yield, productivity and throughput advances made possible by these technical achievements enhance future market share growth for Mobil Solar products.

Introduction

Mobil Solar Energy Corporation manufactures photovoltaic modules based on its unique Edge-defined Film-fed Growth (EFG) process for producing octagon-shaped hollow polycrystalline silicon tubes. Octagon tubes are grown to lengths of up to 5 meters and with area throughput rates of over 135 cm^2/min per furnace. The octagons are cut by lasers into 100 mm × 100 mm wafers which are suitable for solar cell processing. This process avoids slicing, grinding and polishing operations which are wasteful of material and are typical of most other wafer production methods. EFG wafers are fabricated into solar cells and modules using processes that have been specially developed to allow scaling up to high throughput rates. This has all been accomplished in an environmentally benign and safe manner, e.g., wet chemical processing steps have been minimized and almost completely eliminated. As recent improvements in technology are incorporated into its manufacturing line, Mobil Solar is poised to move out of its pilot production phase. The improvements then should lead to increased market share.

The goals of the Photovoltaic Manufacturing Technology Initiative (PVMaT) program at Mobil Solar were to improve the EFG manufacturing line through technology advances that accelerate cost reduction in production and stimulate market growth for its products. The program was structured into three main tasks: to decrease silicon utilization by lowering wafer thickness from 400 to 200 μm; to enhance laser cutting yields and throughput while improving the wafer strength; and to raise crystal growth productivity and yield.

The technical problems faced and the advances made in the Mobil Solar PVMaT program are described in the next Section. We conclude with a presentation of the results of a detailed cost model for EFG module production. This model describes the accelerated reductions in manufacturing costs which are already in place and the future benefits anticipated to result from the technical achievements of the PVMaT program.

Technical Achievements

The outline of the technical work for the original three year Mobil Solar PVMaT program is given in Fig. 1. At the start of PVMaT in April of 1992, Mobil Solar was completing a transition from growth of 400 μm to 300 μm thick octagons. This transition involved implementation of new technology developments and optimization of yields and productivity of 300 μm thick wafers in crystal growth, in laser cutting and in the solar cell and module pilot production line. The PVMaT program work has had two facets: first, it has accelerated the development and testing of technology improvements vital to completion of this transition; at the same time, it has carried out design, development and testing of new prototype equipment with potential for high yields and throughputs for growth of still thinner octagons and laser cutting of wafers.

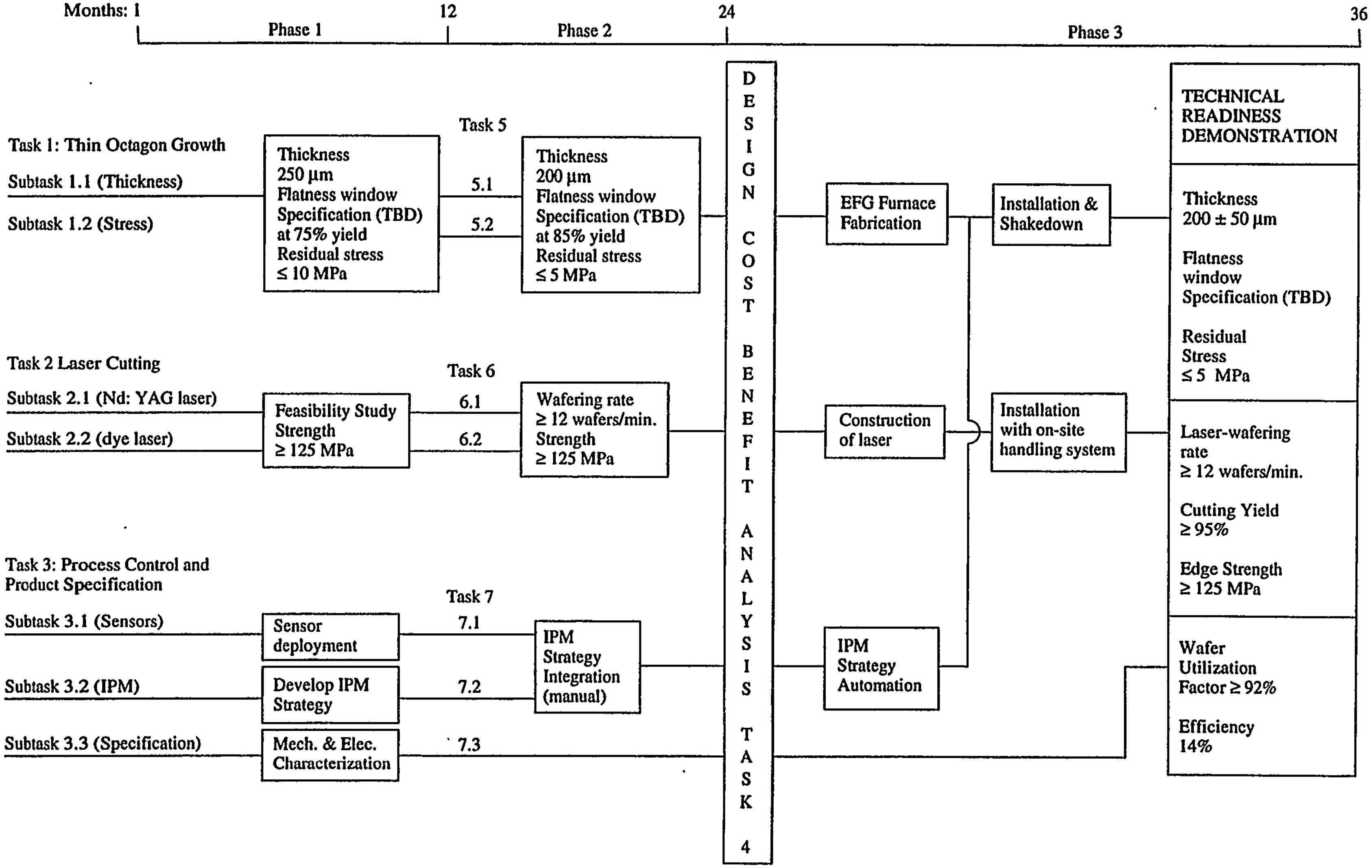


Figure 1. Program Goals Summary – See text for definitions of terms.

The program, shown in Fig. 1, was closed out at the end of October, 1993, just past the mid-point of Phase 2. At that juncture, we were in the process of consolidating and optimizing the growth and cutting of the 250 µm thick octagons to ready them for introduction into the production line; we had completed a transition from a wafer size of 96 mm × 96 mm to 100 mm × 100 mm; and we had reached the final stages of the design of new furnace and laser cutting equipment for 200 µm thick material. On account of the early program termination, a new close-out demonstration was negotiated in November, and the Technical Readiness Demonstration (TRD) scheduled for the end of Phase 3 of the program was advanced to December, 1993, with redefined objectives.

Our revised objectives for the TRD were to produce nominally 250 µm thick EFG wafers in the production line in order to demonstrate the advances in crystal growth and cutting equipment in place at that time, and to fabricate the wafers into advanced design non-EVA based modules. We planned to examine modifications of growth conditions and variants in cell and module fabrication to evaluate the potential for producing 14% average efficiency EFG solar cells on the Mobil Solar production line; the effects of a thickness decrease from 300 to 250 µm on yield in the production line were to be evaluated to demonstrate the ability to meet a target yield of 85% through cutting and flatness and thickness inspection; and an improved laser cutting station and new laser capable of raising the throughput rate by a factor of two were to be tested.

The technical tasks in crystal growth, in laser cutting and in process control and product specification in the program all had a common focus. This focus was on improvement of the EFG octagon material and polycrystalline silicon wafer properties, so as to maximize process yields and solar cell and module efficiency in the production line. The following three sections describe the technical work carried out and highlight the results obtained on projects in various areas of this effort. These sections cover: highlights of technical projects on developments that aided yield and productivity in crystal growth and laser cutting through improvements in equipment and diagnostic techniques; results of several Technical Readiness Demonstrations (TRD's) designed to test procedures for introducing technical improvements into the production line; and the results of solar cell processing and module fabrication experiments demonstrating the performance of thin EFG wafers.

Equipment and Diagnostics Improvements

We identified improvements in EFG crystal growth and laser cutting technology in a number of areas during the course of the program. The new technology included diagnostic tools for on-line octagon monitoring and crystal growth control systems which have potential for raising production line yield and productivity. These improvements were readied for evaluation in the production line. We highlight them here and discuss their status by Task number (see Fig. 1).

Task 5 Highlights

The work in this Task concentrated in development of advanced and new designs of crystal growth equipment for growth of octagons down to 200 µm thicknesses with improved thickness uniformity and flatness, and reduced residual stress. Among the highlights of the work were:

- Specification and detailed engineering design were completed for an advanced EFG furnace for growth of 300 μm thick octagons with an industrially hardened controller, integrated power supply, a new puller design, and an upgraded melt replenishment unit.

- Specification and detailed engineering design were completed for a new concept EFG furnace for growth of 200 μm thick octagons, which included technology to enhance growth stability, allow increased levels of automation, provisions for an enclosed growth chamber to allow growth under a totally controlled ambient, and an increased sensitivity weight sensor for thickness control.

- The transition from an EFG wafer size of 96 mm × 96 mm to 100 mm × 100 mm was completed to standardize wafer dimensions with respect to the rest of the industry.

- Improved furnace component designs were tested to introduce transverse temperature profile variations that were successful in reducing residual stress and increasing octagon tube and wafer flatness.

- A velocity-based axial thickness control system was developed that reduced the thickness variations along the tube length by a factor of about five.

Task 6 Highlights

Phase 1 objectives focussed on improving the strength of EFG wafers by reducing microcracks and damage caused by laser cutting. Goals in the later Phases were to demonstrate increased yields and wafering rates for octagons down to a 200 μm thickness, while maintaining reduced damage levels. The highlights of the accomplishments in this Task were:

- Feasibility studies were completed on two new laser systems, the dye laser and the copper vapor laser. They demonstrated that EFG silicon can be cut with reduced damage and improved wafer edge strength, while at the same time having the potential to achieve the target wafering rates set for the program. Development of the dye laser was found not to be cost effective at this time. A commercially hardened design of copper vapor laser was identified and appears to be promising for a next generation cutting system for EFG tubes.

- A new candidate Nd:YAG laser was identified for EFG tube cutting which has a attractive combination of lower cost, lower divergence with higher power than the current ones in use. It was installed and tested under production line conditions in the TRD with excellent results.

- A new laser cutting station, designed to increase wafer cutting throughputs by a factor of two has been installed and successfully tested on the production line.

- Limited success was demonstrated in cutting of EFG silicon with a Nd:YAG laser and a preheat beam. Although useful high speed cutting conditions were not achieved, the technique shows promise for being able to cut with reduced damage.

Task 7 Highlights

Programs in this task were structured to provide support for the work objectives described above in growth and laser cutting of thin octagons. The support areas included sensor development, crystal growth process control improvements, and wafer characterization and specification. The highlights in this task are summarized next.

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 100 mm × 100 mm 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 was 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 can 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 required before installation and more extensive testing can take place. The single-point information can 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 completed 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 Reference 1.
- The development of a local thickness measurement technique, also suitable for obtaining octagon thickness while the tube is growing, has been completed at BDM International. This utilized Optical Low Coherence Reflectrometry (OLCR).

- The development of an interface imaging system has been completed at KDY Associates. 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 system needs 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 experimented with a control algorithm for thickness based on velocity manipulation. This is 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 work was completed to incorporate this control mechanism to control tube wall thicknesses (see Ref. 1).

- A control algorithm has been developed to enable to 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 As-grown EFG octagon tube and wafer property specifications were addressed in this subtask. These included: thickness uniformity dependence on decreasing tube wall thickness, tube and wafer flatness, wafer edge strength after laser cutting, residual stress and electronic quality. The progress made in achieving program goals was as follows:

- We developed and calibrated an apparatus using the Shadow-Moire interferometric technique to measure residual stress measurements on circularly-cut EFG wafers.[1] Average residual stresses found were in the range of 1–2 MPa, within the program target.

- The dye laser was shown to produce reduced damage and increased wafer edge strength in cutting of EFG material at high speeds. As-cut wafer strengths were in the 60–70 MPa range, while etched wafers measured over 100 MPa, within range of the program goals. The copper vapor laser showed a similar potential for reduced damage high speed cutting.

Technical Readiness Demonstration (TRD)

EFG technology advances developed in the above Tasks were integrated into the Mobil Solar production line on a continuing basis. Implementation of a given advance proceeded in several stages which extended over a considerable length of time, and involved evaluation of wafer performance in all processing steps, extending through solar cell processing to module fabrication. These stages included: a small batch testing period; an intermediate volume evaluation involving several thousands of wafers; and, finally, complete integration of the new technology on a side-by-side basis with the established line to demonstrate and evaluate the benefits of the improvements on a full cost basis. While the cost elements associated with various of the above technology improvements are evaluated and presented in the last section, here we highlight the results of the principal accomplishments in on-line evaluation of EFG technology improvements of the PVMaT program.

The chief vehicle for transferring technology improvements from the research and development phase to the production line was chosen to be the Technical Readiness Demonstration (TRD). The TRD consisted of several week-long runs on a three-shift basis, which produced varying numbers of wafers. The wafers were sent through the entire production line to evaluate yields and solar cell performance on a directly comparative basis with the then-current standard EFG wafer. In the PVMaT program, we carried out two trial TRD's, one in March '93, to complete Phase 1, and the other in September '93, in addition to the full TRD in December '93 which closed out the program. These TRD's did not test all aspects of the technology anticipated to be ready for the TRD planned for Phase 3 of the original 3-year program. Hence, the picture is necessarily somewhat fragmented, as a complete evaluation of all of the technology changes discussed above, or their integration into the production line, were not completed at the time of the closing out of the program in January, 1994. However, an integrated picture is presented in the last section on the cost modelling, where all technology improvements and their cost reductions under development for the entire PVMaT program are discussed in a more complete presentation.

In the full-scale TRD of December '93 which closed out the PVMaT program, polycrystalline silicon octagon tubes of thicknesses down to 250 μm were grown during the four weeks of production. The crystal growth and laser cutting results of the two trial and the full scale TRD's are discussed next and related to fundamental variables identified as responsible for the improvements achieved in the performances during the development of the system design in Phases 1 and 2.

Crystal Growth and Laser Cutting Results

An improved EFG growth system was the central technology advance tested in the first two trial TRD's in March '93 and September '93. The new growth system features led to: a decreased face-center-to-edge thickness variation and, therefore, an improved thickness uniformity wafer; imposition of a preferred horizontal temperature gradient across the octagon face designed to reduce near-interface stress and hence improve flatness of wafers; and reduction of near-interface plastic deformation that reduces residual stress in the wafer. All of these improvements were based on magnetic and temperature field modeling results carried out in Phase 1, which were used to guide the engineering design efforts. Details of these calculations are reported in publications.[2,3] At the time of the development of these improvements, the octagon face width dimension produced 96 mm × 96 mm wafers, hence it is denoted as the "96 mm system" in what follows. In the March '93 TRD, a total of 27 tubes were grown on the two PVMaT research and development furnaces, of which 9 tubes were 250 μm thick and the rest were 300 μm thick. In September '93, the system was operated on production furnaces, and grew 21 tubes, all of 300 μm thickness.

The Mobil Solar production line changed to a 100 mm octagon system, producing 100 mm × 100 mm wafers in November '93. An optimized 100 mm growth system was not available for the December '93 TRD. The 100 mm system thus was forced to use old designs of hot zone components. Equivalent performance was therefore not expected. A total of ten crystal growth runs was carried out. Overall 133 tubes were grown in the December '93 TRD, of which 46 were 250 μm and the rest 300 μm thick.

Laser cutting in the first two trial TRD's was performed with Mobil Solar Nd:YAG lasers. A new model laser, evaluated and tested on a separate subtask on the PVMaT program, as described above, was installed and tested by the time of the December TRD, so that its performance could be compared with the in-house model lasers.

The results for the laser cutting yield, the wafer inspection yield and the silicon utilization factor for the December '93 TRD are summarized in Table 1 and compared to the earlier trials. Results for 300 and 250 µm thick tubes are listed separately in Tables la and lb, respectively. The silicon utilization (factor) in Table 1 is defined as the product of the yields of acceptable wafers in thickness uniformity, in flatness inspection, and in laser cutting. Tabulated results are normalized to average yields in the production line for the same period. The other results given are for the trial TRD of the improved 96 mm EFG system in March '93 and for this same system operated on the production line during September '93. In the production operation at that time, tube growth had been interrupted to improve the flatness yield at the expense of productivity. The objectives of the PVMaT program effort were to eliminate the productivity loss and improve the flatness simultaneously. The differences in system dimension and procedure are reiterated in the table for clarity.

The 300 µm thick tube results are considered first. Comparing the production average with the TRD results, it is clear that the improved 96 mm system allows the elimination of the growth interruption without a decrease in flatness yield. The unoptimized 100 mm TRD growth system, in contrast, performed as well as the 96 mm system in the trial TRD experiment conducted in March '93 but worse than the improved 96 mm EFG system that was operated in the production mode in Sept. '93. However, since the flatness and the laser cutting wafer yields for the 100 mm TRD are lower than that obtained with the 96 mm improved EFG system, this suggests that the 100 mm system yields can be still increased to the best levels achieved in the September '93 production line trials through use of the components of the improved 96 mm EFG system and laser cutting system optimization.

The flatness yield of 250 µm thick tubes grown during the December '93 TRD is lower than in March '93 (see Table 1b). This deficit is in part attributed to the absence of the new designs of hot zone components. Yield of 250 µm thick 100 mm × 100 mm wafers should also increase with the introduction of improvements tested in the 96 mm EFG system.

In another experiment in the March '93 trial TRD, we showed that the flatness yield could be improved by 7% by lowering the growth speed by 19% for 250 µm tubes, as shown in Table 1b. This is a direction that could be pursued in the future if flatness yields for thin wafers are not at acceptable levels. The cost impact of trade-offs among productivity, silicon material utilization and improved efficiencies needs to be examined in detail in order to decide if this is economical. Decreasing wafer thickness improves the cell conversion efficiency (see discussion in the section on cost analysis). Further, it is observed that buckling is nonuniform along the length of a tube. In the region of the tube between 50 and 250 cm of growth, the tubes are buckled more than any other section. Hence, it may be possible to improve the flatness by growing the critical section of the tube, say between 50 cm and 250 cm of growth, with a reduced growth rate, using control methods analogous to those detailed in the Task 7. Productivity could be made up by use of a larger perimeter tube, such as a decagon. This approach was under consideration.

Table 1. Summary of Crystal Growth and Laser Cutting Yields*

(a) 300 μm Tubes

Condition	Wafer Size (mm)	Stop Growth (Yes/No)	Laser Yield (%)	Flatness Yield (%)	Silicon Utilization (%)
Production† average	96	Yes	100.0	100.0	100.0
Trial TRD March '93	96	No	97.4	100.9	98.3
Trial TRD on production line Sept. '93	96	No	103.1	105.2	108.5
PVMaT-TRD Dec. '93	100	No	98.3	100.5	98.8

†The cost model results are based on the yield performance of this case.

(b) 250 μm Tubes

Condition	Wafer Size (mm)	Stop Growth (Yes/No)	Laser Yield (%)	Flatness Yield (%)	Silicon Utilization (%)
Trial TRD March '93	96	No	90.9	97.5	88.7
Trial TRD March '93 Growth rate reduced by 19%	96	No	93.8	104.8	98.4
PVMaT-TRD Dec. '93	100	No	95.8	91.6	87.8

*Normalized using production averages for the corresponding time period.

The laser cutting yields obtained for 300 and 250 μm thick material during the December '93 TRD were lower than the values normally obtained in the production line. This is because the cutting systems were under development and not optimized. The laser cutting yield of silicon tubes was analyzed as a function of thickness and the laser cutting station used, and some differences became apparent. The average cutting yield for 250 μm tube is 2.5% lower as compared to 300 μm tubes. However, the laser station with the new laser introduced in the PVMaT program performed considerably better than the other station with the Mobil Solar laser regardless of tube thickness. For 250 μm thick tubes, the cutting yield with the station equipped with the new laser is 6.3% higher than for the other station. The fundamental studies carried out earlier suggest that this difference arises on account of the higher beam quality of the new laser, and is not related to the cutting station design.

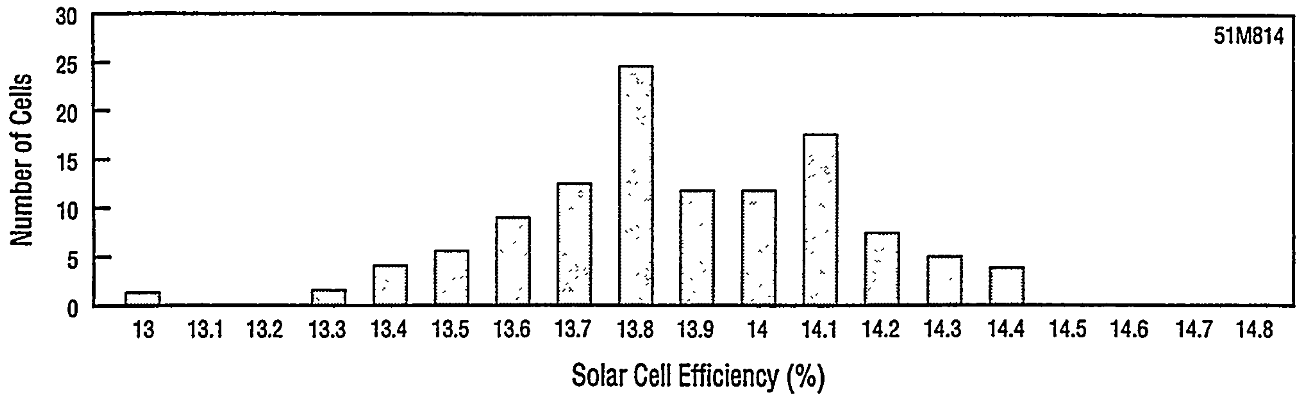
Thin EFG Wafer Solar Cell and Module Performance

The PVMaT program objective required for Mobil Solar to demonstrate that the EFG wafer electronic quality in the thinner 250 and 200 μm thick material has the potential to produce 100 mm × 100 mm 14% efficient solar cells. This capability has been demonstrated for significant numbers of EFG solar cells on a research level with 300 μm thick octagon wafers.[4] The material grown in the December 1993 TRD was processed in the production line to examine its potential for reaching the 14% efficiency level of performance. The results of these studies are discussed next.

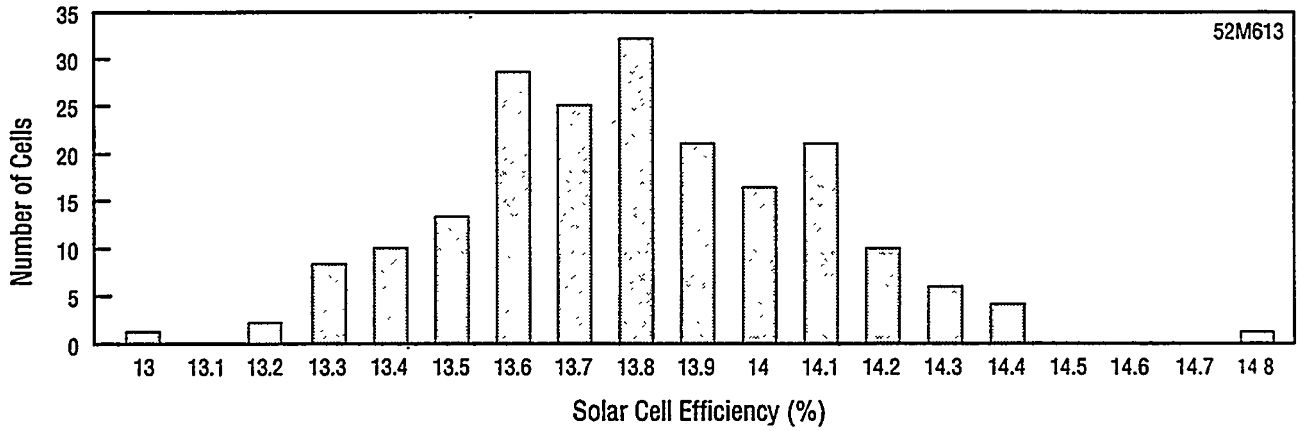
A number of experimental variables in crystal growth were changed in order to attempt to optimize material electronic quality and raise solar cell performance. Unfortunately, the baseline performance levels during the December period were fluctuating due to some suspected unintentional contamination in the crystal growth process. Baseline solar cell efficiencies from the four furnaces used in the runs were all different. This was not ascertained until all the growth was completed and solar cells made. It was not possible to go back and redo some of the matrix because all material was utilized initially. In spite of these difficulties, partial information has been obtained. In all cases, cells made on the 250 μm thick wafers outperformed those made on 300 μm thick material on a relative basis. Oxygen effects were not clearly delineated because of the variation in background contamination levels.

Several variants in solar cell processing parameters were investigated. The sheet rho was decreased from the standard levels, and variable thicknesses of back-surface aluminum were utilized to attempt to enhance the efficiency with back surface field effects. On a relative basis, the lower sheet rho gave slightly better performance than the standard one. No trend was seen with the change in aluminum thickness, indicating that optimal levels of either aluminum or bulk diffusion length have not been reached where cell performance may start to be sensitive to the aluminum thickness.

Solar cell efficiencies for the two best lots of 250 μm thick wafers are shown in Fig. 2. We assume that these best lots represent the optimal levels that can be achieved under current standard production line processing conditions when the as-grown material quality is at its highest levels, i.e., not affected by the accidental contamination that is suspected for a number of the TRD runs. None of the batches in the TRD fell below about 13% efficiency even with this contamination, while the average production line efficiency was near 13.5%. However, the fluctuation in the baseline made it impossible to perform a meaningful matrix of runs on the other variables in order to optimize for 14% solar cells.



Lot No.	No of Cells	Irv (mA/sq. cm)	Voc	Isc (mA/sq. cm)	FF	Pp (mW/sq. cm)
51M814	113	0.14	0.589	30.57	0.77	13.87



Lot No.	No of Cells	Irv (mA/sq. cm)	Voc	Isc (mA/sq. cm)	FF	Pp (mW/sq. cm)
51M814	194	0.14	0.589	30.73	0.76	13.79

Figure 2. Solar cell parameters and histograms for 250 micron thick EFG octagons grown in December TRD. The two lots 51M814 and 52M613, of 113 and 194 cells, respectively, represent the two best batch average cell efficiencies obtained for the TRD material.

Attached as Fig. 3 is a performance curve for an experimental 4 foot by 6 foot Mobil Solar module made with 250 thick µm 100 mm × 100 mm EFG wafers. This module is of an advanced design that incorporates double glass and a non-EVA based encapsulant. Twelve of these modules were shipped to NREL as deliverables in the PVMaT program. Eight were made with 250 µm and the other 4 with 300 µm thickness EFG wafers. The outputs of the modules ranged from 278 to 290 W. The module of Fig. 3 represents a record performance level for this size of utility-scale EFG module.

Cost Elements in EFG Wafer and Module Technology

The process of integrating technology improvements into the production line involves several stages of technology transfer and testing, which were examined in detail earlier. Technology advances emanating from the Phase 1 program accomplishments, such as the new improved hot zone, were tested and made ready for transferring into production in the middle of Phase 2, near the termination of the program. The technology transfer was not completed for other EFG technology advances in crystal growth and laser cutting as their integration into production line operation could not be completed within the time scale of the shortened PVMaT program. These included: new controls and furnace designs in crystal growth; a laser cutting station with a factor of two increase in throughput; a copper vapor laser with potential to reduce cutting damage and raise yields; and conversion of the production line to 250 µm thick octagon and EFG wafer production. The cost benefits of these and other EFG technology improvements anticipated in the future are examined next with presentation of the results of a cost model for wafer and module production at Mobil Solar.

The cost reductions in EFG wafer and module manufacturing at Mobil Solar anticipated from PVMaT program technology advances and follow-on improvements are summarized in Fig. 4. The normalized cost plotted is the variable, or direct manufacturing cost, excluding capital cost and the cost of money. The individual contributions from an advance in wafer production technology, the sole focus of the Mobil Solar PVMaT program, first are broken out separately in Fig. 4. The module cost reduction bar then reflects the contribution of the individual advance being considered. Each new cost reduction is calculated using the previous improvement as the cost base, so that the final bars represent the cumulative cost reductions when all advances are fully integrated into the manufacturing line.

Case 1 represents the cost baseline for 400 µm thick EFG wafers. The major cost reductions in Fig. 4 result from the following improvements:

Case 2: - Wafer thickness reduction to 300 µm
- Average growth length per crucible extended by 28%

Case 3: - Wafer flatness and cutting yield improvement
- Material utilization increase
- Productivity increase (labor cost decrease) in crystal growth

Case 4: - New furnace and controls upgrading for 300 µm tubes

Case 5: - Laser cutting station throughput increase by factor of 2

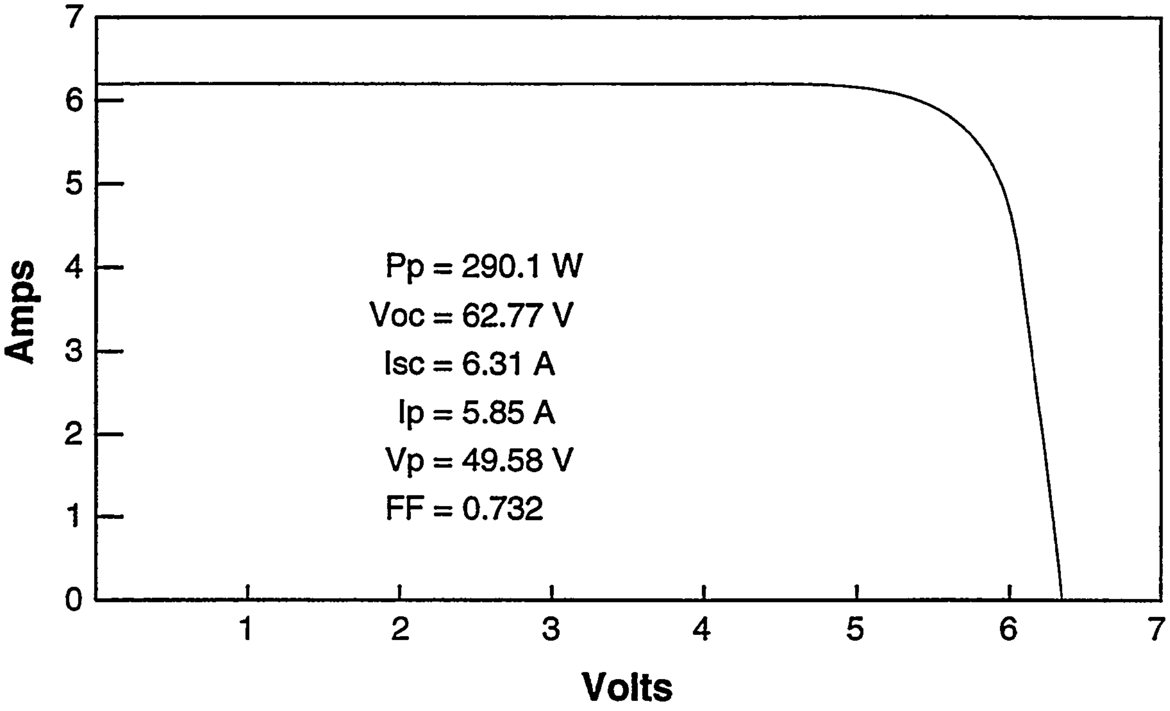


Figure 3. Performance characteristics of a 6 foot by 4 foot Mobil Solar module made with 250 micron thick wafersw and a non-EVA based encapsulant.

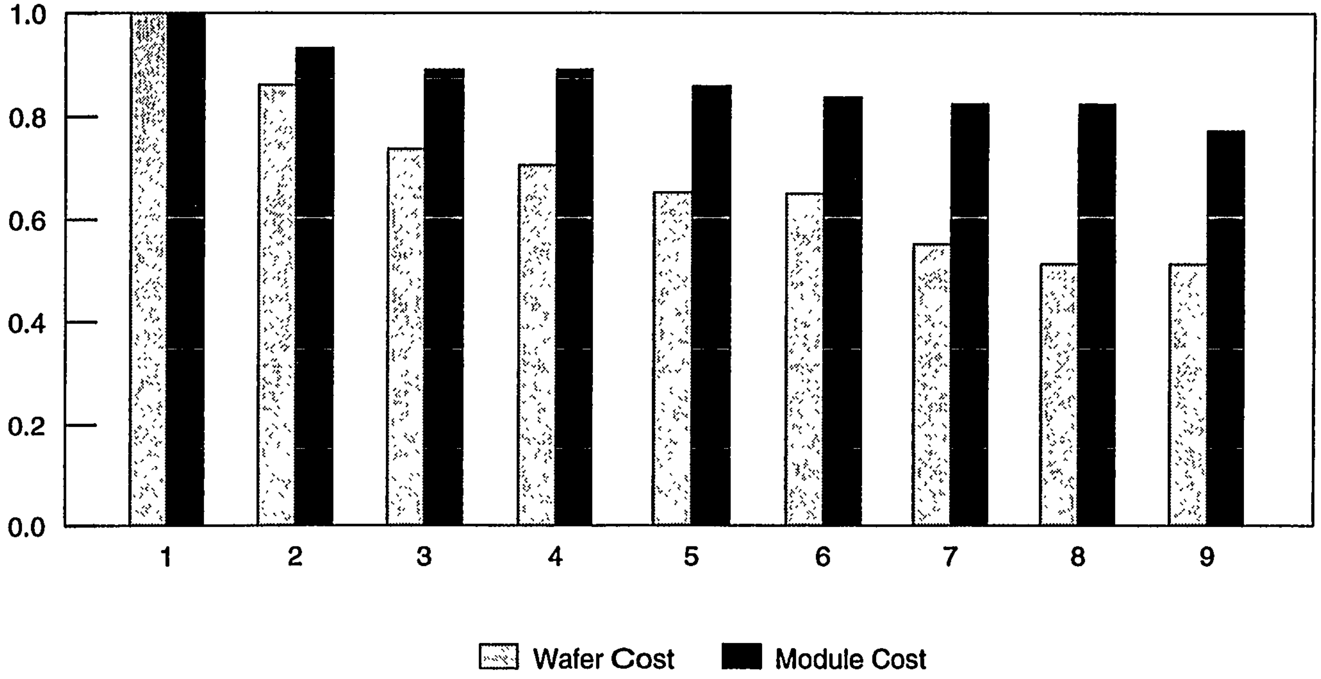


Figure 4. Variable cost reduction elements for PVMaT program and beyond.

Case 6: - Wafer thickness reduction to 250 μm

Case 7: - Advanced laser cutting station, throughput increase by additional factor of three over Case 5
- Mechanical yield improvement

Case 8: - Wafer thickness reduction to 200 μm

Case 9: - Solar cell efficiency increase to 15%

Case 2 represents technology fully integrated into production during the performance of this program. Case 3 advances were tested starting with the trial March '93 TRD carried out at the end of Phase 1, as discussed above, and then completed in the second stage of technology transfer with processing of several thousand wafers through the production line in September '93. A wafer utilization factor in excess of the target of 92.4% (see Fig. 1) was demonstrated. As noted above, this utilization factor is defined as the product of the yields of acceptable wafers in thickness uniformity, in flatness inspection, and in laser cutting. The research, equipment design and development (testing) work on Case 4 and 5 improvements were completed, as noted above, and these advances are ready for integration into the production line. While 250 μm thick wafer performance was optimized at the 96 mm wafer dimension (Case 6) and introduced into production, additional development work still needs to be done to finish the transfer process for the 100 mm × 100 mm EFG wafer. Overall, the cumulative cost reductions predicted up to Case 6 are about 39% for wafers and 15% for modules. The specifications for equipment for Case 7 and 8 technology were in the final stages of completion at the PVMaT program termination.

The value of an incremental cost reduction resulting from octagon and wafer thickness decreases from 250 to 200 μm is small, e.g., compare Cases 7 and 8. The effort to introduce thinner wafers in the pilot line generally requires additional process line engineering and evaluation time in order to maintain yield throughout the production line, which are costly. In general, cost-effective implementation of such thinner EFG wafer production technology will be closely tied to the ability to meet PVMaT wafer edge strength goals in laser cutting, and in softening wafer handling so as not to lose the material savings advantage in yield losses. However, a significant cost reduction impetus for going to 200 μm wafer thickness comes from solar cell efficiency. Efficiency cost impact is shown as Case 9 in Fig. 4, which represents an increase in solar cell efficiency from 13 to 15%. The probability of achieving greater than 15% efficiencies on the thinner EFG wafers is enhanced, as new schemes for solar cell design become accessible when wafer bulk diffusion lengths are consistently maintained of the order or greater than the wafer thickness. Studies of defects and of quality limiting mechanisms in Tasks 3 and 7 focused on developing means to monitor EFG material electronic quality, and did not uncover any material related factors in the thinner wafers in the course of the technology development that would suggest they have a quality penalty.

Figure 5 illustrates the anticipated benefits of technology improvements in stimulating competitiveness of Mobil Solar in photovoltaic markets. Here the technology benefits are related to the Mobil Solar normalized historic module cost and production volume in a cumulative experience curve. Actual data are represented by rectangles, and the top solid line and solid triangles represent the derived least squares fit cost projection. This graph indicates that considerable leverage can be provided by the accelerated introduction of new EFG technology developed under the PVMaT program, Cases 2–7. The vertical line terminating in the cross traces out the cumulative projected

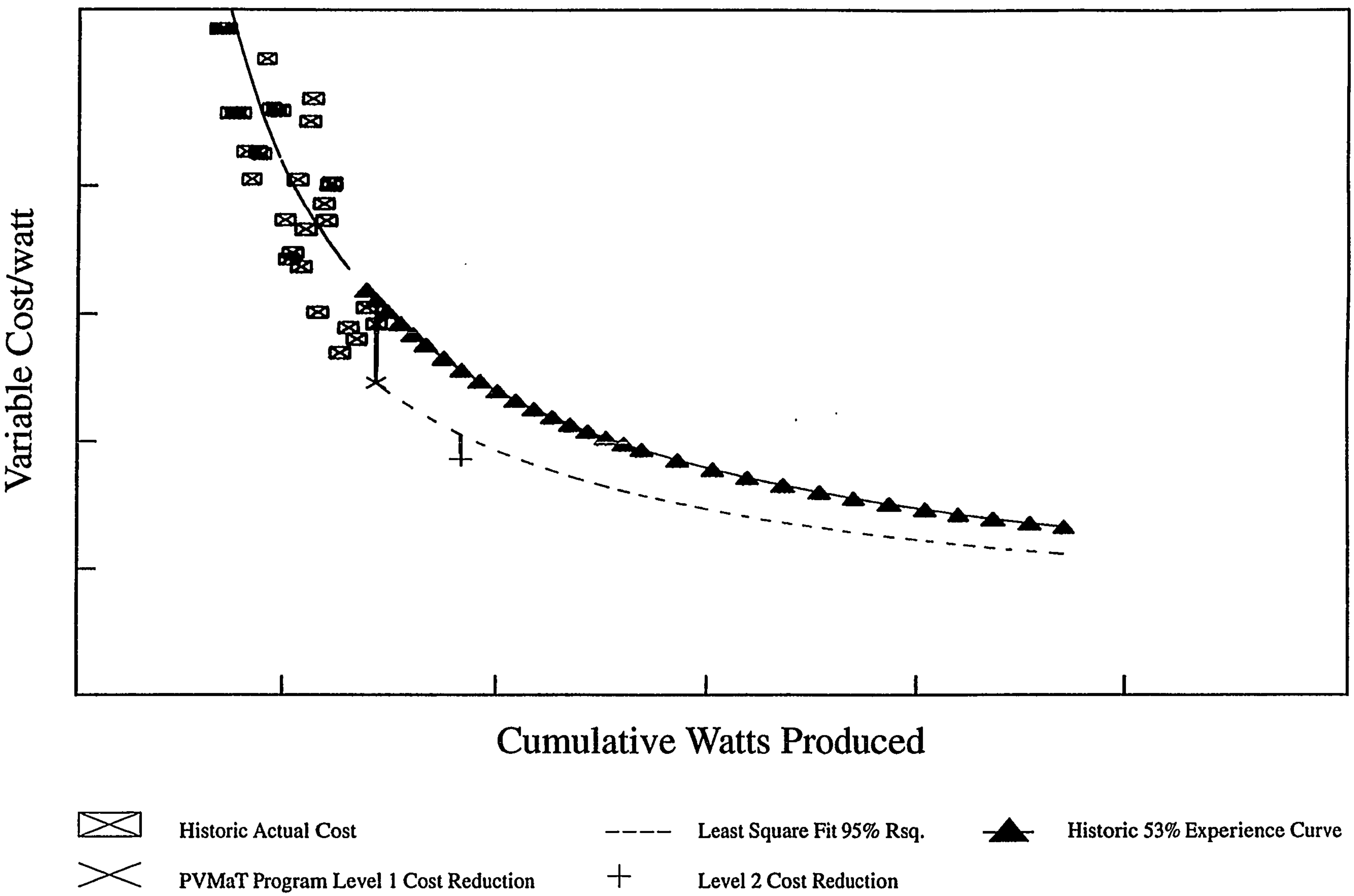


Figure 5. Cumulative Experience Curve. The cost reductions projected for the PVMaT Program (X) and beyond (+) are also marked.

reductions of Fig. 4 from Cases 2–7 of the PVMaT program, designated as Level 1 cost reductions. When the introduction of the Level 1 technology improvements are fully integrated, the experience curve will shift downward to a new location, and a new trend line will be established for the experience curve. This is schematically indicated in Fig. 5 by the bottom solid curve originating at the cross, drawn arbitrarily as the current 53% experience curve. Benefits from implementation of any Level 2 technology, as from Cases 8 and 9, then further depress the trend line, as indicated by the second vertical line terminating as (+). The timing of the introductions will determine the exact magnitude of the cost benefits available from Case 8 and 9 improvements, and these will not be exactly those given in Fig. 4.

PVMaT Accomplishments and Lessons: Future Cost Reduction Elements

The Mobil Solar PVMaT program focussed solely on EFG process improvements which reduce the cost of polycrystalline wafers. Its scope encompassed about one-third of the manufacturing steps in the Mobil Solar production line. The EFG technology improvements identified and demonstrated in the 18 months of the PVMaT program (Cases 2 through 6) reduced module costs about 15% even with this restricted focus on wafer process improvements. Another 10% module cost reduction would arise through improvements planned for Phase 3 but incomplete at the early termination date of PVMaT (cases 7 and 8). Here we provide a critical review of these gains, and use the insights gained from the PVMaT accomplishments to pinpoint areas of EFG technology improvements that will lead to further significant EFG module manufacturing cost reductions. We will no longer restrict ourselves to evaluating wafer process improvements, however, but broaden the scope to include solar cell and module fabrication steps as well.

The strategy we pursued in developing and implementing EFG technology cost reductions involved working on a number of parallel paths of process improvement. We relied on the assumption that the parallel improvements would all smoothly integrate to produce additive cost reductions when taken through the technology transfer phase and into the production line. The major advantage of this course of action is that the development and integration times are minimized, hence saving considerably on costs and enhancing the present value of each individual cost element. The risks of this approach became evident in some areas during the course of the PVMaT program. For example, parallel development in reducing stress (improving flatness) of thinner octagons and increasing wafer size from 96 mm × 96 mm to 100 mm × 100 mm in Task 5 produced unanticipated results during the technology transfer phase of integration of these elements. It was found that straightforward scaling of the dimensions of the improved 96 mm system components in the hot zone did not produce expected flatness changes in the 250 micron thick octagons and wafers. This resulted in the need for additional optimization work to bring yields of the 250 micron thickness wafers up to target levels. The parallel actions for these developments were necessitated because the 100 mm system could not be tested in advance due to the unavailability of a laser cutting facility for the larger size wafers.

Risk exists in development of higher throughput laser cutting and wafer handling equipment in parallel with wafer thickness reduction in Task 6. Here, the additional demands placed on reducing applied loads in thinner wafer handling during the cutting process in order to maintain yields are unknown. Risk was reduced by pursuing laser station design projects and new laser development (e.g., dye and Cu vapor lasers) in parallel with throughput capability upgrading. The former projects included feasibility study of a new "zero-force" mechanism to soften the tube and wafer handling processes during cutting, and a redesign of the laser cutting tower with special attention to alignment tolerances.

Similar issues are raised in the sensor and diagnostic equipment development areas of Task 7. Improved control systems are clearly required to ensure that the thinner octagons can be grown at the same high yields and productivity currently practiced for 300 micron thick tubes. These involve monitors and feedback loops for on-line manipulation and control of thickness uniformity, absolute thickness and temperature fields (for stress reduction and tube growth stability enhancement). However, in a parallel path development strategy, some of the sensors may become redundant or not cost effective to deploy as the growth system evolves with improving designs. In order to minimize thickness nonuniformity and improve flatness at thicknesses down to 200 microns, however, improved controls are very necessary, and eliminating any potential control element prematurely also becomes counterproductive. An increase in inspection yield over the best levels demonstrated in the TRD will produce an additional 5% wafer cost reduction at a relatively low capital investment for equipment improvements.

Program accomplishments, as already noted above, were combined with cost reduction analysis of additional processes in the solar cell and module areas not previously included in the PVMaT program just concluded. The results are summarized next, in closing, to demonstrate the considerable potential that exists in EFG technology improvements for cost reductions in wafers and modules beyond Case 5 of Fig. 4. Cost model application proceeds using Case 5 of Fig. 4 as the baseline to arrive at the following predictions:

1) Modest cell efficiency increases from the current 13.4% level to 14.2% through introduction of 250 micron thick wafers result in module cost reductions of nearly 5%. This can be done through: first, by stabilization of material quality at the highest levels demonstrated in this program by improving consistency of graphite purification, and introducing a more tightly controlled growth environment, e.g., a closed chamber; and with subsequent optimization of cell processing parameters for the thinner wafers. Wafer costs are reduced by less than 2% as a result of the thickness decrease alone.

2) Octagon and wafer thickness reductions from 250 to 200 microns are not warranted unless concurrent low-cost solar cell efficiency enhancement alternatives are available to increase EFG solar cell efficiencies to 15%. The module cost reduction for Cases 8 and 9 was noted above to amount to 5–6%.

3) By far larger cost reductions than gained through a thickness decrease arise from introducing a cheaper source of silicon, and in recycling some of the residual silicon produced in cutting of the octagon (corner and trim losses). In the case considered for analysis, about a 5.5% reduction in module cost is predicted to result from a factor of two drop in silicon feedstock cost and recycling of about 10% of the silicon wasted in cutting. A shot tower technology already exists to carry out the reforming of silicon from an arbitrary shape to spherical pellets and has been costed to be a cost-effective means to achieve these gains.

4) A laser station wafering rate doubling from Case 5 levels provides a significant reduction of 4% in wafer and 1.3% in module costs. The additional throughput rate increase in this area targeted for the Phase 3 goal (Fig. 1) provides little additional benefit (less than 1%) in lowering wafer and module costs. However, if the wafer strength increases anticipated for Phase 3 would raise process yield throughout the solar cell and module fabrication line, this lowers module costs by another 4%. This calculation does not include a potentially larger contribution to cost reduction which would arise from a reduction or elimination of the silicon etching step which currently stabilizes wafer edge strength and mechanical (breakage) yields in subsequent cell and module fabrication steps. Successful deployment of a new laser system, which cuts with reduced damage, such as the Cu vapor laser, would be an important advance to allow reduction of silicon etch time and cost.

5) Material cost reduction in solar cell processing, obtained by introducing lower cost substitutes in the metallization area, produce a 2.5% module cost reduction. Although this involves some research and development, this is anticipated to be relatively inexpensive and does not involve design and introduction of new process line equipment.

6) Module fabrication cost reductions with the new double-glass and non-EVA design, again by finding less costly material substitutes, produce a decrease of about 3% in module costs. Anticipated module lifetime improvements are not factored in this calculation. They produce benefits through extending module life and performance level, and reduce warrantee replacement module costs in the field.

The cumulative benefits of the above improvements produce a total additional cost reduction of about 25% for both wafers and modules beyond Case 5 given in Fig. 4. The added leverage in lowering module cost is a consequence of projects directed at process improvements in solar cell and module fabrication not considered in the original PVMaT program. In total, these predictions demonstrate that EFG wafer and module technology is far from the limit where there is the need to move to high risk research and development to gain cost advantages for some time to come. Simple and cost-effective advances and extensions of current production line technology are available to continue to significantly lower Mobil Solar PV product costs.

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Abstract

This final report describes the work done on the Photovoltaic Manufacturing Technology (PVMaT) Initiative program at Mobil Solar Energy Corporation in the period between April 1, 1992 to January 31, 1994. The objective of this program was to advance the manufacturing line capabilities in crystal growth and laser cutting of Edge-defined Film-fed Growth (EFG) octagons and reduce the manufacturing costs of 100 mm × 100 mm polycrystalline silicon EFG wafers and modules. Cost reductions which were targeted in the program included a decrease in wafer thickness, improvements in laser cutting station throughput and in wafer cut edge quality, and increases in productivity and yield in crystal growth. The EFG manufacturing technology improvements which were demonstrated on the program and fully implemented into the Mobil Solar production line during the program have reduced wafer costs by 13.4% and module costs by 5.2% at this time. These have resulted from a wafer thickness decrease from 400 to 300 microns, improved yield and productivity in crystal growth of 300 micron thick octagons, an increase in run length of 28%, and improvements in control of oxygen that enhance solar cell efficiency. Improvements which were demonstrated but still need to be integrated into the production line will result in additional decreases in wafer and module costs of 21.5% and 8.6%, respectively.

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13. ABSTRACT *(Maximum 200 words)*

This report describes work done by the Mobil Solar Energy Corporation under a subcontract for the Photovoltaic Manufacturing Technology (PVMaT) project. The objective of the program is to advance the manufacturing line capabilities in crystal growth and laser cutting of edge-defined film-fed growth (EFG) octagons and to reduce the manufacturing costs of 100-mm x 100-mm polycrystalline silicon EFG wafers and modules. Cost reductions that were targeted in the program included a decrease in wafer thickness, improvements in laser cutting station throughput and in wafer cut edge quality, and increases in productivity and yield in crystal growth. The EFG manufacturing technology improvements that were demonstrated on the program and fully implemented int the Mobil Solar production line during the program reduced wafter costs by 13.4% and module costs by 5.2%. These resulted from wafer thickness decrease from 400 µm to 300 µm,, improved yield and productivity in crystal growth of 300-µm-thick octagons, an increase in run length of 28%, and improvements in control of oxygen that enhance solar cell efficiency. Improvements that were demonstrated but still need to be integrated into the production line will result in additional decreases in wafer and modules costs of 21.5% and 8.6%, respectively.

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