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Photovoltaic Czochralski Silicon Manufacturing Technology Improvements

Annual Subcontract Report
1 April 1993 – 31 March 1994

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PREFACE

Siemens Solar Industries (SSI) began a three-year, three-phase cost shared contract in March 1992 to demonstrate significant cost reductions and improvements in manufacturing technology. The work has focused on near-term projects for implementation in the SSI Czochralski (Cz) manufacturing facility in Camarillo, California.

The work has been undertaken to increase the commercial viability and volume of photovoltaic manufacturing by evaluating the most significant cost categories and then lowering the cost of each item through experimentation, materials refinement, and better industrial engineering.

The initial phase of the program has concentrated in the areas of crystal growth, wafer technology and environmental, safety and health issues.

Significant contributions have been made by the key personnel involved in the program. They include Dave Tanner in module and cell evaluations, Kim Mitchell, in the crystal growth and wafer areas, and Sergio Vasquez in the environmental, safety and health area.

SUMMARY

OBJECTIVES

The objective of the program at Siemens Solar is to reduce costs in photovoltaic manufacturing by approximately 10% per year. The specific milestones are shown in Table 1. which consists of three focused tasks relating to cost reduction, the wafer, cell and module tasks. The silicon wafer itself contributes about half of the total cost and has the most potential for cost improvement. The cell processing costs are about a quarter of the total costs, with cell efficiency and yield results being most important. Module assembly and packaging costs are the balance, with the module design, both materials and labor, contributing significantly.

Table 1. Cz manufacturing technology milestones.

	Phase 1	Phase 2	Phase 3
Task 1. Silicon Crystal Growth & Thin Wafer Technology			
A. Increase Cz grower productivity by 25%	10%	15%	25%
B. Demonstrate utility of prototype wire saw	•		
Deliver 100 wire sawn wafers	•		
C. Demonstrate 0.010"-thick wire sawn wafers		•	
Deliver 100 0.010" wafers		•	
D. Reduce wafer cost by 30%		15%	30%
Task 2. Silicon Cell Processing			
Reduce cell cost by 30% ($/watt)	10%	20%	30%
Task 3. Silicon Module Fabrication & Environmental, Safety & Health Issues			
A. Reduce module fabrication costs by 35%	10%	25%	35%
Deliver modules demonstrating reduced $/watt		2 modules (20%)	6 modules (25%)
B. Reduce caustic use and waste	Define process and equipment	10% reduction	35% reduction
C. Replace CFC's	Evaluate CFC alternatives		90% reduction in CFC usage

Task 1: Silicon Crystal Growth and Thin Wafer Technology. Crystal growing costs are driven by material growing yields and indirect manufacturing costs such as electricity and machine parts used each time an ingot is fabricated. Wafering costs are driven by labor and the number of good slices yielded per length of crystal processed.

The second year of the contract has focused on throughput of the crystal growing machines. This has been done by using larger diameter crucibles and higher speed growth techniques, and with the implementation of wire saw machines in production to improve the yielded wafers per inch of ingot.

Task 2: Silicon Cell Processing. Cell processing costs are driven by the electrical contacts used, and the labor required for the process steps to clean the wafer, form the semiconductor junction, and apply the contacts.

The second task has been focused on the improvement of the contacting system through experimentation with various contacting pastes, and the automation of handling operations in the cell fabrication process.

Task 3: Silicon Module Fabrication and Environmental, Safety, and Health Issues. Module costs are highly sensitive to labor and materials. The module design tasks are driven by high reliability in the field and lower costs. Included in this task is the environmental work to eliminate chlorofluorocarbon (CFC) usage and significantly reduce the caustic waste volumes.

This year SSI has focused on lower module costs and the complete elimination of CFC usage in the manufacturing processes.

DISCUSSION AND CONCLUSIONS

During phase II (March 1993 through April 1994), several significant manufacturing technology improvements were achieved.

The crystal growing operation improved significantly with an increase in growth capacity. Higher growing throughput has been demonstrated with larger crucibles, higher polysilicon packing density, and higher pull speeds. Approximately 30% of the crystal growing machines were converted to this new method, however instability in the procedure for growth caused a return to the smaller crucibles.

Wafer processing with wire saws progressed rapidly and the operation is completely converted to wire saw wafer processing. The wire saws have proven to yield almost 50% more wafers per inch in production. The capacity improvement generated by wire saws has increased overall manufacturing volume by approximately 50% without any additional expenses in crystal growth. Use of wire saws has made the crystal growth process much more effective with more wafers for a given amount of ingot.

Wire saw yields progressed from 70% to over 90% in the time period reported. This improvement is credited to better understanding of and experimentation with the raw materials feeding the process, specifically the wire, oil and Silicon Carbide, and with experimentation on number of runs per batch of slurry cutting media. One hundred wire sawn wafers .010 inches thick were delivered during the reporting period meeting all deliverables specified in this task of the contract.

Cell processing improvements have focused on better understanding of the contact paste and firing processes. The work with Ferro Corporation has been on-going, with experimental pastes being run periodically. To date, the control samples using the standard production pastes are still the best performers. The cell electrical distribution improved over this period of time by over 4%, and the distribution of cell performance has become tighter.

Module designs for lower material and labor costs have begun with the focus on a new junction box, larger modules with larger cells, and a less costly framing technique. Four modules demonstrating these cost reductions have been delivered during this phase, meeting the contract deliverables.

CFC usage has been completely eliminated in the SSI manufacturing facility during this phase of the contract. Significant reductions in the cost of caustic waste treatment has also been realized.

The contract performance to date is shown in Table 1.

Table 1. Cost Reduction Summary for Phase II

Category	% Reduction in Cost
1. Crystal Growth/Thin Wafers - Large crucible - 43 vs. 29 wafers/inch	8%
2. Cell Improvements - 4% electrical improvement - Large Cell - Automated Systems	4%
3. Module Improvements - Large Module - New J-Box	6%
Total	*22%*

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Figures

SECTION 1.0
CRYSTAL GROWTH AND THIN WAFER TECHNOLOGY

The Crystal Growth and Thin Wafer Technology task under this phase of the contract is focused on three areas: machine hardware improvements for the existing Czochralski (Cz) crystal growers in use at Siemens Solar Industries (SSI), the growth of larger diameter ingots, and the implementation of wire saw slicing machines.

1.1 MACHINE HARDWARE

The graphite redesign work done during the previous year of the program (year 1) which demonstrated an annual cost savings of over $300,000 was verified this year. The lifetime of graphite parts has increased substantially. Typical graphite susceptor usage has gone from 5.2 runs to over 16 runs prior to replacing each part.

Additional focus on throughput has initiated the use of larger diameter crucibles in the existing crystal growers. Initial pilot runs were conducted with no disruption to the production process, and with comparable growth yields. The larger crucibles have demonstrated over 10% improvement in kg/day grown, with virtually no cost addition. This improvement has been implemented in 30% of the production growers to date.

Problems with growing procedures on this new larger crucible has caused yields to drop in the last month, and short sectioned ingot growth. The standard size crucible has been re-instated in all growers. A systematic evaluation of the problem is being done to determine how to implement the large crucibles in production.

The crystal growth volume has increased by 5% during this phase, and represents an overall improvement of approximately 15% from the start of the contract.

1.2 LARGER DIAMETER INGOTS

A significant cost reduction in the total module cost is realized by making larger modules, with larger cells. The development program at SSI under this phase of the contract has focused on this larger cell and larger module.

Larger diameter ingots have been grown in order to increase cell size by 35%. A slightly larger diameter ingot of nominal 5.5" is being grown which has resulted in a 6% increase in ingot cross sectional area. This 6% ingot cross section area increase is a direct improvement in production volume, for no additional cost. A diagram of the new larger ingot is shown in Figure 1-1. This change also included a new ingot shape to maximize the area of the cell from the grown ingot. An analysis of the subsequent processes in the production facility showed that a small flat area is required for machines which align mechanically to the wafer. With the diameter tolerance on as grown ingot being considered, the shape shown in Figure 1-1. with 125 mm flats was designed. This new ingot produces a cell with 35% more active area with reference to the standard 4.05" square cell. This change in production posed no significant problems.

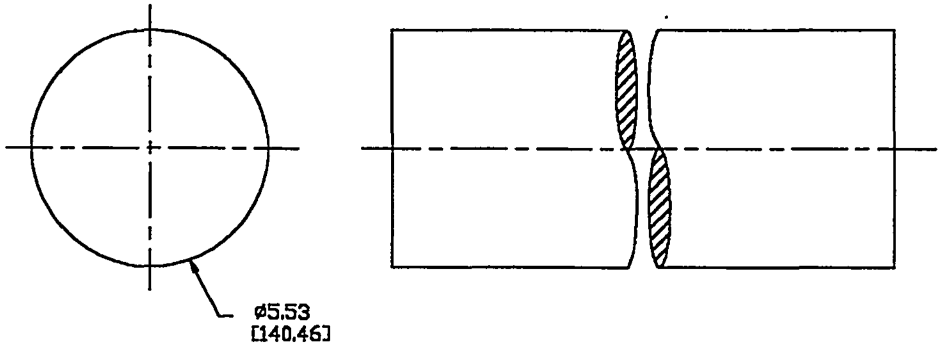


FIG 1

125 MM INGOT

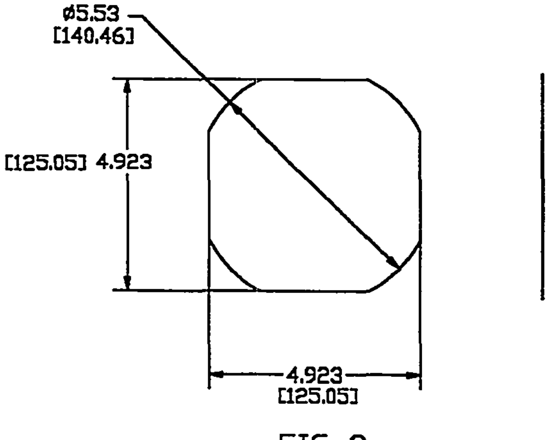


FIG 2

125 MM WAFER

Fig. 1-1 Larger Diameter Ingot

1.3 WIRE SAW IMPLEMENTATION

Wire saw implementation was the focus for wafer fabrication during this phase of the contract. Complete conversion from Inner Diameter (ID) saws to wire saws was accomplished during this phase .

Wafer yield per inch has improved substantially with this change over. In addition to less material lost with each slice, the ability to slice thinner wafers has had a substantial impact. Wafer thickness has decreased by 40% with wire saws; from .021" thick as sliced with ID saws to .013" thick with wire saws. Wafer yield has improved from 29 wafers per inch of ingot with ID saws to over 44 wafers per inch with wire saws, resulting in a greater than 50% increase in capacity. Figure 1-2 shows this improvement in yielded wafers per inch.

Slicing the larger diameter ingot discussed in section 1.2. posed no significant issues for wire sawing.

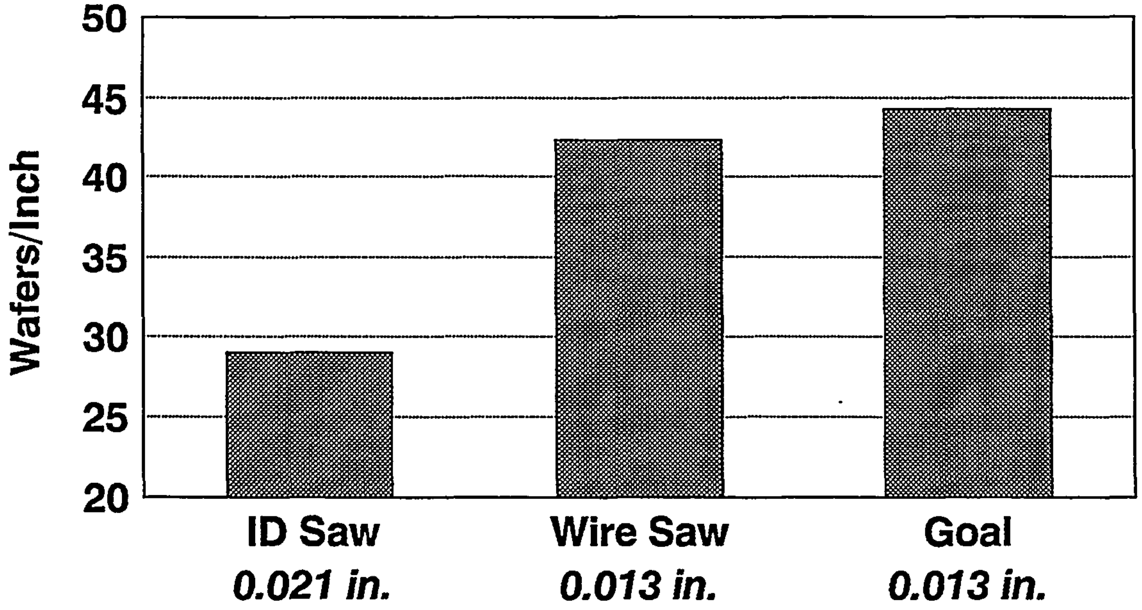


Figure 1-2 Yielded wafers per inch, ID saws compared to Wire Saws.

1.4 WIRE SAW YIELD

Wire saw mechanical yields also improved over this reporting period. Figure 1-3. shows the mechanical improvement seen over the last year, with significant events noted on the chart. The major improvement for 80% yield to 90% in recent months has been a result of the improvement in material quality characteristics of the oil and the wire. The wire must be defect free, and the oil viscosity must be tightly controlled, to achieve greater than 90% mechanical yield.

Another interesting artifact of wire saw yields has been the discovery of a yield dependance on position of a wafer within an ingot. This artifact is shown in Figure 1-4. where mechanical yield is plotted vs. position in ingot length. The interesting point of this data is that the mechanical yield is lower at the ends of the ingot which are cut for placement on the wire saw. A long (>30 inch) ingot is sliced into two approximately sixteen inch slabs which are subsequently sliced on the saw. This lower yield experience may be due to cropping of the ingots into two pieces, or the slicing of the wafers on the saw. This is a subject to be further understood in the next phase of the program.

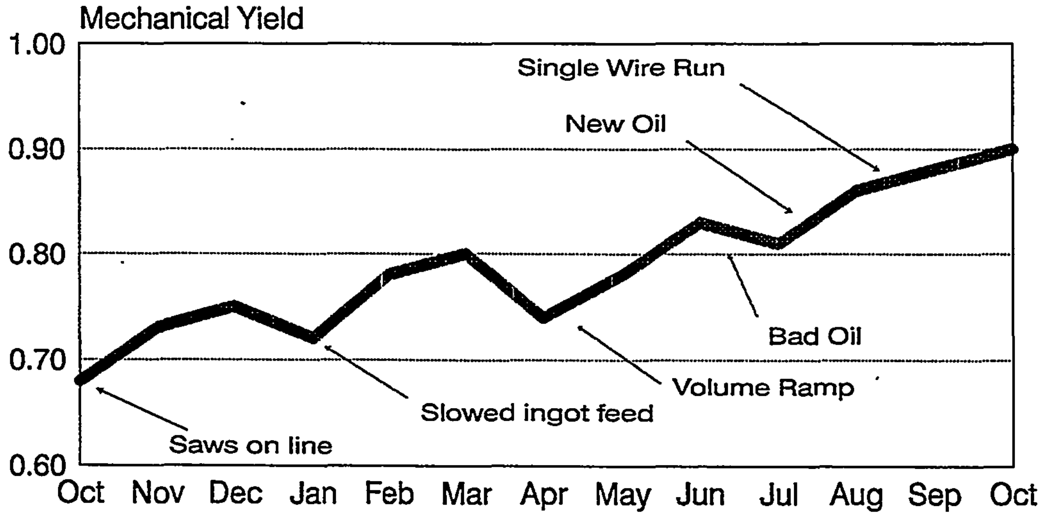


Fig. 1-3 Wire Saw yield improvement.

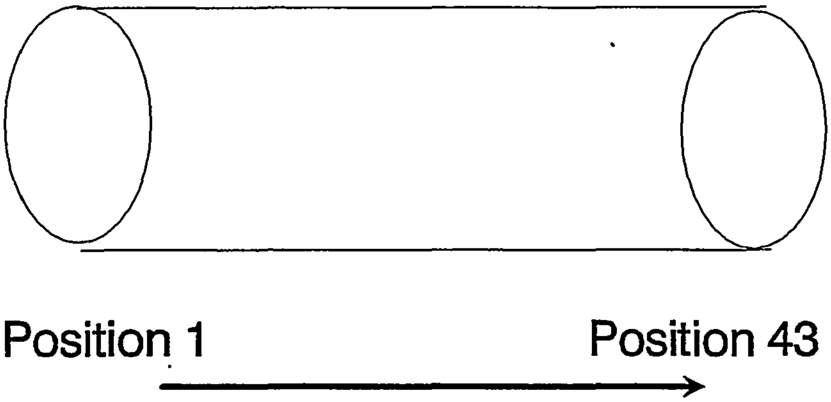


Fig. 1-4a Ingot position

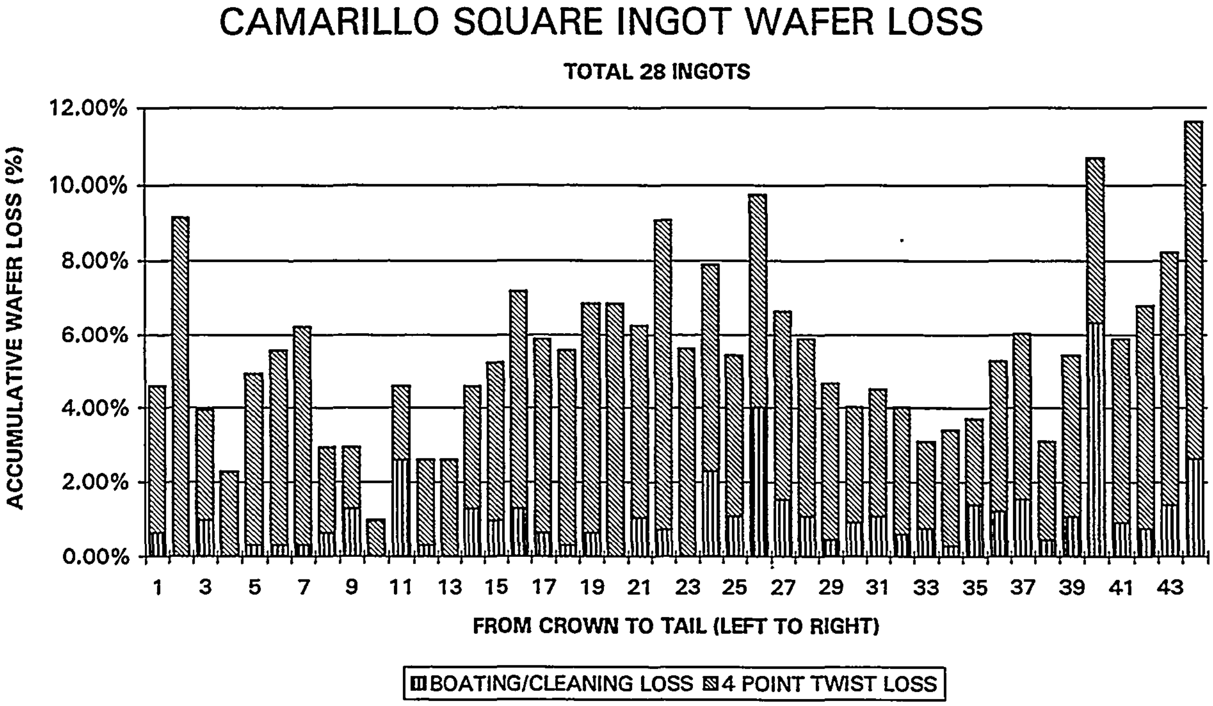


Fig. 1-4b Yield vs. Ingot Position

SECTION 2.0
CELL PROCESSING

The cell processing task of this contract has focused on three items during this phase: increasing average cell performance, contact paste studies, and automated handling equipment for cell processing.

2.1 CELL PERFORMANCE

Improvement in the cell distribution has been consistent throughout this program. Figure 2-1. shows the electrical test amperage improvement comparing initial distribution in 1992, and the comparable time frame for 1993 and 1994. This electrical improvement and tightening of the distribution is credited to better process control in the diffusion area, new equipment for the anti-reflective coating process, and an additional etch step that has been added to the process. This was discussed in more detail in the annual report for Phase I. Additional increases have been obtained with the introduction of process control charting in specific areas of manufacturing. As shown in Figure 2-1, the distribution has shifted up by 4% and the standard deviation has gotten smaller as these control charts have been instituted. This focus on control charting has begun in specific areas of the manufacturing facility, with the goal to have the whole process using control charts during the next phase of the contract.

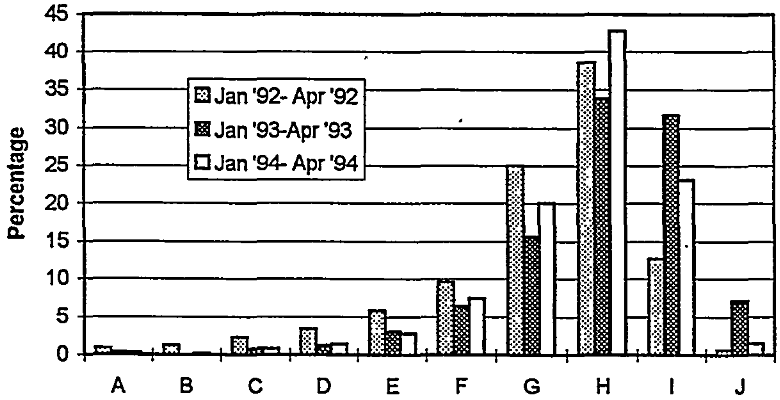
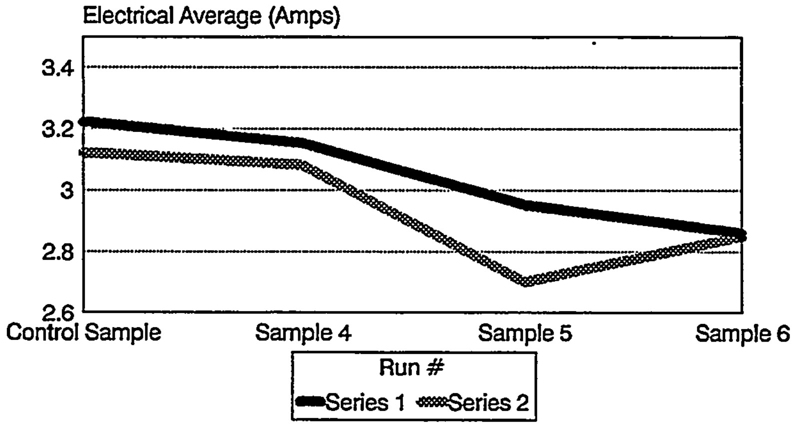


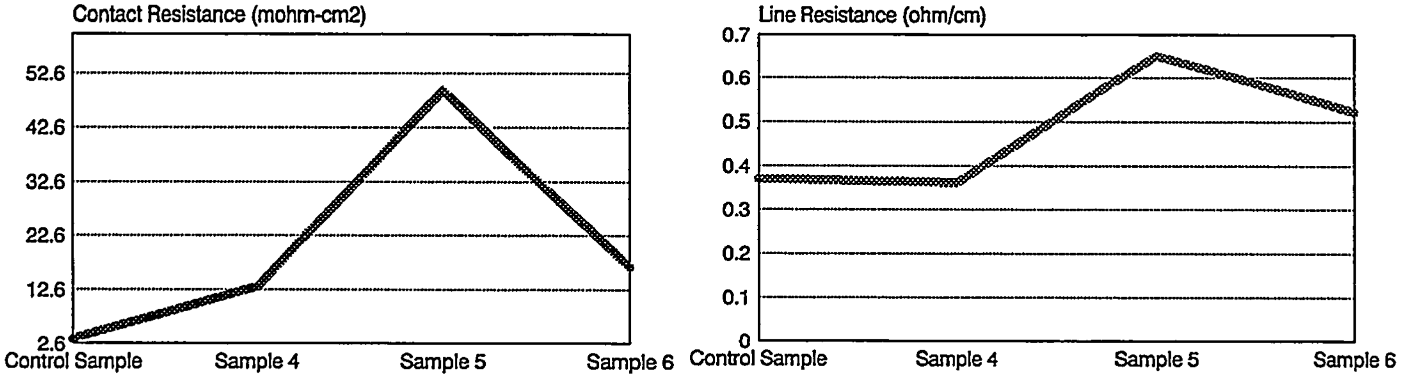
Fig. 2-1 Electrical Distribution Improvement

2.2 CONTACT PASTE STUDIES

A paste study conducted with Ferro Corporation to improve the electrical contacting of cells was performed in which the standard paste formulation was modified in an effort to reduce both the contact resistance to the cell and the linear resistance of the grid lines. The standard paste used in production continues to be the best performer in all categories of electrical amps produced and lowest contact and line resistances. Figure 2-2. (a-c) shows the contact paste comparison study results. More work is planned with Ferro.



a. Electrical performance of cells with various pastes



b. Contact resistance

c. Line resistance

Fig. 2-2 Contact paste comparison study

2.3 AUTOMATED CELL PROCESSING

Automated handling systems have been designed and installed in the cell fabrication area during this phase of the contract. The result has been the reduction of over 50% of the labor required in this portion of the cell process. The automated handling system begins with the anti-reflective coating process and ends with a tested cell. The transfer points are a combination robot, and pick and place mechanism system. A flowchart of the process is shown in Figure 2-3. in which the solar cells are automatically machine handled throughout this area of the production facility. The automated equipment was designed to handle both the 4.05" square cell and the 125 mm semi-round cell discussed in section 1.2.

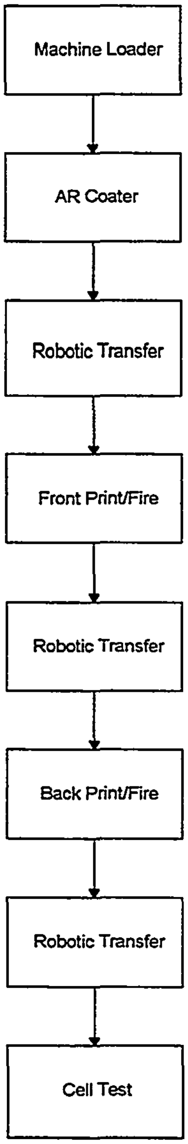


Fig. 2-3 Flowchart showing automated cell processing.

2.4 CELL PROCESSING MECHANICAL YIELD

Yield in the cell line as mentioned above in the wafering and crystal growing processes, is a large driver in the costs of manufacturing photovoltaics. The cell yield is important as it incorporates the cumulative costs of ingot growth, wafer slicing and cleaning and the cell process itself. Over the reporting period, cell mechanical yields have improved by 6%. This is attributed to better handling by robotics, more attention to manual handling steps, and better understanding and training of operations personnel. Additional focus on yield is planned for the next phase.

SECTION 3.0
MODULE FABRICATION AND ENVIRONMENTAL, SAFETY AND HEALTH ISSUES

A majority of the module finishing costs in photovoltaics are in the materials and labor used for fabricating the modules. The requirement of reliability has driven the industry to standardize the laminate design to include glass, EVA, and various back sheet materials which provide an electrically insulating, environmentally resistant package. In working through the opportunity to reduce costs in the module design, three things became apparent during this phase of the contract: the module size has a significant impact on the dollar per watt material cost, the laminate construction is the significant contributor to the labor component of the costs, and the framing and junction box are major material contributors. During this phase of the contract, all three have been addressed.

3.1 75 WATT MODULE DESIGN

To address the larger module and it's affect on reducing the dollar per watt, a larger ingot which could be grown easily in the facility was chosen. The starting design assumptions were to maximize the amount of power in a given module unit. Coupling this assumption with the ingot design, gave a cell area which is 35% larger than the 4.05" square cell. This cell power is further enhanced by the white area of the laminate using larger spacing of the cells. Modules made from thirty six cells in series produce 75 Watts in this new module design. The IV curves for the 75 Watt module are shown in Figure 3.1 a. along with the standard M55 curve in Figure 3.1 b.

Other significant design changes considered were the framing technique and electrical termination used. Two modules were designed, one with the standard aluminum frame and a large junction box, and one with a plastic frame and a two conductor cable assembly. In the final cost summary, the two module techniques were similar in dollar per watt, where the savings of the plastic frame were offset by the labor and expense of the cable assembly technique. The significant cost reduction is mainly due to the larger amount of watts (75 vs. 53) being framed and terminated. The two 75 Watt module designs are shown in Figure 3.2.

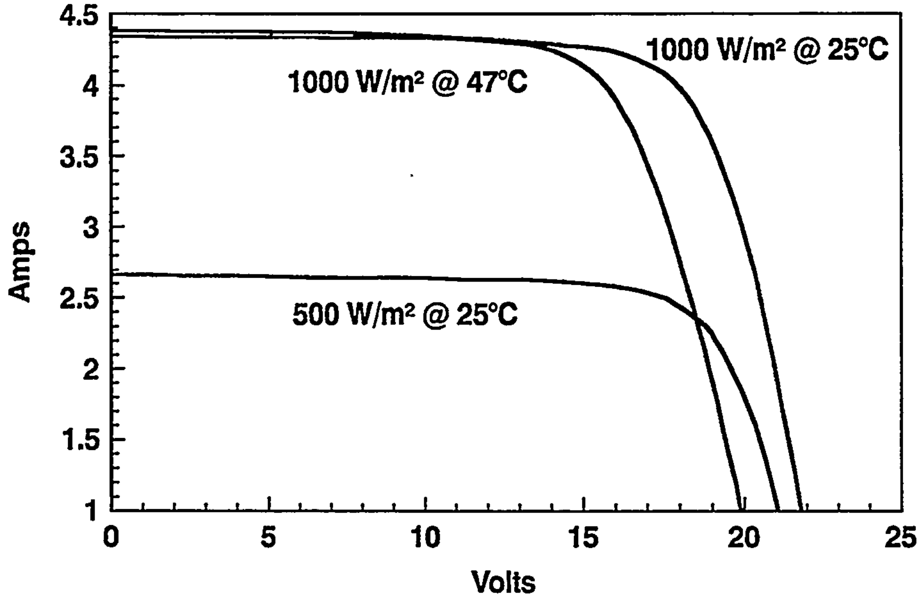


Fig. 3-1a I-V characteristics for a 75 Watt module.

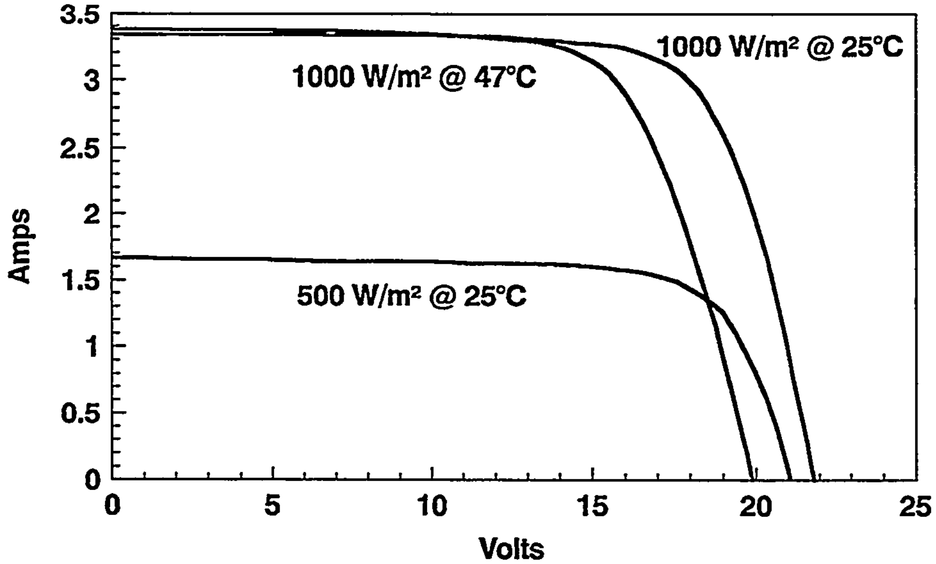


Fig. 3.1b I-V characteristics for a M55 module.

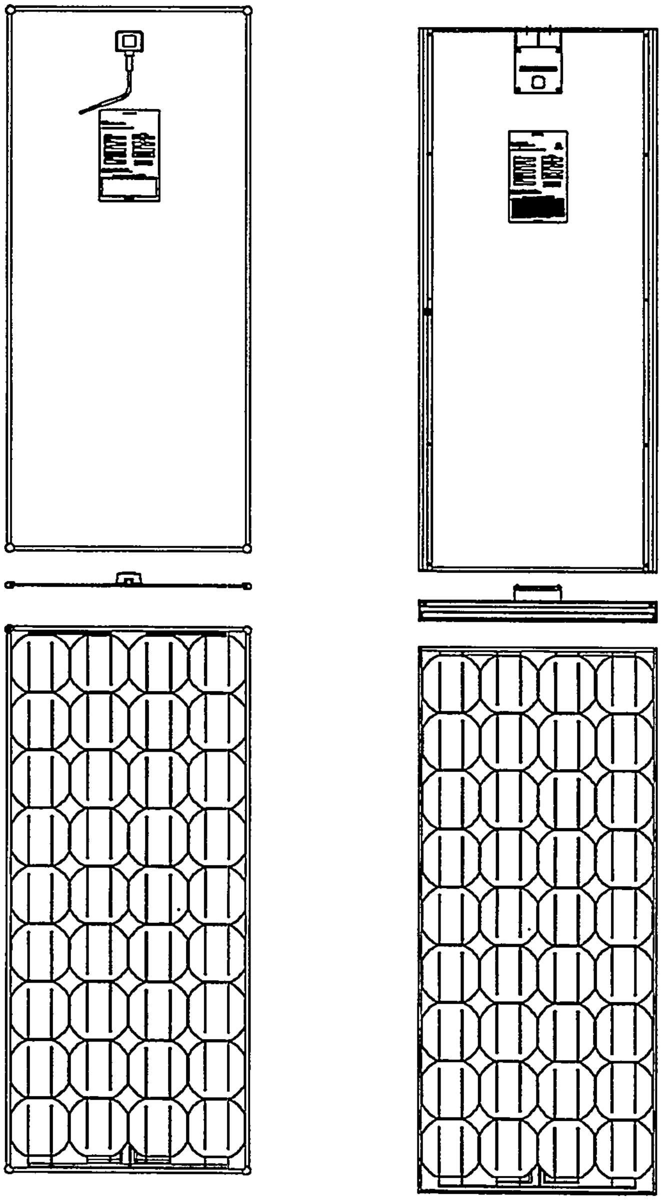


Fig. 3-2 75 Watt module designs.

3.2 SOLDER YIELDS

A significant finding during this phase of the program has been that the yields in the soldering process are the drivers to high yield in the module making process. A primary process control parameter in soldering is the edge condition of the cells being soldered. Figure 3-3. shows the relationship of yield to chipped cells, which results in a lowering of process yield by over 3%. Further studies on solder yield are planned during phase III of the contract.

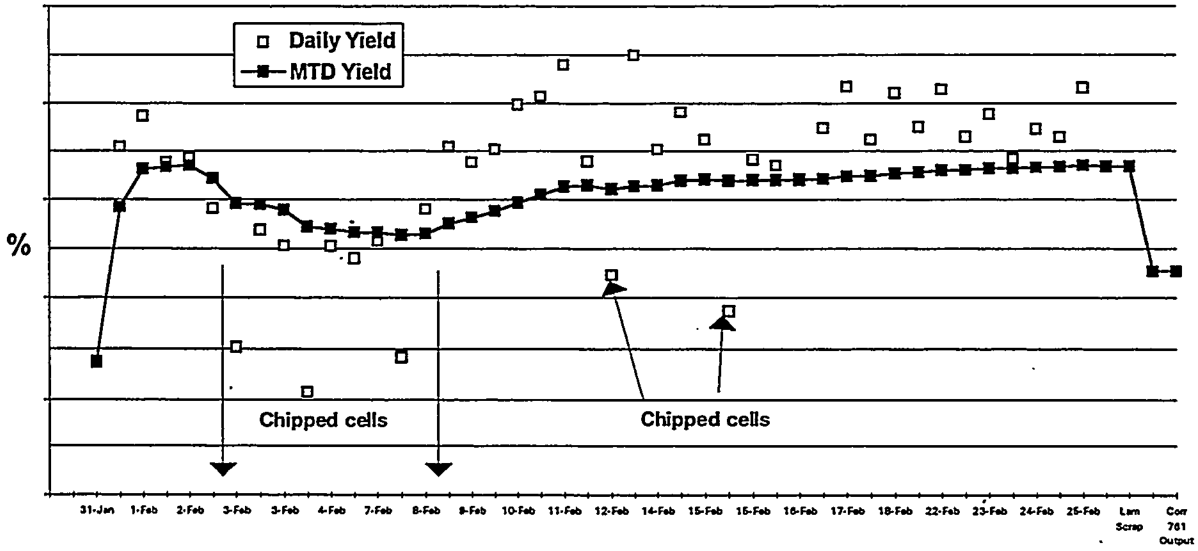


Fig. 3-3 Solder Process Yield

3.3 NEW JUNCTION BOX

A new junction box has been designed which combines the benefit of the wire termination and the large junction box. A cost reduction benefit of over 2% is expected in production. The new junction box allows for wire connections and conduit type fitting connections. The installation of this new design on the module during manufacturing has also been considered, with an open area for laminate ribbon to feed through for electrical connection and larger area contact for gluing to the module back surface. The new design is shown in Figure 3.3. This junction box has been submitted to Underwriters Laboratory for approval, and has failed the first round of testing in the mechanical loading tests. A stronger lid, and ribs for the side walls are modifications currently being done for the next round of submission to U.L.

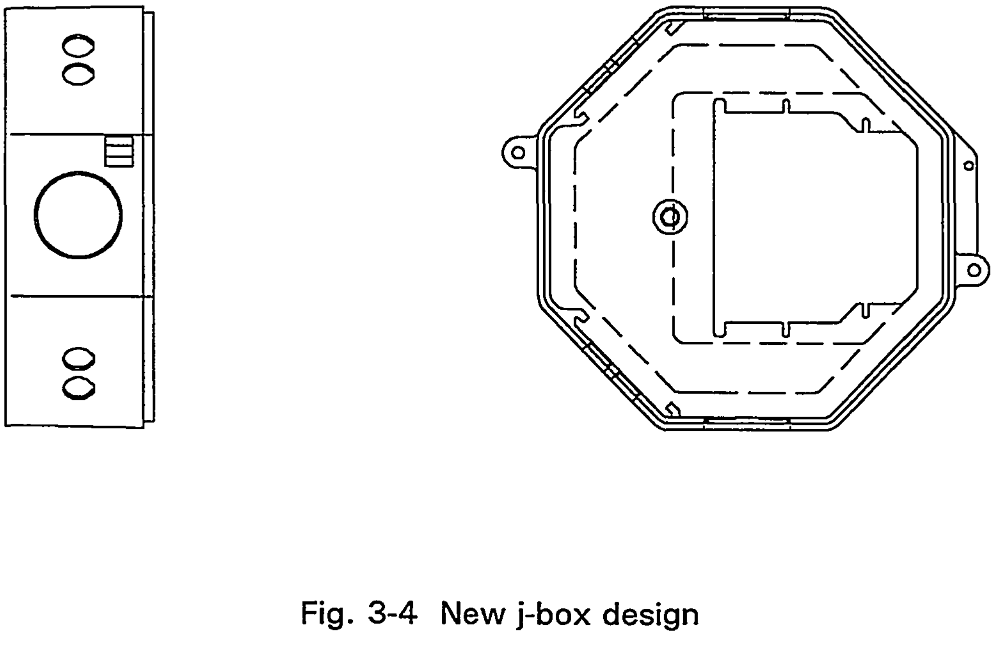


Fig. 3-4 New j-box design

3.4 SEMI-AUTOMATED ASSEMBLY LINE

A design for a semi-automated assembly line for 75 Watt laminate manufacturing has been finished during this phase. The design is a flexible material movement system which relies on fixtures which travel along a track system. The operators of the system place cells on the fixtures which move down the line for final solder connections and laminate lay-up. This design will allow for a 30% reduction in the amount of labor required for assembling 75 Watt laminates. An additional requirement of ergonomic comfort has been included in this design. The system layout is shown in Fig. 3-5.

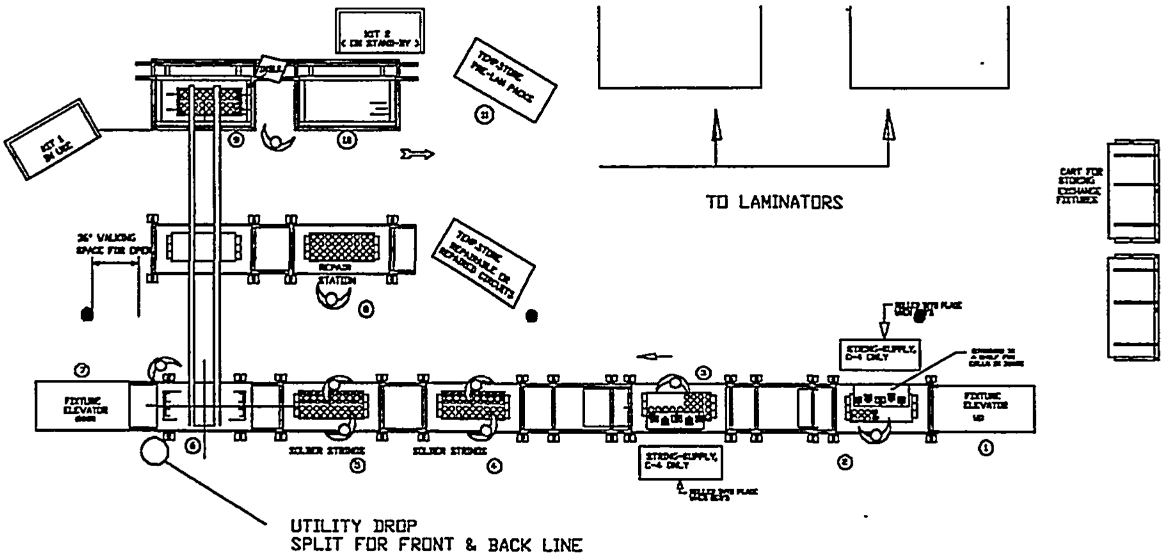


Fig. 3-5 Layout of semi-automated assembly line.

3.5 ENVIRONMENTAL, SAFETY & HEALTH

For the Module Fabrication and Environmental, Safety and Health Issues task, the focus during this reporting period was the complete elimination of CFC usage in the manufacturing process, and the reduction in the amount of caustic waste produced.

CFC usage was discontinued during May of this year by the implementation of a no-clean flux solder paste. The development of the use of this paste was done during the last phase of the contract (Phase 1), with the implementation of its use this year. Complete elimination of CFC use has been accomplished, one and a half years ahead of the contract schedule.

The second focus on reducing caustic waste has been attacked using two methods. The first method is the reduction of waste created per cell processed. This has been accomplished mainly with the use of wire sawn wafers which require less etching to remove saw damage. This reduction in caustic waste per wafer is over 10% for the reporting period of this contract, with the cost and volume per cell processed shown in Figure 3-6. The second method of reducing the caustic waste leaving the facility has been to look at processing techniques to eliminate the water in the caustic waste stream. One such proposal is shown in Figure 3-7. Several proposals have been solicited, with this the most promising. Many other factors must be considered prior to any treatment of waste, for example the safety issues of the system, the local regulatory permits required, and the cost of the hardware. These considerations will be examined during the balance of the contract.

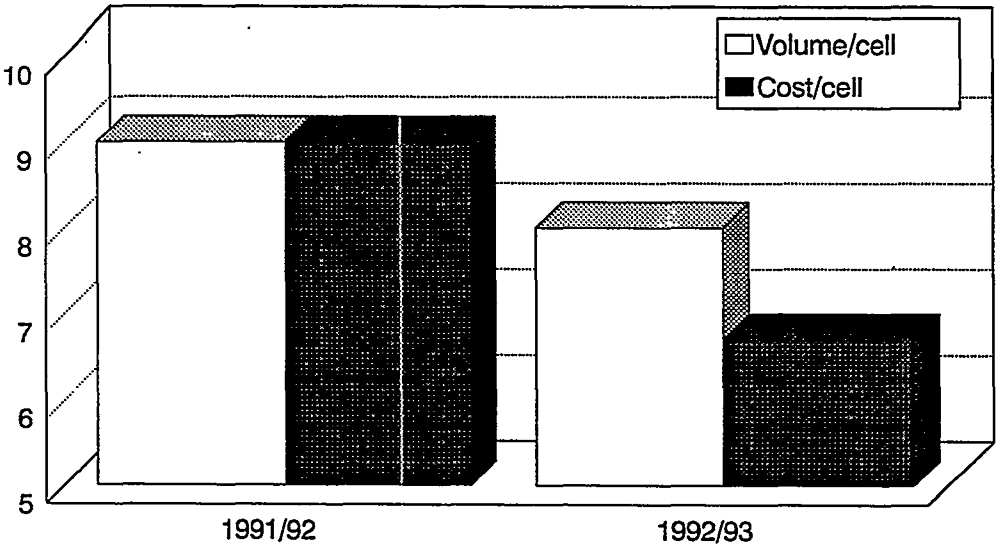


Fig. 3-6 Caustic Waste Cost & Volume per Cell

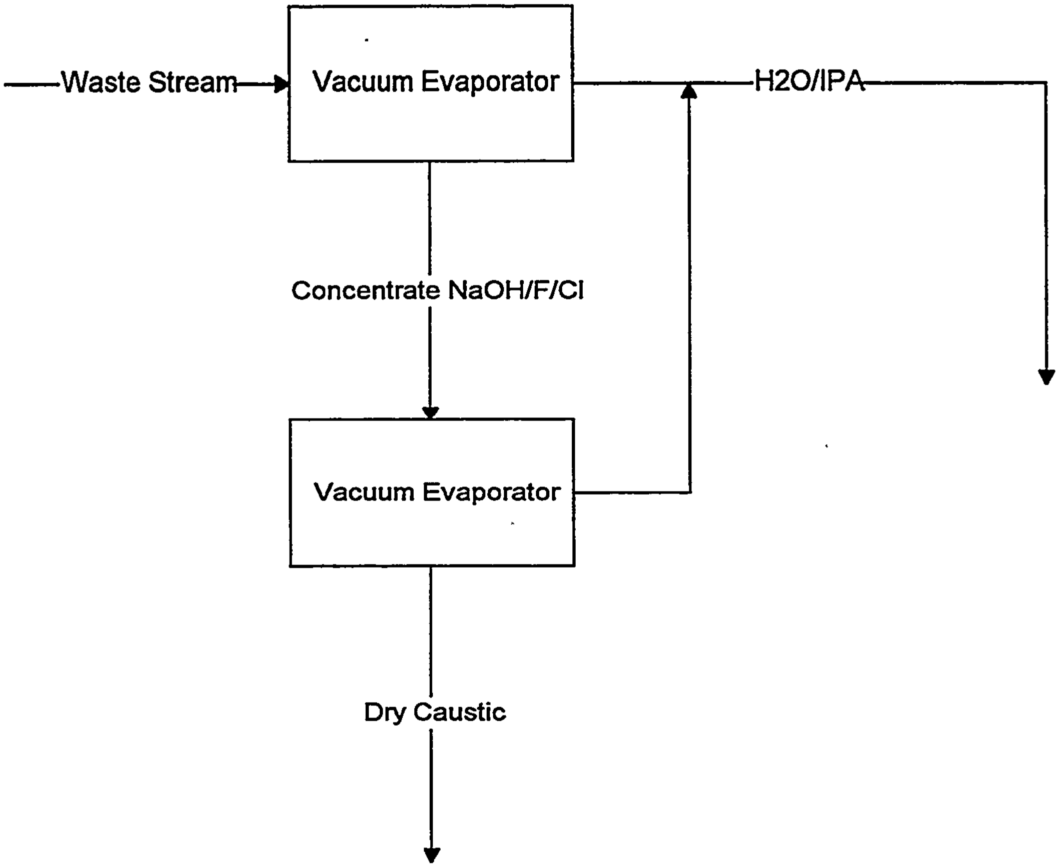


Fig. 3-7 Caustic waste reduction process flow

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13. ABSTRACT *(Maximum 200 words)*

This report describes work performed under a 3-year, three-phase, cost-shared contract to demonstrate significant cost reductions and improvements in manufacturing technology. The objective of the program is to reduce costs in photovoltaic manufacturing by approximately 10% per year. The work was focused in three main areas: (1) silicon crystal growth and thin wafer technology; (2) silicon cell processing; and (3) silicon module fabrication and environmental, safety, and health issues. During this reporting period, several significant improvements were achieved. The crystal growing operation improved significantly with an increase in growth capacity due to larger crucibles, higher polysilicon packing density, and higher pull speeds. Wafer processing with wire saws progressed rapidly, and the operation is completely converted to wire saw wafer processing. The wire saws yield almost 50% more wafers per inch in production, thus improving manufacturing volume by 50% without any additional expense in crystal growth. Cell processing improvements focused on better understanding the contact paste and firing processes. Module designs for lower material and labor costs began with the focus on a new junction box, larger modules with larger cells, and a less costly framing technique. In addition, chlorofluorocarbon (CFC) usage was completely eliminated in the Siemens manufacturing facility during this period, resulting in significant reductions in the cost of caustic waste treatment.

14. SUBJECT TERMS
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