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Photovoltaic Manufacturing Technology, Phase 1, Final Report

Final Subcontract Report
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1.0 INTRODUCTION

This final technical report fulfills the contract requirements of the Photovoltaic Manufacturing Technology - Phase I (PVMaT) program as defined in statement of work RC-0-10057. The PVMaT project, a Department of Energy (DOE) program administered through the Solar Energy Research Institute (SERI), is intended to encourage cooperation with industry and to provide tangible assistance for identifying and overcoming major technical obstacles to improving photovoltaic manufacturing technology.

The objective of this Phase I contract is to identify: 1) current capabilities in manufacturing and process development, 2) manufacturing potentials envisioned to lead to significantly increased production capacities and reduced manufacturing costs, 3) problems impeding the achievement of those potentials, and 4) cost and other requirements involved in overcoming the problems in manufacturing technology. This document describes the company background and goals and summarizes the results of the contract work in the remainder of Section 1. Sections 2,3,4 and 5 provide detail on each of the four tasks defined in the statement of work. These tasks generally correspond to the four objectives stated above.

1.1 Solar Web Background

Westinghouse Electric Corporation, Advanced Energy Systems located in Pittsburgh, PA, has been developing a cost-effective process for manufacturing flat-plate photovoltaic modules from silicon crystals produced in ribbon form using a patented dendritic web crystal growth process. Dendritic web combines the high efficiency, high reliability features of single crystal wafer technology with a low cost manufacturing process that uses less than 20% of the silicon required by other single crystal technologies, and eliminates costly wafer processing steps. As a result of technology readiness demonstrations, which included operation of a manufacturing demonstration facility through 1990, a major effort is underway to establish a larger commercial manufacturing facility in 1992.

Established in January 1991, Solar Web, Inc. is a spinoff company from Westinghouse which incorporates all previous Westinghouse dendritic web photovoltaic technologies, equipment, and technical staff. Future activities dealing with any aspect (marketing, production, development, etc.) of the dendritic web technology developed by Westinghouse, will be carried on by Solar Web, Inc. Westinghouse has expanded upon the Solar Web commercialization plan by making significant investments in the PV systems business (design, installation, and operation). The combination of PV manufacturing and systems engineering is intended to lead Solar Web and Westinghouse to dominant positions in the PV industry.

A manufacturing line currently exists at Westinghouse in Pittsburgh, PA with the capability to manufacture dendritic web based photovoltaic modules. Solar Web, Inc. will operate this manufacturing line with necessary expansions to supply modules to the specialty photovoltaics market. Solar Web has chosen to enter the photovoltaics market through the specialty niche segment due to the unique characteristics of the dendritic web product which include high efficiency, lightweight, and flexibility. Process cost reductions described in this report will position Solar Web to be a major player in the power module market within 3-5 years.

With the original knowledge base intact through Solar Web; Westinghouse has selected Solar Web to perform the requirements of the RC-0-10057 contract. The sole focus of our proposed involvement in the Photovoltaic Manufacturing Technology (PVMaT) Program is to reduce power module manufacturing cost by a factor of 2 to 3 during the program. This goal can be met and exceeded through further development of manufacturing processes and improved module efficiencies, as outlined in this report.

1.2 Summary of Results

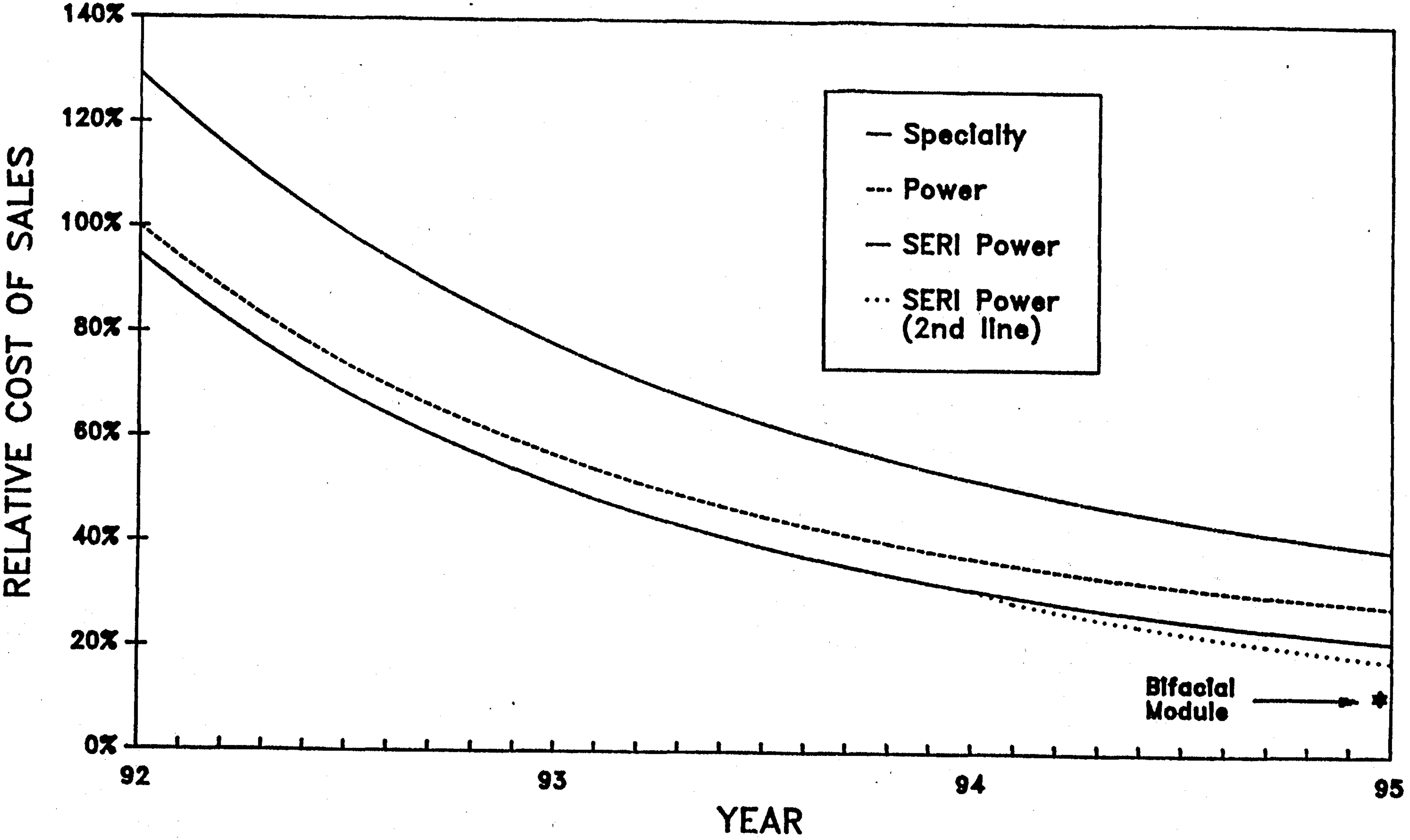
The program goals, which are discussed completely in sections 3 and 4, are structured to exceed the SERI cost reduction goals while maintaining a firm basis of realism by projecting reasonable achievements. As an example of the achievability of the individual goals discussed in the later sections, table 1-1 compares the present baseline, PVMaT goals, and previous single point demonstrations for various process parameters. It is important to realize that previous development programs have emphasized demonstration of single process parameters for a single event, thus demonstrating achievable process bounds. The current PVMaT program is designed to achieve lesser process parameter levels, but on a reproducible, manageable basis. As shown in table 1-1, in all cases, the PVMaT program goals have been met or exceeded on a one time basis during prior development efforts. The goals established for the PVMaT program are achievable, and exceedingly realistic.

Figure 1-1 shows the results of this study graphically in terms of module cost over time. The cost scale is a ratio of our current power module cost to the module cost based on the Solar Web, Inc. business plan. The "Specialty" curve, represents the projected cost of modules for the next four years in the specialty market. The module cost includes direct product cost, factory overhead, marketing, G&A, and capital depreciation. All comparisons of module cost are based on 1991 dollars. This cost decreases in response to planned process development and production capacity increases. The curve marked "Power" represents the estimated product cost with sales concentrated in the power module market and with the same assumed process improvement and capacity expansion as in the first curve. The difference between the two curves lies in the significant higher marketing, G&A, overhead, and module assembly expenses incurred in the specialty market. In the specialty market, custom orders increase module assembly and engineering costs. Marketing costs increase due to the fact that the specialty market is a relatively new and

Table 1-1. Program goals, current baselines, and previous achievements

PARAMETER	1991 BASELINE	PVMaT GOAL	DEMONSTRATED "SINGLE POINT"
CRYSTAL WIDTH	45 mm	62 mm	70 mm
CRYSTAL VELOCITY	1.5 cm/min	2.0 cm/min	2.5 cm/min
CRYSTAL LENGTH	6 meters	10 meters	22 meters
STARTING CRYSTAL WIDTH	75% of full width	100% of full width	100% of full width
TIME BETWEEN CRYSTALS	200 minutes	45 minutes	15 minutes
CELL EFFICIENCY	14.5 %	17.5 %	17.5 %
PROCESS YIELD	85.6 %	96.9 %	100 %

Figure 1-1 MODULE PRODUCTION COST REDUCTION CURVES



underdeveloped market compared to the "commodity" type market for power modules. Participation in the power module market, would result from achieving a competitive cost of sales. The third curve, marked "SERI Power", indicates the impact of the program described in this report on the cost of sales. Under this set of assumptions, the module cost is reduced by a factor of 4.5. By the end of the three year project period an increase in production capacity would further improve the power module costs due to shared overhead, marketing and G&A between the original production line and a new line of identical capacity. The cost of sales at this point is reduced by a factor of 5.5. This is indicated by the curve marked, "SERI Power - 2 lines".

One additional point is shown in Figure 1-1. This point indicates the impact on product cost of a bifacial module design. This potential design feature, unique to dendritic web, enables collection of light and power generation from both faces of the panel. With incorporation of a reflector system to present light to the back side, the module design actually becomes a low level concentrator module. While the bifacial design can have a significant impact on module cost (we show cost reduction by a factor of 7.5) it is treated separately due to the additional marketing and product testing requirements it brings to the business. More information on bifaciality is included later in this report.

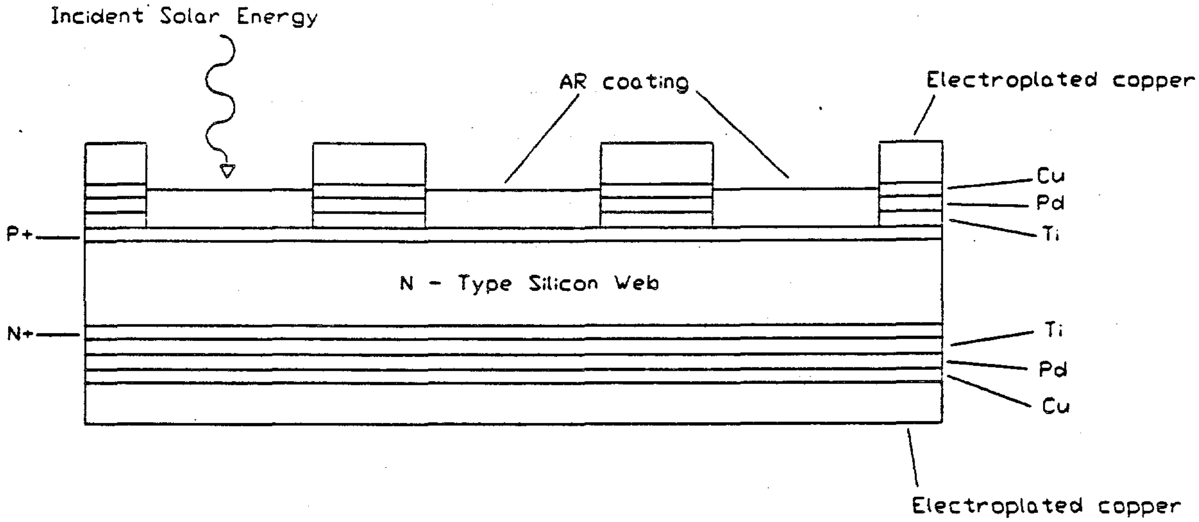
2.0 TASK 1 - PROCESS DESCRIPTIONS

The following is a complete description of the manufacturing processes used by Solar Web, Inc. to produce photovoltaic modules. The general sequence of procedures begins with silicon crystal production (dendritic web growth), continues with cell processing operations, and ends with module assembly. The initial process steps dealing with crystal growth utilize custom furnaces, designed specifically for dendritic web growth. The remaining process steps are based on well-known industrial semiconductor practice and commercially available equipment that have, in some cases, been modified to take advantage of the unique properties of dendritic web silicon, such as thinness, smooth surfaces, long lengths, etc. These features permit economical fabrication of solar modules.

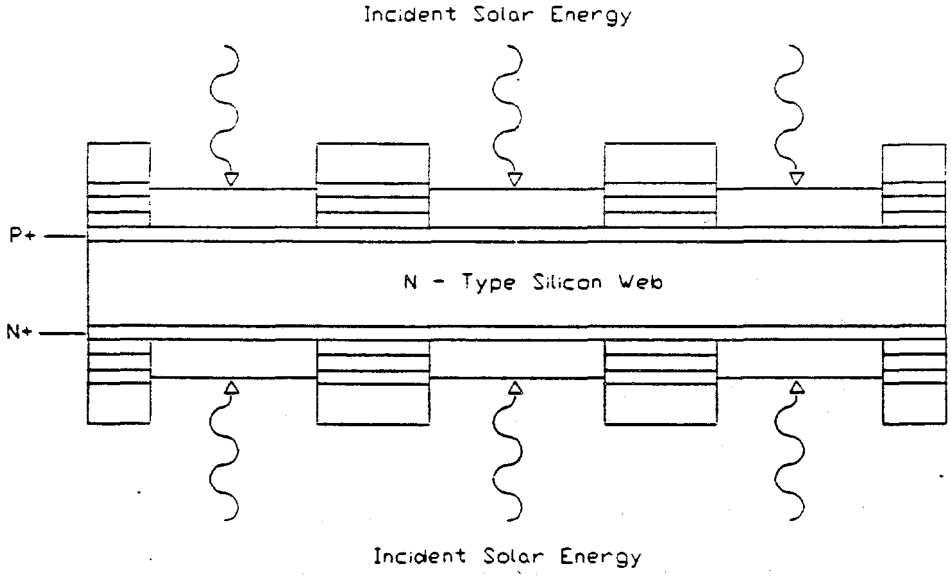
The photovoltaic module which is produced as a result of the operations to be described is illustrated in figure 2-1 and 2-2 through cross sectional line drawings. The construction of both monofacial and bifacial solar cells are shown in figure 2-1. The module layup and the interconnect scheme for the product is shown in figure 2-2.

The current baseline process sequence used to produce dendritic web photovoltaic modules in the Commercial Manufacturing Facility (CMF-91) is outlined in Figure 2-3. To meet financial goals, Solar Web intends to expand production levels and continue modest process development efforts in the 1991-1994 time frame. Changes to the process outlined in Figure 2-3 have been identified, in an effort to increase throughput, decrease cost, and reduce the capital investment. Figure 2-3 also outlines the process which is projected to evolve from the CMF-91 manufacturing method by 1994. This will be referred to as the CMF-94 manufacturing method.

Figure 2-1
Dendritic Web Solar Cell Cross Section Diagram
(Monofacial and Bifacial)

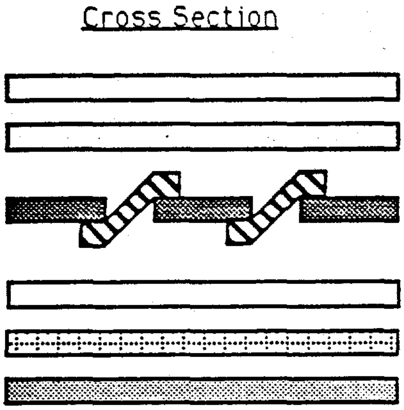


Monofacial Dendritic Web Solar Cell



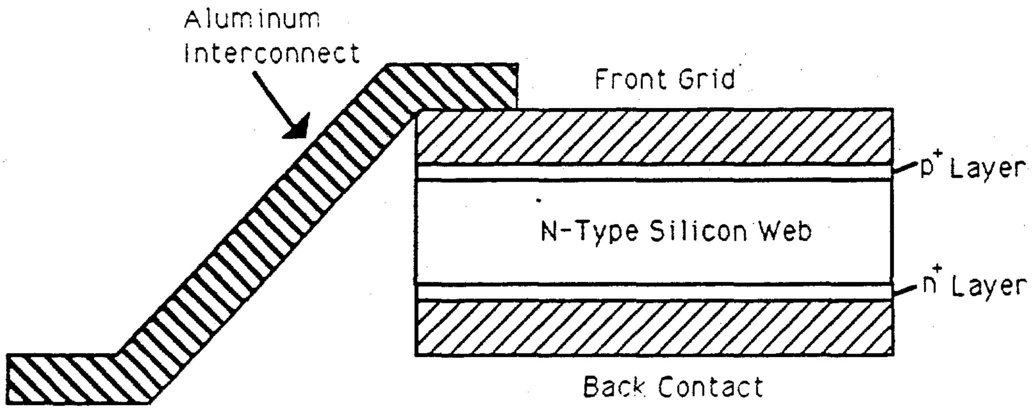
Bifacial Dendritic Web Solar Cell

Figure 2-2
Dendritic Web PV Module Cross Section Diagrams



Material and Thickness	
1/8"	Tempered glass
0.02"	EVA
0.04"	Solar Cells
0.005"	Crane Glass
0.02"	EVA
0.0015"	Tefzel

General Module Layup



General Solar Cell Cross Section

Figure 2-3

Planned Process Sequences for Solar Web, Inc.

	CMF-91		CMF-94
1.	Web Growth	1.	Web Growth
2.	Growth Oxide Removal	2.	Cell Sizing
3.	Cell Sizing	3.	Pre-diffusion Clean
4.	Pre-diffusion Clean	4.	Dopant Spray and Bake
5.	Dopant Spray and Bake	5.	Junction Formation
6.	Junction Formation	6.	Thermal Anneal
7.	Thermal Anneal	7.	Dopant Oxide Removal
8.	Dopant Oxide Removal	8.	AR-coating (AP-CVD)
9.	AR-coating (dip)	9.	Screen Metallization
10.	PR-coating	10.	Tab Removal
11.	Mask and Expose	11.	Cell Test and Sort
12.	Develop and Etch	12.	Cell Intrcon & Mdl Lay-up
13.	E-beam Metallization	13.	Lamination and Trim
14.	Lift-off and Copper Plate	14.	Framing and Rate Power
15.	Tab Removal		
16.	Cell Test and Sort		
17.	Cell Intrcon & Mdl Lay-up		
18.	Lamination and Trim		
19.	Framing and Rate Power		

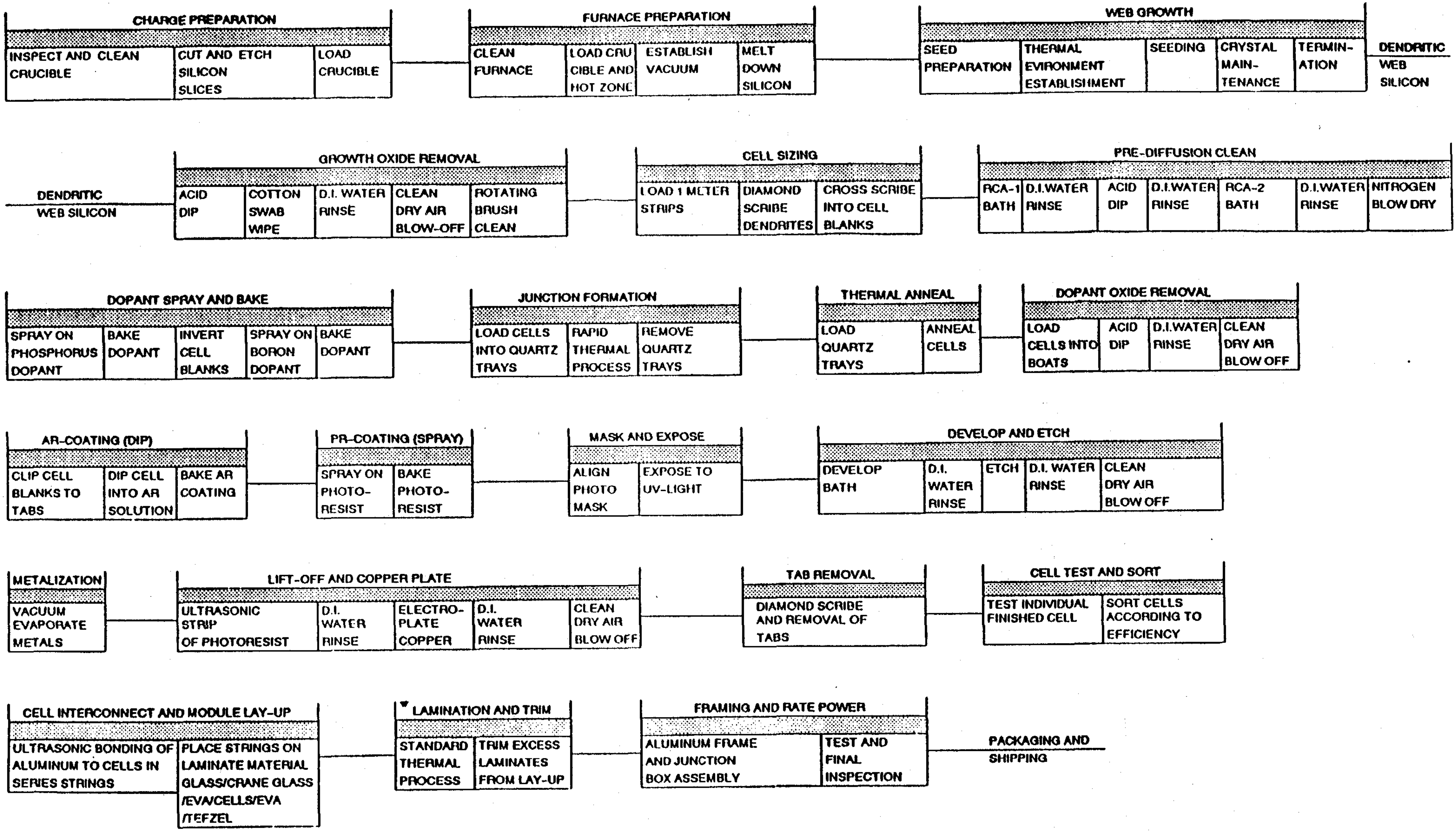


Figure 2-4
Solar Web Inc. CMF-91 Process Sequence

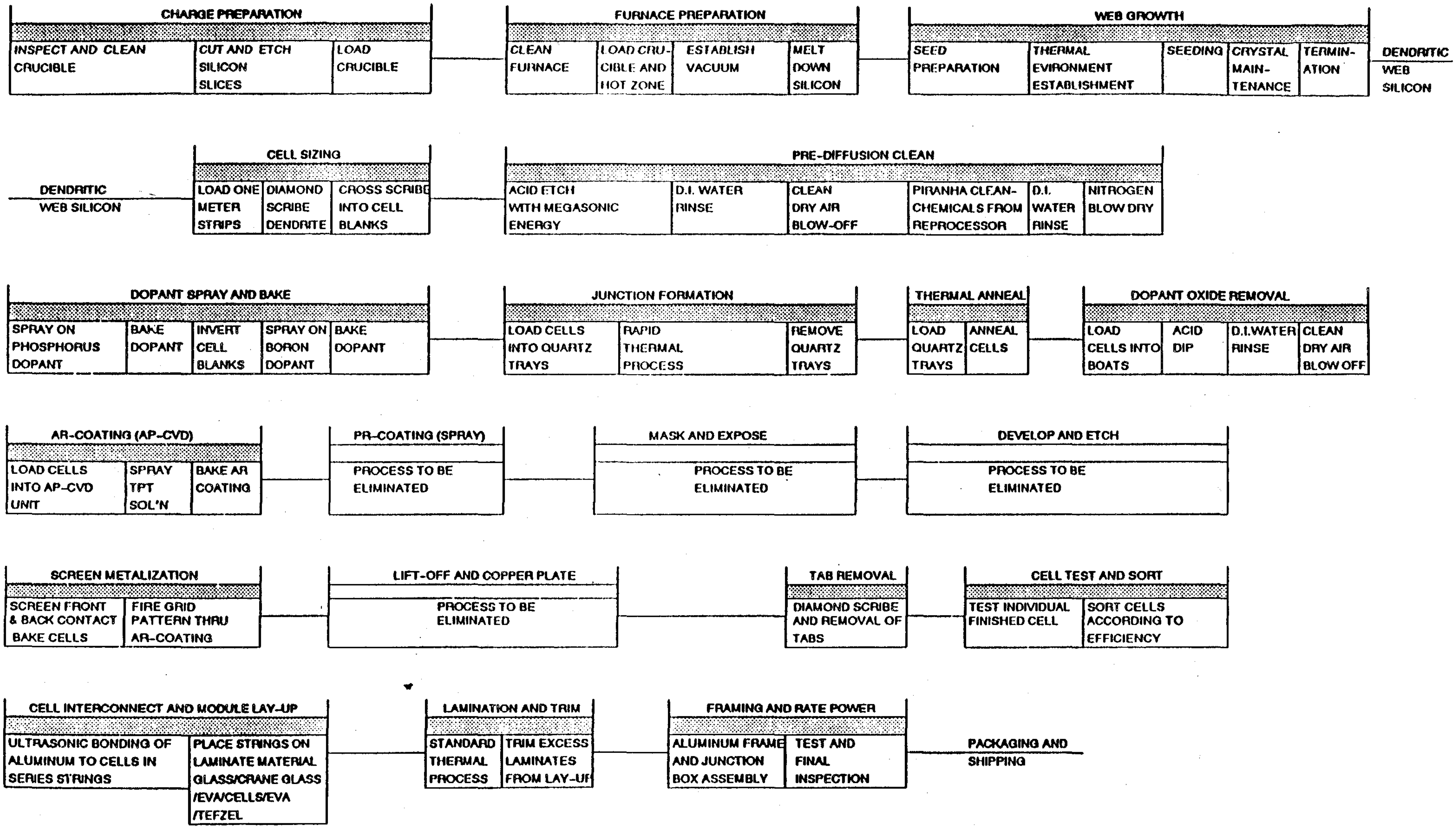


Figure 2-5

Solar Web CMF-94 Sequence

A more detailed process sequence flow chart depicting the CMF-91 unit operations, is shown in Figure 2-4. Figure 2-5 shows the unit operations for the CMF-94 process which evolves from 1991 to 1994. Detailed descriptions of the start-up CMF-91 and improved CMF-94 processes are provided in the following sections.

2.1 Commercial Manufacturing Facility - 1991 Startup

Nineteen sequential process steps are described in the following pages. The process described here refers to the CMF-91 startup process which is the current basis for Solar Web, Inc. production operations.

Step 1. Web Growth

The web growth process is the key to uniqueness of dendritic web material. During this process step, molten silicon is transformed into a single crystal silicon ribbon which can be readily processed into a photovoltaic cell using the techniques described in the remainder of this section.

The ribbons are produced in a web growth furnace with a typical growth run lasting about 10 days (limited by crucible erosion). Each growth run uses a single crucible and charge assembly. During this growth run, approximately twenty crystals are produced which average six meters in length. The crystals achieve a steady state width of 43 mm.

The crystal growth process consists of six readily definable phases; a) furnace preparation; b) seed preparation; c) thermal environment establishment; d) seeding; e) crystal maintenance; and f) termination. With the exception of furnace preparation which is performed once per run and seed preparation which is done en masse at regular intervals to provide a seed supply, each of these phases are repeated for each crystal. Each of these process phases will be described in chronological order.

a. Furnace Preparation

Polysilicon charges and crucible assemblies are prepared for use in the web growth furnaces. Custom quartz crucibles are supplied by any of several quartz hardware manufacturers. Upon receipt from the quartz manufacturer, the crucibles are inspected for size (wall thickness, susceptor fit) and quality (visual inspection under polariscope assessing inclusions, surface quality, and stress). Following inspection, the crucibles are cleaned. Each crucible is etched in a solution of deionized water and hydroflouric acid. The crucible is then dried with clean dry air. The crucible is then ready for installation of a silicon charge.

Polysilicon boules (3" diameter) are sliced into 1/2" discs. These discs are further cut into sections to fit into a standard rectangular quartz crucible with a total charge weight of 280 grams. After sizing the charge to fit the crucible, the charge pieces are etched in a nitric-hydroflouric acid mixture, and rinsed in a deionized water bath followed by a methanol rinse. The charge pieces are then installed in a clean crucible and an appropriate amount of antimony doped silicon wafer is (for resulting 5-50Ω-cm web) added to complete the charge. The crucible/charge assembly is stored in a dessicator until required during furnace loading.

Between operating growth runs in a web furnace (approximately once every ten days) the furnace must be cleaned, recharged, and prepared for growth again.

Following completion of a growth run, the furnace is allowed to cool under argon purge until internal components are cool enough to manually handle. All hot zone components are then removed for cleaning. The used crucible and silicon heel are removed and discarded. The inside of the growth furnace is then vacuum cleaned to remove all oxide deposits. The furnace is ready for recharging and heating at this point.

A clean set of growth hardware and a charged crucible is assembled into the furnace to form the hot zone. The silicon replenishment hopper (containing pelletized polysilicon) is checked and filled. The furnace is then closed and sealed for evacuation. A fully automated sequence is then initiated by the operator. During this sequence, the furnace atmosphere is evacuated and replaced with argon several times to dilute the oxygen level in the furnace. A subsequent evacuation and leak check are performed, followed by a preheat, evacuation, and a final backfill of argon. A flow of argon is established, and the system is opened at the web exit chimney allowing a continuous purge of argon through the furnace.

The temperature of the system is then ramped up until melt down of the silicon charge is achieved. The furnace is ready for web growth operations at this point.

b. Seed Preparation

Seed material for initiating the web growth process is required for every crystal start. A supply of seed is prepared in batches which will serve web growth needs for approximately two weeks. The seed material is a single, twinned dendrite which is grown from the melt in a standard web growth furnace. The single dendrite is pulled from the melt at a high rate of speed (10 cm/min), and spooled on the take-up reel. When sufficient material is generated, the long strands of dendritic seed material are unspooled and cut into 30 cm pieces. The bottom end (oriented material) with growth direction <211> is etched in a nitric/hydroflouric acid mix to a needle point, rinsed in deionized water, and stored in a vacuum dessicator for subsequent use.

c. Thermal Environment Establishment

While the initial thermal environment for crystal growth is established by the shape and arrangement of the internal furnace components, fine tuning of this environment is required occasionally during the growth run. This "fine tuning" takes two forms, thermal profile management, and establishment of the reference temperature. The latter of these must be performed prior to each crystal, the profile management is only required if the profile has seen significant drift or shift.

Setting the reference or "hold" temperature requires touching an etched seed to the surface of the melt, and adjusting the furnace temperature set point (temperature controlled in a pyrometer based digital control loop) until the seed forms a meniscus which remains attached to the melt, yet does not begin freezing at the melt surface. This defines the melting point of silicon and provides the reference temperature by which all temperature settings for the subsequent crystal are compared. Temperature adjustments on the order of 0.1°C are required to determine the hold point.

Thermal trimming to obtain the optimal growth profile is accomplished by the use of movable end shields, and three axis coil movements relative to the hot zone. Observations of the hold temperature at various melt locations, freezing behavior, feed material melting behavior and grown crystal characteristics provide the feedback necessary to adjust the thermal trim of the hot zone. This procedure is generally required prior to the first crystal drawn from the furnace.

d. Seeding

The seeding of the crystal (or crystal start) is performed at the beginning of each crystal, following the establishment of the hold temperature. This process step forms the initial web crystal structure which is propagated in the following two process steps.

With the seed attached to the melt surface at hold temperature, the melt is undercooled. The liquid silicon begins to freeze on the melt surface and a solid "button" propagates from the seed laterally across the melt, symetrically around the seed in the <110> growth directions. When the button reaches approximately 25 mm, the seed is pulled vertically. Due to kinematic effects and thermal profiles, dendrites propagate vertically into the melt at each end of the button, and a web of silicon is formed between the bounding dendrites by surface tension. As the seed moves away from the melt, the web freezes, forming a dendritic web single crystal. Preprogrammed pull speed variations are applied to the seed automatically by the furnace control system, to achieve optimum starting crystal quality.

e. Crystal maintenance

Following seeding, the crystal is growing at full velocity (1.5 cm/min), and nominal thickness (100μm). However, the width is well below the maximum of 43 mm. During the initial part of this growth phase, the web widens gradually (about 1 cm/meter of length) until a width limit is reached as determined by the thermal configuration. When this width limit has been reached after about two meters of crystal length, the crystal continues to grow with a constant 43 cm width.

During this growth phase, several control actions are being taken automatically to maximize the crystal length. The pyrometer based temperature control loop maintains the hot zone temperature at the prescribed set point, and a melt level control system begins to add silicon replenishment to match the mass withdrawal rate of the crystal being pulled. These two loops operate continuously without operator intervention. Once the crystal has been started, the operator initiates closed loop dendrite control. A vision system begins monitoring the edge thickness of the crystal, and adjusts temperature setpoints and coil position to correct for any system drifts while the crystal is growing. The pull speed is maintained constant throughout the crystal life. The operator occasionally aligns the crystal in the growth slot and visually checks for crystal imperfections or terminations during the crystal maintenance process. Terminations which cause pull out of the web from the melt are sensed and alarmed by the vision system.

Once the web exits the furnace, it is pulled onto a rotating one meter diameter wheel and is trapped between the wheel and an idler belt. This rotating wheel provides the constant pull of the crystal from the melt. The crystal exits the wheel/idler belt system 180^0 from the point of entry and enters a web cutting station, which is attached to the rear of the furnace. Here, the web is cut automatically into 1 meter strips for transfer to the next process operation. The front end of the crystal continues to grow from the melt as the back end is cut into the individual strips. Inspection of these strips at the next process station allows continuous feedback to the furnace operator for controlling thickness and resistivity of the crystals.

f. Termination

The termination phase is included in this process description for completeness. This phase is simply the end of a continuous length of crystal. Following termination, the crystal growth process is started again at the thermal environment establishment phase. The importance of identifying the termination phase lies in the frequency and causes of termination. Terminations are caused by loss of melt temperature control, oxide particulates in the melt, silicon ice particle generation in the melt, loss of single crystal structure among others. Minimizing each of these terminations is a goal of the program to be discussed in tasks 2 and 3. The current process averages approximately one termination every six meters of crystal length. After each of these terminations the average time to re-establish crystal growth is approximately 150 minutes. Maximizing length and minimzing time between crystals (TBC) are keys to increasing furnace area throughput.

Step 2. Growth Oxide Removal

This step removes the oxide precipitates from the web surface, which form during growth of silicon. These oxides originate from the reaction of molten silicon with the quartz crucible during crystal growth.

The web is received in 1 meter lengths from the growth area and the resistivity and thickness are measured. After web quality inspection, lengths of web are manually loaded into boats and etched in a HF:DI-H_2O solution. They are then rinsed with deionized water (DI-H_2O) and dried with a clean dry air blow off. The strips are then loaded into a semi-automated brush station where precipitates which are non-soluble in the etch solution are mechanically removed.

Step 3. Cell Sizing

The dendrites are removed prior to cell processing to improve utilization of silicon and throughput capabilities of the process equipment. Other advantages of cell sizing include the elimination of several material handing steps between subsequent processes, thereby reducing direct labor and improving factory yield.

The CMF-91 process line implements a diamond scribing technique to seperate the as-grown dendritic web into individual cell blanks. The dendrites are removed from the 1 meter long strips with two longitudinal scribers. Following dendrite removal, the strips are cross-scribed to length for cell processing. The process size includes a 1mm tab at each end of the cell blank for fixturing purposes.

Step 4. Pre-diffusion Clean

To improve the quality of the front and back junctions and therefore the overall performance of the finished solar cell; the web surface is cleaned of any organic and/or metallic contaminants. Cleaning, which minimizes the amounts of contaminants on the surface, is accomplished by the reaction of impurities with RCA I and RCA II chemistries. RCA I removes organics while RCA II chelates metals from the surface.

The cell blanks are manually loaded into boats and given a standard RCA I & II pre-diffusion clean in an automated wet bench.

Step 5. Dopant Spray and Bake

The dopant spray and bake process creates the diffusion sources necessary to produce the p^+n front surface and n^+n back surface junctions.

After cleaning, the cell blanks are manually placed into a frame which is loaded onto an automated dopant spray and bake station. The frame is transported through the spray and bake regions on a conveyor belt. Liquid metalorganic precursors containing n-type dopants are sprayed onto the cleaned web cell blanks and baked to remove excess organic carriers.

The frames are manually inverted and placed in the second unit to coat the opposite surface with p-type dopants. The Phosphorus (n-type) and Boron (p-type) dopant coatings become the diffusion sources for the next process step.

Step 6. Junction Formation

This process produces the thermal energy required to diffuse the n and p-type dopants into the base creating the p^+n front surface and n^+n back surface junctions. The p^+n junction provides the sink which collects the photogenerated charge carriers. The n^+n junction is incorporated to reflect photogenerated minority carriers from the back to the p^+n junction, therefore, reducing back surface recombination and increasing cell efficiency.

The cell blanks are manually removed from the dopant spray frames and stacked onto a quartz tray. Each stack is two cells high with the phosphorus sources facing each other. A rapid thermal diffusion process is used to simultaneously diffuse the p and n dopants to form the p^+nn^+ cell structure. Optimum diffusion is achieved in this "flash" process which is substantially faster than the conventional tube diffusion process. Due to the differing diffusion coefficients of boron (front-side dopant) and phosphorus (back-side dopant), a p^+n junction of 0.15-0.25 μm is formed on the front-side and a n^+n junction of 0.30-0.40 μm is formed on the back-side.

Step 7. Stress Relieving Anneal

After junction formation, the quartz trays are manually loaded onto a conventional belt furnace. The rapid heat-up and cool-down of the flash diffusion cycle creates quenched in defects (vacancies etc.) and the cells must be annealed to remove these defects. The optimum annealing temperature and time has been determined and effectively restores the minority carrier lifetime of the finished cell.

Step 8. Dopant Oxide Removal

The junction formation process creates a dopant oxide glass on both surfaces of the cell which must be removed. The cell blanks are manually loaded into boats and then given an HF-etch to remove the dopant glass. This process is performed in an automated wet bench.

Step 9. Antireflection (AR) Coating

An antireflection coating is applied to the surface of the silicon to improve coupling of the incident light into the base of the solar cell.

A TiO_2/SiO_2 AR coating is applied by a semi-automated dip coating process. The cell blanks are manually clipped onto the dip station and lowered into the AR solution. The speed at which the cell is withdrawn from the solution determines the thickness and refractive index of the AR coating. The cell blanks are then baked in an infrared furnace to harden the AR coating.

Step 10. Photoresist Application

Photoresists are photosensitive materials that exhibit chemical resistance, have film-forming properties, and are reasonably adherent to various surfaces. A positive PR becomes soluble in a NaOH solution (developer) after exposure to ultraviolet light (UV). Therefore it is possible to transfer a pattern to the material underlying the positive PR, by covering the areas of PR which should remain with an UV-reflective or absorptive mask and exposing the uncovered PR to the UV light. The exposed areas are removed when placed in the developer solution.

Photoresist, which will be used to define the grid metallization pattern, is applied in the same manner as the liquid dopants in process step number 7. A thickness of 1μm has been determined to produce the optimum pattern transfer definition. Monfacial cells have only the front surface coated, while bifacial cells have both sides coated.

Step 11. Mask and Expose

After PR application the cell blanks are placed between two mask plates defining the grid pattern and exposed to UV light. If monofacial cells are to be made, only the front p^+n surface is exposed to UV-light to form the grid pattern. If bifacial cells are being fabricated, each side is exposed by two passes through this station. It should also be noted that for different cell applications (concentrator, etc.) may require different mask designs.

Step 12. Develop and Etch

The cell blanks are manually loaded into boats and placed in the PR development solution. After development, the samples are etched in an HF:DI-H_2O solution to transfer the grid pattern through the AR coating to the silicon surface. This wet bench station is semi-automated by a robotic arm which transfers the manually loaded boat to each solution.

Step 13. E-beam Metallization

The first metallization step is the sequential E-beam evaporation of Titanium/Palladium/Copper (Ti/Pd/Cu), each layer being 30 nm thick. Titanium acts as an effective diffusion barrier of Copper and low resistant contact to silicon. Palladium inhibits galvanic reaction between Titanium and Copper. The copper provides a seed layer which enhances the electroplating process.

The cell blanks are manually loaded onto a rotating drum which is placed into the E-beam vacuum system. The cell blanks are metallized on the front-side first and then inverted (without breaking vacuum) to metallize the back-side. The use of vacuum metallization minimizes the effect of shadowing and creates a low resistance contact to the cell surface.

Step 14. Lift-off and Electroplating Copper

The metallized cell blanks are manually removed from the E-beam drum and loaded onto a specially designed frame for the lift-off and Copper (Cu) plating process. The loaded frames are placed into a PR lift-off solvent to remove the excess vacuum coated metal and PR coating, thus exposing the grid lines for the electroplating step. From here, the frames are placed into the Cu-plating bath where Cu is applied to the Ti/Pd/Cu seed layer. The Cu-plating reduces the resistive losses of the thin vacuum deposited grid pattern.

Step 15. Tab Removal

The cell blanks are placed into a semi-automated cell sizing system which uses diamond scribes to remove the 1 mm tabs on each side of the finished solar cell. The 1 mm tabs serve only as a process fixturing aid and have limited power generating capabilities.

Step 16. Cell Test and Sort

Individual cells are tested using a commercially available photovoltaic cell tester which categorizes the cells by relative output performance. The system uses a Xenon strobe lamp to illuminate a cell with a 100 mW/cm^2 pulse simulating AM1.5 conditions. The system is currently manually operated. Tested cells are sorted and placed in appropriate storage cassettes.

Step 17. Cell Interconnect and Module Lay-up

Sorted cells are loaded into an interconnect system specifically designed to handle dendritic web cells. The system automatically series connects cells into strings by ultrasonically bonding an aluminum interconnect to the electroplated copper. No additional coverage (shadowing) of the front surface is incurred. The strings are then placed on a lay-up of front surface encapsulants consisting of low iron glass, and ethylene vinyl acetate (EVA). The module lay-up is then moved into the bus bonder station where copper busing is ultrasonically bonded to the ends of strings connecting them in parallel. The remaining back surface encapsulation materials, consisting of crane glass, EVA, and Tefzel, are then positioned on the back surface of the strings to finish the module lay-up.

Step 18. Lamination and Trim

The module is loaded into an automatic laminator that encapsulates the finished module lay-up using preprogrammed parameters. Following this step, the laminates are trimmed of excess materials and readied for framing.

Step 19. Frame Assembly and Rate Output Power

The final steps of the sequence include manual fitting of an aluminum frame to the laminate and installation of the junction box. The completed assembly is tested with a standard module tester. The open circuit voltage, short circuit current, and maximum output power at standard test conditions are measured and categorized. All appropriate labels are affixed and the module is readied for shipping.

2.2 Commercial Manufacturing Facility - 1994 Operations

The following fourteen steps describe the CMF-94 process operations. Note that the process has been shortened by five steps from CMF-91. In all cases, higher throughput is assumed over the CMF-91 line. Where no process change is anticipated from the CMF-91 line, this is noted. Please refer to Section 2.1 for these descriptions.

Step 1. Web Growth

With the exception of the seed preparation, and the seeding web growth phases, this process step is unchanged. Planned improvements between CMF-91 and CMF-94 are expected to improve average crystal length to 7.5 meters, and reduce time between crystal starts to 60 minutes. Throughput improves by a factor of 1.2.

a. Furnace Preparation

This process step is unchanged from the CMF-91 process.

b. Seed Preparation

The seed material for this process is no longer the single twined dendrite as in CMF-91, but a fully formed piece of web material from a previous growth run. A 35-37 mm wide piece of web about 40 cm long is shaped at one end to provide an optimum starting geometry (protruding, sharpened dendrites). A fine nozzle abrasive jet system is used to shape the end of the web, followed by a light acid etch to finish the shaping. The finished web start material is rinsed in deionized water, and stored in vacuum dessicator for subsequent use.

Following use in the web seeding operation at the furnace, sections of web less than 37 mm wide are saved for future use in this seed preparation operation, providing a continuous self propagating supply of start material.

c. Thermal Environment Establishment

This process phase is unchanged from the CMF-91 process line.

d. Seeding

The seeding of the crystal (or crystal start) is performed at the beginning of each crystal. This process step propagates the web seed crystal structure from a piece of web produced previously.

A pre-shaped web seed is attached to the pull wheel via a seed clip. The melt temperature is set at a few degrees above the hold temperature, and the web seed end is positioned at the top of the furnace exit chimney about 50 cm above the melt surface. The operator then initiates the automatic web start sequence with a simple keystroke at the furnace control panel. The furnace control system drives the web seed to within 0.1 mm of the melt surface, as the operator guides the web into the growth slot. The melt is automatically undercooled and allowed to equilibrate. Following equilibration at the proper melt undercooling, the web is driven into the melt to form a meniscus and immediately withdrawn under a series of preprogrammed pull speed and temperature steps. The initial web seed is propagated as a growing crystal at the seed width, and with microstructural quality equal to or better than the web started with a dendrite seed.

e. Crystal maintenance

This process phase is unchanged from the CMF-91 process line, other than the fact that the crystal now starts at a 35 mm width and achieves full width within 1 meter.

f. Termination

This process phase is unchanged from the CMF-91 process line, other than the previously noted improvements in crystal length and time between crystals.

Step 2. Cell Sizing

The same cell sizing technique used in the CMF-91 process will be utilized in the improved CMF-94 process. The only change is the order in which the process is performed. Cell sizing will be implemented prior to growth oxide removal to take advantage of an improved non-mechanical raw web cleaning process.

Step 3. Pre-diffusion Clean

This process combines the growth oxide removal and prediffusion clean steps of the CMF-91 process into one chemical wet bench.
After cell sizing the cell blanks are manually loaded into boats and receive an etch in a HF:DI-H_2O solution. The hydroflouric bath is fitted with specially designed megasonic transducers which emit high frequency pressure waves. The pressure waves strike the cell blanks and remove (carry away) any precipitates which are non-soluble in the etch solution. The cell blanks are then rinsed and dried by DI-H_2O and clean dry air blow off. This non-mechanical approach to growth oxide removal integrates step 2 of the CMF-91 into step 3 of the CMF-94 process line.

To improve the quality of the front and back junctions and therefore the overall performance of the finished solar cell; the web surface is cleaned of any organic and/or metallic contaminants. Cleaning which minimizes the amounts of contaminants on the surface, is accomplished by the reaction of surface impurities with an ultra pure Hydrogen Peroxide : Sulfuric acid (Piranha clean) solution.

The cell blanks, already loaded in megasonic boats, are transferred to a semi-automated wet bench where they receive a piranha clean prior to junction formation. The piranha solution is delivered to the wet bench from a chemical reprocessor. Cost reductions include, implementation of the megasonic boats which can hold more web material, elimination of a material handling step, and the incorporation of the piranha-piranha chemical reprocessor has reduced chemical waste disposal at this process by 98%.

Step 4. Dopant Spray and Bake

This process is unchanged from the CMF-91 manufacturing line.

Step 5. Junction Formation

This process is unchanged from the CMF-91 process line. The incorporation of new and higher throughput equipment will be utilized.

Step 6. Stress Relieving Anneal

This process is unchanged from the CMF-91 process line. The incorporation of new and higher throughput equipment will be utilized.

Step 7. Dopant Oxide Removal

This process is unchanged from the CMF-91 process line. The incorporation of new and higher throughput equipment will be utilized.

Step 8. Atmospheric Pressure Chemical Vapor Deposition (AP-CVD) AR Coating

An antireflection coating is applied to the surface of the silicon to improve coupling of the incident light into the base of the solar cell.

A TiO_2 AR coating is applied by a conveyorized atmospheric pressure chemical vapor deposition (AP-CVD) unit. The cell blanks are manually placed on the conveyor belt and the front surface is coated with the optimum thickness of TiO_2 from a tetraisopropyl titanate (TPT) source.

The benefits of the AP-CVD technique over the CMF-91 dip process are improved uniformity, increased coupling of incident light into the cell, higher throughput, and improved process reliability.

Step 9. Screen Metallization

After AR application the cell blanks are metallized using a screen printing technique. The metallized cells are fired in an infrared furnace to drive the grid lines through the AR coating thus making contact to the silicon surface. The screen metallization process will replace the photolithography, vacuum metallization, and copper plating steps (steps 10-14) used in the CMF-91 process line. Technology improvements in screen printing equipment (smaller line definition) and the relatively low capital investment needed to obtain this equipment has made this metallization technique a cost competitive option to the vacuum metallization process sequence.

Step 10. Tab Removal

This process is unchanged from the CMF-91 process line. The incorporation of new and higher throughput equipment will be utilized.

Step 11. Cell Test and Sort

This process is unchanged from the CMF-91 process line. The incorporation of new and higher throughput equipment will be utilized.

Step 12. Cell Interconnect and Module Lay-up

This process is unchanged from the CMF-91 process line. The incorporation of new and higher throughput equipment will be utilized.

Step 13. Lamination and Trim

This process is unchanged from the CMF-91 process line. The incorporation of new and higher throughput equipment will be utilized.

Step 14. Frame Assembly and Rate Output Power

This process is unchanged from the CMF-91 process line. The incorporation of new and higher throughput equipment will be utilized.

3.0 TASK 2 - POTENTIAL PROCESS CHANGES/BENEFITS ASSESSMENT

This section serves to identify and describe the potential web growth, and cell or module process changes that can lead to significantly increased production and reduced manufacturing costs. The long range potential benefits of these improved processes are also discussed.

Each discussion is divided into three sections covering background on the identified improvement, development goals, and impact on product cost for a commercial facility producing 4.1 megawatts/yr.

The capital savings, labor savings and production yield improvements calculated in this section are based on a constant 4.1 MW/yr plant output. The capital equipment requirements, materials use, and labor requirements are then reduced to account for improvements in unit throughput, yield and efficiency. The cost of product is then generated based on the lower cost of production for a constant factory capacity.

The baseline process to which comparisons are made to quantify improvements, is a 4.1 MW/yr factory operating with 1991 technology.

Due to the highly interactive and complex nature of individual process changes in determining the reduction in module cost of sales, the details of cost calculations will not be discussed here. The estimates of the impact of process changes on product cost which are detailed in this section were made with the assistance of several computer models which have been developed at Westinghouse and Solar Web, Inc. The following validated models provide a fully integrated assessment of impact on total product throughput and cost:

1. Web growth throughput and labor estimator - This model determines materials usage requirements, and useable web throughput per furnace based on over 20 variable input parameters which statistically define the web growth process.

2. Materials usage/costing model - This model calculates materials quantity requirements and costs based on variable process efficiencies, unit materials costs and plant throughput.

3. SIMAN process simulation model - This extensive model mathematically and graphically simulate the entire module production process from web growth through module assembly. Statistical descriptions of each process are provided as input; output from this model helps determine labor requirements, facility throughput, and equipment utilization as well as process flow logistics.

4. Solar Web Financial Model - This model incorporates input from each of the previous models, and business growth assumptions and determines direct product costs and cost of sales. This model allows accurate assessment of real product costs for Solar Web, Inc. which include all associated capital, overhead, marketing, and administrative costs as well as direct product and labor costs.

3.1 Summary of Results

The proposed development tasks include improvements in the following areas:

- * Web Growth
    - Charge preparation
    - Crystal length
    - Growth velocity
    - Starting crystal width

  - Full crystal width
  - Base material quality
  - Run length
  - Productive growth time
- Silk Screen Metallization
- AP - CVD Antireflection Coatings
- RTP Coin Stack Diffusion
- SiO_2 Surface Passivation
- Double Antireflection Coatings
- Factory Automation
- Statistical Process Control
- Bifacial Module Design

A summary of the potential benefits resulting from each of these development tasks is provided in Table 3-1 which identifies the process improvements and the major impact on product cost. Five areas of impact are noted:

Direct Labor Reduction
Absolute Efficiency Improvement
Production Yield Improvement
Silicon Utilization
Reduction in Capital Expenditures

Each row of Table 3-1 indicates the effect of changing a single process parameter or step as identified later in this section. Each row assumes no other process change is being accomplished in parallel. The value of this calculation is to give some indication of the relative impact of the process change on the total cost improvement figure. Due to interactive effects (i.e. increasing web length decreases the relative impact of time between crystals, and the full impact of improvements identified in crystal starting width cannot be realized without increasing steady state web width) the individual impacts cannot be summed to reflect a total program impact. By using the models described previously, and individual assessment of the cumulative effects, a total integrated benefit is arrived at for each impact area. This represents the net benefit assuming all development areas were successfully completed and implemented.

A brief discussion of each of these impact areas follows.

Direct Labor Reduction

This number is the reduction in number of technicians required to operate a process line which produces 4.1 MW/yr. Utilizing CMF-91 technology, the number of technicians required would be 322. The reduction in the number of technicians required in a 1995 production plant operating at 4.1 MW/year would be 202, assuming success in all process development areas. This is a direct labor reduction of 63%.

Absolute Efficiency Improvement

This number indicates the absolute average cell efficiency improvement (ie. a 1% absolute change takes cell efficiency from 14.5% to 15.5%). The total improvement due to all process changes is estimated to be 3.0%. The CMF-91 base efficiency is 14.5% Improvements in efficiency decrease the number of furnaces required (capital) and labor requirements when production line power output is held constant.

Production Yield Improvement

This value represents the absolute process yield improvement due to process changes. Process yield is defined as the total useable area of web material produced by the furnaces divided by the total active

Table 3-1
Potential Savings Due to Process Changes

Process Change	Direct labor reduction in	Absolute efficiency improvement	Production yield improvement	Silicon utilization	Reduction in capital expenditures
	(technicians)	(%)	(%)	(%)	(k$)
Charge preparation	1			20.0	15
Web width (43 to 63 mm)	30				2,340
Growth velocity (1.5 to 2.0 cm/min)	38				2,970
Average crystal length (7.5 to 10 m)	77			3.6	2,340
Starting crystal width (35 to 63 mm)	85			13.5	6,570
Time between crystals (90 to 45 min)	120				2,610
Run length (10 to 20 days)	2				180
Crystal quality	17	1.0	1.7		1,470
Silk Screen Metallization	3		1.8		1,870
AP-CVD AR-Coating	7	0.3	0.9		450
Coin Stack Diffusion	4	0.3			595
Oxide Surface Passivation	11	0.6	0.9		1,050
Double AR-Coatings	10	0.8			810
Factory Automation	13		4.0		720
Statistical Process Control	4		2.0		360
Bifacial Module Design	84	9.0*			6,480
TOTAL INTERACTIVE EFFECT OF PROCESS IMPROVEMENTS **	202	3.0	11.3	32.0	14,800

* the absolute increase in conversion efficiency which a monofacial module must have to produce an equivalent amount of power obtained from a bifacial module.

** bifacial improvements are not included in the total interactive effect of all process improvements.

area of finished modules. The estimated improvement in process yield due to all recommended process changes is 11.3%. This yield improvement also decreases capital and labor requirements for a fixed capacity plant.

Silicon Utilization

The silicon utilization improvement number represents the savings in silicon material usage for a constant module power output from the factory. This savings gets incorporated into the direct materials cost for the factory. A total savings of 32% is indicated for silicon in Table 3-1.

Reduction in Capital Expenditures

This column represents the estimated savings in capital expenditures as a result of process eliminations or yield, throughput, and efficiency improvements. By holding plant output constant in total power rating of modules produced per year, these improvements reduce the required number of furnaces. The major component (85%) of capital expenditure reductions is due to furnace purchase reductions. Approximately 15% of the capital savings is due to elimination of process steps and associated equipment, or throughput improvement of cell processing equipment.

The total savings in capital due to this program (for a 4.1 MW/yr plant) is estimated to be $14.8 million.

One of the tasks described in this section covers the development of bifacial power modules. The potential impact of bifacial modules is shown in Table 3-1, but is not included in the total effective process savings numbers. The bifacial design is not a standard power module, and is expected to require additional marketing and a product acceptance period to become a viable product in the power market. Therefore, the bifacial impact is treated separately in the cost of sales calculation.

Table 3-2 shows the relative projected cost of power modules as a function of time under several different program assumptions. The baseline cost is that of power modules produced by Solar Web, Inc. during 1992 according to the current business plan. The first three years of Table 3-2 parallels the three year development program. During the fourth year the process line is running with all process improvements which are implemented after being developed for the first three years. In real time, these years would be 1992 through 1995; assuming timely implementation of a SERI funded process development program.

The cases illustrated in Table 3-2 are 1) no SERI development program with internal Solar Web development as projected in the Solar Web financial plan; 2) internal Solar Web development plus accelerated process development due to SERI funding as per the program described in this report; 3) SERI funded process development plus addition of a duplicate process line, thus increasing plant capacity to 8.2 MW/yr; 4) SERI funded process development with no additional production capacity, but incorporation of bifacility in the product; and 5) SERI funded process development with additional capacity and bifaciality.

The results presented in this table indicate that product costs can be reduced by a factor of 4.5 within 4 years providing the described program is put in place. However, if the projected improvements are realized on schedule, the incentive exists for Solar Web to install additional capacity for year 4, reducing the module cost by a factor of 5.5. If bifacialty is included as a product feature, the module cost can be further reduced by a total factor of 7.5 in the 4 year time frame. The bifacial calculation includes additional marketing and overhead to account for the costs of introducing a new product into the market.

Table 3-2 Power module cost reductions resulting from process improvements (% of initial cost)

SERI Development Program	Additional Production Line	Bifaciality	YEAR 1	YEAR 2	YEAR 3	YEAR 4
			100%	57%	37%	29%
X			95%	52%	31%	22%
X	X		95%	52%	31%	18%
X		X	95%	52%	31%	17%
X	X	X	95%	52%	31%	13%

3.2 Charge Preparation

Background

The charge preparation process step described in section 2, is presently a labor intensive operation which is inefficient in the utilization of high cost silicon. This operation has been in place since the early days of web growth with little change. The advent of manufacturing operations provides the incentive to optimize this process. The slicing of boules into well defined shapes is required due to the small size and rectangular form of the web growth crucibles. Polysilicon is available in both chunk and pelletized forms which are more economical. The size of standard chunk material is too large for web growth applications, but the pelletized form holds promise for initial charge assembly. Pelletized silicon is presently used in the process as replenishment feedstock.

Development Goals

The proposed process improvement for the charge preparation area involves elimination of silicon boule slicing, disc sizing, and etching steps. A reasonable process development goal in this area would be to eliminate the silicon boule cutting, sizing, and cleaning operations and replace them with leading pelletized silicon into crucibles.

Impact on Product Cost

The impact on product cost from this process step improvement would come from capital equipment savings, silicon utilization, silicon cost reduction, organic waste removal costs, and direct labor. The cost of a $15,000 silicon slicing saw is eliminated, in addition to the factory floor space and ventilation systems required to house and handle the sawing operations. The technician who saws, sizes, and etches as many as 20 charges per day would not be required. The sawing operations lose as much as 25% of the starting material due to a combination of kerf loss and sizing losses. In addition, the boule material is approximately 3 times as expensive as pelletized silicon. The combination of cost, and material loss for this process step is about 20%. This entire silicon cost loss could be made up by forming initial charges with 100 % pelletized silicon product.

Benefits

The following anticipated cost benefits are based on a changeover of initial charge material from polysilicon boules to pelletized silicon stock in a 4.1 MW plant, assuming no concurrent changes in other process parameters:

Direct Labor Savings	1 Technician
Silicon Utilization Savings	20 %
Capital Expenditure Savings	$15K

3.3 Web Width

Background

During the last decade of web technology development programs, the maximum attainable web width has increased from 30 mm to 70 mm. The current width basis for the manufacturing line is 43 mm, even though high volume throughput demonstrations (over 1.0 square meter/furnace/week) have been made at 57 mm web widths. Thermally induced stress with subsequent web buckling and plastic strain becomes a problem above 40 mm, and 57 mm wide web can be difficult to grow consistently and process with acceptable yields using the present growth hardware. Internal furnace growth hardware determine the web width, and the existing furnace design can easily accommodate web widths up to 65 mm without modification.

Development Goals

Given the prior successes at crystal widths up to 70 mm, and particularly at 57 mm, any development plan should include a goal of improving steady state crystal width. Since the unit cell size for the processing line is 19 mm, web width should be targeted in integer multiples of 19 mm plus the width loss due to dendrite removal (3 mm). If smaller widths are targeted outside the context of development milestones, significant changes to fixturing for downstream processing operations might be required. Therefore, the next target width beyond the present 43 mm should be 62 mm, which would yield one single and one double width (38 mm) cell per cell length of material.

Impact on Product Cost

To take advantage of the additional web area as usable material, increases in web width necessitate changing cell fixturing and cell width, unless the web width is increased to a full 62 mm. If full width web starts are achieved simultaneously with the width increase, usable throughput is simply increased by the ratio of the included usable cell widths (57/38 = 150% for 62 mm web). If web starts are less than full width, several variables determine the increase in throughput (starting width, widening rate, crystal length,and number of crystals grown per unit time). For estimating purposes one could assume about two-thirds the increase of the full width start case (a 33% throughput increase for a web width increase to 62 mm). Any increase in usable web throughput has a major impact on product cost by proportionally decreasing the number of furnaces required for a given production facility output (capital expenditures). A web width increase would not directly decrease the number of operators required to operate a furnace, but would decrease the total number of operators required through the decrease in number of furnaces required.

Benefits

Any increase in web width requires complete replacement of the growth lid and shields ($1500/furnace). Since these are accounted for as materials costs and have an expected lifetime less than one year, no incremental product cost would necessarily be incurred. A change to 62 mm can be accommodated in the present furnace design with little or no modification. New chimneys and vertical thermal modifiers will be required ($500/furnace) for effecting the stress reduction required for wider web. Other than scaling input materials for the increased throughput, no other cost increases are anticipated.

The following anticipated cost benefits are based on a web width increase to 62 mm in a 4.1 MW plant, assuming no concurrent changes in other process parameters:

Direct Labor Savings	30 Technicians
Capital Expenditure Savings	$2,340K

3.4 Growth Velocity

Background

Growth velocity is a characteristic of the specific hot zone hardware design, and is governed by the rate of heat dissipation from the growth front. The faster the heat can be removed, the faster the web will crystallize. For a given hot zone design, increasing pull rate of the crystal will decrease web thickness, and vice versa. A 100 micron web thickness appears to be optimum for this process based on maximizing mechanical yield in subsequent process steps, and maximizing growth speed. Growth velocity is presently 1.5 cm/min for production of 100 micron thick web. Growth velocities up to about 2.0 cm/min for 100 micron web thickness have been demonstrated in laboratory experiments, however high production mode throughputs were not achieved due to additional web terminations introduced by the high speed growth hardware design. Even higher velocities are theoretically possible with modified growth hardware.

Development Goals

Development efforts from the last few years have shown that it is possible to increase velocity to 2.0 cm/min. Computer modeling of the growth interface was beginning to show promise prior to the end of the prior development program. Promising growth hardware design concepts are available but require testing with data feedback to the computer model. Unlike web width changes, web velocity changes are ideal process modifications, in that they only affect throughput, and not physical size. Therefore, furnace and downstream processing equipment design is not affected. A reasonable goal for a three year program would be to increase growth velocity at 100 micron web thickness to 1.75 cm/min within two years, with a subsequent increase to 2.0 cm/min by the end of the third year.

Impact on Product Cost

The furnace throughput is increased by the ratio of the new growth velocity to the old velocity multiplied by the ratio of growth hours to actual hours in a seven day week. The latter ratio can be assumed to be .85 for estimating purposes. As time between crystals decreases and crystal lengths improve, this ratio will increase. Increasing growth velocity to 2.0 cm/min would therefore increase throughput by 13%. Any increase in usable web throughput has a major impact on product cost by proportionally decreasing the number of furnaces required for a given production facility output (capital expenditures). A growth velocity increase would not directly decrease the number of operators required to operate a furnace, but would decrease the total number of operators required through the decrease in number of furnaces required.

Benefits

Any increase in growth velocity will require complete replacement of the growth lid and shields ($1500/furnace). Since these are accounted for as materials costs and have an expected lifetime less than one year, no incremental cost should be incurred. Any changes in growth speed discussed here can be accommodated in the present furnace design with no modification. New chimneys and vertical thermal modifiers will be required ($500/furnace). Other than scaling input materials for the increased throughput, no other cost increases are anticipated. Aside from the increased throughput, this improvement would be transparent to processing operations.

The following anticipated cost benefits are based on a growth velocity increase to 2.0 cm/min in a 4.1 MW plant, assuming no concurrent changes in other process parameters:

Direct Labor Savings	38 Technicians
Capital Expenditure Savings	$2,970K

3.5 Average Crystal Length

Background

Average crystal length has increased from about 1 meter to over 5 meters in the last decade. Most of this improvement has been due to stabilization of the melt, reduction of the thermal stress levels in the web, control procedure development, and minimization of feeding related terminations. The baseline manufacturing facility will be expected to average at least 6 meters in crystal length due to improvements in the furnace temperature control systems. Longer crystals are generally a result of eliminating the current major termination modes. Therefore, improved closed loop temperature control, melt level control, crucible design, stress control, and oxide control are viewed as the key issues involved in improving crystal length beyond the present average. In theory, continuous crystal lengths are possible over the length of the run.

Development Goals

By attacking the major web termination mechanisms, one could expect to make a significant impact on average crystal length. A statistical survey of termination causes indicates that the major causes at this time appear to be related to ice formation, and oxide induced terminations. A program geared to melt stabilization, melt thermal profile control, and oxide management would have a goal of linearly increasing average web lengths to 10 meters by the end of a three year program, while at the same time decreasing the spread in the distribution of crystal lengths.

Impact on Product Cost

The throughput increase due to increased crystal lengths decreases exponentially with length and is a strong function of other system parameters. With decreases in time between crystals, increases in length have a diminished effect, and vice versa. Given no other concurrent process improvements, an average length increase to 10 meters will increase furnace throughput by 16%. Any increase in usable web throughput has a major impact on product cost by proportionally decreasing the number of furnaces required for a given production facility output (capital expenditures). An average crystal length increase would directly decrease the number of operators required to operate a furnace, due to the higher self sustainablilty of the crystal, and the reduction in the number of crystal starts required. This process improvement would also decrease the total number of operators required through the decrease in number of furnaces required.

Benefits

Any changes in crystal length discussed here can be accommodated in the present furnace design with no modification. Hardware for crucible purging and control software amount to $500/furnace If changes to the lid and or susceptor are required, the additional cost could increase by $4000/furnace; however this can be viewed as a materials cost. Other than scaling input materials for the increased throughput, no other cost increases are anticipated.

The following anticipated cost benefits are based on an average crystal length increase to 10 meters in a 4.1 MW plant, assuming no concurrent changes in other process parameters:

Direct Labor Savings	77 Technicians
Silicon Utilization Savings	3.6 %
Capital Expenditure Savings	$2,340K

3.6 Starting Crystal Width

Background

Starting crystal width is presently targeted for 35 mm in the production factory. Full width web starts have been demonstrated in individual experiments, but are still not readily achievable due to stress effects (web seed buckling). While techniques presently being optimized for 35 mm starts will be applicable (with modified parameters), stress reduction work through vertical thermal profile modifications will be required for full width starts at 43 mm. Once full width starts have been achieved, the technology would probably be applicable at any width provided sufficient stress reduction is achieved at higher widths. Optimization of start process parameters would be required at the new width.

Development Goals

Development efforts to achieve full width starts at 43 mm would be started immediately in any development program, due to the potentially large payoff. Further increases in starting width would have to wait for full crystal width development. A goal for this process improvement would be to follow, within 6 months, any increases in crystal width by full width starts at that new width. This close follow of starting width to full crystal width will minimize the silicon utilization losses associated with the widening process.

Impact on Product Cost

The throughput increase due to full width web starts is 12.5% at 43 mm. If no other process improvements are made, other than increasing full crystal width to 62 mm, process improvement increases furnace throughput by 64%. The improvement to full width starting eliminates dual cell sizes, and maximizes utilization of silicon. The number of technicians required decreases with the reduction in number of furnaces that occurs with higher throughput furnaces.

Benefits

Any changes in starting width discussed here can be accommodated in the present furnace design with no modification. However, new chimneys and vertical thermal modifiers will be required ($500/furnace). Other than scaling input materials for the increased throughput, no other cost increases are anticipated. Aside from the increased throughput and cell size distribution, this improvement would be transparent to processing operations.

The following anticipated cost benefits are based on a starting web width increase to 62 mm in a 4.1 MW plant, assuming no concurrent changes in other process parameters:

Direct Labor Savings	85 Technicians
Silicon Utilization Savings	13.5 %
Capital Expenditure Savings	$6,570K

3.7 Time Between Crystals

Background

Time between crystals (TBC) is defined as the total non-growth time in a run divided by the number of crystals produced. It is essentially the average a lapsed time from the end of one crystal the beginning of the next. Presently targeted for 140 minutes in the production factory, average TBC for experimental runs has been observed as low as 20 minutes for week long runs. A statistical analysis of production demonstration runs identified failed start attempts, furnace maintenance tasks, unaccounted time, and successful start attempts were the primary components of TBC. New web start techniques are promising to reduce failed starts from 88% to 15% of all start attempts. Improved operating efficiency, automation, process control, and low maintenance furnace design will further reduce TBC. Successful start attempts averaged 12 minutes each, and should eventually take less time with improved starting techniques. It presently appears that something on the order of 15 minutes might be a lower limit to TBC.

Development Goals

Until the last two years, no program had been specifically designed to reduce TBC. In the research and development programs which drove prior work in web growth, this parameter was not critical, and in most situations, not even measured. By simply bringing attention to the importance of TBC, and instituting some basic process charting, TBC was reduced from at 6 hours to under 200 minutes. Development efforts would be geared towards a decrease in TBC to 45 minutes by the end of the three year program. It is anticipated that further reduction of TBC would be a result of productivity improvements in the factory, and continued improvement in starting techniques in future years. Production management, furnace and post growth process automation, and process control will also play a major role in reduction of TBC.

Impact on Product Cost

The throughput increase due to TBC reduction decreases exponentially with decreasing TBC, and is about 9% at 60 minutes; 2% at 45 minutes, and 1% at 15 minutes, with the present development path assumptions. These estimates take into account increases in length, which decreases the effectiveness of TBC reduction. If no parallel process improvements in TBC were assumed, a direct increase in throughput of 19% would be realized for a TBC decrease to 45 minutes. Any increase in usable web throughput has a major impact on product cost by proportionally decreasing the number of furnaces required for a given production facility output (capital expenditures). A TBC decrease would directly decrease the number of operators required to operate a furnace. This process improvement would also decrease the total number of operators required through the decrease in number of furnaces required.

Benefits

Any changes in TBC are primarily related to operator technique and utilization and can be accommodated in the present furnace design with no modification. Minor control software modifications might be required (primarily control parameter adjustment). Significant investments in process control software might be required. Other than scaling input materials for the increased throughput, no other cost increases are anticipated.

The following anticipated cost benefits are based on a decrease in average time between crystals to 45 minutes in a 4.1 MW plant, assuming no concurrent changes in other process parameters:

Direct Labor Savings	120 Technicians
Capital Expenditure Savings	$2,610K

3.8 Run Length

Background

Run length is presently targeted for 10 days in the production factory Crucible lifetime and/or oxide accumulation is the determining factor in maximum run length. The silicon-quartz reaction erodes the crucible wall thickness and produces silicon oxides which accumulate on the cooler furnace internals during the growth run. Given time, the crucible wall eventually breaches, destroying the molybdenum growth hardware as the molten silicon aggressively wets and attacks the molybdenum. The accumulating layers of silicon oxides increasingly fall into the melt or onto the growth hardware, terminating crystals and changing hot zone emissivity. Current crucible designs have been run for up to 12 days continuously. However, limiting runs to 10 days provides some margin of safety.

Development Goals

Increases in crucible wall thickness or use of a non-reactive crucible material can lead to increased run lengths. While extending run length has never been a direct goal of development programs in past, alternative crucible materials have been investigated in the past in attempts to reduce oxide generation. Since those attempts, several years ago, significant advance have been made in the area of high temperature materials fabrication. A program goal of doubling run length by crucible redesign in the first project year or two would be reasonable. Doing this work early would allow minimal impact on the growth hardware design which would be developed for high speed, wide growth.

Impact on Product Cost

The furnace throughput increase due to increased run length is minimal. The initial factory operation calls for an 8 hour furnace turnaround time between runs, which translates to a 97% utilization of available time.

Completely continuous runs could therefore only increase throughput by 3%. Doubling run length would raise throughput by 1.5 %. However, the reduction in number of cycles, through increased run length, may have an undetermined positive effect on furnace performance. Molybdenum growth hardware life may be extended with less thermal cycling, and fixed materials costs such as silicon heel loss and crucible costs would be halved. Any increase in usable web throughput has a major impact on product cost by proportionally decreasing the number of furnaces required for a given production facility output (capital expenditures). A run length increase would directly decrease the number of operators required to operate a furnace, due to fewer furnace turnaround per year. This process improvement would also decrease the total number of operators required through the decrease in number of furnaces required.

Benefits

Any changes in run length are related to crucible redesign and can be accommodated in the present furnace design with no modification. It is assumed that perturbations in the heating distribution of the crucible/melt system due to crucible material or thickness changes can be accommodated by coil location and/or minor shielding changes. These are essentially zero cost changes. Aside from scaling input materials for the increased throughput, no other cost increases are anticipated.

The following anticipated cost benefits are based on a run length increase to 20 days in a 4.1 MW plant, assuming no concurrent changes in other process parameters:

Direct Labor Savings	2 Technicians
Capital Expenditure Savings	$180K

3.9 Crystal Quality

Background

The web crystal is basically a single crystal structure which enables high efficiency solar cells to be produced. However, minority carrier lifetime, and hence efficiency, is limited by the presence of dislocations in the crystal structure, and decoration of these dislocations with electrically active impurities, primarily oxygen. Since great care is taken to ensure that the crystal growth atmosphere is relatively oxygen free, the primary source of oxygen is from the quartz crucible. Dislocation sources have been researched in past programs with the conclusions that their sources are primarily internal web stress which is thermally generated, and dislocation sources (quick freezing silicon droplets) at the dendrites. Low stress growth configurations (unfortunately low throughput also) have been designed and tested in the past, producing significantly lower dislocation density web.

Other aspects of crystal quality involve producing web with minimal frequency of crystal structure loss, and minimum oxide deposits on the crystal surface. At present, a third dendrite branches into the web structure approximately every 3 meters. While this "third" dendrite can be thermally removed (grown out) without necessarily terminating the web, the cell sizing operation downstream suffers about a two percent yield loss due to the removal of the affected section of web from the process stream. Oxides which deposit on the web surface during growth, neccesitates the web cleaning process step which costs labor, capital, and a 1% yield loss.

Development Goals

The resulting cell efficiency can be improved by improving the quality of the basic web material through improved hot zone design and crucible. In conjunction with other web process improvement areas, the thermal stress, oxygen levels, "third" frequency, and oxide deposits can be minimized. A goal of improving cell efficiency by 1% due to crystal quality can be set for a three year program. Other goals would be the reduction of third frequency by a factor of two, and the elimination of the web cleaning process step.

Impact on Product Cost

It is estimated that the removal of oxygen from the silicon melt, or minimizing the dislocation density in web could easily improve absolute cell efficiency by 1%. By decreasing the "third" frequency by a factor of two, the yield in the cell sizing process step would be improved by about 1%. The elimination of oxides from the web surface would eliminate the entire web cleaning process step, removing the entire 0.7% yield loss due to this step as well as the capital equipment, labor and materials required for web cleaning. These three electrical and mechanical yield savings translate directly into capital equipment, and labor savings by requiring less web area for a given factory power output. This process improvement would also decrease the total number of operators required through the decrease in number of furnaces required.

Benefits

The following anticipated cost benefits are based on a crystal quality improvements outlined above in a 4.1 MW plant, assuming no concurrent changes in other process parameters:

Direct Labor Savings	17 Technicians
Absolute Efficiency Savings	1 %
Production Yield Improvement	1.7 %
Capital Expenditure Savings	$1,470K

3.10 Silk Screen Metalization

Background

Currently grid metallization is accomplished by a process sequence involving photolithography, vacuum metallization, and copper plating. This metallization technique requires a high level of processing knowledge and skill to maintain product quality. Cost improvements to this type of metallization process would require substantial development funds and qualification testing. Also any incremental increase in production capabilities requires a large capital investment.

Another metallization technique used by PV manufacturers is Screen Printing. This technique requires less capital investment for incremental increases in production and process control is simplified by the elimination of several processing steps. Processes and corresponding equipment which are eliminated with the implementation of screen printing are photoresist application, mask and expose, develop and etch, vacuum metallization, and strip and copper plating. Screen printing can also be implemented with a high degree of automation, further reducing labor requirements with each incremental increase in production. Disadvantages incurred by the implementation of current screen printing equipment in place of vacuum metallization is the loss of efficiency due to increased grid line shadowing and grid line resistivity losses. It has been determined that the absolute loss in efficiency would approach 0.7%. But the cost of this efficiency loss can be more than offset by the savings which will result from the following development program.

Development Goals

The current vacuum metallization process will be replaced with silk screen metallization. Initially, the process parameters for silk screen metallization after AR-dip coating will be determined. A second phase of development will qualify screen printing with AP-CVD antireflection coatings. Improvements in the areas of grid line resistivity and grid line width have been identified as high-payoff development areas. The relationships between paste conductivity (materials) and print definition (equipment) will be investigated. The goals of the program would be to reduce grid finger resistivity by a factor of 2 and to lower contact resistance by a factor of 10, therefore allowing a possible reduction in the width of the grid fingers from 100 μm to 70 μm. Improved grid finger width would reduce power losses due to shadowing. The overall effect of each improvement would be to increase efficiency by 0.7% absolute.

Impact on Product Cost

Silk screen metallization will have a substantial reduction of capital investment for incremental increases in processing capabilities. Cell processing would no long require PR Spray and Bake, Mask and Expose, Develop and Etch, Vacuum Metallization, and Strip and Cu-plating. Automated material handling methods have been identified and would require little effort to fully automate the silk screening process. Therefore, it can be expected to have a reduction in the labor required while simultaneously improving production yield. Benefits shown below also reflect capital and labor savings brought about in the web growth area due to efficiency and yield improvements for a given level of production.

Benefits

Direct Labor Savings	3 Technicians
Capital Expenditure Savings	$1870K
Production Yield Improvement	1.8%

3.11 Atmospheric Pressure Chemical Vapor Deposition (AP-CVD) Antireflection Coating

Background

After light passes through the cover glass and the transparent laminates that holds it to the cell, it encounters the antireflective coating, a transparent layer designed to reduce the amount of reflected sunlight. Bare silicon cells can have a mirror like appearance and reflect about 30% of the sunlight. Reflection losses can be reduced by proper choice of an antireflective (AR) coating.

Currently, application of the AR coating is done by a dip coating method. The solution used to form the AR coating is a mixture of SiO_2/TiO_2. The method presently involves a considerable amount of material handling and does not lend itself to full automation. An additional pitfall with the current method is a "meniscus" which forms at the bottom of a cell blank after removal from the liquid solution. This meniscus reduces the amount of material which can be processed into a finished solar cell.

Development Goals

It is our intent to qualify AP-CVD of TiO_2 for application as an AR-coating. The approach would include qualification of AP-CVD in conjunction with silk screen metallization. The development program will determine if an AR-coating should be deposited prior to silk screen metallization or after grid metallization. The study will include investigations of film thickness relationships with antireflective capabilities to determine the process parameters required for an optimum AR coating. Automation of this process step and its integration into the the evolving CMF-94 process line will also be developed.

Impact on Product Costs

Implementation of AP-CVD antireflection coating will be fully automated thus increasing processing uniformity with the elimination of operator error. Increased throughput and silicon utilization will be achieved by eliminating lost material due to the formation of the meniscus seen in the dip coating method. Where the dip-coating process requires 11 cm of web and the AP-CVD process would only require 10 cm of web material to produce a finished cell. A 10% increase in silicon material utilization will be acheived.

Application of TiO_2 by AP-CVD will also produce a refractive index better matched to laminate materials. Therefore, reducing the amount of reflected incident light which will increase short circuit current by 2%. The corresponding absolute increase in cell efficiency would be 0.3%. Benefits shown below also reflect capital and labor savings brought about in the web growth area due to efficiency and yield improvements for a given level of production.

Benefits

Direct Labor Savings	7 Techicians
Capital Expenditure Savings	$450K
Improved Efficiency	0.3% absolute
Production Yield Improvement	0.9%

3.12 Coin Stack Diffusion

Background

Currently simultaneous front and back junction formation is performed by rapid thermal processing (RTP) of cells stacked two deep. This method, developed by Westinghouse is well suited for high volume throughput of solar cells. The thermal mass (cells stacked two deep) of the defined process is the only limiting factor on throughput improvements. Therefore, a disadvantage arises from the high capital investment for incremental increases in production levels.

Development Goals

It is proposed to develop RTP junction formation stacking cells six deep. The approach would first define a workable process for diffusing cells stacked four deep and then developing a six cell deep process. Qualification of the process would include production of high efficiency finished cells and determination of the junction depth through spreading resistance measurements.

Impact on Product Cost

A successful development program would reduce the capital investment for RTP equipment and the direct labor required by a factor of three.

Improvements in junction quality will occur with improved understanding of the thermal distribution and its relationship to the thermal mass in the RTP furnace. The improved junction (reduced reversed saturation current) is expected to increase efficiency 0.30 % absolute. Benefits shown below also reflect capital and labor savings brought about in the web growth area due to efficiency and yield improvements for a given level of production.

Benefits

Direct Labor Savings	4 Technicians
Improved Efficiency	0.3% absolute
Capital Expenditure Savings	$595K

3.13 Surface Passivation

Background

To achieve high cell conversion efficiency, the surface recombination of the photogenerated carriers must be reduced to near zero. Reducing this kind of recombination leads to an improvement in the open circuit voltage (and to a lesser extent, short circuit current). This reduction in surface recombination velocity can be achieved by depositing a passivating oxide layer (SiO_2) on the front and rear surfaces of the cell. An SiO_2 layer negates the surface recombination centers and thus decreases the recombination velocity. This passivation effect can be seen in Figure 3-1 which shows that the SiO_2 passivation increases both the short wavelength and long wavelength response of the cell.

Developments Goals

The work depicted in the Figure 3-1 was carried out at the Westinghouse Science and Technology Center (STC). The method used to deposit the oxide is compatible with the baseline sequence used in CMF-91.

To apply the surface passivation technique to the CMF-91 process would require a determination of the most cost effective method of creating the SiO_2 layers. The basic method used by STC was to grow the oxide on the cell's surface in a tube furnace using a wet or dry oxygen ambient. The required SiO_2 thickness, to effectively passivate the surface, is generally about 10 nm. Although applicable, this quartz tube furnace method would require a large capital expenses.

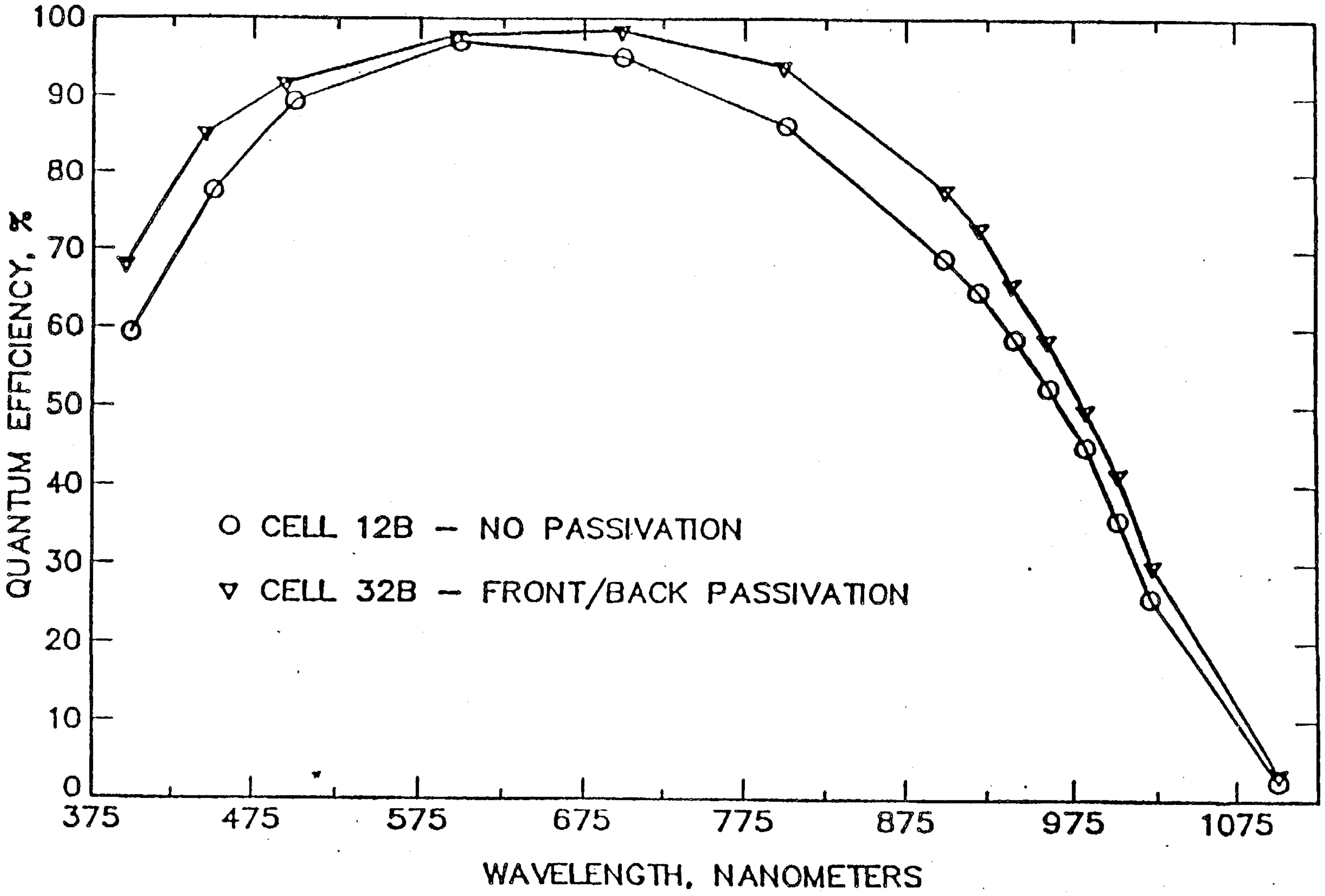

100
90
80
70
60
50
40
30
20
10
0
QUANTUM EFFICIENCY, %
375
475
575
675
775
875
975
1075
WAVELENGTH, NANOMETERS
○ CELL 12B – NO PASSIVATION
▽ CELL 32B – FRONT/BACK PASSIVATION

Figure 3-1

A more attractive method would be to grow the passivating oxide using rapid thermal processing (RTP). This process has been used in the manufacturing of transistors to form high quality gate oxides, and would be applicable to our solar cell process. Any excess capital costs would be less than the tube furnace oxidation method discussed above and the throughput rate would be greater.

In addition to these two methods, the deposition of the SiO_2 by atmospheric pressure chemical vapor deposition (AP-CVD) will be investigated. This method, if successful, would have the least impact on production cost and throughput. The unknown feature is the effectiveness of these AP-CVD layers in tying up the surface recombination sites. Also it should be pointed out that this method will lead to the ability to create double antireflection coatings (Refer to Double AR coating).

Impact on Product Cost

It has already been demonstrated that an increase of cell efficiency of 0.60% absolute can be expected by silicon dioxide surface passivation. If AP-CVD of SiO_2 proves successful the only capital investment would be the addition of a SiO_2 deposition head to the TiO_2 AP-CVD system. Benefits shown below also reflect capital and labor savings brought about in the web growth area due to efficiency and yield improvements for a given level of production.

Benefits

Direct Labor Savings	11 Techicians
Capital Expenditure Savings	$1,050K
Improved Efficiency	0.6% absolute
Production Yield Improvement	0.9%

3.14 Double Antireflective Coating

Background

Currently, a single antireflective coating is applied to form a thin impedance matching layer, with an optical thickness around one-quarter wavelength (QW) at wavelengths near the peak of the incident spectrum. Even though a single optical coating reduces reflection from 30% (bare silicon) to 10%, there is still a significant benefit by further reduction in reflectance. A reduction of reflectance to 8%, 6% and 4% would increase cell efficiency by 0.32%, 0.64% and 0.96% (absolute) respectively.

Development Goals

It is our intent to extend the knowledge obtained from the surface passivation study and Atmospheric Pressure CVD study to develop a double antireflective coating. This program would focus on the incorporation of the method chosen in the SiO_2 passivation study into a process sequence with the TiO_2 AP-CVD system to produce a high quality low cost double antireflection coating.

To achieve a double coating consisting of SiO_2-TiO_2 the AP-CVD method developed would be directly applicable. A review of the SiO_2 deposition methods examined during the surface passivation study would be revisited and the best method would be investigated for this application. With the expected coating being SiO_2 on silicon and TiO_2 on SiO_2 it should be possible to use the surface passivation equipment to create the first optical layer, therefore, utilizing the equipment for two purposes simultaneously. The TiO_2 would be applied with the AP-CVD equipment.

Impact on Product Cost

Double AR coatings have been demonstrated to reduce surface reflectance to a value between 4% and 5%. If we assume 100% success as 5% from 10%, the cell efficiency can be expected to increase by 0.8% absolute. Benefits shown below also reflect capital and labor savings brought about in the web growth area due to efficiency and yield improvements for a given level of production.

Benefits

Direct Labor Savings	10 Technicians
Capital Expenditure Savings	$810K
Improved Efficiency	0.8% absolute

3.15 Factory Automation

Background

Solar Web is in the unique position of expanding its production capabilities in the form of a new manufacturing facility over the next several years, and it is our intent to eliminate manual material handling where cost effective. Automated material handling has been shown to increase production efficiency and factory yield while reducing labor requirements and other factory overhead expenses.

Development Goals

High mechanical loss processing areas associated with dendritic web solar cell manufacture have been identified during operation of the Photovoltaic Manufacturing Demonstration Facility (PMDF). Automation of these areas will be done with equipment to handle either web material or fixtures. The process areas and improvements which have been identified for automation in the CMF-94 facility are listed below:

Process Area	Automation
Cell Sizing	Cassette feed to system
Growth Oxide Removal and Pre-diffusion Clean	Integrate both systems using one robotic arm transfer system
Dopant Spray and Bake	Automatic frame loader and frame inverter

Junction Formation	Automatic frame unload and quartz tray loader
Dopant Oxide Removal	Automatic quartz tray unloader and boat loader
AR-coating	Boat unload (entrance) and boat load (exit)
Screen Metallization	Same as AR-coating
Tab Removal and Cell Sizing	Automated cell loader and sorter

Potential Impact on Product Cost

Automation of cell blank and fixture material handling will improve factory yield from an initial 86.5% to above 90%. Benefits shown below also reflect capital and labor savings brought about in the web growth area due to efficiency and yield improvements for a given level of production.

Benefits

Direct Labor Savings	13 Techicians
Capital Expenditure Savings	$720K
Production Yield Improvement	4.0%

3.16 Statistical Process Control

Background

In module design it is well known that the final product efficiency is limited by the least efficient cell in the module. Therefore it is necessary to test and sort each cell prior to interconnection whether connection is made in series or parallel. This aspect of module manufacture demands a traditional approach to quality control with 100% inspection of each cell produced to guarantee predictable module output and customer satisfaction.

In the web growth and cell processing areas it has been shown that certain process parameters and product measurements track the quality of the final product. By using Statistical Process Control (SPC) during manufacture to monitor these parameters it will be possible to improve product quality, reduce production waste, and reduce overall manufacturing cost.

Development Goals

The following is an outline of the methodology to be used to implement a meaningful SPC program.

I. A written quality policy formalizing the procedure for Web growth, Cell processing and Module manufacturing will be composed.

II. A written specification describing in detail what has to be done, how it has to be done, and how inspection or test will show that it has been done.

III. Determination of the capabilities of each process sequence. Once the capabilities have been determined they can be compared to the specifications. If adequate agreement is acheived the limits of each parameter related to product quality can be used to monitor the process in a real time manner.

IV. Selection of hardware and statistical methods for data analysis. Proper implementation will allow for the identification of short and long term trends which will be useful in fault finding and maintenance planning.

Impact on Product Cost

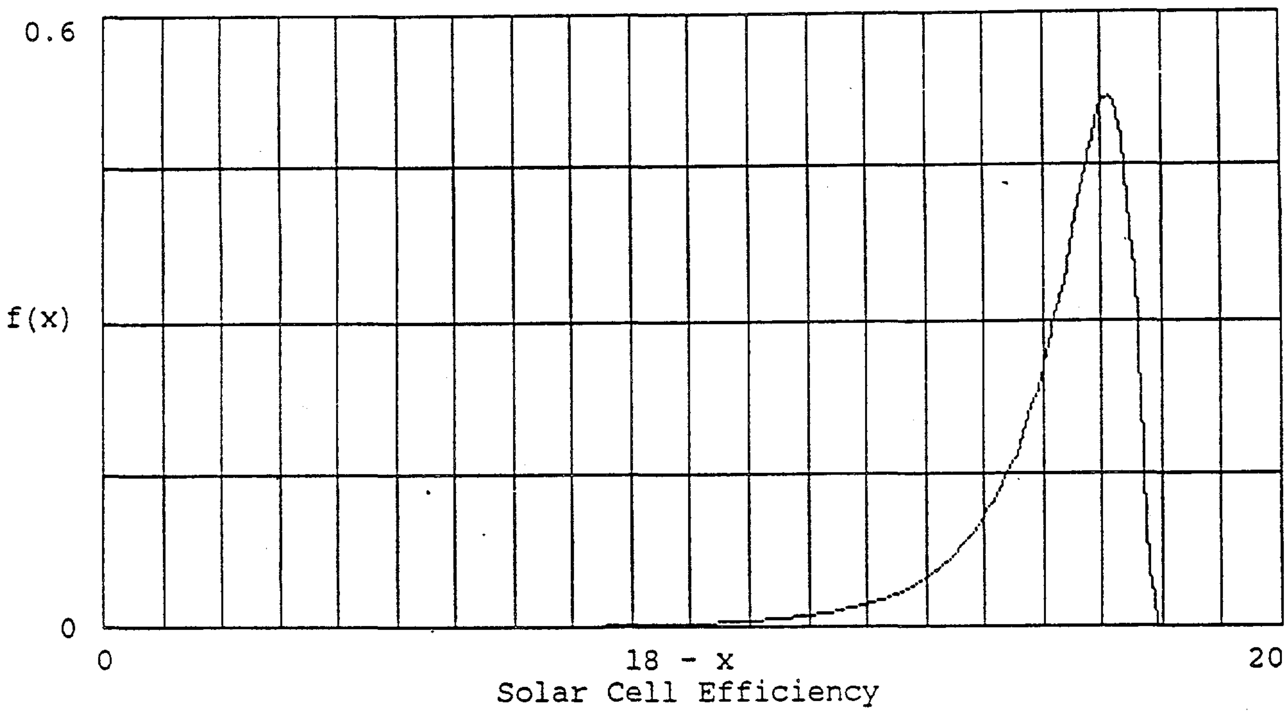
Statisical Process Control will tighten the standard deviation of cell efficiency about the mean efficiency. Figure 3-2 shows distribution of cell efficiency of the CMF-94 process for 1995 without SPC monitoring. If this facility was assumed to be at a production level near 4.0 megawatts/year and SPC was implemented an increase in cell efficiency standard deviation is expected. Figure 3-3 depicts the new efficiency distribution and percent increase in production volume due to a tightening of standard deviation of 0.5 about the mean. Benefits shown below also reflect capital and labor savings brought about in the web growth area due to efficiency and yield improvements for a given level of production.

Benefits

Direct Labor Savings	4 Technicians
Capital Expenditure Savings	\$360K
Production Yield Improvement	2.0%

FIGURE 3-2

f(x) = % of cells at a given efficiency



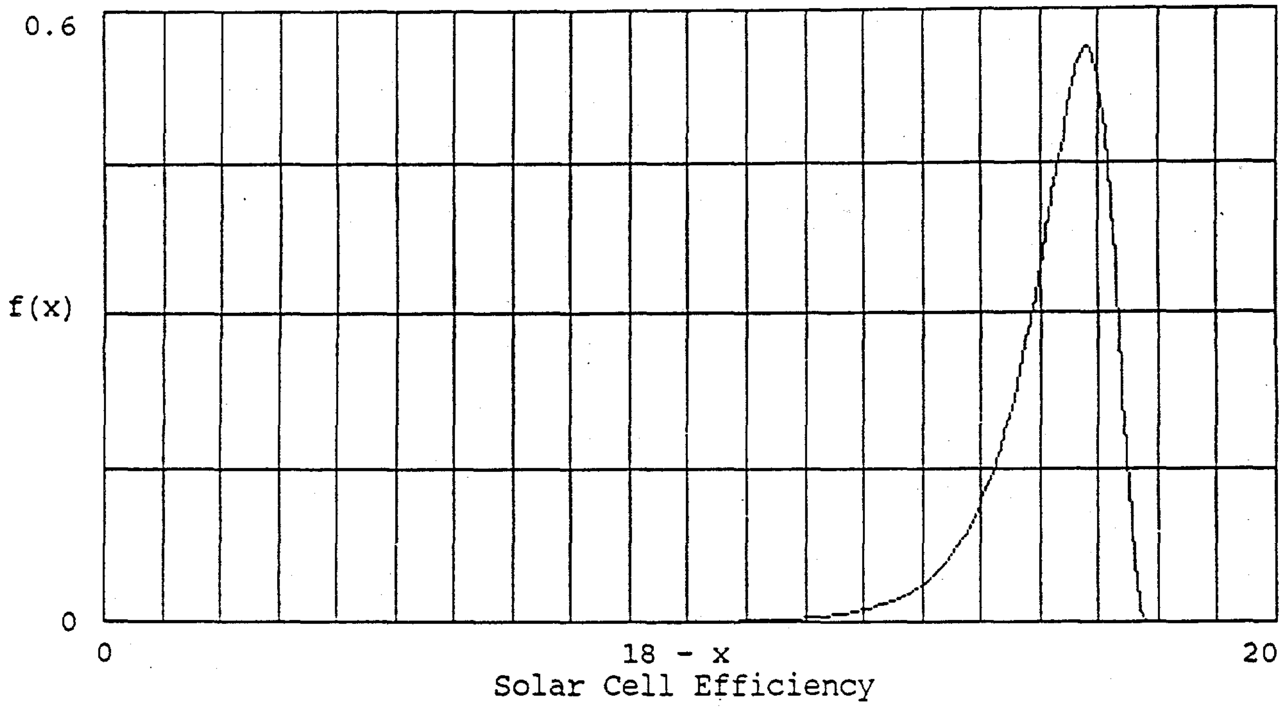
Mean solar cell efficiency:	$\mu = 15.8 \cdot \%$	Production Yield:	$Y = 88 \cdot \%$
Standard deviation:	$\sigma = 1.7$	Cell Area:	A = 57 cm^2

$$\text{Watts\_produced\_per\_year} = 4.096 \cdot 10^{6}$$

percent_increase_in_production_volume = 0·%
over $\sigma = 1.7$ for lognormal distribution

FIGURE 3-3

f(x) = % of cells at a given efficiency



Mean solar cell efficiency: $\mu = 15.8 \cdot \%$ Production Yield: $Y = 88 \cdot \%$

Standard deviation: $\sigma = 1.2$ Cell Area: $A = 57$ cm^2

$\text{Watts\_produced\_per\_year} = 4.189 \cdot 10^{6}$

$\text{percent\_increase\_in\_production\_volume} = 2.3 \cdot \%$
over $\sigma = 1.7$ for lognormal distribution

3.17 Bifacial Module Design

Background

A bifacial cell has a back surface electrical metallization grid of the same form as the front surface. These cells show an increase power output since carriers generated by light incident on the back surface will be collected and will be additive to carriers generated due to front surface illumination. Such cells have been fabricated on both N and P type material with varying resistivity. N type cells have shown back illuminated conversion efficiencies up to 13.05% and front illumination conversion efficiencies up to 14.50%, or a back to front efficiency ratio of 90%. P type cells, which typically have longer minority carrier diffusion lengths, have shown a back to front ratio as high as 95%. A number of bifacial power modules have been fabricated using a cusp reflector design to direct light to the back surface of the module while maintaining front illumination. Indoor measurements (Xenon flash lamp) indicate an increase in module power output equivalent to a 63% improvement over the front surface conversion efficiency.

Development Goals

Bifacial cell performance will be evaluated for cells manufactured in the CMF-94 production line. Key issues to be explored are the performance of bifacial cell with screen printed grid metallization and AR coating requirements of the back surface.

Several bifacial module designs will be evaluated. Designs will be evaluated for improved power generation, manufacturability, and cost.

Bifacial module designs will be reviewed with PV systems engineers for reliability and installation requirements. Other issues to be reviewed and quantified are the additional power gained from the back surface and the cost of installation nessecary to take full advantage of bifacial modules.

Impact on Product Cost

Bifacial cell and module manufacture would increase the production capabilities (watts/yr) of the commercial manufacturing facility by 60% with minimal increase in manufacturing cost. If a 10% increase in module costs is assumed, a 50% decrease in final product cost would be realized.

Benefits

Direct Labor Savings	84 Technicians
Capital Expenditure Savings	$6,480K
Improved Efficiency	9.0% effective

Effective efficiency improvement is defined as:

The absolute increase in conversion efficiency that a monofacial module must show to produce an equivalent amount of power obtain from a bifacial module design.

4.0 TASK 3 - PROBLEMS IN ACHIEVEMENT OF COST SAVINGS

The following discussions identify and describe the problems that may impede the achievement of the potential benefits discussed in Task 2. Where applicable, any common technology barriers among the Photovoltaic Manufacturing Industry have been identified as generic problems.

4.1 Charge Preparation

Preliminary test results indicate a silicon pellet charge is feasible. The anticipated problems involved with changing the charge preparation process involve material quality control, melting behavior, and single sourcing of the silicon material. The melting behavior of a crucible full of silicon shot is uncertain at this time. Previous tests with shot melting uncovered various problems such as balling up of the melt due to the low volume of initial material for the melt (low material packing factor), exploding of the pellets during meltdown (presumably from trapped gas), and melt cleanliness problems due to the high surface area of the pellets which can adsorb significant quantities of air. Furnace evacuation problems might be anticipated due to susceptibility of the lightweight pellets to movement by gas flows, and virtual leaks created within the packed pellet volume. Material quality is a potential problem, as was discovered during investigation of pellet material sources for replenishment feeding material. Of approximately 5 potential vendors available about 4 years ago, only one could supply material which had acceptable material quality for feedstock. Along with material quality concerns comes the problems with relying on the material supplier to maintain quality standards for the product.

Changes in the material quality can be very difficult to detect as sources of poor product quality. However, this problem is generic to any source of material used in the process. Since only one vendor is currently known to be available for adequate pelletized silicon material, this presents a business logistics problem. Should the vendor go out of business, or suddenly raise prices the web production process could be in jeopardy. Multiple sourcing options would have to be explored as part of this program. The existing process currently has the capability for multiple vendor sourcing.

4.2 Web Width

The anticipated problems involved with increasing web width are well known, after several years of research and development on web width limiting phenomena. Reduction of thermal stress to eliminate resultant web buckling and plastic strain will be the major problem to solve in attempting to grow stably at widths above 43 mm. The thermal stress reduction will be solved primarily by linearization of the vertical thermal profile. Growth hardware must also be designed which gives an appropriate thermal profile at the growth interface to permit attainment of steady state width, sufficiently high widening rates, and acceptable thermal melt stability. Problems associated with improving these thermal profiles involve accurate simulation of furnace conditions in the thermomechanical computer model, and translation of model results into appropriate growth hardware modifications. In addition, accurate determination of actual thermal profiles can be difficult as well as statistical assessment of the degree of "growth stability" at extended widths. Due to the highly interactive nature of hot zone characteristics, one difficulty will be maintaining quality growth while increasing widths (i.e. width increases should not occur at the expense of other process parameters such as web length, and velocity). Finally, coordination of design efforts with other programs which impact hot zone design, such as growth velocity development, need to be managed effectively. Minimal reconfiguration problems are expected to occur with incorporation of a wider growth system.the existing furnace that are primarily related to instrumentation, but nothing is anticipated that cannot be handled within the existing furnace structure. None of these problems are expected to be generic to the PV industry due to the uniqueness of the dendritic web growth system.

4.3 Growth Velocity

As was the case with web width, the problems associated with increasing growth velocity are well known through the experience of past development programs. Increasing growth velocity involves designing growth hardware that is capable of removing heat from the growth interface at a rate commensurate with the desired pull speed and web thickness. This program would share many of the problems of the web width program, and the two would have to be very closely integrated. Again, problems will surface in ensuring that the computer model reflects reality, accurate determination of thermal reality, and statistical assessment of success. Integration of the velocity improvements into a total growth system without adversely affecting other growth parameters will also present problems. No problems are anticipated with incorporation of a high speed growth system into the existing furnace structure. None of these problems are expected to be generic to the PV industry due to the uniqueness of the dendritic web growth system.

4.4 Average Crystal Length

Increasing average crystal length requires addressing the causes of crystal termination. The primary causes of termination are insufficient temperature control, oxide particulates in the melt, ice generation in the melt, third dendrite generation, and degeneration of the single crystal structure into a polycrystalline state. Optimization of the closed loop control systems and melt level control on the current furnaces is expected to minimize the terminations due to temperature control, and third dendrite generation. It is expected that most of the terminations will be due to oxide in the melt; either striking the crystal directly, or nucleating ice in the undercooled environment. Problems likely to be encountered in trying to improve crystal length will primarily be associated with the oxide control area. Finding an appropriate crucible material that does not react with the melt to produce oxides may prove difficult. Finding an economical and readily manufacturable replacement for quartz may be the second part of this problem. The thermal geometry of the hot zone may also be affected by a change in thermal conductivity of the crucible material. Another scheme for oxide control involves purging of the atmosphere directly above the melt surface. Problems with this approach will probably center on perturbations introduced to the thermal geometry, or even the crystal itself. The problems associated with single crystal degeneration can be tied to oxide control, melt thermal profile control, or thermal stress control. Therefore, most of the problems common to growth velocity improvement and web width improvement can be considered as potential problems in the development of increased crystal lengths also. Statistical verification of impact of process changes on crystal length is not necessarily a problem. However identification of the termination mode of the crystal is sometimes very subjective and can create problems in identifying the statistical distribution of termination causes. Other than oxide control, which may be generic to silicon crystal growth technology, none of these problems are expected to be generic to the PV industry.

4.5 Starting Crystal Width

Improving crystal start widths is a relatively new endeavor in the web growth development program. As with time between crystals, and run length, until the advent of a program geared towards manufacturability of web was started, the importance of this process parameter was overlooked. Much has been learned in the last year during the development of web starts. Problems in achieving full width starts include those of the web width development program. These are primarily related to thermal stress reduction. If a web seed is inserted into a high stress thermal field, the web has been known to buckle, or even shatter. Improving beyond the 35 mm starting width will require immediate stress reduction work. Part of the evaluation of start success during the optimization phase involves a microstructural characterization of the web to determine the post-start quality. Implementing this type of feedback into a high throughput statistical evaluation may present difficulties. Another problem associated with web starts are the ability to efficiently manufacture, the optimum crystal end shapes which are required for effective attachment to the melt, and start success. Other problem areas which will require investigation are; the variation of the start technique and parameters for different crystal widths or growth hardware designs, the establishment of proper starting thermal profiles prior to dipping the seed, and the logistics of propagating web seed from widening crystals for starts less than full width. None of these problems are expected to be generic to the PV industry due to the uniqueness of the dendritic web growth system.

4.6 Time Between Crystals

A statistical analysis of the production demonstration runs identified failed start attempts, furnace maintenance tasks, unaccounted time, and successful start attempts as the primary components of TBC. Problems in improving TBC can be categorized into those associated with optimizing the crystal start technique, and those associated with manufacturing productivity. The problems with optimizing the crystal start technique are identical to those for developing full width crystal starts. Both of these efforts are focussed toward improving the start success rate. Since successful start attempts presently only take about 12 minutes each, little would be gained in decreasing the actual start procedure time. Manufacturing productivity improvements routinely involve problems like worker motivation, production management, and task optimization. In addition, problems associated with establishing an effective statistical process control system would be encountered in efforts to minimize TBC. Identification of appropriate process parameters to monitor, data acquisition methods, data analysis, presentation, and feedback methods are all potential problems. Once the process control techniques are identified, problems will occur in the effective implementation and routine maintenance of such a system. With the exception of those problems dealing with web start development, all of these problems should be generic to the PV industry and any other high throughput manufacturing environment.

4.7 Run Length

Since improvements in run length are predicated on crucible redesign, any problems would be associated with providing a new crucible material or wall thickness which would enable the run length extension. Increasing wall thickness of the crucible could possibly cause problems in the thermal geometry of the hot zone. Since the inner surface of the crucible is held at the melt temperature, and heat flow is from the susceptor to through the crucible wall, the outer wall of the crucible would have to run at a higher temperature. This means the crucible on average has to run hotter, and the temperature difference between the susceptor and the melt is higher. It is not clear that this effect is significant enough to cause major growth problems, however the potential does exist. A potential problem with run length extension occurs if a quartz crucible is used. Oxide buildup inside the furnace could substantially increse web termination due to oxide falling in the melt. This problem would require management if high throughput were to be maintained throughout the long growth run. Other problems related to run length extension would be identical to those are anticpated for crystal length development which are associated with the replacement of the quartz crucible with another material. None of these problems are expected to be generic to the PV industry due to the uniqueness of the dendritic web growth system.

4.8 Crystal Quality

Problems associated with improvement of crystal quality are identical to some of those described for web width development and crystal length development. Any of the problems discussed above that relate to thermal stress management, crucible material changes, and improved temperature control are common problems which will be approached in the improvement of crystal quality. These three areas impact dislocation density, oxygen accumulation in the web, oxide accumulation on the web surface, and third dendrite generation on the web material. Aside from the generic problem of oxygen impurities in silicon which can be applied to all silicon crystal growth techniques, these problems are unique to denritic web growth because of the unique crucible and web geometry.

4.9 Silk Screen Metallization

Screen printing as a grid metallization technique has shown significant potential as a cost effective process. Advantages seen over the current vacuum metallization process are the low capital investment for increase production capabilities (increase throughput) and improved production yields through automation (reduced mechanical loses).

In general this metallization technique is used by most solar cell manufacturers and the following process development barriers which must be overcome are considered generic to the photovoltaic industry.

The technology barriers which must be overcome for implementation of screen printing into the CMF-91 process sequence are:

1. Identification of equipment capable of printing linewidth less than 70 micrometers.

2. Identification of a conductive paste material to be used as a grid contact.

   The material must be of high enough conductivity to carry collected photogenerated current with minimal resistive power loss.

3. Determination of a firing technique which drives the printed grid contact through the AR coating onto the emitter surface.

   The process must create a low resistive contact without shorting the shallow emitter. Control over the process temperature and cooling rate must be maintained so there is no detrimental effects on the bulk lifetime of the device. Typically temperatures above 700°C will degrade the bulk minority carrier lifetime if a very slow ramp down cooling is not performed.

4. Determination of the process parameters necessary to incorporate screen printed metallization with the automated ultrasonic bonding interconnect process.

5. Evaluation and testing of optimal grid designs for minimal power losses that arise from grid contact shadowing.

4.10 AP-CVD Antireflection Coating

Use of AP-CVD to form a TiO_2 antireflection has been demonstrated in past development programs. Refractive indices equal to or better than the SiO_2/TiO_2 dip process have been obtained.

Technology barriers which must be overcome for implementation of an AP-CVD antireflection coating process are:

1. Determination of an effective TiO_2 etch chemistry to transfer the photolithographically defined grid pattern the emitter surface.

   This process sequence will be utilized during the evolution of the CMF-94 process.

2. Determine if AP-CVD can deposit a uniform AR coating on a cell that has been metallized by screen printing. Also determine if the temperature profile require by the AP-CVD process will simultaneously fire the screen printed contact.

3. Modification of the ultrasonic bonding parameters to allow bonding of aluminum interconnects through the AR coating to screen printed metalization.

4.11 Coin Stack Diffusion

In this technique, dopants derived from liquid precursors are driven into the cell structure using short time-high temperature heat pulses such as are obtained from rapid thermal annealing systems. Currently, cells are stacked two high with the phosphorus sources in contact with each other and no cross contamination from dopant migration of one surface to another has been observed. Cells with efficiencies as high as 15.2% have been obtained on n-base web material.

To increase the throughput of this process and therefore reduce capital investment in additional RTP systems it is proposed to increase the thermal mass (number of cells stacked) in a single diffusion run by a factor of 2 and then 3.

Technology barriers which must be overcome to improve throughput of this process are:

1. Development of a process which maintains uniform thermal distribution throughout the processing area of the RTP system.
2. Eliminate deformation of the web strips during processing.
3. Maintain negligible cross contamination from boron and phosphorus dopant migration.

4.12 Surface Passivation

The reduction of surface recombination inherent to <111> oriented silicon web material, plays a key role in improving cell conversion efficiencies. Oxidation of the front and back surfaces has been shown to passivate (reduce) surface recombination effects and improve cell conversion efficiencies as much as 0.6% absolute.

Technology barriers which must be overcome to take advantage of oxide passivation are:

1. Determination of the most cost effective method for growth or deposition of a SiO_2 layer.

2. Identification of high throughput equipment which will generate an oxide passivation layer.

3. If high temperature thermal processing is necessary to form the SiO_2 layer, requirements on time-temperature relations must be determined to maintain minority carrier lifetime.

4.13 Double Antireflective Coating

This program will focus on the method chosen in the oxide passivation study and incorporate it into a process with the TiO_2 AP-CVD system to produce a high quality low cost double AR coating.

Technology/Time/Cost barriers which must be overcome to take advantage of double AR coatings are:

1. The timing of the oxide passivation work must overlap with this study. Therefore additional man power will be required for implementation of double AR coatings.

2. Determination if the method used to produce a passivating oxide layer is compatible with the TiO_2 deposition method technique in forming a double AR coating.

4.14 Factory Automation

Incorporation of automated material handling equipment has a significant cost reduction potential.

Technology/Cost barriers which must be overcome to take advantage of automation benefits are:

1. The unique properties of the dendritic web material must not impede implementation of off-the-shelf material handling equipment.

2. Fixtures compatible to each process environment must be developed.

4.15 Statistical Process Control

Real time data acquisition and dedication of process owners are the keys to implementation of a successful SPC program.

Technology barrier which must be overcome are:

1. Identification of monitoring equipment capable of measuring process control parameters in a non-destructive manner.

2. Qualifaction of measurement techniques and determination of throughput capabilities when direct measurement of a cell in process is required.

4.16 Bifacial Cell and Module Design

The potential reduction in the dollar per watt cost of PV modules is termendous. Bifaciality is considered to be the key to realizing large scale PV power generation systems which would be cost competive with conventional generation plants.

Technology/Reliability barriers which must be overcome to take advantage of the additional power from bifacial modules are:

1. A low cost module design which incorporates a method to reflect incident light to the back surface.
2. A module design which minimizes installation costs and does not transfer cost to the PV system.
3. Performance of bifacial modules as to their reliability and power output must be established.

5.0 TASK 4 - DEVELOPMENT APPROACHES

The approaches which will be taken to solve the problems identified in Task 3 (and meet the goals of Task 2) are identified in this section. These approaches are organized as individual tasks which could be carried out under a proposed PVMaT program. Since a single task may produce solutions for more than one process problem, these tasks do not necessarily relate to items in sections 2 and 3 on a one for one basis. The problems which are being solved by a particular task are identified in the task description. In each of the development approach descriptions to follow, costing and scheduling estimates are included. These estimates provide what is presently considered the optimum approach for successfully completing all development tasks in a 3 year time frame.

5.1 Development Approach Summary

The following discussions detail each of the individual tasks in terms of content, cost, and schedule. The entire assembly of tasks described here fall into a 3 year schedule. Figures 5-1a,b,c show timelines over these three years for each of the subtasks within a main task element. Milestones are noted where appropriate quantifiable parameters are available.

A total of thirteen major task elements have been identified which, if successfully implemented and fully funded, have a high probability of realizing the potential process cost savings identified in Section 3.0 (Task 2). Four of these task elements deal essentially with web growth throughput improvements (full width seedings, oxide control, high velocity growth, and web width development), while most of the others deal with

Figure 5-1a PROGRAM SCHEDULE
DENDRITIC WEB MANUFACTURING TECHNOLOGY
PHOTOVOLTAIC MANUFACTURING TECHNOLOGY – PHASE I

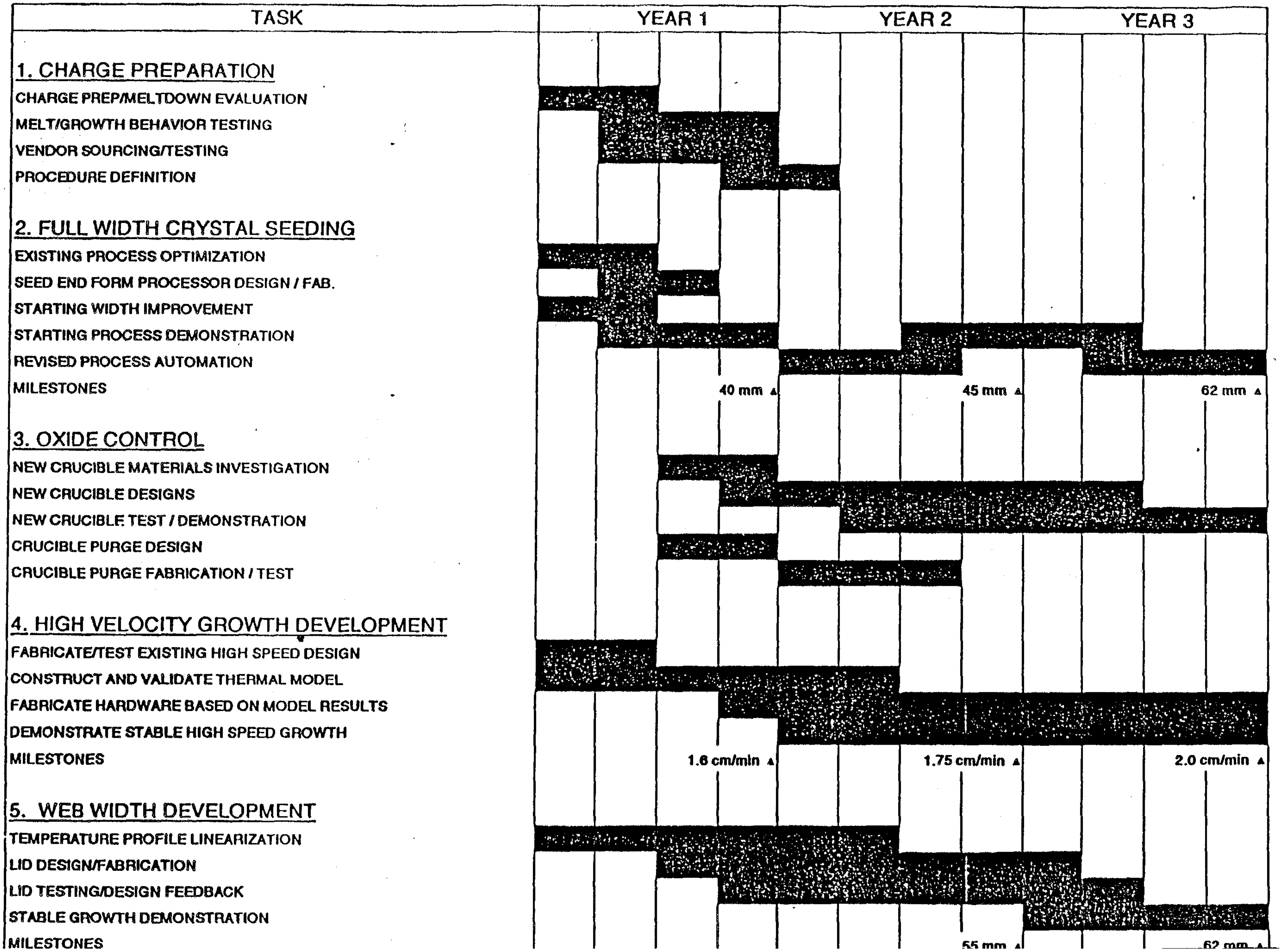


TABLE 5.1b PROGRAM SCHEDULE
DENDRITIC WEB MANUFACTURING TECHNOLOGY
PHOTOVOLTAIC MANUFACTURING TECHNOLOGY – PHASE I

TASK	YEAR 1				YEAR 2				YEAR 3			
6. SCREEN PRINTED METALLIZATION												
PROCESS DEVELOPMENT WITH EQUIPMENT VENDORS	■	■										
MASK AND CONDUCTIVE PASTE SELECTION	■											
INTERNAL PROCESS DEVELOPMENT	■	■	■	■								
PROCESS DEMONSTRATION				■								
7. AP–CVD ANTIREFLECTION COATING												
PROCESS DEVELOPMENT WITH EQUIPMENT VENDORS	■	■	■									
INTERNAL PROCESS DEVELOPMENT			■	■								
PROCESS DEMONSTRATION				■								
8. COIN STACK DIFFUSION												
PROCESS DEVELOPMENT WITH EQUIPMENT VENDORS			■	■								
INTERNAL PROCESS DEVELOPMENT					■	■						
PROCESS DEMONSTRATION							■					
9. SURFACE PASSIVATION												
PROCESS DEVELOPMENT WITH EQUIPMENT VENDORS	■	■	■	■	■	■						
INTERNAL PROCESS DEVELOPMENT			■	■	■	■	■	■				
PROCESS DEMONSTRATION								■				
10. DOUBLE ANTIREFLECTION COATINGS												
PROCESS DEVELOPMENT WITH EQUIPMENT VENDORS	■	■						■	■			
INTERNAL PROCESS DEVELOPMENT									■	■		
PROCESS DEMONSTRATION											■	

TABLE 5.1c PROGRAM SCHEDULE
DENDRITIC WEB MANUFACTURING TECHNOLOGY
PHOTOVOLTAIC MANUFACTURING TECHNOLOGY – PHASE I

TASK	YEAR 1				YEAR 2				YEAR 3			
11. FACTORY AUTOMATION												
PROCESS DEVELOPMENT WITH EQUIPMENT VENDORS	■	■	■	■	■	■	■	■				
SOFTWARE DEVELOPMENT	■	■	■	■	■	■	■	■	■	■	■	■
MATERIAL HANDLING VERIFICATION										■	■	■
EUIPMENT PURCHASE AND INSTALLATION							■	■	■	■	■	■
12. STATISTICAL PROCESS CONTROL												
PROCESS/CELL PARAMETER IDENTIFACTION	■	■	■	■	■							
MONITORING EQUIPMENT IDENTIFICATION & DEVELOPMENT				■	■	■	■	■	■			
SPC SOFTWARE AND HARDWARE IDENTIFACTION & DEVELOPMENT									■	■	■	■
13. BIFACIAL CELL AND MODULE DESIGN												
REVIEW CURRENT DESIGNS WITH PV SYSTEMS ENGINEERS									■			
EVALUATE MODULE MANUFACUTRING COSTS										■		
BIFACIAL CELL DESIGN									■	■		
FABRICATE AND TEST CELL DESIGN											■	■

cell efficiency, process yield, and silicon utilization. Other task areas address process control, automation, and module efficiency.

While process development efforts would be carried out over a three year period, most of the product cost impact would not be realized until the cost saving features are fully implemented in the process lines approximately 1 year later. Reference to Figure 1-1 illustrates this fact.

The estimated schedule and cost for such a program is based on 10 years of experience in process and technology development in dendritic web silicon utilizing the pilot production line and Photovoltaic Manufacturing Demonstration Facility at Westinghouse. Manpower estimates are realistic assessments of the effort required based on recent DOE funded programs which enabled the process to develop from an R&D program into its present manufacturing state.

Capital

The cost estimates include capital purchases over and above what is required for production operations given none of the process changes identified in this report. This includes process equipment which would need to be purchased to prove and implement the potential cost savings, and three web growth furnaces which would be committed to development activities rather than production.

Materials

The total cost also includes materials for normal operation of both web growth and processing steps related to the development effort. Web required by processing operations is costed at a rate which is indicative of the selling cost of the final product less the value added by the processing and module assembly areas. Materials costs also include manufacturing of parts or equipment modifications. A major component of the materials cost in the web growth studies is the cost of molybdenum hardware manufacturing for the anticipated hot zone changes.

Labor

Manpower for these development projects consists primarily of engineering. 53% of the manpower projected goes into engineering, while the remaining 47% covers technician time.

The source of manpower would be a combination of existing employees, new hires, on-site consultants, and off-site consultants operating through subcontracters. These consultants could be tapped from Westinghouse, (thus utilizing previous experience in the dendritic web process), universities, and private industry dealing with photovoltaic manufacturing processes. The estimated ratio of outside consultant time to internal engineering time is approximately 1.4.

New hires would be brought in to perform development work providing that there is anticipated continuous work in that particular expertise with Solar Web after the end of a three year program. This is included in the estimate. These new hires are also included in the financial plan to estimate product cost in $/watt.

5.2 Charge Preparation

Figure 5-1a shows the time frame over which this task would occur, and outlines the projected scheduling of some subtasks which are presently anticipated. The charge preparation task corresponds directly to the charge preparation improvements outlined in sections 3 and 4. This task designed to allow replacement of the silicon boule slicing and cleaning operations presently used in charge preparation. Tasks would involve evaluation of crucible loading and initial melt down characteristics. Web growth characteristics would have to be carefully monitored to ensure that the growth process is not adversely affected by the process change. If problems are evident at this point, interaction with the silicon vendor may be required to identify product quality requirements. A search would be made to identify alternate vendors of suitable material, and material from each source would require testing Finally, the new charge preparation procedure would have to be generated and optimized. Estimated costs which would be required to complete such a program are as follows:

Capital (K$)	0
Materials (K$)	4
Man Months	
Engineers	8.0
Technicians	8.0
Consultants	4.0

5.3 Full Width Crystal Seeding

Figure 5-1a shows the time frame over which this task would occur, and outlines the projected scheduling of some subtasks which are presently anticipated. This task addresses the starting crystal width an time between crystal improvements outlined in sections 3 and 4. The initial effort in this task would be to optimize the existing web start procedure, optimizing crystal quality, and start success. During optimization, the seed end form structure definition will evolve, and a machine to generate such end forms will be required. The design and fabrication of this machine for factory use will be part of this task. The focus will then move toward identifying solutions to starting at increasingly larger widths up to the current full width of the crystal. This task will require close interaction with the thermal profile linearization work in the web width improvement task. As the starting widths are increased, it is anticipated that some changes in the procedure and start parameters will occur. Demonstrations of the resulting crystal quality, start success, and growth compatibility will have to be made prior to implementing the process change in the production line. This will have to be integrated into the the automation package which presently exists in very basic form. One of the three web furnaces required for the development program has been included in the capital cost for this task. Estimated costs which would be required to complete such a program are as follows:

Capital (K$)	90
Materials (K$)	24
Man Months	
Engineers	15.0
Technicians	40.0
Consultants	23.0

5.4 Oxide Control

Figure 5-1a shows the time frame over which this task would occur, and outline the projected scheduling of some subtasks which are presently anticipated. The oxide control task addresses the crystal length, crystal quality, and run length improvements outlined in sections 3 and 4. This task is divided into two of the most probable approaches to success which are currently envisioned. The first set of subtasks would concentrate on identifying a new crucible material. Vendors of potential materials would be approached for information on fabricability, thermal properties, and cost. Materials experts would be consulted on potential materials choices. Test crucible would be fabricated and tested in the growth furnaces. As in all other tasks, growth characteristics will be closely monitored to identify any potentially adverse effects on web growth. The second approach would be performed in parallel, early on in the program. A means of modifying the growth hardware around the melt cavity will be designed to allow gas purging or vacuuming of the melt surface gas. This system will be fabricated and tested on a furnace. Iterations to the design are probable, but an answer as to whether the concept works would be available by the middle of the second year of the program A solution of this type would be viewed as a temporary solution until an alternate crucible material is found. Therefore the crucible material program would continue, if necessary, throughout the remainder of the three year program. Estimated costs which would be required to complete such a program are as follows:

Capital (K$)	0
Materials (K$)	72
Man Months	
Engineers	30.0
Technicians	40.0
Consultants	15.0

5.5 High Velocity Growth Development

Figure 5-1a shows the time frame over which this task would occur, and outline the projected scheduling of some subtasks which are presently anticipated. The high velocity growth development task addresses the growth velocity improvements outlined in sections 3 and 4. The initial program tasks would take up from where earlier velocity development programs left off about two years ago. Several potential growth hardware designs are available which could be fabricated and tested. Work would be started to take the existing thermal model, validate it based on furnace measurements, and modify the model where necessary. This will aide in providing guidance for further design modifications to increase growth velocity. Initial growth velocity milestones will be targeted for 1.6, and 1.75 cm/min. As more information is gained at these velocities, extension to 2 cm/min should be a less onerous task, and some benefit will be gained for the process line if the full objective is not achievable. All changes to growth hardware would have to be demonstrated to ensure that there is no adverse effect on crystal quality or growth furnace throughput, prior to incorporation of the new growth hardware in the process line. One of the three web furnaces required for the development program has been included in the capital cost for this task. Estimated costs which would be required to complete such a program are as follows:

Capital (K$)	90
Materials (K$)	150
Man Months	
Engineers	22.0
Technicians	60.0
Consultants	45.0

5.6 Web Width Development

Figure 5-1a shows the time frame over which this task would occur, and outline the projected scheduling of some subtasks which are presently anticipated. The web width development task addresses the web width, starting crystal width, crystal length, and crystal quality improvements outlined in sections 3 and 4. A primary focus of this task is stress reduction in the crystal. Solutions to this problem aide the development of all four areas identified above, but is particularly critical to advancing web width. The initial part of this task would perform work to linearize the vertical temperature profile, a well known contributor to thermal stress in the web. New growth hardware would be designed and fabricated based on previously performed analysis. An iterative design process would begin, closely coupled to the velocity improvement task, which couples data from the web furnace with a mathematical thermal stress model in an attempt to advance stable web width. AS with most other tasks, all changes to growth hardware would have to be demonstrated to ensure that there is no adverse effect on crystal quality or growth furnace throughput prior to incorporation of the new growth hardware in the process line. A final design width of 62 mm would be targeted, however interim milestones would be set up to allow a full understanding of the process characteristics, and provide a useful width improvement should the final target not be reached. One of the three web furnaces required for the development program has been included in the capital cost for this task. Estimated costs which would be required to complete such a program are as follows:

Capital (K$)	90
Materials (K$)	144
Man Months	
Engineers	23.0
Technicians	40.0
Consultants	45.0

5.7 Screen Printed Metallization

Figure 5-1b shows the time frame over which this task will be performed. During this year work with equipment vendors and outside consultants will be done to specify the production line equipment and the materials for its operation. A testing unit will be purchased and internal process development will be done to define the production process and to optimize its operation. After the process is defined production equipment will be ordered and installed. Finally the defined process will be demonstrated for its applicability to the overall production process. Costs which are incurred in performing this task are as follows:

Capital (K$)	512
Materials (K$)	64
Man Months	
Engineers	7.0
Technicians	12.0
Consultants	5.0

5.8 AP-CVD Antireflection Coating

Figure 5-1b shows the time frame over which this task will be performed. During this year work with equipment vendors and outside consultants will be done to specify the production line equipment and the materials for its operation. Testing will first be performed at outside facilities to qualify vendor equipment. After qualification production equipment will be ordered and installed. On the new production equipment internal process development involving characterization of the quality of the AR coating will be performed. Near the end of this time period the production process will be define and demonstrated. Costs which are incurred in performing this task are as follows:

Capital (K$)	270
Materials (K$)	30
Man Months	
Engineers	2.0
Technicians	3.0
Consultants	7.0

5.9 Coin Stack Diffusion

Figure 5-1b shows the time frame over which this task will be performed. During this 15 month period work with equipment vendors and outside consultants will be done to specify the production line equipment and the materials for its operation. Testing will first be performed at outside facilities to qualify vendor equipment. After qualification production equipment will be ordered, installed and put into operation using the current define process method. The old production equipment will be used in an internal process development program which will determine a method(s) to control thermal distribution and to increase thermal mass that can be processed in a single unit. Characterization of the quality of the material process by the new production method will be performed by outside consultants. Near the end of this time period the production process will be define and demonstrated. Costs which are incurred in performing this task are as follows:

Capital (K$)	325
Materials (K$)	32
Man Months	
Engineers	3.0
Technicians	3.0
Consultants	5.0

5.10 Surface Passivation

Figure 5-1b shows the time frame over which this task will be performed. During this 24 month period work with equipment vendors and outside consultants will be done to specify the production line process, equipment and materials for its operation. Testing will first be performed at outside facilities to qualify several oxidation techniques as possible passivation methods. For the first 6 months work will focus on development of AP-CVD as the oxidation (passivation) technique. If AP-CVD deposition proves effective as a passivation technique this equipment will be ordered and installed at the same time as the AP-CVD AR equipment. The information obtained during this time will be used to initiate the double antireflection coating task since these two tasks will become a single process step. The production equipment (AP-CVD) or test equipment (alternate method) will be used in an internal process development program which will determine the final production process which is applicable to the double AR coating task. Characterization of the quality of the material process by the new production method will be performed both internally and with outside consultants. Near the end of this time period the production process will be define and demonstrated. Costs which are incurred in performing this task are as follows:

Capital (K$)	270
Materials (K$)	96
Man Months	
Engineers	4.0
Technicians	6.0
Consultants	14.0

5.11 Double Antireflection Coatings

Figure 5-1b shows the time frame over which this task will be performed. During this 18 month period work with equipment vendors and outside consultants will be done to specify the production line process, equipment and materials for its operation. Testing will first be performed at outside facilities to explore AP-CVD of SiO_2 as possible intermediate layer with TiO_2 to form the double AR coating. This work will coincide with the initial passivation study performed. If AP-CVD deposition proves effective as a passivation and AR coating technique this equipment will be ordered and installed at the same time as the AP-CVD AR equipment. In the event that AP-CVD of SiO_2 and TiO_2 does not simultaneously produce an effective double AR coating and passivation layer the information obtained during the surface passivation study will be used to initiate the second phase of this study. The second phase of this study will focus on alternative methods of forming a double antireflection coating. The production equipment (AP-CVD) or test equipment (alternate method) will be used in an internal process development program which will determine the final production process which is applicable to the double AR coating task. Characterization of the quality of the material process by the new production method will be performed both internally and with outside consultants. Near the end of this time period the production process will be define and demonstrated. Costs which are incurred in performing this task are as follows:

Capital (K$)	0
Materials (K$)	64
Man Months	
Engineers	5.0
Technicians	4.0
Consultants	2.0

5.12 Factory Automation

Figure 5-1c shows the time frame over which this task will be performed. During this 36 month period work with equipment vendors and outside consultants will be done to specify the equipment necessary to automate the production line as outlined in section 3 (TASK 2). Software and material handling capabilities of off the self equipment will be developed and verified. The production equipment (soft and/or hard automation) will be purchased and installed. Near the end of this time period the production process will be define and demonstrated. Costs which are incurred in performing this task are as follows:

Capital (K$)	1579
Materials (K$)	56
Man Months	
Engineers	7.0
Technicians	17.0
Consultants	7.0

5.13 Statistical Process Control

Figure 5-1c shows the time frame over which this task will be performed. During this 36 month period work with equipment vendors and outside consultants will be done to specify necessary equipment and software to implement SPC. Costs which are incurred in performing this task are as follows:

Capital (K$)	400
Materials (K$)	0
Man Months	
Engineers	8.0
Technicians	24.0
Consultants	12.0

5.14 Bifacial Cell and Module Design

Figure 5-1c shows the time frame over which this task will be performed. During this 12 month period work with PV systems engineers will identify an acceptable module design which will reduce the overall costs in both module manufacture and system installation. The study will also include work on the design and fabrication of bifacial solar cells to be used in the new module design. Costs which are incurred in performing this task are as follows:

Capital (K$)	0
Materials (K$)	64
Man Months	
Engineers	1.0
Technicians	2.0
Consultants	1.0

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16. Abstract (Limit: 200 words)

This report examines the cost-effective manufacture of dendritic-web-based photovoltaic modules. It explains how process changes can increase production and reduce manufacturing costs. Long-range benefits of these improved processes are also discussed. Problems are identified that could impede increasing production and reducing costs; approaches to solve these problems are presented. These approaches involve web growth throughput, cell efficiency, process yield, silicon use, process control, automation, and module efficiency. Also discussed are the benefits of bifacial module design, unique to the dendritic web process.

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