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Final Report for Photovoltaic Manufacturing Technology Phase I

Final Subcontract Report
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Sec. 1.0 — INTRODUCTION AND OBJECTIVES

The expansion plan for photovoltaic module manufacturing at Photon Energy, Inc., consists of four stages. Stage 1 is composed of a batch process and company structure capable of meeting the early consumer market requirements at ~\$3.50/watt sales prices up to 1 MW/yr. Stage 2 is a semi-continuous process capable of meeting the initial utility market demands at sales prices of ~\$1.50 to \$2.00/watt at ~3 MW to 13.5 MW yearly outputs. Stage 3 is a fully continuous, automated process capable of achieving high profit margins at less than ~\$1.00/watt (present day dollars) at yearly outputs in the 50 to 250 MW/yr. range. By Stage 4, enough experience with the technology and automation will have been gained to anticipate float glass plants providing up to 14 square miles (400×10^6 ft^2) of photovoltaics per year at ~11-12 watts per square foot outputs. These ~4 Giga-watt factories will require huge investments; however, the market for photovoltaics should also be huge by that time.

The Photovoltaic Manufacturing Technology Initiative is designed to help accelerate the early stages of this sizable engineering project. The objectives under this Phase I subcontract are four-fold:

* Identification of the current capabilities in manufacturing and process development,
* Identification of manufacturing potentials envisioned to lead to significantly increased production capacities and reduced manufacturing costs,
* Identification of problems likely to impede the achievement of those potentials,
* Cost and other requirements involved in overcoming the problems in manufacturing technology.

The most time-consuming area of effort was found to be the proper evaluation of each of the steps regarding their potential for lower costs and higher throughput. The best solutions for the majority of these improvements were forced to fit a "cradle to grave" philosophy. That is, not only did the manufacturing costs per watt need to be considered for this cost minimization, but also the cost per installed watt. Ease of installation of the modules in the field must be considered in order to truly minimize the costs of photovoltaics.

Each of the above objectives under this Phase I subcontract have been explored and studied. Some of the details of these tasks are reviewed below.

Sec. 2.0 — TASK 1:
DESCRIPTION OF OVERALL PROCEEDURES

A re-estimation of technological development goals and present manufacturing capabilities was undertaken. Fig. 2.1 shows a generic flow diagram of the process steps involved in the Photon Energy, Inc. (PEI) process. The labor allowances (in hours/day) associated with each major step are indicated in Chart 2.01 for the present batch process and the Stage 2, semi-continuous process. The misc. catagory is composed of supervisors, fill-in workers, and set-up workers.

It is apparent that markedly different labor costs are associated with different parts of the process. In the present batch process, the glass preparation, encapsulation preparation, encapsulation assembly, and finishing steps account for 43% of the total direct labor. This represents a "cost" of 0.200 hours/ft^2 of module. The semi-continuous plant requires a total direct labor "cost" of 0.070 hours/ft^2 of module. The needs for automation in these labor intensive steps are apparent. The productivity factor to be gained by this first-level automation is a reasonable 2.9 times. The productivity factor to be gained by Stage 2 for the entire process is approximately 2.6. Though only conservative gains are projected, the engineering requirements to accomplish these goals are significant.

In Chart 2.01, it is also apparent that the thin-film deposition processes are already minimally labor intensive. The direct labor "cost" of 0.113 hours per ft^2 is to be reduced to 0.088 hours per ft^2 (a 30% improvement) simply by combining the belt-driven deposition steps for the tin oxide and CdS layers into one manned operation. Further future potential savings in the deposition steps are to automate the on and off loading mechanisms for the subsequent deposition steps.

All these areas of labor-reduction through automation will require simultaneous pursuit in order to attain the milestones described in the next section.

Chart 2.01

Labor Allocation Goals (in man-hours per day)
for
Present Batch Process
and Semi-Continuous Plant

Task	Batch Process (Hours Per Day)	Semi-Continuous (Hours Per Day)
Glass Preparation	48	72
Tin Oxide Deposition	24	24
CdS Deposition	24	8
CdTe Deposition and Heat Treatment	24	24
Division and Electroding	56	48
Encapsulation Preparation	32	16
Encapsulation Assembly & Finishing	48	40
Testing, Sorting, & Packing Product	16	24
Miscellaneous	24	64
Total Hours per Average Day	296	320
Glass Prep., Encapsulation Prep., Encapsulation Assembly & Finishing	128	128
Plant Throughput (Ft^2 per month)	12,800	36,800

Sec. 3.0 — TASK 2: IDENTIFICATION AND DESCRIPTION OF IMPROVEMENTS TO PROCESS WITH LARGEST POTENTIAL BENEFITS

As described in Sec. 1.0, the PEI process has three distinct sections:

1) Glass Preparation,
2) Thin film depositions, and
3) Module encapsulation, finishing, testing, and packing.

The labor requirements and the potential for automation are also significantly different in each section. A study was undertaken of direct labor costs and production support labor costs for various processing scenerios ranging from nearly pure batch processing to nearly fully automated module processing. The manufacturing schedule for Stages 1 to 3 are shown in Fig. 3.1.

In the present batch type (Stage 1) process, the glass preparation steps are done on semi-automatic washers with significant labor intensity, the depositions of the active materials are done on a belt-driven system in a continuous, though separately operational, stepwise fashion. The crystal-growing step is a batch step. The interconnection steps, electrode evaporation steps, and encapsulation steps are all done batch-wise. A great deal of labor is utilized for the encapsulation and finishing steps.

In the envisioned fully continuous type (Stage 3) process, all glass preparation, all depositions, the crystal growing step, the interconnection, the electrode evaporation, up to the encapsulation assembly step, are to be done in a fully automated and continuous fashion. The encapsulation preparation steps are to be fully automated and the assembly step is likely to be done automatically with the aid of robotics.

In the intermediate, semi-continuous type (Stage 2) process, all the steps are to be done continuously in the manner of the fully continuous type process. However, many of the separate steps will be run discreetly, with holding buffers in-between steps. Until a significant amount of experience with each step is achieved, it is believed that the incorporation of these discreet, though functionally identical, steps into a fully continuous and synchronous line is capital risky. The encapsulation preparation steps will be fully automated by this time through sufficiently engineered progressive die work. The assembly steps during this stage, however, are expected to remain as human labor rather than robotics, until significant experience with the process is obtained. The glass preparation steps are done nearly automatically, but will remain somewhat labor intensive.

This type of automation growth strategy allows for a great deal of versatility. The critical steps during automation can be prototyped, tested, and then either incorporated into the existing production line, scrapped completely, or re-prototyped. In addition, the investment in the more expensive, fully automated robotics steps are able to be delayed until the company is profitable enough to be able to increase invested capital in order to gain only pennies per watt lower costs.

The process steps which in the near term (Stage 1, 2, and 3) can result in the largest labor cost reduction through automation, have been identified. Both technological advancements and engineering and automation efforts can result in large labor reductions in the following steps:

* Automation of the glass handling and preparation steps,

* Development of a progressive die for encapsulation preparation steps,

* Automation of the remaining module handling steps (encapsulation and finishing) steps,

* Streamlining of the testing, sorting, packing, shipment and deployment of solar modules from the end of fabrication to the field,

* Mechanization and synchronization of on and off loading steps for all applicable process steps (for fully continuous Stage 3).

In the longer term (Stage 3 and 4), significant labor cost reductions will further reduce the costs per installed watt in the following process areas:

* Robotics implementation into the encapsulation assembly steps.

* Advancement of encapsulation technology that allows for more continuous-line applicability.

* Attainment of the capability to produce modules on a roll to roll basis (significant technological program).

The second major area for significant cost savings is from a material handling and usage perspective. Further optimization of the deposition steps will allow a significant reduction in materials usage. Also, instead of disposing of the overspray, etc., a significant amount of engineering work is expected to be utilized for further development of scrubbing and recycling of raw materials (alcohols, solvents, tellurium, and cadmium). Safe handling and recycling of industrial materials is important to PEI's commitment to remain an environmentally friendly industry.

Sec. 4.0 — TASK 3: IDENTIFICATION AND DESCRIPTION OF POTENTIAL PROBLEM AREAS

The manufacturing goals of PEI have been structured with the idea of having cost reduction goals that are compatible with realistic automation methods. The versatility of a low cost process, based on early market requirements, allows a quite conservative approach to these automation questions. The generally low costs of processing are only partially dependant on automation so that a fully continuous, fully automated plant is not required in order to meet the cost requirements of the photovoltaic market for several years.

A Request for Proposal was recently sent to Mick Fitzgerald of The Automation & Robotics Research Institute through The University of Texas at Arlington in order to initiate a program to better assess the costs involved in the automation of the encapsulation and finishing steps of the process. The issues of automation are of basically two types:

1) Problems someone has already solved; the solution is therefore an evaluation, selection, and procurement issue, or

2) Engineering problems solvable through engineering focus, capital, and time.

It is believed that very few substantial problems will exist in achieving the costs goals in production through automation engineering. The capital equipment necessary to achieve these costs in production is a substantial amount, yet quite small relative to the needs of many other photovoltaic technologies.

For the plant growth schedule discussed in Sec. 3.0, the following costs for direct labor and equipment depreciation have been developed. These are costs incurred for every square foot of module started through the process and will be increased proportionately by the yield loss value. The cost per watt is obtained by dividing the cost per square foot by the module output per ft^2 in any stage.

The direct labor cost goals (before yield) are:

Stage 1 - - - - - - - - - - - - - - $2.61/$ft^2$

Stage 2 - - - - - - - - - - - - - - $1.01/$ft^2$

Stage 3 - - - - - - - - - - - - - - $0.43/$ft^2$

The estimated capital equipment requirements, based on a 5 year, straight line, depreciation schedule are (before yield):

Stage 1 - - - - - - - - - - - - - - $0.25/$ft^2$

Stage 2 - - - - - - - - - - - - - - $0.36/$ft^2$

Stage 3 - - - - - - - - - - - - - - $0.43/$ft^2$

The boundary conditions for the engineering programs that are to achieve these goals are therefore:

1) That the reduction in direct labor requirements of 2.6 times going from Stage 1 to Stage 2 be accomplished with less than approximately 44% increase in capital equipment expense, and

2) That the reduction in direct labor requirements of 2.3 times going from Stage 2 to Stage 3 be accomplished with an approximate 22% increase in capital equipment expense.

These constraints on the costs of additional capital are felt to be realistic at the present time, but only in the case where the engineering effort to achieve these goals has been substantially supported by the government.

The projected costs have the potential to be reduced even further through additional technological advancement. One of the longer term "cost-reducers" listed in Sec. 4.0 is the advancement of an improved encapsulation technology that allows for more continuous-line applicability. In the past, PEI has observed that there are some incompatability issues with the mainstream types of lamination technologies used in several other photovoltaic companies. The development of a laminatable encapsulation system would reduce the cost of equipment and labor for the encapsulation step significantly. The cost projections made at PEI do not consider this extra savings based on a technological advancement in encapsulation of this type.

In addition, roll to roll photovoltaic processing capabilities would allow for considerable savings in both production costs and in installation costs in the field. The labor costs would likely be reduced to less than $0.20 per square foot if the associated encapsulation system can also be done fully in line. The installation costs could also then be reduced to insignificance. A number of significant technological issues exist with this approach, but the low-cost potential indicates that efforts must be included in any long term projections for both encapsulation technology improvements and for roll-to-roll processing capabilities.

Sec. 5.0 — TASK 4:
SCHEDULE AND COSTS REQUIREMENTS

As in most engineering based programs, the requirements to achieve the manufacturing cost goals is a question of money, manpower, engineering expertise and time. The schedule for implementation of Stage 1, 2, and 3 are shown in Fig. 3.1.

The engineering costs involved with achieving the objectives of PEI have not been fully evaluated at this time; However, a reasonable estimate of the expected engineering and technician costs follow, with gross percentages utilized for other direct costs, fringes, and overhead allocations. These percentages are based on past history at Photon Energy, Inc.

Chart 5.01
Manpower Estimates For Automation
And Longer Term Technology Advancement
(in Thousands of Dollars)

Automation Area	Stage 2 Direct Labor	Stage 3 Direct Labor
Glass Handling & Glass Preparation	$29.6	$18.3
Encapsulation Preparation	33.0	44.3
Assembly & Finishing	98.2	71.7
Testing, Sorting, & Packing	40.1	18.3
On-Off Loading	46.1	33.0
Scrubbers & Recycling	59.7	55.9
Material Usage Minimization	66.8	33.0
Assembly Robotics		86.4
SUBTOTALS:		
Direct Labor	374	361
Other Direct Costs (25%)	93	90
Total Direct	467	451
Overhead (110%)	514	496
Subtotal	981	947
G&A (30%)	294	284
Total Costs	1,275	1,231

Longer-Term Technology Advancement

In-Line Encapsulation	258
Roll-to-Roll Processing	308

SUBTOTALS:

Direct Labor	566
Other Direct Costs (25%)	142
Total Direct	708
Overhead (110%)	779
Subtotal	1,487
G&A (30%)	446
Total Costs	1,933

TOTALS FOR AUTOMATION AND TECHNOLOGY ADVANCEMENT:

Direct Labor	374	927
Other Direct Costs (25%)	93	232
Total Direct	467	1,159
Overhead (110%)	514	1,275
Subtotal	981	2,434
G&A (30%)	294	730
Total Costs	1,275	3,164

Sec. 6.0
DISCUSSION AND SUMMARY

It has become quite apparent during the re-evaluation of the manufacturing goals under this subcontract that there is a significant competitive advantage at PEI regarding the ability to track a conservative automation course with great success. Due to the low cost of capital equipment required for the thin film depositions, and the simplicity of the operation of the processing equipment, low costs per watt are achievable at quite small factory sizes. Automation costs money. The technologies presently saddled with high capital costs to produce modules sold at ~$4.50/watt will be forced to implement capital costs that are higher-still in order to substantially reduce their market prices.

The ability to subsidize the engineering efforts through the Photovoltaic Manufacturing Initiative will allow a significant acceleration toward the achievement of even lower-cost photovoltaic products at PEI in a significantly shorter time frame than it otherwise may.

PHOTOVOLTAIC MODULE PROCESS AT PHOTON ENERGY, INC

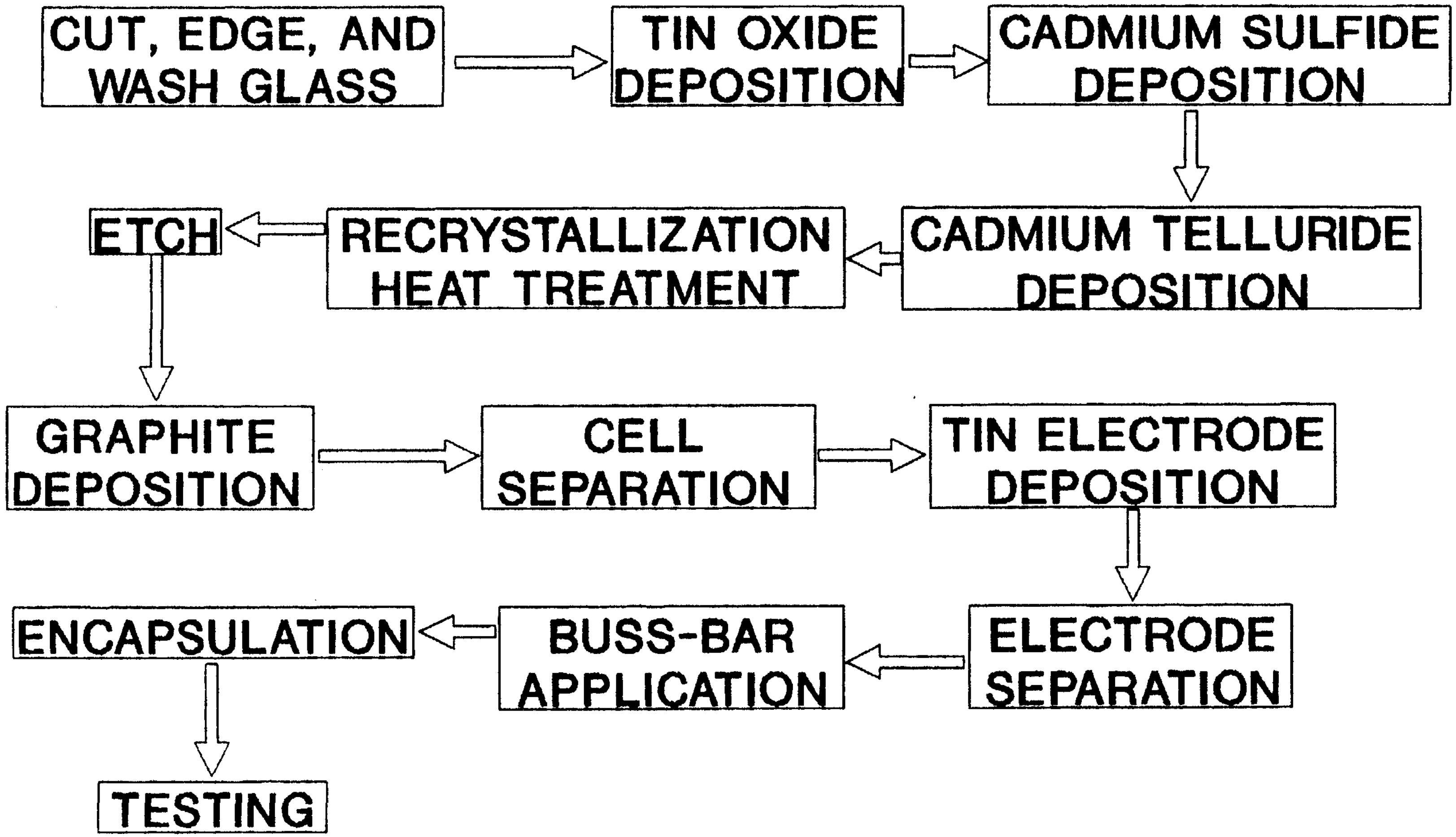

Fig. 2.1

PROJECTED FACTORY OUTPUT RATE SCHEDULE

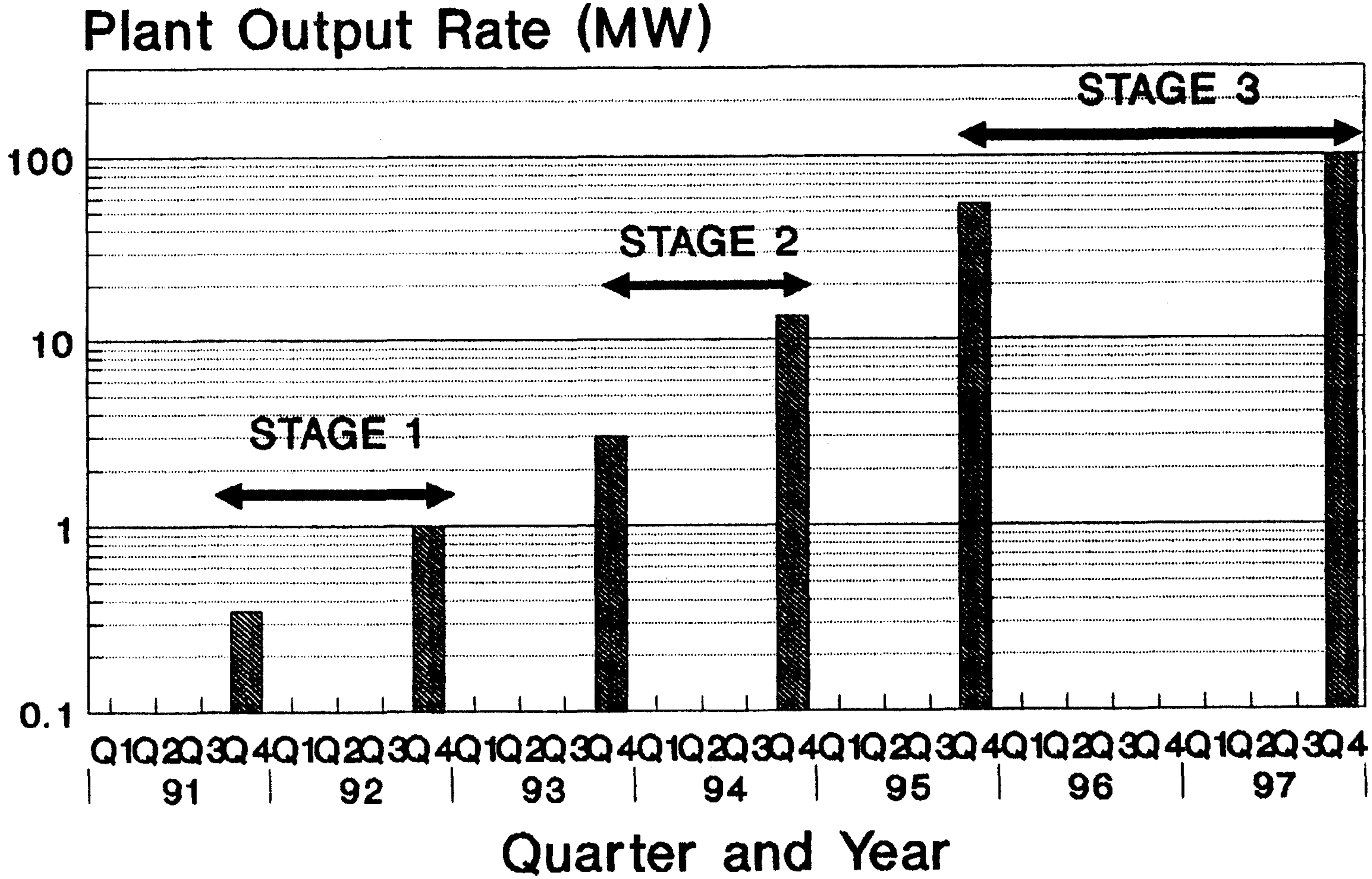

Fig. 3.1

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16. Abstract (Limit: 200 words)

This report summarizes the analysis of photovoltaic module manufacturing done by Photon Energy, Inc. Photon Energy's four-stage expansion plan for photovoltaic module manufacturing is explained. Explored and studied were the following: current capabilities in manufacturing and process development, potential for increasing production and reducing manufacturing costs, problems likely to impede increased production and reduced manufacturing costs, and costs and other requirements involved in overcoming problems in manufacturing technology.

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